Thermal Energy Recovery and Utilisation from Surface Water in the City Centre of Amsterdam

By

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Abstract

The growing energy demand, along with more greenhouse gas emissions, highlights the need for renewable alternatives to fossil fuels. One promising option for space heating is aquathermal energy from surface water (TEO), especially in areas with a significant amount of surface water. However, TEO systems generally require substantial spatial integration, which poses challenges in dense urban areas such as the historic city centre of Amsterdam. In particular, limited (sub)surface space and existing infrastructure complicate implementation. Quay walls may offer a potential solution for the spatial integration of TEO, but the conditions under which this would be technically, spatially, and economically viable remain unclear.

This research investigates the feasibility of utilising TEO in historic city centres, with a case study in Amsterdam. It focuses on the potential for integration into quay walls. A linked modelling approach was used to assess the spatial requirements, CO_2 reduction, and investment costs under various heating demand scenarios and system base loads. Heating demand was varied based on different retrofitting levels, and first-order TEO system designs were developed accordingly.

The results of the study indicate that a higher base load to be covered by the renewable source (TEO), combined with less retrofitted buildings results in significantly higher spatial requirements. This could potentially complicate quay wall integration. However in most scenarios, TEO systems could be integrated into the quay walls.

The CO_2 reduction was assessed for all scenarios. For increased base loads covered by TEO systems and high retrofitting levels of the buildings, the CO_2 reduction was the highest. This would outperform the all-electric scenario.

Financially, the lower retrofitting levels would result in slightly lower investment costs per dwelling. The effect of a higher base load delivered by TEO systems was found to be relatively minor. Although the TEO systems require a significantly higher financial investment, the national costs could be lower. This should be studied further in future research.

Preface

During the writing of this thesis, there have been many people that helped me through. I would like to take the opportunity to thank them sincerely.

First of all, I would like to thank my supervisors: Edo Abraham, Martin Bloemendal and Harry de Brauw. Thank you for inspiring me, but also to help me bringing this research to a higher level. You have guided me nicely throughout this process and have given me a great starting point for my professional career. In addition, I highly valued all of your critical reflections on my work, opinions and my overall performance. I am also very grateful for your encouragement, while also allowing me to freely explore the subject. This has greatly inspired me.

I would also like to thank Jan Peter van der Hoek. You have been my main inspiration to explore the field of aquathermal energy. Since my BSc thesis (and the BSc course) you have helped me but also allowed great and impactful discussions to emerge. I am very grateful to have been under your guidance for the greater part of my academic career. You have also helped me achieve my first ever award for my BSc thesis, for which I cannot thank you enough. I will take these insights and all this inspiration with me for the rest of my professional career.

Finally, I want to express my gratitude towards my family, friends and close ones. Thank you all for your encouragement, enthusiasm and critical reflections. Discussions with you has greatly improved my vision and grabbing the essence of my thesis. I am very grateful to have you all in my life.

Omar van der Marel
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Contents

1 Introduction

1.1 Energy demand

The ever-growing energy demand has been a topic of research for centuries. Research suggests that as early as the 16th century, energy consumption was rising (Warde, 2007). This study states that this increase is obviously relative, as it has grown exponentially over the last decades. However, it should be noted that the energy demand continues to rise. In recent years, or decades, this has been seen globally. BP p.l.c. (2022) stated that the demand of primary energy has increased globally, by nearly 6% in 2021. While most of the increase is covered by renewable energy sources, fossil fuels still are a significant part of our primary energy demand, being around 83% on a global level. This is to decrease to such a level, that low-carbon energy sources should account for approximately 88% of the primary energy demand by the year 2100 (Riahi et al., 2022). The percentage will not be pursued to be higher, or even up to 100%, as this would lead to significantly complex situations, with limited knowledge and modelling capabilities (Hansen et al., 2019).

Furthermore, with increasing energy demand it is inevitable that emissions of greenhouse gasses (GHG) will be enlarged in parallel. The global ambition is to decrease these GHG emissions by 30-45% in 2030 in comparison to current projections for that year (United Nations Environment Programme, 2022). The conventional techniques behind the production of energy (fossil fuels), are therefore slowly decreasing in favourability and thus the focus is on other means, such as renewable energy.

In The Netherlands, this is already visible in its energy demand. The energy consumption is slowly decreasing (BP p.l.c., 2022). Even if it's relatively slow, the country is actively trying to lower the energy demand. This decrease is quantified in the country's targets from the 2019 Climate Act, which states that the emissions from GHG should be reduced by approximately 49% by 2030 and 95% by 2050. These emissions should be decreased by the respective amounts when comparing to the levels as measured in 1990 (International Energy Agency, 2020).

Many different procedures have been initiated to achieve these reductions of emissions. The generation of on- and offshore wind- and solar energy is one of the most prevalent examples when it comes to achieving a carbon-free electricity system, to name an example. Also, mobility is one of the sectors where The Netherlands intends to decrease the total emissions, for instance with zero-emission zones and vehicles. Additionally, agricultural land use should be developed further to decrease its emissions in a smarter way. Furthermore, The Netherlands also sets a goal for carbon-free built environment. The country has set up several supportive targets, that assist it with achieving this goal. These targets are mainly about the (decrease of) the natural gas demand. An example is that in 2030, approximately 1.5 million households should be gas free, as well as roughly 15% of public and commercial buildings, as stated by the International Energy Agency (IEA, 2020).

To achieve these supportive targets, many different approaches can be chosen. One of these approaches would be to decrease the energy demand of the built environment. According to the Dutch National Energy and Climate Plan (NECP), this is one of the main pillars for achieving the overall objectives. The main challenges for this approach are the technical understanding and the proper financial aid (Ministerie van Economische Zaken en Klimaat, 2019).

Moreover, in order to decrease the energy consumption in The Netherlands, it is vital to understand the value of insulation measures. Ministerie van Economische Zaken en Klimaat (2019) expects insulation to play a large role in the above mentioned NECP. It is expected that measures taken have a design life of more than 20 years, with the exception of heating installations (such as high efficiency boilers) with a design life of approximately 15 years. This would cause a significant contribution to the European targets for 2030; measures to decrease the energy demand are expected to account for approximately 32.5% (Kampman & Van De Water, 2018).

1.2 Renewable energy

There is much to investigate when it comes to making the built environment more sustainable. To decrease the CO_2 emissions, actions other than insulation measures can be pursued. For instance, the utilisation of renewable energy. Renewable energy is one of the main methods to make the built environment more sustainable.

However, the concept of renewable energy is not a completely new development that has been done from scratch. To name an example, there is evidence that wind energy has been utilised as early as four centuries BC (Sørensen, 1995). The development of wind energy is still thriving, with an expected increase of production by 2050 of 9 to 15 times compared to the amount of energy produced in 2019 (BP p.l.c., 2023). When combined, wind- and solar energy will be responsible for approximately 50% to 75% of the generated power by 2050 (BP p.l.c., 2023).

There are more forms of renewable energy, such as hydropower. Hydropower has developed into a more effective and sustainable way of energy production. Today, it accounts for more production of electricity than all renewables combined, and it's expected to remain one of the largest sources of electricity for the coming decade, as stated by the International Energy Agency (IEA, 2023).

Other than the oldest renewables known to mankind, other alternatives have been developed throughout the last centuries. As mentioned above, solar energy is rapidly becoming the most utilised form of renewable energy. However, the discovery of photovoltaic effect has been believed to be done in 1839, by Becquerel (1839). Since then, many developments have been made and it's still growing to be one of the most significant sources of renewable energy by 2050 (BP p.l.c., 2023). Another example is the development of bioenergy. Bioenergy consists of all the energy that can be produced from biomass, which finds its origin in the 19th century (Morey, 1826). In recent years, there is a notable transition from traditional to modern bioenergy. It is expected that the amount of energy produced from bioenergy will be doubled by 2050 (BP p.l.c., 2023).

1.3 Heating

In addition to electricity production, other forms of energy are being fed by fossil fuels. Heating is a significant source of the global energy demand, with a share of approximately 50% of the total energy being used in buildings globally. This varies with geographical location, with the EU using approximately using 60% if all energy demand in buildings for space heating. In warmer environments, far less space heating is required, if any. Generally, natural gas is the main energy source for it and accounts for 44% of the total energy used for space and water heating (BP p.l.c., 2023). This causes great amounts of emissions of GHG.

To decrease these GHG emissions that result from heating, alternatives for natural gas need to be found. Several alternatives have been studied, for example solar thermal collectors. These devices are designed to be utilised in commercial and residential buildings. It can be used for heating, cooling as well as domestic hot water (Wang et al., 2016). Although needing low maintenance, low CO_2 emissions (Allen et al., 2008; Ardente et al., 2005) and a reported low payback period (Allen et al., 2008), there are disadvantages regarding such innovations. Spatial requirements often become an obstacle, especially in urban areas where space is limited (Juanicó, 2008). Additionally, uncertainty about weather conditions (enough sunshine), a decrease of aesthetic value and operational challenges are mentioned as the general limitations of solar thermal energy (Chan et al., 2010).

Another renewable method of space heating is wood-stove heating. Although through modern design and meeting specific requirements this could be a viable heat source (Carvalho et al., 2013), it is generally considered to be a very inefficient and unsustainable heating method. Meyer et al. (2008) concluded that heaters that met the Australian requirements would on average emit 9.4g $PM_{2.5}$/kg wood. This is accentuated by the fact that it is by far the largest $PM_{2.5}$ pollutant in Australia, four times larger than industrial vehicles and equipment and approximately five times larger than light diesel vehicles. This leads to increased health problems, in parallel with great health costs of annual health costs of almost $4000 per wood heater (Robinson, 2011). $PM_{2.5}$ is the collective term for the particular matter, which are sized 2.5 microns or smaller. It's a cocktail of pollutants, consisting of liquid drops as well as solid fragments (California Air Resources Board, n.d.). When inhaled, many different adverse health effects can occur. Recent studies confirm this and see many concerns to exposure to $PM_{2.5}$ (Thangavel et al., 2022).

Renewable natural gas is an energy source that is produced by enhancing the quality of biogas. CO_2 is removed from the biogas, which leads to increased concentrations of methane in the biogas, above 90%. This is so comparable to concentration levels of natural gas produced from fossil fuels, it could replace its use (Mamun & Torii, 2017). Although it could serve as an economically attractive option, there are several drawbacks for the use of renewable natural gas. Combustion and production would still lead to the emission of several GHG, predominantly methane, due to its production process (Bakkaloglu et al., 2022; Nisbet et al., 2020). This has a significant impact on the renewability of renewable natural gas, and it therefore forms a major drawback.

Furthermore, geothermal heating is another renewable alternative that's been widely used for millennia (Cataldi, 1993). Geothermal heating is achieved when geothermal energy is utilised for various heating purposes. These purposes range from space heating to bathing and swimming. Even agricultural drying and other industrial purposes have been reported to be a direct appliance from geothermal heat (Lund, 2015). Relatively little space requirement, great potential of renewability, and lower energy payback period have been reported as benefits when comparing to other renewable heat sources. However, high investment costs and limited applicability of the subsurface are some of the major drawbacks, among others (Geothermie Nederland, n.d.).

Finally, aquathermal energy is an alternative to natural gas that is used to heat (residential) buildings. The concept of aquathermal energy is that heating and cooling can originate from thermal energy from water. The source of this thermal energy can be in the form of surface water (TEO), wastewater (TEA) and drinking water (TED). One of the world's oldest aquathermal energy projects is estimated to be active since approximately 1937. The installation is located in Zürich, Switzerland and recovered heat from the Limmat river to heat up the parliament building. It is reported that the system's heat pump is the oldest heat pump still in operation (Zogg, 2008). Other parts of Europe later began developing aquathermal energy systems. The Netherlands used the river Meuse as a heat source in 1983 to cover the heat demand of the county hall in Limburg (van Geffen, 2012). In chapter 2, aquathermal energy will be explained in further detail.

1.4 Problem description

This section will briefly introduce the problems in a problem description. The objectives of the conducted research will be further elaborated on in chapter 3.

In the built environment, an alternative needs to be found for the natural gas that's used for the increasing energy demand of this significantly dense part of the world. Many renewable energy solutions have been sought after and have been explored in research. However, not every source of renewable energy is able to be used in the built environment, due to their respective emissions, or high costs seem to be obstacles for their full utilisation in these areas.

Aquathermal energy can be used as a renewable energy source in a built environment, with surface water, wastewater and drinking water all in the vicinity of a dense city. Amsterdam is such a city with plenty of surface water in its area. However, there will be obstacles to overcome. Especially when it comes to historical city centres. Spatial challenges, as well as meeting the increasing heating demand, along with economic viability are generally the crucial elements to make a successful alternative for natural gas usage. Finally, to achieve the sustainability goals, the CO_2 emissions should be taken into consideration, as this is a great difficulty to decrease in historic city centres.

2 Literature review

In this chapter, a comprehensive analysis about aquathermal energy will be presented. The three sources will be touched upon and will conclude with a brief comparison. Furthermore, a clear distinction between open and closed TEO systems will be made whereafter the different design choices for both systems will be explored. Moreover, various cases of TEO systems in The Netherlands will be explored, whereafter their respective conclusions can be drawn, and knowledge can be acquired and insight for future research can be gained. After an understanding of aquathermal energy has been founded, the role of the quay walls and their structural characteristics will be elaborated on, whereafter spatial challenges and opportunities will be found. Another section is dedicated to the positioning of the trees along the quay walls. In addition, the relation between quay walls and energy delivery is explored. The final section of this chapter is dedicated to the characteristics of the historical city centre of Amsterdam and how present research explored the opportunities to find a heating alternative for this part of the city.

2.1 Aquathermal energy

To counter the increasing natural gas consumption, aquathermal energy can be used as a source of renewable energy. This section aims to briefly elaborate on the use and processes of aquathermal energy on a general level. Thereafter the different heat sources (TEA, TED and TEO) will be discussed. The latter source (TEO) will be divided in two parts: open and closed TEO systems. The section will be concluded by some examples of TEO systems in The Netherlands. Aquathermal energy is a method of using local sources for producing heat and cold. This method utilises the water sources in the available area to recover the thermal energy from these water bodies. There are three different sources to be distinguished: wastewater (TEA), drinking water (TED) and surface water (TEO).

2.1.1 Thermal energy from wastewater (TEA)

The process of thermal energy recovery with a source of wastewater, is called TEA. TEA consists of recovery, storage, and transportation of heat from wastewater (Waternet, 2022). This process is summarised in Figure 1. The process starts at the wastewater source. The heat is generally recovered by a heat exchanger, which then transports the heated water to a buffer. This buffer regulates the direction of the transported heat. When the outside temperature is low enough to increase heating demand, the heat recovered from the wastewater is transported to a heat pump. This heat pump raises the temperature of the water to the desired temperature so it can be used for (space) heating in dwellings and other buildings. If the heat recovered from the wastewater is insufficient to cover the heating demand, an ATES can be used to heat up the buildings, where the ATES is regenerated with cold in winter. In summer, this process could be reversed; the heat extracted from the wastewater can be used to regenerate the ATES This process is displayed in Figure 2. Technically, wastewater could be used for cooling. However, due to the temperature being relatively constant at 10 to 15 degrees Celsius (Kleiwegt et al., 2023), cooling is often not a viable solution (Waternet, 2022).

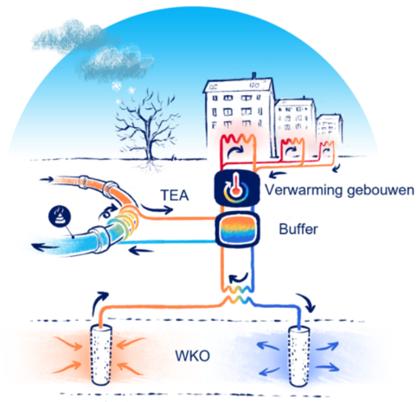

Figure 1: TEA System Overview, regenerating the ATES and providing dwellings with heat in winter (Waternet, 2022)

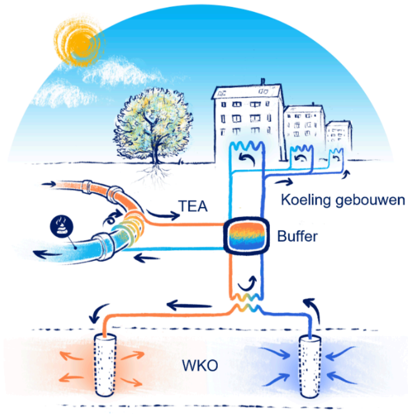

Figure 2: TEA System Overview, regenerating the ATES and providing dwellings with cold in summer (Waternet, 2022)

There are three main distinguishable sources of wastewater where the thermal energy can be recovered; the sewage pipelines, filtered wastewater located at the sewage treatment plant and directly from heat sources in dwellings (shower and hot tap water).

If the wastewater from the sewage pipelines is utilised for thermal energy recovery, the process is commonly labelled as Riothermia (Van Weeren et al., 2018). Riothermia is a common form of TEA. It can also be applied without the use of an ATES. This is because the temperature of wastewater is relatively constant and can therefore be used directly. However, it should be noted that riothermia can also be used to regenerate an ATES. Figure 3 displays an example of riothermia, without usage of an ATES.

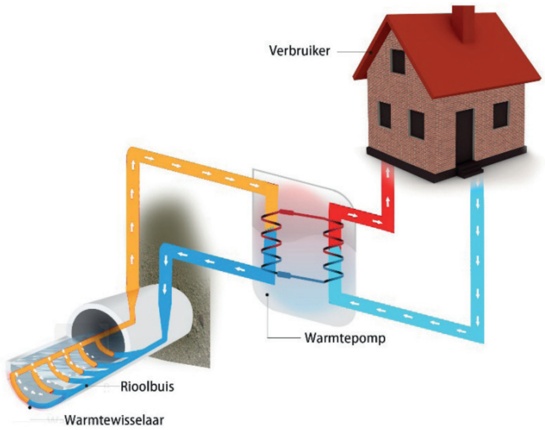

Figure 3: Riothermia diagram, without ATES (van Weeren et al., 2018)

Other benefits of riothermia include the distance the heat covers when being transported to the users. When dwellings are considered, the recovered heat can be directly transferred to the buildings. In addition, as mentioned above, the temperature of the source stays relatively constant. This would ensure a significantly stable heat recovery source. Therefore, the heat can be recovered throughout the whole year. However, since the potential in summer is still substantially higher than in winter, for collective solutions an ATES is a necessity when designing TEA systems (Waternet, 2022).

However, there are also drawbacks to the usage of riothermia. One of the main drawbacks would be the potential influence on the wastewater treatment plants later in the water treatment chain. Recent studies have concluded that there is an influence of riothermia on the nitrogen concentration in the effluent of a wastewater treatment plant. When heat is taken from the sewage system, therefore decreasing the influent's temperature, elevated concentrations of nitrogen have been found (Meddeler & Noij, 2021). Research is still needed to gain full understanding of its influence. This influence can be evaded by recovering the heat using the effluent of the wastewater treatment plants, but this drastically increases the temperature the heat needs to cover to reach the end users.

Another negative aspect of riothermia is the potential formation of biofilm as well as sedimentation. The efficiency of the heat recovery could be reduced to 50% after a matter of weeks. Proper rinsing of the pipelines as well as the heat exchangers could prevent the decrease in efficiency of the heat recovery and an efficiency of 80-90% would still be achievable. Another solution would be a permanent increase of the flow rate, but this is not possible for all sewage systems (Wanner, 2006). Additionally, sedimentation could form a significant problem regarding TEA systems. Sedimentation potentially causes a lower efficiency, a higher needed capacity of the pumps as well as a significant economic impact. This is due to the system's downtime when it's being cleaned (Rijksdienst voor Ondernemend Nederland [RVO], 2015).

Finally, the (limits of) potential for collective heating is often subject of discussion. It is often mentioned that small to medium wastewater treatment plants could potentially provide heat for neighbourhoods or clusters up to approximately 1000 dwellings. The larger wastewater treatment plants could provide heat to much larger clusters or multiple neighbourhoods (De Fockert et al., 2022).

Heat sources in the dwellings can also provide heat that can be recovered. One example of these local heat sources is shower water. According to van der Hoek (2012), 40% of the total heat loss of a modern dwelling leaves the building through heated drinking water. It is therefore expected to be of great value regarding heat recovery.

A shower heat exchanger can be directly installed under a shower. Cold water goes into this heat exchanger, as well as the heated-up shower water effluent. The colder effluent from the shower water is leaving the heat exchanger to the sewage. The heat from this effluent is then recovered and brought back to the general heater of the dwelling. This can be a natural gas boiler or a heat pump. The water is then being heated up to a sufficient level for consumption. A schematic overview is given in Figure 4.

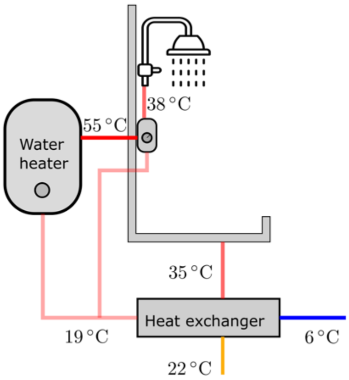

Figure 4: Shower water heat recovery (Nagpal et al., 2021)

Having a heat source and consumer in the vicinity of the shower can be very favourable conditions regarding heat recovery. Other benefits, as mentioned in studies include the redundance of storage and the emittance of heat losses due to a short distance (Deng et al., 2016). This research also found that the energy recovery efficiency was found to be approximately 57%. However, there are also drawbacks to shower heat exchangers. Corrosion and fouling are mentioned as one of the main decreases in efficiency of shower heat exchangers. Additionally, the installation of shower heat exchangers in existing buildings can prove to be an obstacle, making the projects financially not feasible on a large scale.

All in all, TEA systems offer great opportunities for heat recovery. With a relatively constant temperature, the potential can be identified easier than normal. It also creates opportunities for heat recovery without ATES in some cases. However, technical challenges need to be overcome as well as the transport distances. For collective solutions especially, the transport distance will be relatively difficult to overcome. This is because the larger wastewater treatment plants are generally located (far) outside of the city centre.

2.1.2 Thermal energy from drinking water (TED)

Thermal energy could also be recovered from drinking water. This form of aquathermal energy recovery is commonly known as TED. TED is the name of the recovery, storage, and transport of thermal energy from drinking water (Waternet, 2022). Figure 5 displays the general process of TED. Generally, the process of TED could be described similarly to that of TEA systems. However, the source of the heat is different; the thermal energy is recovered from drinking water. Another key difference between the two processes is that the temperature of the drinking water is not constant, as opposed to sewage water coming from the dwellings. Generally, this inconsistency is greater with smaller diameter pipelines and a smaller inconsistency is found with bigger diameter pipelines. The temperature of the drinking water is strongly influenced by the temperature of the subsurface (De Fockert et al., 2021). This is the reason that the application of TED is generally only viable in combination with an ATES. This way, the ATES can be regenerated in summer, while cold from the ATES can be used to cool the dwellings. This process is visually summarised in Figure 6. In winter, the opposite process is initiated; the ATES is regenerated with cold from the drinking water pipeline while heat is being used from the ATES to heat up the same dwellings (Waternet, 2022).

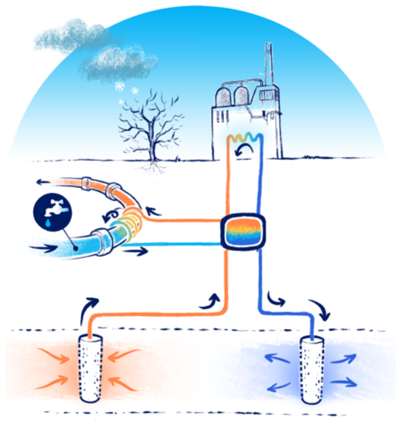

Figure 5: TED System Overview, regenerating the ATES and providing a building with heat in winter (Waternet, 2022)

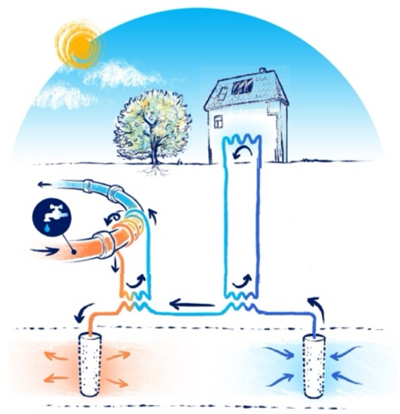

Figure 6: TED System Overview, regenerating the ATES and providing a dwelling with cold in summer (Waternet, 2022)

A great advantage of TED systems is the efficiency due to the cleanliness of the source water. Drinking water is filtered to a degree so that fouling in a heat exchanging system barely happens (De Fockert et al., 2021). This also ensures that no additional (extensive) filtering system is necessary in TED installations, which brings technical, as well as economic benefits. Other advantages include the possibility of a positive influence on the drinking water quality. If heat is recovered in summer, the drinking water in the pipeline will decrease in temperature and this leads to a decreased chance of the growth of bacteria. When cold is recovered in winter, where the pipelines are cold and will therefore increase in temperature, less energy is needed for the drinking water to be heated up to a sufficient temperature in the dwellings (Waternet, 2022). As a final advantage, a relative certainty of capacity can be observed when TED is considered. A reliable flow rate and temperature can be estimated since this is monitored by drinking water companies (De Fockert et al., 2021).

It should be noted that there are drawbacks regarding TED systems. An often-mentioned drawback is that the potential is not as high as other aquathermal energy alternatives. TED potential is generally contained in the larger diameter pipelines and carry a potential heat recovery of approximately 50 kW_{th} to around 10000 kW_{th} which would be equivalent to 15 to approximately 3500 dwellings (De Fockert et al., 2022). Another topic of research is that safety of the drinking water quality and the effect of thermal energy recovery on it. Since drinking water companies have the primary task to deliver clean, safe drinking water to the end-users, they wouldn't want to indulge in energy recovery if the safety of the water quality cannot be guaranteed. The effect of thermal energy recovery on the microbiological quality of drinking water is still a topic of research and can also not always be guaranteed (Ahmad et al., 2020; De Fockert et al., 2021; Van Der Hoek et al., 2018; Zhou et al., 2020).

In conclusion, TED can potentially be a beneficial method for heat recovery. A relatively constant flow rate and a good quality ensure an efficient system that could provide heat and cold, especially combined with an ATES. However, it should be mentioned that the potential is relatively limited and the microbiological effects on the drinking water haven't been fully explored and should therefore been taken into consideration before designing TED systems.

2.1.3 Thermal energy from surface water (TEO)

The final component of aquathermal energy is TEO, where the thermal energy is recovered from surface water. Typically, TEO is considered to be the recovery, storage and transport of thermal energy from surface water (Waternet, 2022). The source of the thermal energy recovery is surface water, and this is what distinguished TEO from TEA and TED. Surface water has increased in temperature over the years, making it an interesting source for thermal energy recovery. Recent studies found that surface water in The Netherlands increased in temperature by more than 2 ºC on average, with a particularly high number of days exceeding a water temperature of 20 ºC compared to 100 years ago (Centraal Bureau voor de Statistiek [CBS] et al., 2020).

Figure 7 displays the process of TEO. As can be seen in this figure, the heat from the surface water is extracted during summer, where an ATES can be regenerated. At the same time, cold can be provided to the dwellings from the ATES. Figure 8 shows the process in winter, where the ATES provides the dwellings with heat. This is taken to a (collective) heat pump whereafter the water is raised to a sufficient temperature for heating purposes in the dwelling(s).

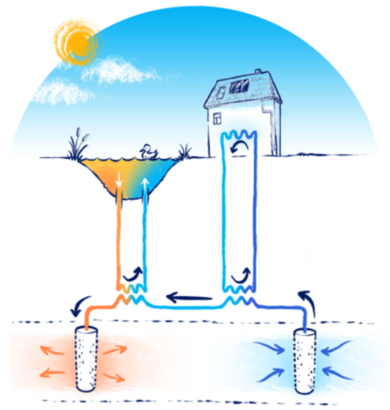

Figure 7: TEO System Overview, regenerating the ATES and providing a dwelling with cold in summer (Waternet, 2022)

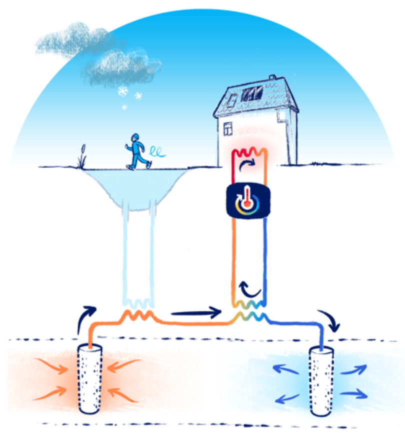

Figure 8: TEO System Overview, regenerating the ATES and providing a building with heat in winter (Waternet, 2022)

2.1.4 Open vs. Closed TEO systems

It should be noted that Figure 7 and Figure 8 describe TEO systems that utilises direct extraction of the surface water to recover heat. This is commonly referred to as an open system (Kleiwegt et al., 2023). There is another alternative to an open system, the closed system. A thorough distinction should therefore be made to understand key differences and to gain more insights into different design choices.

The TEO system that directly extracts water from the surface water, is generally known as an open system. After filtering, the water is pumped into the TEO system, where it first enters the heat exchanger. This is where the heat is transferred and the water with decreased temperature is then pumped back into the original source of surface water. The water with an increased temperature because of the heat exchange, will then be distributed through the pipe system, where it can be used to regenerate an ATES. Alternatively, the heated water can be directly used by a heat pump to increase the temperature to a sufficient level for the end users. However, this would imply that heat will be recovered in winter, which results in a further decrease in temperature of the surface water. Hence the reason why TEO systems without the use of an ATES are often not permitted (Waternet, 2022). When the process of cooling is considered, the opposite process will occur. The temperature of the extracted surface water will be slightly raised and then pumped back into the source water.

The efficiency of such open systems strongly relates to its location of implementation. Each individual location should be closely evaluated on different design choices. An example of these design choices is the water level of the surface water. On the top layer of the surface water, where the temperature is generally the highest, more heat can be recovered than in deeper parts of the surface water. However, an inlet of a TEO system should always be submerged. In water bodies with (strongly) fluctuating water levels, this is a critical design consideration (Kleiwegt et al., 2023).

Another essential aspect when open systems are considered is that of short circuiting. Short circuiting occurs when the outlet of the TEO system influences its own inlet. This is especially a problem when the flow direction and or/flow rate of the surface water is changeable. With tidal flows as well as seasonally influenced surface water, this should be accounted for and a proper distance between in- and outlet should therefore always be safeguarded. From practical examples, it can be seen that this distance is very variable (STOWA, 2020). From this study, it was observed that the necessary distance between the in- and outlet of the TEO system at different location varied from 25 metres to approximately 500 metres. No correlation can be attributed between the distance and other elements of the TEO system, such as heat demand, heat supply, etc. It is therefore generally situational and should be examined for every new project. Delft3D-FLOW is an extensive and validated model that can simulate the thermal processes and can therefore give insights on the short circuiting of multiple TEO systems (Gerritsen et al., 2008; Van ’t Westende, 2021).

Finally, the ecological impact of open TEO systems needs to be considered. Since the necessity for filtering surface water before entering an open TEO system, certain organisms will be impacted. They enter the filtering system at the inlet, whereafter the filtering cycle can be fatal to these organisms. Measures can be taken to reduce the ecological impact, such as thorough design of the filters. When the heat exchanger could be sufficiently protected using only coarse filtration, the ecological impact is reduced when compared to fine filtration (Van Meerkerk & De Fockert, 2022). The other ecological factor to take into consideration is that the temperature of the surface water alters when heat or cold is recovered from it. Studies are still being conducted to estimate the effects on the watersystem when a change in temperature of surface water occurs as a consequence of TEO systems (De Fockert, De Groot-Wallast, et al., 2021).

However, research also suggests that TEO systems can have a positive effect on the ecology. When the heat would be extracted from (urban) surface water, its temperature will decrease. This will cause the outdoor temperature to decrease during the night and would therefore have a positive effect on the urban heat island effect (Kleiwegt et al., 2017). An additional mentioned ecological benefit mentioned by Kleiwegt et al. (2017) is that the growth blue-green algae is decreased with a lower temperature as a result of cold discharge from the TEO system. However, the opposite could also occur when the temperature of the surface water increases when cold is extracted.

Closed systems can also be utilised to recover thermal energy from surface water. The main distinction with open systems is that in closed systems the heat exchanger is placed directly in the surface water. The surface water is therefore not extracted and not pumped back into the source. The water with an elevated temperature can then be transported to an ATES, or it could be directly used by a heat pump to be utilised by end users. A system overview of a closed TEO system (without regeneration of an ATES) is displayed in Figure 9.

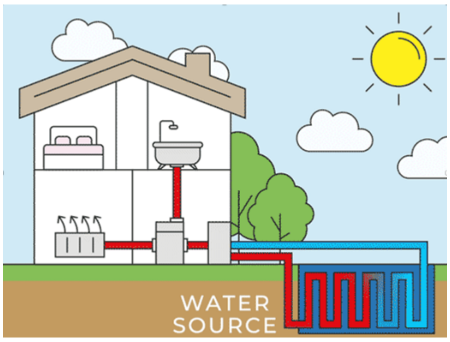

Figure 9: Closed TEO system overview, without ATES (Thermal Earth, n.d.)

A great advantage is that closed systems are not as prone to contamination as open systems (Kleiwegt et al., 2023). Because the heat exchanger is placed directly into the surface water, the system will not be in direct contact with the water. However, fouling is still possible on the surface of the heat exchanger. This will lead to a decreased efficiency of heat recovery. By upscaling the size of the heat exchanger, this can be compensated. Additionally, it is of great importance to ensure enough background flow of the surface water. If this is not the case, the temperature of the surface water will stabilise around the temperature of the water inside the heat exchanger. This would then cause thermal energy recovery an inviable process, as it would be practically impossible (De Fockert & Harezlak, 2022).

An additional influence on the efficiency of closed systems includes the heat transfer capacity. The heat transfer capacity is greatly impacted by material choice (Van Meerkerk & De Fockert, 2022). Plastics are often used for closed TEO systems since robustness of these systems is crucial. This will then impact the total performance of the system. More space and therefore materials are necessary to reach the desired capacity. Studies have found that the amount of power in relation to the volume used by closed systems is 1.8 kW/m^3, whereas open systems have been found to have the ability to produce 32.6 kW/m^3. This makes closed systems better viable for smaller clusters (<30 kW) and open systems would be better suited for larger clusters (>300 kW). Material costs and CO_2 are therefore also increase per kW in closed systems (Van Meerkerk & De Fockert, 2022).

Finally, closed systems have a limited ecological impact, when compared to open systems. Similar to open systems, the resulting change in temperature is the largest influence on the surrounding ecology. Since the thermal energy is exchanged without in- and outflow of the water, the ecological impact is typically quantified by the alteration in temperature of the surface water (Van Meerkerk & De Fockert, 2022).

In conclusion, open and closed TEO systems have different design considerations. The open systems extract the surface water to recover thermal energy (heat or cold). For closed systems, the heat exchange happens directly in the surface water. These differences between systems generally result in different design choices. The efficiency of heat transfer capacity is significantly higher with open systems than with closed systems due to more efficient materials being used. Drawbacks of open systems include the risk of short circuiting. This can be countered by efficient spacing between systems as well as sufficient modelling of the surface water flow rate and direction. Closed systems on the other hand have a risk of fouling, which can be compensated for by the use additional space. This is the main driver for making closed systems generally only efficient for local, small-scale project as opposed to open systems that would be more suitable for larger, collective systems. Finally, the ecological impact can potentially be significantly larger for open systems, making maintenance of these systems more complex and imperative. It should be noted that the exact ecological impact is still a topic of research.

2.1.5 TEO systems in The Netherlands

As stated in Section 1.3, TEO systems has been around for many decades. Also in The Netherlands, many different projects have been initiated where TEO systems were utilised for recovery of thermal energy. These projects offer valuable experiences and insights that can be used in research and projects going forward. This section will therefore provide a comparison between different TEO cases in the Netherlands and what can be learned from them.

The first highlighted project is Blaricummermeent. This TEO project is initiated in 2007, in Blaricum. In total, 950 newly built dwellings were appointed to be supplied with renewable energy sources. An ATES system with three source pairs (so three heat storages and three cold storages). The technique is designed in very similar fashion to Figure 7 and Figure 8, where counter current exchange occurs between the ATES source and the heat grid towards the houses. An external technical space is added, where the heat pumps feed the heat grid and the monitoring- and electrical enclosure is located. Finally, the dwellings are presented with individual heat pumps to cover space heating, cooling and warm tapwater (De Bruin, 2020).

Surface water is the source of the regeneration of the ATES. During the summer, the heat sources of the ATES are regenerated. According to Eteck, a large operator of ATES systems, this is a viable option, due to the distance to the source as well as the size of the project. This has been deemed a crucial factor to determine whether aquathermal energy projects can be successful (De Bruin, 2020).

Another collective TEO system is located in Houten and is targeted at a neighbourhood called De Mossen. It is constructed in 2000 and therefore the oldest collective source heat grid in The Netherlands (De Bruin, 2020). Similar to Blaricummermeent, the system consisted of ATES that, together with a surface water source for regeneration (in this case a small pond) fills a local heat grid. In addition, an individual heat pump initially covered the peak supply for the 325 dwellings. When the neighbourhood was extended in 2018, the extra 110 dwellings were constructed with a cooling unit as well as a natural gas boiler. The baseline heating was covered with the existing heat grid, while the peak supply was achieved with the previously mentioned units.

Several smaller loops connect to the main distribution pipeline of the system (backbone) which then distribute the heat extracted from the ATES to the households. Individual peak supply solutions would upgrade the temperature of the heat to a sufficient level. This made the system fairly vulnerable for malfunctioning and therefore a financially less attractive project. The responsible party, Duurzaam Wonen BV, indicates that in future projects the preference will be a collective heat pump with a heat interface unit due to easier maintenance and therefore a financially more attractive option to consider (De Bruin, 2020).

Furthermore, another case has been realised in Den Bosch, in the neighbourhood of Hinthamerpoort. A body of surface water named De IJzeren Vrouw regenerates heat for an ATES system, which delivers heat to approximately 450 dwellings. Since the surface water is only used for regenerating heat, the TEO system operates at a surface water temperature of 17°C or higher. To counter negative effects on local ecology, the temperature of the effluent cannot go below 9°C. Approximately 3460 GJ is generated by the TEO system. To ensure enough heat for the inhabitants of the neighbourhood, the heat is collectively upgraded to 70°C and distributed to the dwellings (De Bruin, 2020). As a back-up, a natural gas boiler was replaced with a high-temperature heat pump.

TEO was found to be a good and sustainable solution. However, during the course of this case, the alternative of using drycoolers for regeneration was considered. A dry cooler installation is placed on the roof, where a heat exchanger, together with fans produce heat and/or cold. This principle is shown in Figure 10. The greatest advantage is the lower investment costs. However, TEO systems have significantly lower electricity demands and produce significantly less noise pollution (De Bruin, 2020).

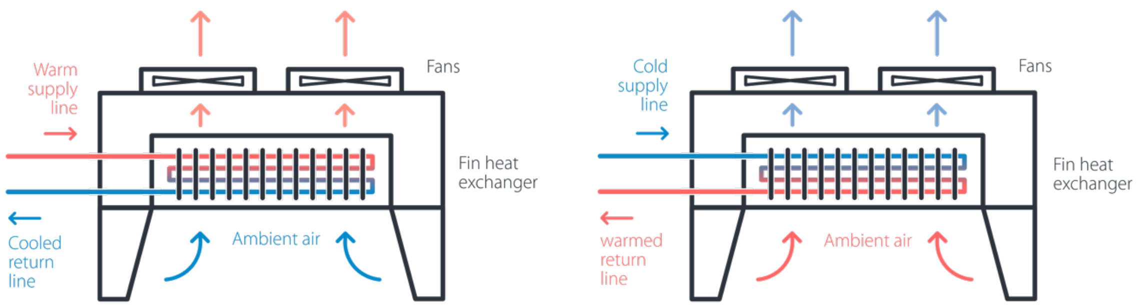

Figure 10: Dry cooler systems delivering cold (left) and heat (right) adapted from Energie PLUS Concept GmbH (n.d.)

All in all, TEO systems have been in The Netherlands for more than two decades. Several lessons can be taken from these running projects, as stated by De Bruin (2020). Technical as well as organisational challenges have been established.

From a technical point of view, the feasibility of TEO systems depends on the location it will be designed for; the source should be available within a reasonable range, in combination with a sufficient energy demand from the surrounding consumers. Surface water is a relatively reliable source of heat. However, it should be noted that TEO systems require a sizable amount of maintenance, and a reliable back-up is therefore advised. To reduce maintenance, the right materials should be chosen accordingly. Additionally, the usage of an ATES drastically increases the TEO potential of a body of surface water.

On an organisational level, aquathermal energy recovery is still considered to be a challenge. Appropriate collaboration is therefore fundamental to further increase the potential of TEO systems as a reliable and sustainable alternative to natural gas for heat production.

2.2 Quay walls

Dutch cities have always been designed to heavily interact with the surrounding water. Many urban areas in The Netherlands could develop and grow as a result of using water in the city. As quay walls are a significant part of the city's image but could also potentially be used for thermal energy recovery, it is important to gain an understanding and unveil the potential. This section will therefore explain the use of the quay walls and how they could be utilised for energy delivery to its surroundings.

2.2.1 Structural renovation

From the iconic canals of Amsterdam to the extensive polder systems, water plays a central role in shaping the Dutch landscape and culture. The formation of the canals in The Netherlands dates back centuries and is deeply rooted in the country's geography and history. The low terrain, characterised by a significant amount of flat land and a network full of rivers and lakes, solutions were ought to be found for logistical problems. This includes transportation, drainage and flood control. As early as the Middle Ages, Dutch engineers began constructing canals to reclaim land, facilitate trade and manage water levels. Throughout the years, the characteristics of these quay walls have changed significantly and from the 17th century onwards, they were designed to have the same façade as they have today (Gemeente Amsterdam, n.d.).

From the 1800s, the municipality of Amsterdam is responsible of the management of the quay walls, creating a far more uniform façade and therefore a discernible image of the entire city. Quay walls are therefore essential components of the canal's infrastructure in The Netherlands. They provide structural support along the edges of these canals, creating a barrier between land and water. However, quay walls have additional purposes, especially in urban areas. The canal network in Amsterdam is a unique example of urban quay walls. In Amsterdam, approximately 600 km of quay walls along 165 canals form a major part of the city's character. Many of the quay walls are in need of renovation. Approximately 200 km of quay walls have been prioritised by the municipality for restoration. Many of those 200 km quay walls in Amsterdam are not designed for the current safety measures. This led to the collapse of approximately 8 km of quay walls in the last few years (Kade 2.020, n.d.).

To do this, an understanding needs to be found regarding the current state of the quay walls. In Figure 11, a section of a typical quay wall is displayed. Generally, the foundation of the walls is made of wood. Every meter along the length of the quay wall, three to four wooden posts which carry a wooden floor. This wooden construction carries the quay walls along the canals. The wooden foundation has been designed to constantly be below the surface of the water, while no air can enter the system. This allowed it to be sufficient for many centuries. Failure occurs when the wooden beam has been damaged to the degree that soil can enter the canals, which could lead to sinkholes inland (Gemeente Amsterdam, 2023).

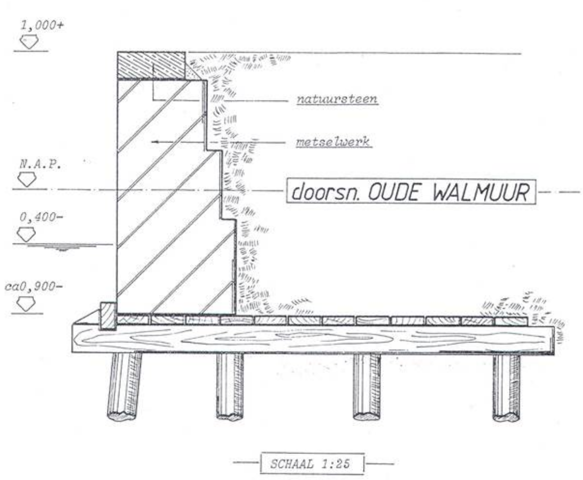

Figure 11: Section of a typical Amsterdam quay wall (Gemeente Amsterdam, 2023)

Renovating these old structures is a complex challenge that requires a great strategy. Innovative renovation methods are therefore preferred by the municipality. One example of this innovation is the Steenwijkwand, as presented in Figure 12. The wooden foundation is replaced by concrete as well as a steel post to further strengthen the foundation of the quay walls. The concrete L-shape of the foundation allows for more space to be utilised in the subsurface, such as underground waste containers as depicted in Figure 12.

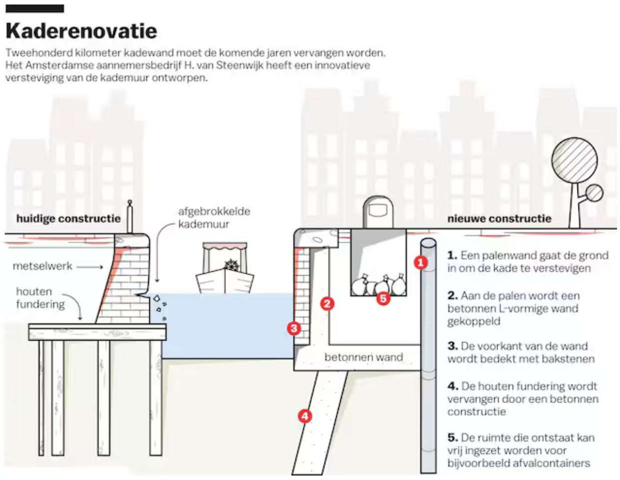

Figure 12: Quay wall renovation as executed by H. van Steenwijk (Pen, 2018)

2.2.2 Trees

Amsterdam is reportedly one of the greenest cities, with approximately 1 million trees within the city's boundaries today. These trees are spread out throughout most parts of the city. Ever since around 1340, the trees have posed to be a crucial element in the city's streetscape. In the 1600s, many trees were planted along the canals of the historic city centre. The trees that were planted, were a significant source for purification of the air, as well as the fortification of the present quay walls (Sustainable Amsterdam, 2023). In the historic city centre, most of the approximately 9.600 trees are located along the canals (Masseur, 2024). Therefore, these significant entities should not be overlooked entirely. Some of these trees carry a protected or even monumental status.

The ongoing need for the maintenance of these (protected) trees has been known for decades (Oldenburger, 2008). One of the more significant risks to the trees is the renovation of the quay walls along the Amsterdam canals. The renovations could potentially require costly and risky operations, such as the moving of trees to a temporary space, also called a "tree hotel" or a complete removal of the tree in question.

On the other hand, the trees could pose a hazard to the subsurface of the urban environment. Among other problems, the tree roots could put upward pressure on the infrastructure on the surface level. Additionally, tree roots can spread far and wide, potentially creating great damage to pipelines that are present in the vicinity of the trees (Shi et al., 2023), but also damaging the surrounding tiling. This is illustrated in Figure 13 below.

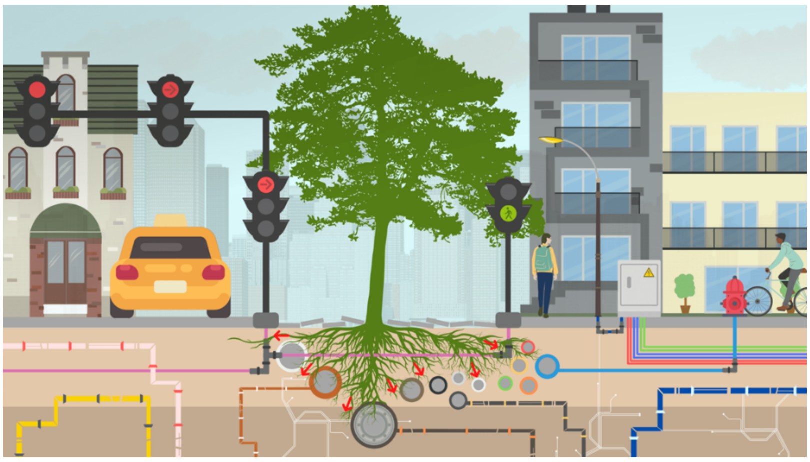

Figure 13: Tree rooting and its influence in an urban environment (Treebuilders, n.d.)

Innovative technologies are being developed to apply tree root control in the context of Amsterdam's quay walls. This could prevent further damage to the tree's surroundings and the tree itself. Additionally, the structural stability of the quay walls could be safeguarded and the damage to the surrounding cables and pipelines could be limited.

One of these examples is practised by Treebuilders (n.d.), which combines different approaches, to allow the best conditions for trees to grow and specializes in this practice in urban areas. This allows for necessary air and water flow for the tree, as well as for the stability of the tree to further increase. By creating underground rootable space for the trees, they can be safely integrated in existing and new urban environments.

This has also been done in quay walls. In Leeuwarden, Treebuilders implemented a system that controls the tree rooting, installed in direct contact with a quay wall. This would greatly reduce the tree rooting volume (J. Faas, personal communication, August 28, 2023).

In Amsterdam, the typical tree that is present along the canals is an Ulmus 'Dodoens', which is a type of elm (Masseur, 2024). According to J. Faas (personal communication, August 28, 2023), the tree rooting volume can be reliably estimated. This can be done with or without the *Boombunker* (translates to: "Tree Root Bunker"). Tree rooting calculations can be done as detailed in Appendix A. Figure 1 shows that with a normal growth of the trees and a life cycle of approximately 60 years, 33 m^3 is needed for the tree to grow sufficiently without any measures taken. When the boombunker is installed, (see Appendix A, Figure 2) approximately 14,1 m^3 of rooting volume is needed for the same tree growth. Therefore, much space can be preserved, which is very significant in dense urban environments such as the historic city centre of Amsterdam.

It remains challenging to implement such systems in every urban environment, however. It requires a greatly integral design strategy that involves many different approaches in the early design stages (J. Faas, personal communication, August 28, 2023). It is therefore essential to gain insights on the spatial influence of other elements of the subsurface in the urban environment, such as TEO systems.

2.2.3 Energy delivery

The objective of the municipality regarding the quay walls is to renovate accordingly and contributing towards a functioning and futureproof city (Gemeente Amsterdam, 2022). The establishment of this objective in combination with the innovative ways of renovating the walls might be the right set of circumstances to create sustainable and multifunctional quay walls.

An example of a multifunctional quay wall relating to sustainable energy production is Energiedamwanden (n.d.). Energiedamwanden aims to collect heat from a body of surface water (like a canal) and deliver it directly to the buildings alongside the quay walls. The quay wall is installed with a closed TEO system and therefore functions similarly to the system as described in Figure 8. The heat is collected from the surface water, through the quay walls and is then transported to the dwellings where a heat pump upgrades the heat to a sufficient temperature for various uses. The refrigerant running through the system is then rapidly cooled down and prepared to run through the system again to recover more heat from the surface water. Figure 13 presents an overview of a system, similar to the Energiedamwanden system. Advantages of Energiedamwanden are numerous. Energiedamwanden can be utilised to provide heat as well as cold, can be used year-round and there is no subtraction of the surface water as it is a closed system. However, similarly to the closed system as explained in Section 2.1.4, Energiedamwanden carries the highest potential in areas with low energy demand densities. For applicability in denser areas, such as city centres, a significant amount of space (quay walls) is required for the solution to be technically viable (De Fockert & Harezlak, 2022). The required space, however, is hardly ever available in dense urban areas such as the city centre of Amsterdam.

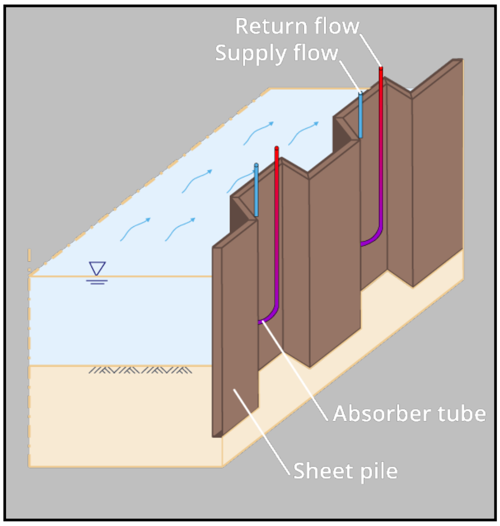

Figure 13: Quay wall as a heat source, as developed by (Future Energie Technologies, n.d.)

Quay walls can also be utilised for energy recovery in a different manner; with open TEO systems. As stated in Section 2.1.4, open TEO systems carry more potential on a neighbourhood level, making it a more viable option in city centres. Callic develops such projects where the quay walls can be integrated with the inlet systems of TEO systems. An example is given in Figure 14. The development of underground TEO systems is applied significantly more, especially in areas with limited available space. Prefabricated installations are preferred, as they can be applied much easier in dense urban areas with limited space (H. Biemond, personal communication, October 3, 2023). However, it should be noted that this will almost always require customisation, especially in very dense areas such as the city centre of Amsterdam.

Figure 14: Inlet of a TEO-system integrated in a quay wall (H. Biemond, personal communication, October 3, 2023)

2.3 Historic city centres

The Dutch built environment is responsible for approximately 15% of the country's energy consumption (Segers et al., 2020). According to Gemeente Amsterdam - Ruimte en Duurzaamheid (2020), 25% of Amsterdam's emissions of CO_2 originate from the built environment. 52% of the built environment's emissions are caused by the homes and their usage of natural gas. For the city centre, the costs for a sustainable alternative for this natural gas usage is approximated to be the highest, however the heat demand is the greatest in this area of the city of Amsterdam (Van Den Dobbelsteen et al., 2019).

In the Transitievisie Warmte, Gemeente Amsterdam (2020) determined the optimal alternatives to natural gas for all neighbourhoods of the city. This strategy is determined for residential buildings as well as non-residential buildings. A significant number of neighbourhoods in Amsterdam are envisioned to be connected to some sort of heat grid in the future, phased from 2020 to 2030, or from 2032 and beyond. Other options include all-electric solutions, requiring a costly solution that only utilises electricity for heat production. This is often used for less densely populated neighbourhoods or neighbourhoods constructed after 1990. Another solution is the installment of district heating networks. The Transitievisie Warmte describes that a heating network would be the most desirable solution for residential buildings outside of the city centre, due to their relatively high density of heat demand and their great potential for insulation methods. Furthermore, a local ultra-low temperature heat grid is mainly appointed to neighbourhoods with mostly utility buildings and/or neighbourhoods that consist of many newly developed residential buildings, since they both have a great heat- as well as a cold demand. In the Transitievisie Warmte, it is decided that the residential buildings are connected to the existing natural gas grid. In The Netherlands, natural gas boilers are present in approximately 89.5% of residential buildings (Centraal Bureau voor de Statistiek [CBS], 2021). However, a clear focus on natural gas reduction of 70% was established. This is partly done by replacing the natural gas in the gas grid by green gas, hydrogen gas or hybrid solutions such as a natural gas boiler in combination with a heat pump. Insulation also forms a valuable strategy towards the natural gas reduction.

The latter policy can be ambiguous, but the historic city centre carries many obstacles to overcome. One of these obstacles is the difficulty to apply renovation in many of the buildings in this part of the city. Policies have set a limit to the alteration of the inner city's visual character, due to its UNESCO World Heritage status. However, research suggests that the correct insulation approach could lead to a very significant amount of natural gas reduction. Research conducted Dang et al. (2024) showed that this can be achieved in the city centre of Amsterdam.

Other than the difficulty to renovate the monumental buildings, it should be noted that the profound solution for the gas grid, hydrogen gas and green gas, are not widely available (Van den Dobbelsteen et al., 2019). Furthermore, sustainability of these gases is not as great as expected (Bakkaloglu et al., 2022; Korberg et al., 2023; Nisbet et al., 2020; Weidner & Guillén-Gosálbez, 2023). These studies have shown that the environmental performance of mainly hydrogen gas is not as beneficial as initially was found. Therefore, it would be wise to look for alternatives in the historic city centre of Amsterdam and find more favourable solutions to the use of natural gas.

One of these alternatives that could be attempted is residual heat. Figure 15 shows that district heating, originating from waste incineration plants, serve the neighbourhoods on the outer parts of the city of Amsterdam. However, as shown in the figure, this is not where the heat demand is the greatest. Currently, there are no plans by the municipality to serve the inner-city district with this district heating (Gemeente Amsterdam, 2020) and the infrastructure would be an economically unattractive solution as found in previous studies (Van den Dobbelsteen et al., 2019).

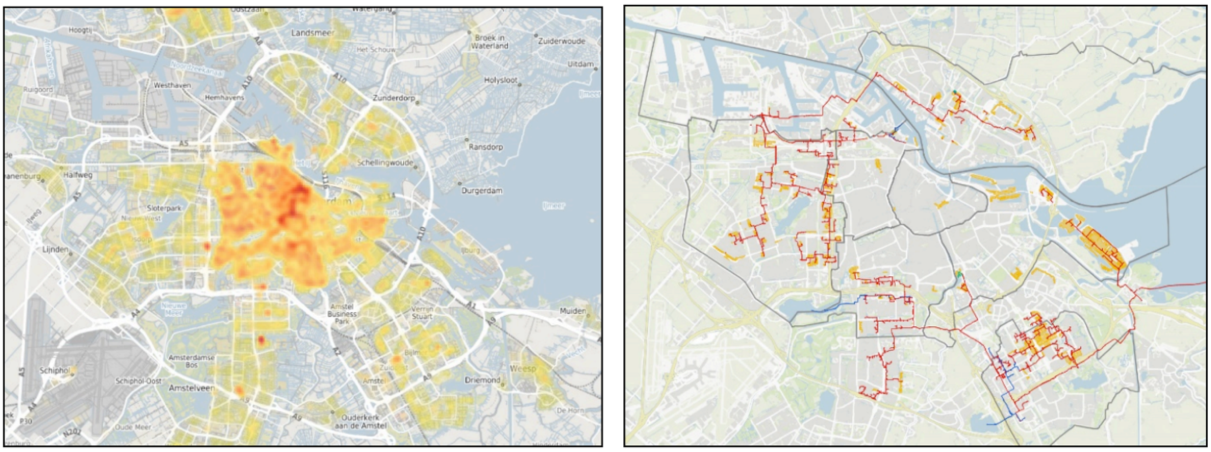

Figure 15: Heat demand in Amsterdam (left) and Amsterdam district heating system (right) (Van den Dobbelsteen et al., 2019)

3 Objective & research questions

This chapter describes the objectives of the present research. The knowledge gaps from the literature review will be filled in by the aims of this research. To achieve the objectives, research questions should be formed. The main research question and its division in sub-research questions is therefore presented. Finally, the thesis outline will be elaborated on. This should guide the reader through the thesis and give some perspective on the links between the sections in the thesis.

3.1 Research objectives

The overall objective is to provide an initial analysis to provide sustainable and affordable energy in the historic city centre of Amsterdam through the implementation of TEO systems. Options in the form of different scenarios (i.e. changing the determined variables) should be explored. The outcomes of this research, give the municipality a perspective on how these TEO systems could be utilised in the city centre of Amsterdam. An initial, first order estimation of the application of TEO systems, and their integration in the quay walls for this area should be developed, and this could be used for further in-depth research and exact implementation.

TEO systems could potentially be a great solution to the ever-changing climate issues, but this comes with a variety of challenges. This section will describe the main problems that arise from preliminary research and subsequent objectives for this research.

First of all, there are various spatial challenges when it comes to thermal energy recovery from surface water. Being a dense urban area, Amsterdam copes with a lack of space to implement these interventions into the city's neighbourhoods.

In addition, the central heating network of Amsterdam requires a significant amount of space (Van den Dobbelsteen et al., 2019). This space is not available in a historic urban area such as the city centre of Amsterdam. Underground, the space required for a central heating network is largely occupied by the diameter of the pipelines. TEO might be a good solution since it could be integrated with a smaller network.

It is insufficiently known how the TEO systems can be installed in a dense urban environment like Amsterdam, especially considering the historical and monumental state of the inner-city's buildings and surroundings. Many different components are needed and (public) space might be needed to accomplish this. Heat exchanging systems, infrastructure and storage all need space to operate. Furthermore, a lack of space means that the available space is very economically valuable and therefore its increasingly difficult to implement cost-effective solutions. All in all, cost effective and spatially efficient solutions that utilise aquathermal energy do not yet exist.

This space might be available on ground level, but it may well be possible to install (parts of) these systems underground. It is unknown what these possibilities are at this moment. The renewal of certain quay walls might lead to a valuable and excellent opportunity to install parts of the desired TEO systems, although it's insufficiently known if this is applicable to most areas in the city centre of Amsterdam. Integration in the quay walls might also be a solution to the problem regarding a lack of space for the heating network infrastructure (e.g., the large diameter pipelines) (Van den Dobbelsteen et al., 2019). Finally, space within residential buildings might be necessary for the systems to operate effectively. This is also an opportunity to be explored.

Additionally, more technical challenges arise when TEO, such as the distribution, storage and how a new heat grid would look like in the (historical) city centre and how this would be integrated in the existing urban energy infrastructure. Quay walls are being renovated in the (near) future (Gemeente Amsterdam, 2022) and could therefore provide a (partial) solution to the spatial issues, so this should be further examined.

The energy network, heat and electricity, that is currently utilised, does not include a (large scale) heat grid. Therefore, if TEO systems would cover the energy demand of the surrounding residential buildings, an extra heat grid needs to be implemented. Extra (urban) space might be needed, and further research is needed to investigate the opportunities.

Other than the previously mentioned challenges, the energy storage demands additional analysis too. More knowledge is needed on (seasonal) heat/cold storage, especially in dense urban areas, where space is (very) limited. Opportunities on local storage systems should be explored. A study is needed to be presented with more insights on these hot/cold storage in a dense, urban area. After this, the appropriate design choices need to be considered, and these could then be evaluated on their applicability.

Finally, financial insights should be studied. One of the objectives is to provide both sustainable and affordable energy to the inhabitants of Amsterdam. Therefore, a cost analysis should be made in order to further evaluate the design choices; other than effectiveness, the economic viability is a significant consideration to be made.

After all these elements are investigated, certain design choices could be determined. This would then form a stepping stone that should indicate the applicability of TEO systems and storage in the city centre of Amsterdam. To name an example, a TEO system should be adequately sized. A system that is designed to be too small scaled would be economically inefficient, whereas a large system faces severe spatial challenges and has a significant impact on the surface water system (Kleiwegt et al., 2023). This is one among the various divergent requirements that need to be determined to discover the potential applicability of TEO systems in Amsterdam.

3.2 Research questions

In order to find the solution to the problem(s) and achieve the objective as stated above, research questions need to be formulated. The main research question will be as follows: "*How can thermal energy recovery from surface water be integrated in the existing urban environment and energy systems in houses in Amsterdam?"*

This main research question will be supported by the following sub-research questions:

- *What are spatial and retrofitting requirements for different levels of TEO use?*
    - It should be explored what spatial requirements TEO systems carry. There could be spatial implications, on the surface, or perhaps subsurface. Additionally, retrofitting should be considered and what the required amount of retrofitting is for TEO systems to be viable in the historic city centre of Amsterdam.

- *How could quay walls be used for TEO installations?*
    - Quay walls should be explored as a part of the spatial challenges of TEO systems. If these renewable energy solutions can be integrated in the quay walls, the logistical problem that Amsterdam carries regarding the subsurface could be (partially) tackled.

- *How do different design choices affect energy delivery?*
    - The level of insulation, energy demand, (the components of a) TEO installation, available space, base supply/peak demand, among other design choices, can affect the amount of and type of (renewable) energy that can be delivered to the consumers. Additionally, the spatial, and integration constraints can limit the energy delivery.

- *How much CO_2 can be reduced in different scenarios?*
    - It should be explored how these design choices impact the CO_2 reduction. The reduction of CO_2 emissions is compared as a measure to assess the different scenarios.

3.3 Approach

The research questions as presented in Section 3.2 will be answered throughout the research. To accomplish that, this research consists of several chapters. The distinction will be touched upon in this section.

Roughly, this thesis will provide context in Chapter 1. After Chapter 1, a literature review is given in Chapter 2. In this chapter, the principles of aquathermal energy recovery are presented as well as an introduction to quay walls. Finally, in Chapter 2 historical city centres will be touched upon regarding renewable energy solutions and the challenges that come with that. The following chapter, Chapter 3 will then aim to find the knowledge gaps. Chapter 3 will conclude with the research questions, that aim to fill in the found knowledge gaps. Chapter 4 describes the methodology applied in the research. The different aspects of the input for the integration of systems will be touched upon as well as a description of the tested scenarios. The different methods of data analysis will be described in Chapter 4 as well as the adaptations done to simulate different scenarios. The methods consist of analysing the area with available data, which translates to heating demand. This heating demand can vary on insulation level of the dwellings. Then, the base load that can be delivered through TEO systems can be determined, whereafter spatial requirements can be considered. This integration of systems can then be assessed based on the (savings of) CO_2 emissions and a first order estimation of investment costs. Chapter 4 concludes with a description of the case study as well as the assumptions that were deemed necessary for the research. In chapter 5, these inputs are presented, thus the results are produced. These results are then be compared per scenario. Chapter 5 ends with a discussion where these results are interpreted. Chapter 6 contains reflections, with limitations and recommendations and will therefore provide a stepping stone for future research and application in practice. Chapter 7 will be the conclusion of the findings. The thesis overview is presented in a flow chart in Figure 16.

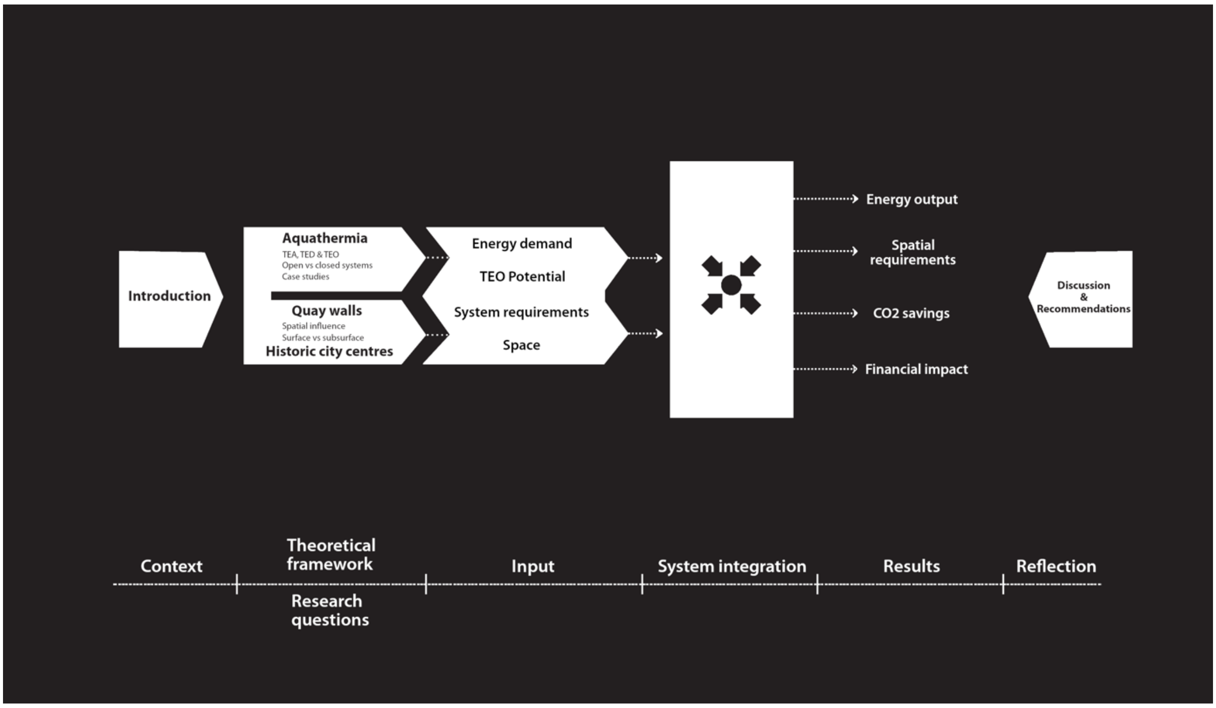

Figure 16: Approach of the research, presented as a flow chart

Figure 16 shows that the input of the model is based on the theoretical framework. The model will produce the results as shown but will also provide potential new input for the model. After all, system requirements and energy demand are prone to fluctuation but are also sensitive to the energy output of a potential new (renewable) energy source. Therefore, the model can provide new input for further iterations. It is important to note that this isn't done in this thesis due to a lack of time and resources, this will be further discussed in Chapter 6.

4 Methodology

In this chapter the methodologies used in this thesis are described. These consist of the input data, the setting of the scenarios that will be explored, the case study and the assumptions and limitations. Firstly, the linkage and overall description of the research will be discussed in Section 4.1. In Section 4.2, the input data that is necessary for the models will be presented. This consists of the coordinates, the heat demand and spatial characteristics. The CO_2 reduction and the economic impact of the proposed systems will form the assessment framework and will be described in Section 4.3. The different set scenarios will be elaborated on in Section 4.4. Section 4.5 will present the case study of the research, where an overview of the study area is presented. Finally, the assumptions and limitations will be discussed in Section 4.6, evaluating the accuracy and resolution of the system integration.

4.1 Description

In general terms, this study will utilise multiple datasets and models to be combined. Gathering these qualitative and quantitative data, relevant results will be found to determine the potential utilisation of the thermal energy from surface water in Amsterdam. This section will therefore briefly describe the use of these models as well as their use and relevance to the projected results.

Firstly, the building characteristics should be distinguished. These will provide insights to the heat demand. The building characteristics of the chosen area will then be coupled with the model that was used in the study by Dang et al. (2024). This will provide the heating demand of the area on three different levels: original, retrofitting to MT-ready, and retrofitting to LT-ready. This will then be used further on as the heating demand. Then, the base load can be determined, further accompanied with the peak demand.

When the base load and the corresponding peak demand has been determined, the sizing of the system can be calculated. This is done according to calculations as performed by Viessmann (2018) and insights from H. Biemond (personal communication, June 21, 2024). This will then be expressed in squared metres, which could provide relevant insights into the spatial feasibility of these installations as well as their potential for quay wall integration.

Then, to assess the designed TEO systems, an assessment framework should be formed. In this study, this consists of the CO_2 emission reduction and the economic impact. The CO_2 reduction can be determined as a function of the base load and peak demand, with their respective CO_2 emission factors. This will determine the system's effect on the CO_2 emissions. Furthermore, the costs of the systems should be determined to have a subtle understanding of the costs of these TEO systems in these conditions. These costs will reflect the investment costs, expressed in euros. Finally, to interpret the financial impact of the systems, the costs of each scenario can be expressed in euros per dwelling. This could then be compared, to assess the financial impact of the taken design choices. In addition, this can provide a first order estimation into the feasibility of a potential business case, which could provide for a stepping stone for future research. An overview of the utilisation of different datasets and the assessment framework is given in Figure 17.

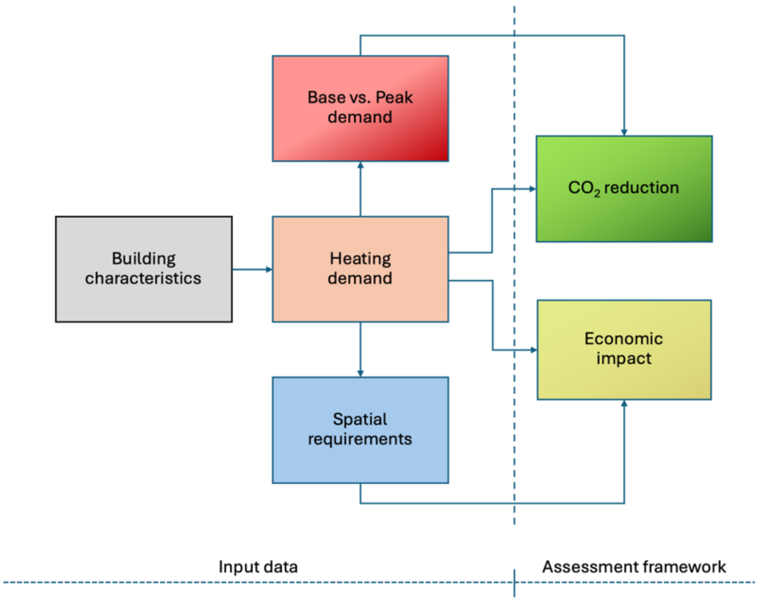

Figure 17: Description of the methodology of the research

4.2 Generation of site-specific input data

To achieve the objectives as stated in Section 3.1 and to answer the questions of Section 3.2, the relevant data should be gathered whereafter an integration of these datasets should be formed. This section of the Methodology chapter will provide the description of different used datasets as well as their origin and how the data was created. The data consists of the coordinates of the buildings, the heat demand that can be derived from the buildings, the spatial characteristics of TEO systems, the methods to derive the CO_2 reduction and the economic impact of the systems.

4.2.1 Building characteristics

To gain an understanding into the heat demand of the buildings in the study area, the geographical location should be analysed. This will provide details of the building entities and therefore the structure that the neighbourhood or studied area consists of.

First of all, the relevant buildings for the research must be established. For this research, these are only the residential buildings. This is done by retrieving the data from shapefiles that originate from the BAG Kadaster. The dataset containing the shapefile was provided by Amsterdam Institute for Advanced Metropolitan Solutions (AMS Institute). From this dataset, the relevant elements were selected that affect the heat demand, further on in the integration of the systems. These relevant elements will be linked with the heat demand modelling performed by Maéva Dang from AMS Institute (Dang et al., 2024). This system will be elaborated on in detail in Section 4.2.2.

The elements are therefore chosen to be the surface area of the building, the year of construction, geographical information (postal code and street name), the building type and the protected status of the building. The latter refers to the monumental status of a building, as mentioned in Section 2.3.

Furthermore, the presence of cavity walls has been determined. This was based on the assumption that cavity walls exist when the year of construction is 1946 or later (Dang et al., 2024; Kaandorp et al., 2022). The preparation of this data is performed in a similar method as Van Burk (2023). Similarly to that research, the considered building types are limited to apartments, semi-detached and terraced residential buildings, due to the lack of other building types in the historic city centre of Amsterdam. Additionally, the protected status is only made for the buildings constructed before 1946. A visual overview of the residential building groups for this research is given in Figure 18 below.

In conclusion, the coordinates of the buildings taken into consideration carry significant data that is used further in the integration of the systems. In a selected area, the surface area, the construction period (year), the geographical information, building type and protected status will be utilised in further sections.

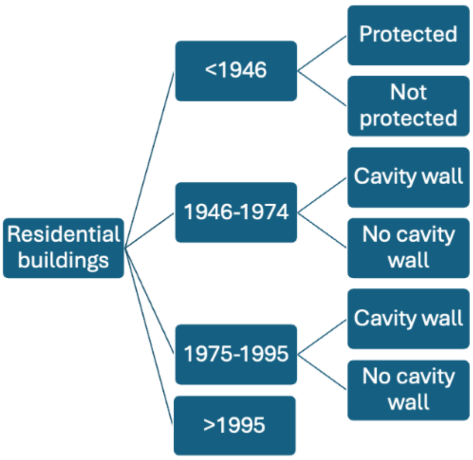

Figure 18: Grouped residential buildings

4.2.2 Heat demand

When an understanding of the buildings is established, as stated in Section 4.2.1, the heating demand should be determined. This data was provided (and created) by Maéva Dang from AMS Institute. This data contains the heat demand that can be used for different building types, years of constructions and protected status. Additionally, the heat demand differs for the level of retrofitting (Dang et al., 2024).

Retrofitting buildings to make them more sustainable involves alteration of the structure, façade or systems of the building. This is often set to be a challenge for buildings in historic city centres, due to a variety of reasons (Stanojević et al., 2021). A building's structural capacity could be at risk when implementing renewable energy sources or energy efficient insulation measures, due to the age of the building. Furthermore, the monumental status of a building in a historic city centre could impose an additional challenge when retrofitting is planned to be implemented. A balance between retrofitting and heritage preservation should always be found.

Therefore, Dang et al. (2024) developed a modelling approach that determines the necessary elements and requirements for residential buildings in historic city centres to be retrofitted to be sufficient for lower temperature heat. Aquathermal energy can then more efficiently supply these buildings with heat. Data from this model have been created and used for this research.

Many different measures were taken into consideration, resulting in different heat demands per residential building types in the city centre. First of all, ground floor insulation is a measure used among all archetypes, resulting in a great decrease in heat demand. Gap sealing, which improves the air tightness of a building, had the same results among all archetypes. Finally, the improvement of the existing (natural) ventilation was also found to be a viable retrofitting measure among all archetypes. Other than these three retrofitting measures, different glazing, wall-, roof- and floor insulation has been determined among different archetypes.

These archetypes and their respective retrofitting measures have then been grouped. Their division is based on the same elements as mentioned in Section 4.2.1. Therefore, for the retrofitted heat demand, this data has been used. This resulted in an annual heat demand in kWh/m^2. These demands are categorised and can be calculated per building, by multiplying the respective value by the surface area of the building. This results in the heating demand of the residential buildings in the selected area. Important to note is that this heating demand represents the space heating demand as well as the hot tap water demand.

Finally, this data has been created and provided for multiple retrofitting levels. The original demand was provided for reference, where the heating demand can be modeled for the original situation without aquathermal energy recovery being a viable solution (Averfalk & Werner, 2018) meaning no retrofitting measures have been taken. The data has also been provided for retrofitting levels that would theoretically make most buildings suitable for low temperature heating systems, such as aquathermal energy. Finally, the data has also been provided for retrofitting levels that would make the buildings suitable for a minimum of medium temperature heating systems. This would allow for multiple scenarios, that could alter the retrofitting level, potentially resulting in an altered CO_2 reduction and a different financial impact. This takes certain assumptions into consideration, which will be briefly mentioned in Section 4.4.

After determining the heat demand per building type, the heat demand can be presented in two different ways: a load curve and a load duration curve. Both alternative offer varying purposes and benefits.

A load curve presenting the heat demand, does so over a certain period, generally a year. The start of the load curve initiates at the first day or hour of the selected time period. The load curve presents great insights into the moment of the year the heating demand is the highest and the lowest in one overview. This would be especially useful when an installation should be designed on an individual basis (Pardo et al., 2012).

The load duration curve, similarly to a load curve, represents the heat demand over a certain period, also generally annually. However, the key difference is that the load duration curve initiates at the day or hour (depending on the required level of detail) with the highest heat demand and ends at the day or hour where the lowest heat demand is measured or modelled. The information of the load curve, where specific loads are presented at certain periods of time, is lost when it's translated to a load duration curve. However, the load duration curve is generally more suited for determination of base and peak load (Pardo et al., 2012). Therefore, for the analysis in this research, this method was chosen as it is a crucial design choice when considering TEO systems (Cardose et al., 2022). The difference between the two curves is visually summarised in Figure 19 below.

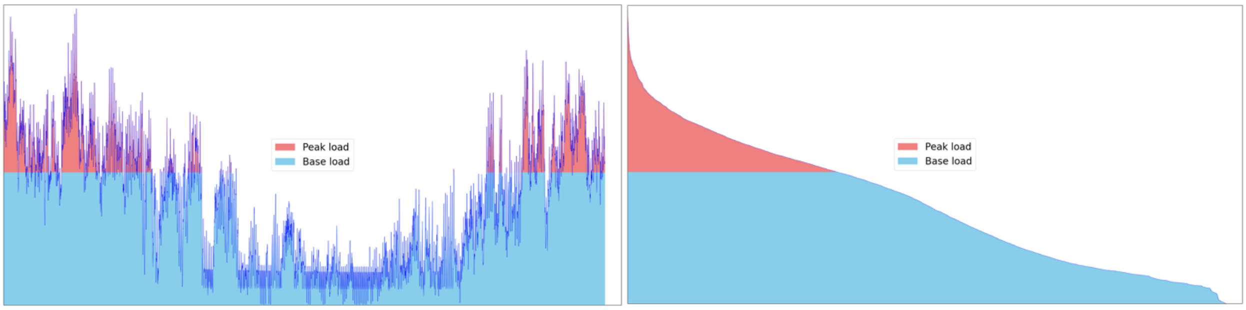

Figure 19: Load curve (left) vs. Load duration curve (right). Adapted from Kabeyi & Olanrewaju (2023)

4.2.3 Peak vs. base load

After producing the load duration curve of the set area, the peak loads should be established, which would be covered by aquathermal energy. This is determined by a few factors. These will be elaborated on in this section, as well as their expected influence on the results.

As stated in Section 4.2.2, the heat load duration curve can be used to determine the base load that an installation must produce and the remaining load should be covered by another installation, also known as the peak supply. This would result in differently sized systems (Viessmann, 2018) and an altered share of the heat being produced by aquathermal energy recovery, while the rest is being covered with a peak installation, such as natural gas boilers and/or e-boilers. Additionally, the CO_2 reduction and economic impact will be altered, depending on the determined base load and added peak load, due to the different elements of the TEO installation depending on the amount of kW of the system (B. Konneman, personal communication, March 20, 2024).

To determine the base load of the system, a sensible value has to be considered. This would then give a rough estimate for the ratio of the base load and maximum demand (at hour 1 of the load duration curve). There are studies that suggest a base load that is approximately 90% of the total heat demand (Schilling et al., 2019). This should therefore be taken as one of the values of the base load.

Other studies suggest that the base load can be expressed as a percentage of the peak demand (Koster et al., 2022). This study suggests that these values fluctuate around approximately 30%, meaning that a value of approximately 30% of the peak load should be taken into consideration for the base load. This should roughly translate to approximately 85% of the heat demand can be covered in total by the base load (Koster et al., 2022). However, this is still a topic of discussion, as the study done by Koster et al. (2022) mentions. For the values to be taken, this could provide a good alternative. Therefore, approximately 30% of the peak demand will be taken as the alteration of the base load.

Determining the base load will have various effects on the remaining elements of the TEO system, such as the spatial characteristics and the CO_2 emissions. However, the base load is also impacted by various characteristics. The base load will be delivered by heat pumps. This implies that the adequate systems must be chosen to be able to deliver the base load of the heat demand. According to Viessmann (2018), the temperature of the source as well as the outgoing water greatly impacts the characteristics of the heat pumps.

4.2.4 Spatial characteristics

The spatial characteristics are of great importance to create a viable energy delivery system in an urban environment, especially of the integration of the planned installation in the quay walls should be considered. It is therefore important to make use of the correct installments for a TEO system. This can be divided in a few sections. The heat exchanging system; the monitoring- and electrical enclosure and the collective heat pump(s).

For the heat exchanging system, it has been established that for great, collective systems, a installation will suffice when the size is approximately a standard intermodal container, or 6000x2400x2590 mm (l x w x h) (H. Biemond, personal communication, October 3, 2023). In various other collective TEO projects carried out, this space was proven to be sufficient. An example of these projects has been realised by Callic (n.d.) and has been proven to be sufficient for more than 4000 users. This project also struggled with a lack of space in the subsurface, but with the technical solution as found by Callic, it was proven to be possible.

A similar solution will be used for the monitoring- and electrical enclosure. These components are integrated in the inlet/heat exchanger system as mentioned above. For an ATES, a space of 1600x400x1800 mm (l x w x h) is necessary for monitoring and electrical enclosure (H. Biemond, personal communication, June 21, 2024). Including all other elements such as pipelines, electronic enclosures and buffers, the total space required at this stage of the TEO system would be approximately the size of a standard intermodal container. These would be approximately 6000x2400x2590 mm (l x w x h) (H. Biemond, personal communication, June 21, 2024). The latter can all be placed on top of the ATES installation, and this shall be utilised in the integration of the models.

Finally, a vital element of the system is the integration of the heat pumps. A representative heat pump installation guide has been used for the spatial characteristics and requirements (Viessmann, 2018). This takes many different elements into consideration, such as temperature of the in- and outlet, heating output in kW and power consumption in kW. The minimum adequate clearances mentioned in the document can then be translated to the roughly estimated spatial requirements that meet the energy requirements. Different energy demands lead to different heating output requirements, requiring different clearances and therefore the corresponding size of the heat pump system. The calculations used in the script are therefore adapted from Viessmann (2018).

To get first order estimation of the practical (spatial) feasibility of the system related to quay wall integration, a general rule should be applied. In the historic city centre of Amsterdam, the space along the canals is very limited. As stated in Section 2.2.2, there are trees present along most of the canals in the city. As a result, the tree roots can pose a problem for installing TEO systems in the quay walls. As a rule of thumb, it could be said that the tree roots reach approximately as far as the crowns of the trees (J. Faas, personal communication, August 28, 2023). From Masseur (2024), it can be taken that the crowns of the trees have different distances between them. For the most part, the lengths between the crowns it was observed to be approximately 6 metres. Therefore, a length of a maximum of 6 metres would allow for space for installations. This step requires more in-depth research in future studies. The available width (perpendicular to the canals) remains unclear. It could therefore not be effectively studied what the spatial applicability is for these TEO systems, but a first order estimation could be given, through the length of the systems. It is recommended to further investigate this issue in future research.

4.3 Assessment framework

To evaluate the outcomes produced by the methods as mentioned in Section 4.2, an assessment framework has been developed. This framework serves as the basis for analysing significant aspects relevant to the research objectives and ensures that each scenario is assessed using the same criteria.

The framework comprises two key criteria, CO_2 reduction and the economic impact. Where applicable, quantitative indicators and qualitative considerations are integrated to provide a holistic view. In the following subsections, each component of the framework will be described in detail, including the rationale behind its inclusion, the method of assessment, and its role within the overall analysis.

4.3.1 CO_2 Reduction

Different initiatives have started to understand the significance of the Dutch water system and how it can play a role of a technology rich system to replace natural gas. The need to decrease the natural gas consumption as well as the associated GHG emissions, increased the knowledge acquired for aquathermal energy projects throughout the years, by realising more projects. This trend is visible in The Netherlands, but also throughout Europe (Benning, 2022). This led to new developments regarding the calculation surrounding CO_2 emissions of aquathermal energy recovery installations. Stichting Nationale Koolstofmarkt [SNK] (2022) proposed calculation methods based on these developments.

First of all, one needs to determine what the boundaries are of such (aquathermal) projects. The project plan must generally establish boundaries for the location of the project, including the water medium from which the thermal energy is extracted, as well as the related auxiliary systems. Examples of the auxiliary systems include ATES systems, a buffer, and the (existing) pumps of a sewage system (in case of riothermia, for example).

Additionally, when electricity is generated from the existing electricity-grid, the basic premise is that the CO_2 emissions of the electricity will be calculated in accordance with the method as developed by Planbureau voor de Leefomgeving [PBL] et al. (2021), which will be further elaborated on further on in this section.

Heat pumps or another type of pump will be a crucial component for an aquathermal energy project to be utilised, potentially with a buffer. Therefore, these elements of the installation should be part of the project plan and therefore, the scope of the CO_2 emission calculations. However, the pumps that are required to transfer the water medium from the buffer to the heating system of the building is not part of the scope. This is due to the fact that these are also required in the situation with natural gas boilers. This means that these pumps are considered to be redundant (SNK, 2022).

After determining the scope of the project plan, the comparison between the baseline situation and the projected situation should be initiated. In essence, the baseline situation can be defined as the situation when the project would never be installed. This can be compared to the new, envisioned situation. The upper part of Figure 20 gives a visual summary of the distinction between the baseline situation and the envisioned project.

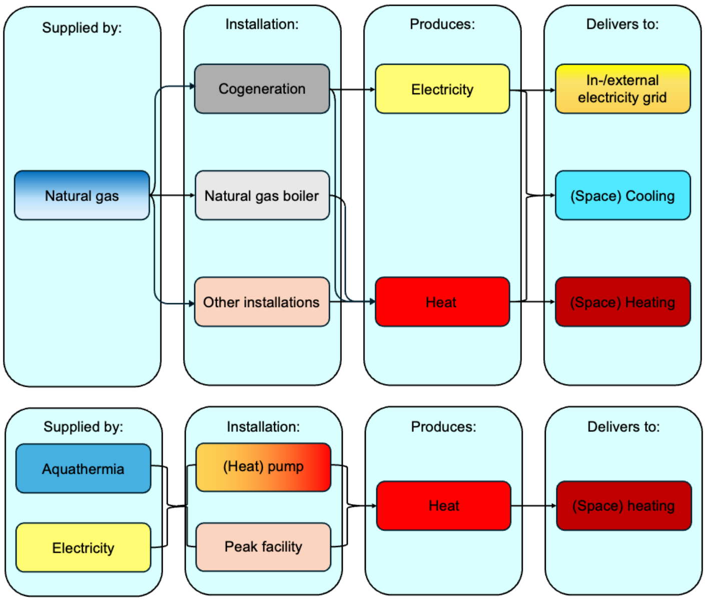

Figure 20: CO_2 reduction: current situation (top) and envisioned situation (bottom). Adapted from Stichting Nationale Koolstofmarkt (2022)

As can be seen in the figure above, the main distinction between the two diagrams is that the baseline situation, (space) heating is mainly being initiated by the original natural gas boilers, whereas in the projected situation this is done by a combination of aquathermal energy and electricity. Other installations or cogeneration can add to the heat and electricity production in the current situation, whereas the heat in the projected situation is produced by a combination of heat pump(s) and potentially other peak facilities. These can be in the form of natural gas boilers, hydrogen gas boilers or other pumps, being supplied by aquathermal energy, electricity or potentially the gas supplier. These pumps will then supply the buildings with heat.

When this baseline situation has been established, the CO_2 emissions of the baseline situation can be determined. For this, the calculation methods of Stichting Nationale Koolstofmarkt (2022) have been used. The total baseline CO_2 emissions of a certain year (in kg CO_2) can be calculated as

$$CO_{2_{baseline\ year}} = E_{year} \times SpecCO_{2_{baseline}},$$

where E_{year} denotes the heat delivered in GJ and the specific baseline emissions (in kg CO_2/GJ) is noted as $SpecCO_{2_{baseline}}$. The latter element of the formula is different per chosen installation of the project. Often however, the baseline situation is referred to the situation with natural gas boilers, as in this thesis. The formula for the specific CO_2 emissions in these instances is as

$$SpecCO_{2_{baseline}} = \frac{CO_{2_{natural\ gas}}}{\eta_{boiler} \times h},$$

where $CO_{2_{natural\ gas}}$ is known as the emission factor of CO_2 (in kg CO_2/Nm^3). The value for this was chosen to be 2,134 kg CO_2/Nm^3, according to the most recent findings (CO2emissiefactoren, 2024). Furthermore, η_{boiler} is the efficiency of the natural gas boiler (-), which is assumed to be approximately 0,973 (Stichting Nationale Koolstofmarkt, 2022). and *h* is the heating value of natural gas (in MJ/Nm^3). The heating value has a narrow range in The Netherlands, with the higher heating value of natural gas in The Netherlands being approximately 35,17 MJ/Nm^3, while the lower heating value of natural gas being approximated to be 31,65 MJ/Nm^3 (Henriquez et al., 2024).

When the baseline emissions have been established, the projected emissions should be simulated. This is performed using similar methods as the baseline emissions. The simplified calculation, from Stichting Nationale Koolstofmarkt (2022) for the projected annual CO_2 emissions (in kg CO_2/year) is as

$$CO_{2_{project}} = e_{hp} \times CO_{2_{e-project}},$$

with e_{hp} being the annual electricity consumption of the heat pumps, and $CO_{2_{e-project}}$ notes the emission factor of electricity (in kg CO_2/kWh). The latter translates to the CO_2 emission of the electricity produced that supplies the heat pump(s) of the necessary power.

However, this calculation method would be valid if the heat pump was the only element of the project. As mentioned in Section 4.2.3, an alternative peak supply might be needed for an overall viable solution. Therefore, the CO_2 emissions of such peak supply facilities should also be accounted for. During this research, the peak supply has been restricted to natural gas. These calculation of the total CO_2 emissions of the project (in kg CO_2/year) should therefore be extended and performed as

$$CO_{2_{project}} = \left(e_{hp} \times CO_{2_{e-project}}\right) + \left(E_{peak} \times SpecCO_{2_{baseline}}\right),$$

where E_{peak} denotes the annual amount of natural gas needed for the peak supply and the $SpecCO_{2_{baseline}}$ is taken from the earlier calculations for the situation for natural gas. This means that it is assumed that the peak supply (natural gas) will be projected to have the same heating value henceforward.

The $CO_{2_{e-project}}$ (or the emission factor of the used electricity) usually fluctuates and it is highly advised to proactively actualise this value for each project. At the time of writing, the accurate CO_2 emission factor of electricity in The Netherlands is roughly 0,30 kg CO_2/kWh (Schoots & Hammingh, 2019).

Although the CO_2 emission factor summarises the annual average amount of CO_2 that is emitted through the production of electricity, it is also subject to change. It has declined fast over the last for years for the Dutch Electricity Grid, due to the rapid integration of renewable sources for the production of electricity, resulting in a lower CO_2 emission and therefore lower emission factor. This should therefore be accounted for when calculating the CO_2 emission of the project in the calculation methods above. It is projected that the CO_2 emission factor will drop to 0,21 kg CO_2/kWh by 2025, and to 0,09 kg CO_2/kWh in 2030. It is expected to further decrease this emission factor to 0 kg CO_2/kWh, by having all electricity produced by renewables. However, it is unclear when this will be achieved (Planbureau voor de Leefomgeving [PBL] et al., 2021). In this research, a visual projection will be provided to show the country's ambition to have a CO_2 emission factor of 0 kg CO_2/kWh. A summary of the CO_2 emission factors will be given in Table 1.

Table 1: CO2 emission factors and their projections

Year	CO_2 emission factor (kg CO_2/kWh)	Source
2020	0,30	(Schoots & Hammingh, 2019)
2025	0,21	(Planbureau voor de Leefomgeving [PBL] et al., 2021)
2030	0,09	(Planbureau voor de Leefomgeving [PBL] et al., 2021)
20xx	0	(Planbureau voor de Leefomgeving [PBL] et al., 2021)

Finally, the reduction will be determined by the difference between $CO_{2_{project}}$ and $CO_{2_{baseline\ year}}$. This will provide percentage of CO_2 emission reduction and will be calculated as

$$CO_{2_{reduction}} = \frac{\left(CO_{2_{baseline}} - CO_{2_{project}}\right)}{CO_{2_{baseline}}} \times 100\%.$$

4.3.2 Economic impact

After the termination of the CO_2 savings of the interventions, the final element that has to be examined are the costs of the total considered system. The costs will be determined through the outcome of the heat demand and spatial requirements, as stated in Sections 4.2.2 and 4.2.4 respectively. To perform the calculations of the costs, key figures will be used from the database of Waternet, provided by B. Konneman (personal communication, March 20, 2024). Next, the costs of the individual components will then be summed, whereafter the costs per kWh and per dwelling can be determined accordingly. This will be utilised to compare the scenarios, which will be further explained in Section 4.4.

However, one of the main calculations contributing to the economic feasibility is the number of pipelines. This is a common element that increases the prices of the connection per dwelling significantly. Schilling et al. (2019) have found two formulas that estimates the total length of the necessary pipelines of the required heat grid. A distinction is formulated between the primary grid and the secondary grid. The primary grid transports the heat from the source to the heat transfer station (in Dutch: warmteoverdrachtstation), which transports it to the secondary grid that leads towards the consumers. The length of the primary grid is assumed to be 1 meter, due to the implementation in the quay walls. For the secondary grid, Schilling et al. (2019) distinguishes the main pipelines of the secondary grid and the branched pipelines of the secondary grid. The length of the main pipelines of the secondary grid are calculated as follows:

$$l_{main} = \alpha * \sqrt{2} * \sqrt{A_{area}},$$

where α is the so-called bypass factor, which accounts for the "detour" that the pipelines must make to connect all the buildings to the grid. Additionally, A_{area} represents the surface area of the study area. The 1333 dwellings, the surface area was measured to be approximately 14,9 ha. For smaller clusters, the surface area was chosen to be approximately 11.178 m^2 per 100 dwellings, as it is the average of the total surface area. Furthermore, the length of the branched pipelines was calculated as follows:

$$l_{branched} = \frac{1}{4} * \frac{1}{2} * \alpha * \sqrt{2} * \sqrt{A_{area}},$$

with the same parameters as mentioned above. The total of $l_{branched}$ and l_{main} are then added up and this contributes to the total length of the secondary grid, that distributes the heat from the quay walls to the dwellings.

4.4 Scenarios

To compare the results produced by the various input data and interpret their outcome, different boundaries must be set, distinguished and grouped as different scenarios. Therefore, this section will elaborate on the different scenarios set for a comparative analysis.

First of all, the reference case should be established, which is not deemed a scenario per se, but should serve as a reference for the assessment framework of the research. The heat demand is examined for the current situation, without any further retrofitting measures. This then provides a set of parameters that can be compared in all scenarios. For example, the CO_2 reduction is compared to the current (i.e. reference) CO_2 emissions. These current CO_2 emissions is then compared with the reduced CO_2 emissions of each respective scenario. Calculations for the current situation will follow the same methodology as described in the previous sections in Chapter 4. However, since no TEO system will be put in place, the spatial characteristics and the economic impact of the installation of such systems will be omitted.

After setting this current situation, the parameters that could be altered should be determined. One of such parameters is the level of retrofitting needed, resulting in a different heat demand. The data as described in Section 4.2.2. has been modelled in two different groups: retrofitting to medium temperature heat demand (MT) and retrofitting to lower temperature heat demand (LT). The retrofitting levels of the buildings have been described by Dang et al (2024). In summary, the retrofitting level is higher for the LT scenarios than for the MT scenarios. This change will likely result in a different heat demand of the area. Therefore, this will be one of the parameters to be altered.

The other parameter subject to change is the chosen base load for that the TEO systems can be designed for. If a larger base load is considered, the spatial requirements for a TEO system will likely increase. This be a barrier for the integration of TEO systems in quay walls. This element is therefore an essential part of the assessment.

Furthermore, an important alternative scenario is considered. This would be driven by policies on full electrification of heating in some areas, through the sole utilisation of air sourced heat pumps. This is an individual heating solution as opposed to the collective heating solutions as proposed in the previous scenarios.

To confine the research and compare the effect of the alteration of the parameters on the results, these alterations have been grouped. Each group has its own set of parameters, which will then be compared to the other scenarios. Table 2 presents a summary of this group of scenarios.

Table 2: Summary of the different scenarios

	Scenario LT-1	Scenario LT-2	Scenario MT-1	Scenario MT-2	Scenario 5 all-electric
Retrofitting level	High	High	Medium	Medium	High
Base load	90% of total heat demand	30% of peak demand	90% of total heat demand	30% of peak demand	100% (monovalent)

For all scenarios, the costs will be calculated according to the methods in Section 4.3.2. However, due to the cluster size being a possible design choice, this should also be altered. For all scenarios, the cluster size will therefore be 100, 200, 500 and all dwellings in the chosen area. This could lead to a different economic impact per dwelling and should therefore be altered. The cost calculation is done though the same methodology throughout the scenarios for all chosen cluster sizes. So for a smaller cluster size, the heat demand was calculated and therefore smaller cluster sizes resulted in a lower heat demand with a significantly smaller load duration curve, etc. An exception would be the all-electric scenario, where clustering isn't considered due to the individual nature of the heating solution.

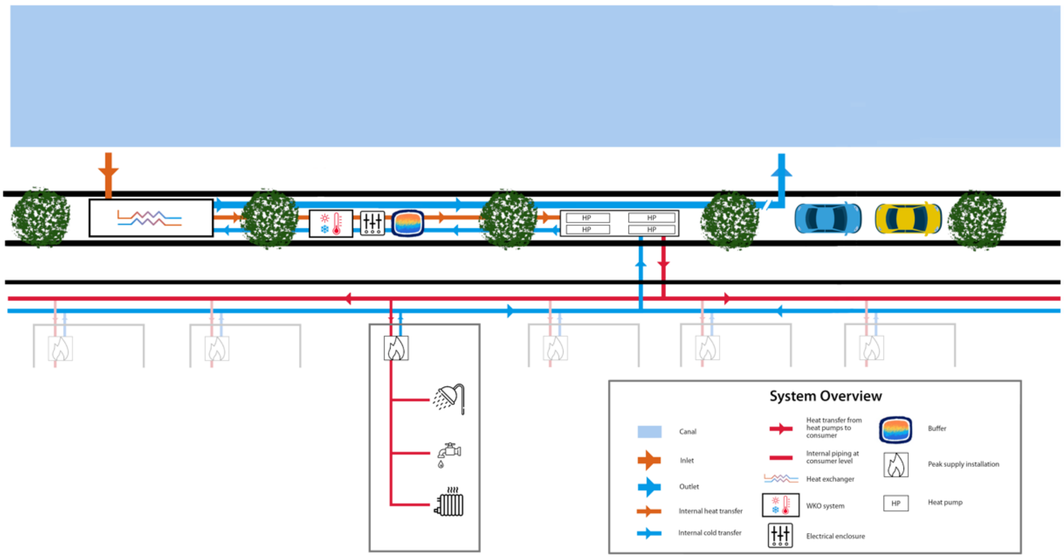

Figure 21: Overview of the system in the historic city centre of Amsterdam

Figure 21 shows a visual summary of the potential implication of TEO systems in the historic city centre of Amsterdam. It depicts that all installations, that could be placed outside of the buildings, are located in the quay walls. This is based on several different assumptions, as mentioned in Chapter 4. The system functions similarly to the TEO system as mentioned in Section 2.1.4. There are a few key differences, however.

The first notable difference is the heat from the canal is being transferred directly to the heat exchanger. This decreases the number of source-pipelines significantly, resulting in lower costs. The thermal energy is then being transferred to the ATES, which stores the heat when extracted by the heat exchangers. The ATES is accompanied by an electrical enclosure that serves as a control panel, and a buffer, to ensure robustness and controlled heat distribution.

Furthermore, the heat is transferred from the ATES to the section of heat pumps. How many heat pumps are necessary depends on the heating demand (including retrofitting levels), the operating temperature and the chosen base load, as stated in chapter 4. These heat pumps then serve the upgraded heat (to the designed temperature) to the neighbourhood. This then distributes the upgraded heat to the buildings individually. The heat in the buildings could be upgraded, if necessary, by a peak facility as described in Chapter 4. Showers, hot tap water and space heating utilise this (upgraded) heat inside the dwellings.

The cold water then follows the opposite path: from the consumers through all the previously mentioned steps until it reaches the ATES. In addition, after extracting heat from the surface water, the cooled water should then be transferred to the outlet of the system. As stated in Section 2.1.4, the distance between inlet and outlet typically varies greatly, to limit the effect of interference of the TEO system. It should be noted that this is not scaled in Figure 21.

For all scenarios, the system will look similar. Differences can be found in the size of the TEO system (with differently sized heat pumps). Other than that, the temperature regime is vastly different. For scenarios LT-1 and LT-2 (LT heat grid) the temperature to be delivered to the dwellings is approximately 45 °C. For scenarios MT-1 and MT-2, this temperature is raised to approximately 60 °C. For the final scenario, the infrastructure as presented in Figure 21 wouldn't be necessary. The system in the all-electric scenario would consist of a heat pump on the outside (façade) of the building, a heat pump inside of the building, a buffer and a boiler (CE Delft, 2021).

4.5 Case study: Kadijken

The chosen neighbourhood was Kadijken. This area is located in Stadsdeel Centrum of Amsterdam. To gather input data (e.g. BAG Kadaster data as mentioned in Section 4.1.1) and gain insights into the process of the installment of a TEO system in the historic city centre of Amsterdam, a representative neighbourhood, or area, should be considered. Kadijken would suffice as a representative neighbourhood. The location of this neighbourhood is given in Figure 22.

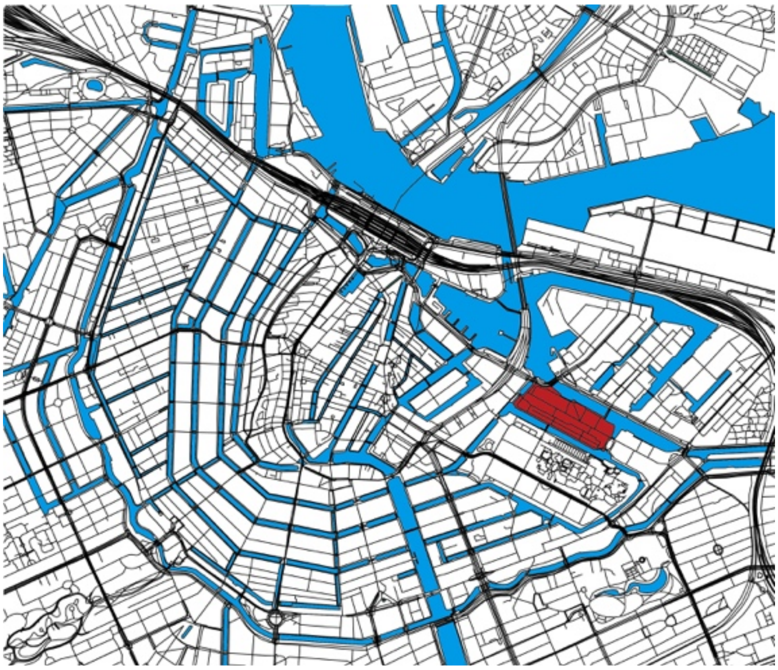

Figure 22: Location of Kadijken within the city centre of Amsterdam

The neighbourhood consists of 1.333 residential buildings. Table 3 presents an overview of the construction period of the residential buildings of the area. Generally, the largest group, approximately 58,6% of the residential buildings in the area are constructed before 1945. For the historic city centre of Amsterdam this is the relatively largest group, with approximately 45,9% accounting for residential buildings constructed before 1900. Additional analysis shows that approximately 58,3% of the residential buildings in Kadijken were constructed before 1905.

This is significantly higher than the European average, where Furtado et al. (2023) noted that over 40% of Europe's residential buildings were constructed before the 1960s. Buildings constructed before that period often have a significantly decreased energy performance.

As can be seen in Table 3, the years of construction in the first group range from 1005 to 1945. 1005 is most likely not the actual year of construction. However, the Gemeente Amsterdam accounts for the unknown years of construction with a default value of 1005 (De Haan, n.d.). In the study area, there are 155 residential buildings that hold this default value.

A similar analysis has been done regarding the building types, as seen in Table 4. Approximately 98,3% of the residential buildings in Kadijken are apartments. This corresponds with the entire historic city centre of Amsterdam, where approximately 96,1% of the buildings are apartments.

Table 3: Construction periods of residential buildings in Kadijken and the historic city centre of Amsterdam

Year of construction	Number of residential buildings in Kadijken	Percentage of total	Number of residential buildings in historic city centre of Amsterdam	Percentage of total
1005 – 1945	784	58,8%	32.658	63,6%
1946 – 1974	58	4,4%	1.428	2,8%
1975 – 1994	412	30,9%	11.274	22,0%
>1995	79	5,9%	5.950	11,6%
Total	1.333	100%	51.310	100%

Table 4: Building types of residential buildings in Kadijken and the historic city centre of Amsterdam

Building type	Number of residential buildings in Kadijken	Percentage of total	Number of residential buildings in historic city centre of Amsterdam	Percentage of total
Apartments	1.311	98,3%	49.295	96,1%
Semi-detached	2	0,2%	122	0,2%
Terraced	20	1,5%	1.893	3,7%
Total	1.333	100%	51.310	100%

Therefore, Kadijken is an area in the historic city centre of Amsterdam where the construction periods and building types correspond with the average of the entire historic city centre of Amsterdam. The largest fraction of the residential buildings in the area was constructed before 1900 (41,2%). Additionally, almost all of the residential buildings (98,3%) consist of apartments, which is greatly in line with the entire historic city centre of Amsterdam (96,1%). This analysis will be the basis for determining the heat demand and therefore the design choices of a TEO system in this part of the historic city centre.

As for the heat demand, this was found to be relatively high. Figure 23 displays the modeled data for the heat load duration curve for the current situation, with no retrofitting measures taken.

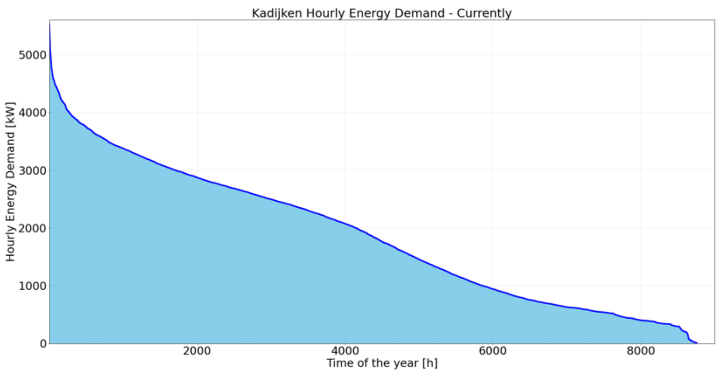

Figure 23: Heat demand duration curve for the original situation

The peak heat demand (displayed in the most left point of Figure 23) reached a value of approximately 5.525 kW and a mean of approximately 1.871 kW. Annually, the area has a total heat demand of approximately 16.385.932 kWh, or 58.989 GJ. The average heat demand per dwelling would then be approximately 44,3 GJ annually.

4.6 Assumptions

This section will discuss the different assumptions underpinning the models used as well as their expected effect on the results. First of all, as mentioned in Section 4.2.1, the presence of cavity walls is assumed only for residential buildings constructed after 1946. However, the presence of cavity walls is often ambiguous, and corresponding data is unavailable at the time of writing. The cavity walls are theoretically used for retrofitting by installing cavity wall insulation, resulting in a significant decrease in heat demand for space heating. When cavity walls are disregarded from the model, the heat demand will increase and will result in an altered design of a TEO system. However, as mentioned, due to a lack of data, this element cannot be implemented in this research.

Secondly, the TEO potential is assumed to be enough to fulfill the heat demand of the chosen area in this research. This is based on the data as taken from Omgevingswarmtekaart (Waternet, 2022). The dataset suggests that the TEO potential surrounding the Kadijken is approximately 207.193 GJ/year. It is therefore likely that this would theoretically enough to supply the area with heat. However, further research would be needed to further analyse the TEO potential and if legislation for a TEO installation is (theoretically) possible.

Furthermore, as mentioned in Section 4.2.1, the presence of cavity walls is assumed for residential buildings constructed after 1946. However, the presence of cavity walls is often ambiguous, and corresponding data is unavailable at the time of writing. The cavity walls are theoretically used for retrofitting by installing cavity wall insulation, resulting in a great decrease in heat demand for space heating. When disregarded, the heat demand will increase and will result in an altered design of a TEO system, potentially leading to a higher cost and a decreased CO_2 reduction. However, as mentioned, due to a lack of data, this element cannot be implemented in this research.

The assumption about the protected status of the residential buildings in the historic city centre of Amsterdam derived from Dang et al. (2024). This research suggests that there are buildings constructed after 1946 with a protected status, however these are significantly less present. This might affect the overall heat demand, but the expected alteration is small due to the small number of addresses that have a protected status constructed after 1946. Therefore, this distinction will not be made in this research.

Additionally, the spatial data of the integration of the systems will be limited to a brief overview of the requirements for installment of TEO systems. This will include various assumptions. For instance, as mentioned in Section 2.1.4, the distance between inlet and outlet of TEO systems can be a significant design choice. However, this will not be part of the current study. This distance should be further examined in future research, given the extensive efforts required for an accurate estimation of this element of TEO systems' design. Furthermore, another spatial characteristic, as mentioned in Section 2.2.2, is the rooting of the trees. At this stage of the research, determining the exact impact of the trees is challenging. Nevertheless, when considering the design of the TEO systems, a general assumption of available space in the subsurface could be the space between the areas underneath the crowns of each individual tree (J. Hiemstra, personal communication, August 23, 2023). This leads to another assumption; along the canals of Amsterdam, an average of 6 meters is available for space in the subsurface, along the length of the canals (Masseur, 2024). Future research would be necessary to fully inventorise the available space in the subsurface, including tree root planning. It is recommended to standardise spatial characteristics that determine the applicability of TEO systems as a whole.

The availability of space in the subsurface is very scarce in a historical city centre such as Amsterdam. As a result, certain assumptions regarding this availability had to be made. Many elements have not been taken into consideration through thorough analysis, such as the rooting of trees, or the presence of cables and/or existing pipelines. The predicted effect to the result of this assumption is the outcomes on the spatial feasibility of mentioned TEO installations, including their power supply. This could be omitted by making an inventory of the elements present in the subsurface. In the Netherlands, this is a legal requirement before starting any excavation or ground-disturbing activities. It ensures that you receive detailed and accurate information about the location of underground utilities such as communication- and electricity cables as well as gas-, water-, and other pipelines. This is done to prevent damage or accidents that involve these assets (Kadaster, n.d.). It is therefore recommended to study this aspect of the integration in further research, so the applicability and the accuracy thereof can be improved.

Another example of additions to the spatial characteristics of these systems is a potential analysis of the available space on the surface. In this research, only the subsurface was considered, since the water level of the canals never exceeds the level of the quay walls. This is more efficient for the recovery of thermal energy from the surface water next to it, especially with a varying water level (De Fockert & Harezlak, 2022). However, it could still be chosen that space on the surface of the quay wall would be (made) available for the placement of (parts of) a TEO system. This could require the purchasing of this space, potentially leading to higher investment costs. In the city centre of Amsterdam, these areas are typically parking spots.

Another option would be the inclusion of an empty dwelling for the use of the technical installations, although that would also carry significant costs in dense urban areas such as Amsterdam.

Another, important assumption is the validation of the used heat demand data. Although calibrated using real consumption data, the model used to generate the data cannot take into consideration the occurrence of discrepancy between modeled consumption and actual consumption, especially in the building types and energy labels that are greatly represented in the historic city centre in Amsterdam (Majcen, 2016). However, the impact on the results of the current research will be limited. The outcome will provide a better understanding of the different scenarios, as they will all be compared within the same order of magnitude. Therefore, the comparative results are expected to remain unaffected. However, the resolution of the accuracy of the exact numbers should be reconsidered in future research.

Also significant is the absence of the coincidence factor (or diversity factor) in the research. Due to limited technical resources, the coincidence factor was not taken into consideration when determining the heat demand of the clusters. This leads to an increased heat demand in this study. Research is being conducted to determine the exact impact of this factor on the heat demand (Knobben, 2020; Pedersen et al., 2007). Although other studies suggests that in areas with a dense heating demand and lower operating temperatures, the coincidence factor would lead to a decreased design of the heating systems (Weissmann et al., 2017). In future studies it would therefore be recommended that the effect of the coincidence factor would be properly accounted for when determining the heat demand for TEO systems.

Moreover, an important assumption is that cooling is not considered in the presented research. Although lower temperature heating could supply cooling to the residential buildings, the research was initially designed to consider solely the residential heat demand. This assumption is built upon the lack of knowledge and technical evidence that cold can be sufficiently supplied to the (monumental) buildings in historic city centres, with a generous amount of existing buildings present (Junasová et al., 2022).

Another assumption was made in the calculation CO_2 emission reduction. As stated in Section 4.3.1, the CO_2 emission calculations are limited to the emissions of the electricity and natural gas usage of the TEO installations. In practice, there will likely be an increase in CO_2 emissions, due to the construction and manufacturing of new heating infrastructure, retrofitting measures and operational activities. Alterations to these calculations in future research would be necessary for a more accurate calculation of the CO_2 emissions. However, for the scope of this research, the CO_2 emissions in all scenarios will be compared with this assumption taken into consideration.

The CO_2 emissions have been calculated using the formulas as described in Section 4.3.1. Although this model is relatively thorough and regularly consulted, possible shortcomings and simplifications could be present that alter the results. Therefore, it could be valuable to apply a much more comprehensive model. E.g. a life cycle analysis (LCA) could be performed, which could lead to altered results. Further research would then be necessary.

The calculation of the costs brings assumptions too. For example, the costs of retrofitting are not taken into consideration for this study. Generally, retrofitting takes 10 years to be executed (Dang et al., 2024), which impacts the business case. A significant variation also is the actual implementation of retrofitting by the homeowners. Additionally, costs can greatly be reduced by combining the retrofitting measures with other maintenance and repair (De Groote & Lefever, 2016). Due to these great variations in costs, these have been disregarded throughout this study.

Finally, the financial impact of the systems has been determined based on a number of assumptions as well as example projects. Only limited technical resources were available, which led to a limitation of applicability. Additionally, in studies as performed by Dang et al. (2024), investment costs and operational costs are highly dependent on many different aspects. Therefore, it is expected that, given the exact boundary conditions as performed in this research, the accurate costs would be increased in comparison to the results in this study. That being said, the cost analysis as performed in this research would give a quantitative comparison of scenarios. In future studies, it would be recommended to include cost optimisation in a potential model. This would further increase accuracy as well as applicability for processes such as policy making.

5 Results and Discussion

This chapter focuses on the results of the integration of the models. How the integration performs and what the results will tell us are formulated in the discussion. The analysis of the data is elaborated on in Section 5.1. In this section, the results of all five scenarios will be presented. The comparison of the scenarios will be displayed in Section 5.2, where the results will be summarised and their significance will be discussed.

5.1 Data analysis

In this section, firstly a summary of the performed analyses will be briefly mentioned. After that, the steps of the data analysis will be elaborated on in the following sections. The section concludes with a set of parameters that can be altered to compare the differences between the scenarios as established in Section 4.4.

5.1.1 LT-1 scenario

The integration of different systems starts with the categorization of the residential buildings in the area. The BAG Kadaster data has been analysed to discover the relevant elements of the dataset. First it was necessary to identify the residential buildings of the area. Then, the relevant columns have been selected as described in Section 4.2.1. This data was then coupled to the data that holds the building type of the residential buildings. This resulted in the corrected groups, as described in Figure 18 in Section 4.2.1, with the numerical data as seen in Table 3.

These results then required coupling to the retrofitting heat demands. This was done by preparing the data as retrieved from AMS as mentioned in Section 4.2. The data from AMS contains information about the heat demand of different residential building types, grouped as described in Figure 18 in Section 4.2.1. However, the data was in the unit of kWh/m^2, so these numbers were multiplied by the surface area of each individual building. This created the retrofitted hourly heat demand of the different buildings, over the timespan of a complete year (8760 hours). Additionally, this data was also provided for the reference scenario, where no insulation methods (or retrofitting) was applied whatsoever. The (retrofitted) hourly heat demands were then divided per building type, construction year and the presence of cavity walls.

As a next step, these heat demands were then collectively summed, for each retrofitting level. This resulted in significantly different heat load duration curves. For the LT retrofitting level, this is as depicted below in Figure 24.

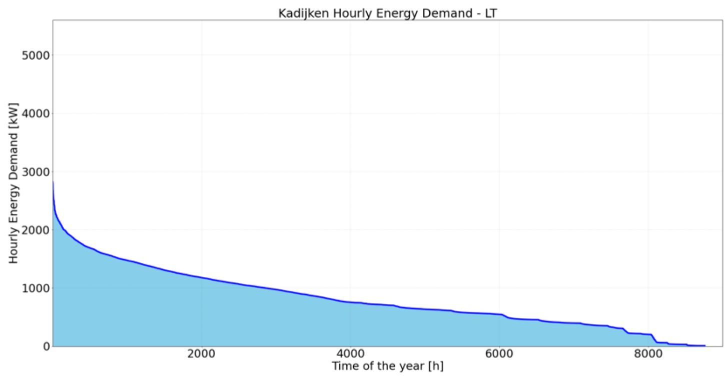

Figure 24: Heat demand duration curve for the LT-1 scenario

This translates in an even lower heat demand for each individual dwelling, compared to the original situation. As can be seen in the heat load duration curve in Figure 24, the hour with the highest demand (on the very left of the graph), held a value of approximately 2.821 kW, with a mean of approximately 808 kW. More significantly, the annual heat demand of the area was calculated to be approximately 7.083.787 kWh, or 25.502 GJ. Each residential building would therefore consume approximately 19,1 GJ after retrofitting to the maximum level. Therefore, compared to the original situation, the heat demand would then be decreased by approximately 56,8%.

When the heat demand is determined for the retrofitting scenario, the next step is to determine the base- and peak load of the system per retrofitting scenario. As stated in Section 4.2.3, the base load can be determined from the load duration curves. This will determine the further dimensioning of the system. For the original state of the residential buildings, with no retrofitting measures taken, it could be stated that determining the base load of the system would be a rather difficult process, as the design would have to be relatively large and costly.

In Figure 25 a visual representation is displayed for the scenario where the residential buildings are retrofitted to their maximum extent. In this scenario, the base load is determined to be approximately 1.194 kW. This is approximately 90% of the total annual heat demand, as determined in Section 4.2.3. This value is represented in the figure above by the red line. For the remaining 10%, a peak facility is necessary. The base load to be covered by the TEO system is approximately 42% of the peak demand.

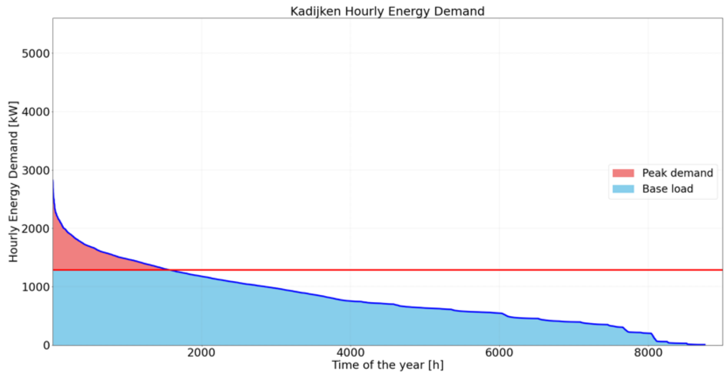

Figure 25: Determination of the base-/peak load for the LT-1 scenario

This would then translate into a TEO system, with certain spatial characteristics, accordingly. As seen in the document provided by Viessmann (2018), system 302.D230 from Vitocal has a great variation in operating temperatures. The operating temperatures partially determine the system's characteristics. However, due to the retrofitting level, an operating point of 45 °C would be sufficient. This is under the assumption that this would be sufficient including the heat loss during transportation. The source has always been determined to be 15 °C.

According to Viessmann (2018), this results in a heating output of 322 kW per heat pump. To cover this heat demand, a total of 4 systems is necessary. This results in a total system of approximately 5,9 x 3,6 x 2,0 metres (l x w x h). This would have to be combined with the heat exchanging systems and pipelines as well as the installation for the ATES, as described in Section 4.2.4. In total, the amount of space necessary for all installations in the quay walls would be approximately 50,04 m^2. With a maximum length of approximately 5,9 metres, it seems that this installation is practically feasible.

When the spatial characteristics have been established, the CO_2 emissions were then established in this scenario. This was done according to the method mentioned in Section 4.3.1. For every scenario, the specific CO_2 emission baseline for the natural gas boilers was found to be approximately 69,3 kg CO_2/GJ. In the first LT-scenario, the total CO_2 emissions for the Kadijken area was approximated to be around 1.767 tonnes of CO_2 if the natural gas boilers were used to cover the entire heat demand. This translates to approximately 1.325 kg of CO_2 per dwelling.

In the scenario as shown in Figure 25 above, the base load would be covered by the TEO source. This was found to supply approximately 6.399.833 kWh annually. To cover this heat demand, according to the COP as described by Viessmann (2018), the annual electricity consumption would be roughly 1.209.798 kWh, or 363 tonnes of CO_2 emitted. The peak demand as visualised in Figure 25 above, will be produced by natural gas throughout the calculation. Therefore, the remaining 683.953 kWh to be supplied by natural gas roughly translates to 171 tonnes of CO_2 emitted.

However, as mentioned in Table 1 in Section 4.3.1, the CO_2 emission of electricity is expected to progressively decrease. This results in the expected CO_2 emissions to further decrease. A summary is given in Table 5 below. In addition to the CO_2 emission, the reduction in comparison to the original situation will be presented.

Table 5: Prognosis of the CO_2 emissions of the LT-1 scenario

Year	Annual CO_2 emission of TEO system ($kgCO_2$)	Total annual CO_2 emission ($kgCO_2$)	Annual CO_2 emission per dwelling ($kgCO_2$)	Reduction in CO_2 emission
2020	362.940	533.562	400	69,81%
2025	254.058	424.680	319	75,97%
2030	108.882	279.505	210	84,18%
20xx	0	170.623	128	90,34%

As can be seen in Table 5 above, the CO_2 reduction directly after implementation would be approximately 69,81%. The maximum reduction of the system in this scenario would increase to approximately 90,34%. The remaining CO_2 emissions would be caused by the peak facilities, in this case natural gas boilers.

The investment costs have also been studied for the different retrofitting levels. Figure 26 below displays the investment costs per dwelling, when the buildings would be retrofitted to the LT level. Four points have been taken and have been plotted. When a trendline was plotted for the points, a trend can be seen that the investment costs per dwelling increased, when the chosen number of dwellings decreased. On the other side, it can be seen that the slope of the line decreases, resulting in a lower benefit when the number of dwellings chosen increases further. Due to the lowered sample size, it remains open where the optimum value would be located on the graph. However, the analysis could suggest that the optimum value is between 500 and the maximum number of dwellings, which was 1.333 during this study. The lowest value for the costs has been calculated to be approximately 22.907 euros per dwelling, for the highest cluster size.

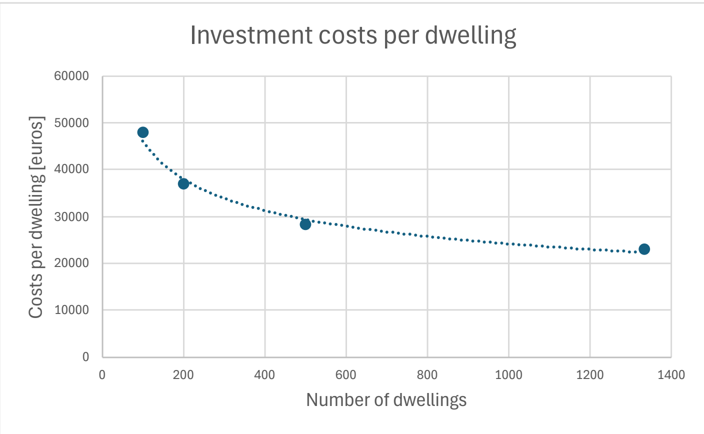

Figure 26: Investment costs of the TEO systems for the LT-1 scenario

This is only slightly higher, when compared to other studies comparing investment costs of LT heat grids (Dehens, 2022), which stated that the investment costs would be approximately 21.500 euros. However, this study considered a cluster size of 500 dwellings. The investment costs of the TEO systems would be approximately 29.000 euros per dwelling when clusters of 500 would be chosen, which is significantly higher than stated by Dehens (2022).

5.1.2 LT-2 scenario

In the situation of this scenario, the heat demand is the same as in Section 5.1.1. However, the ratio of base load and peak load needs to be altered. When this was chosen according to (Koster et al., 2022), 30% of the peak demand, or approximately 846 kW was a result. This will be presented in Figure 27. The red line represents the value for the determined base load of the TEO system. Approximately 77% of the total annual heat demand would then be covered. The remaining 23% should be covered by the peak facility.

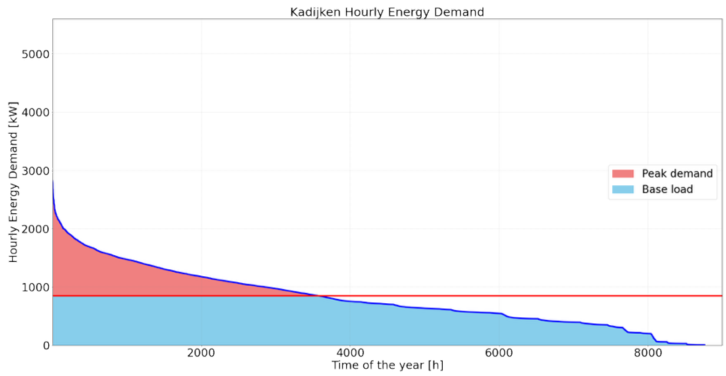

Figure 27: Determination of the base-/peak load for the LT-2 scenario

Then, the spatial characteristics can be determined according to Viessmann (2018). This can be derived, and the chosen system is therefore 302.D230. This translates to different dimensions of the TEO system. Due to the same retrofitting level, the operating temperature of the system is the same as in Section 5.1.1, which is 45 °C.

This results in a heating output of approximately 322 kW per heat pump. To cover the heat demand, a total of 3 systems is necessary. This results in a total system of approximately 5,9 x 3,6 x 2,0 metres (l x w x h). In total, the amount of space necessary for all installations in the quay walls would be approximately 50,04 m^2. This is the same amount of space required as the previous scenario. This is mainly due to the nature of the allowed clearances for maintenance and ventilation (Viessman, 2018). The practical feasibility seems plausible due to the maximum length of 5,9 metres.

After the spatial characteristics, the system's CO_2 reduction was calculated. In the same way as Section 5.1.1, approximately 1.767 tonnes of CO_2 would be emitted if the natural gas boilers were used to cover the entire heat demand, or approximately 1.325 kg of CO_2 per dwelling.

When the base load, that is covered by the TEO source, is decreased, the CO_2 reduction will be impacted. Annually, the TEO system should cover the base load of approximately 5.444.977 kWh. According to Viessmann (2018), system 302.D230 has a COP of approximately 5,29. Therefore, roughly 1.029.296 kWh of electricity is needed. This translates to roughly 309 tonnes of CO_2 emissions. As stated in Section 4.3.1, the emission factor of electricity is projected to decrease in the future. The peak demand will still be produced by natural gas. Therefore, 1.638.809 kWh will be supplied by natural gas, which equals approximately 409 tonnes of CO_2 emissions. As shown in Table 6 below, the immediate CO_2 reduction is 59,39% while it is projected to increase up to approximately 76,87% as the grid becomes fully green.

Table 6: Prognosis of the CO_2 emissions of the LT-2 scenario

Year	Annual CO_2 emission of TEO system ($kgCO_2$)	Total annual CO_2 emission ($kgCO_2$)	Annual CO_2 emission per dwelling ($kgCO_2$)	Reduction in CO_2 emission
2020	308.789	717.615	538	59,39%
2025	216.152	624.978	469	64,63%
2030	92.637	501.463	376	71,62%
20xx	0	408.826	307	76,87%

Finally, the investment costs have been calculated. Figure 28 below shows the investment costs per dwelling for this scenario. The lowest costs were found with the largest cluster size, approximately 22.487 euros per dwelling. The trendline shows, a trend that shows that the investment costs per dwelling increased, when the chosen number of dwellings decreased. Only slight differences in the trends were observed for the cost vs. cluster size, when compared to the LT-1 scenario. This is likely due to the same space needed for the TEO system as well as the pipelines that need to be installed with the heat grid. Lengths of the primary and secondary grid have a great influence on the investment costs of any heat grids (Bianchi et al., 2022).

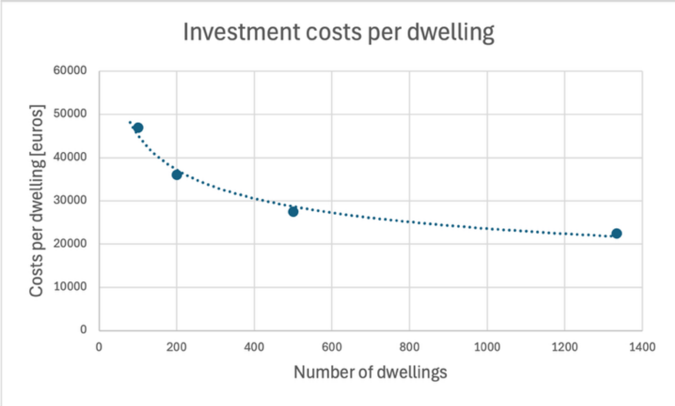

Figure 28: Investment costs of the TEO systems for the LT-2 scenario

5.1.3 MT-1 scenario

As displayed in Figure 29, the heat demand is increased when the MT retrofitting level is considered, when compared to the LT retrofitting level. This heat demand was then also analysed and a different TEO system would have to be designed. Similarly to Section 5.1.1, the systems were integrated, and the analysis was performed.

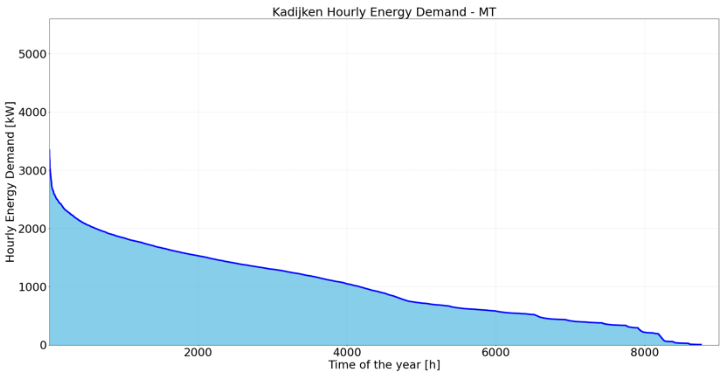

Figure 29: Heat demand duration curve for the MT-1 scenario

In Figure 29, the heat demand of the area is displayed when the residential buildings are retrofitted to an increased level of insulation measures (MT-ready). The maximum value, or the hour with the highest demand, was found to be approximately 3.347 kW and a mean of approximately 1.010 kW. On an annual basis, the heat demand was found to be approximately 8.846.054 kWh, or 31.846 GJ. This translates into an annual heat demand per residential building of roughly, 23,9 GJ. Annually, this reduces the heat demand by approximately 46,0%.

When the base load was chosen when 90% of the annual heat demand was covered, approximately 1.480 kW would be needed. This is indicated by the red line in Figure 30 below. For the remaining 10%, a peak facility is necessary. The base load to be covered by the TEO system is approximately 44% of the peak demand.

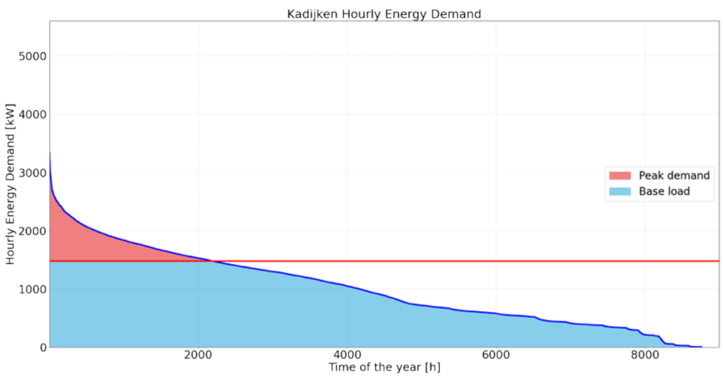

Figure 30: Determination of the base-/peak load for the first MT-1 scenario

Following the determination of the base load of the TEO system, the right spatial characteristics were established. A significant consideration when compared to the LT level, is the correct operating temperature for the TEO system. As mentioned in Section 5.1.1, Viessmann (2018) describes how the systems from Vitocal have different operating temperatures. Due to the retrofitting level, 60 °C would be a sufficient operating temperature. The previously mentioned report shows that a heating output of 299 kW per heat pump would be needed, with system 302.D230. To cover this demand, a total of 5 systems is necessary. According to the calculations as provided by Viessmann (2018), this results in a total system of approximately 9,4 x 3,6 x 2,0 metres (l x w x h). This would have to be combined with the heat exchanging systems and pipelines as well as the installation for the ATES, as described in Section 4.2.4. In total, the amount of space necessary for all installations in the quay walls would be approximately 63,28 m^2. Practically, this scenario likely seems to be significantly less favourable. This is due to the necessary length of approximately 9,4 metres. It might require the compensation of one or more trees, which is unlikely to happen given their monumental status. Therefore, integration in the quay walls seems improbable for this scenario.

The CO_2 emissions were then calculated accordingly. For the MT retrofitting level, the total CO_2 emissions for the Kadijken area was approximated to be around 2.206 tonnes of CO_2 if the natural gas boilers were used to cover the entire heat demand, or roughly 1.655 kg of CO_2 per dwelling.

The base load as presented in Figure 30 above would cover approximately 7.985.045 kWh annually. This heat demand would be covered with an electricity demand of roughly 2.140.763 kWh, due to the COP of 3,73 as taken from Viessmann (2018). This electricity demand was found to be equivalent to approximately 602 tonnes of CO_2 emissions annually. The peak demand will be, as in Section 5.1.1, produced by natural gas throughout the calculation. Therefore, the remaining 861.008 kWh to be supplied by natural gas roughly translated to 215 tonnes of CO_2 to be emitted by the natural gas boilers yearly.

Similarly to Section 5.1.1, the CO_2 factors of electricity will likely decrease. This resulted in the expected CO_2 emissions to further decrease. After implementation, approximately 61,16% of CO_2 emissions are reduced, that increases to approximately 90,27%. A summary is given in Table 7 below.

Table 7: Prognosis of the CO_2 emissions of the MT-1 scenario

Year	Annual CO_2 emission of TEO system ($kgCO_2$)	Total annual CO_2 emission ($kgCO_2$)	Annual CO_2 emission per dwelling ($kgCO_2$)	Reduction in CO_2 emission
2020	642.229	857.021	643	61,16%
2025	449.560	664.352	498	69,90%
2030	192.669	407.460	306	81,54%
20xx	0	214.792	161	90,27%

The investment costs have also been studied for the different retrofitting levels. Figure 31 displays the investment costs of the total systems per dwelling, when the buildings would be retrofitted to the MT level. The four points for the different cluster sizes have been taken and have been plotted. When a trendline was plotted for the points, a similar trend can be seen as the previous two scenarios. The investment costs per dwelling increased, when the chosen number of dwellings decreased. This is in a similar pattern as the previous scenarios (LT-level), although the costs seem to be the lowest at a cluster size of 500 dwellings, with costs of 25.273 euros per dwelling.

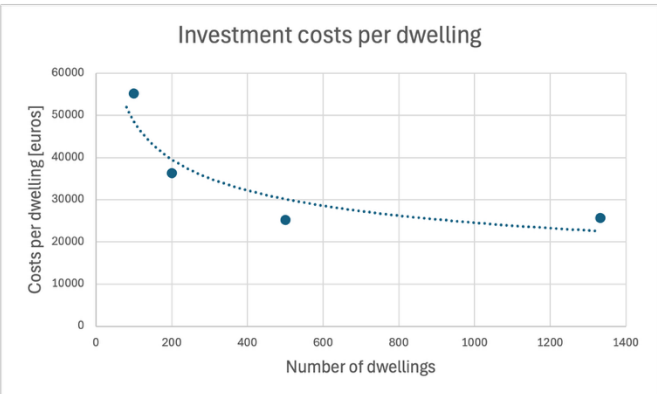

Figure 31: Investment costs of the TEO systems for the MT-1 scenario

5.1.4 MT-2 scenario

For the final scenario, the overall heat demand is presented in Figure 29 in Section 5.1.3. Once again, the base load to be covered by the TEO system was adjusted. This was approximately 30% of the peak demand was taken. This translates to approximately 1.004 kW. In Figure 32 below, this is displayed, where the red line represents the value for the base load of 1.004 kW. This provides approximately 73% of the total heat demand. For the remaining 27%, a peak facility is necessary.

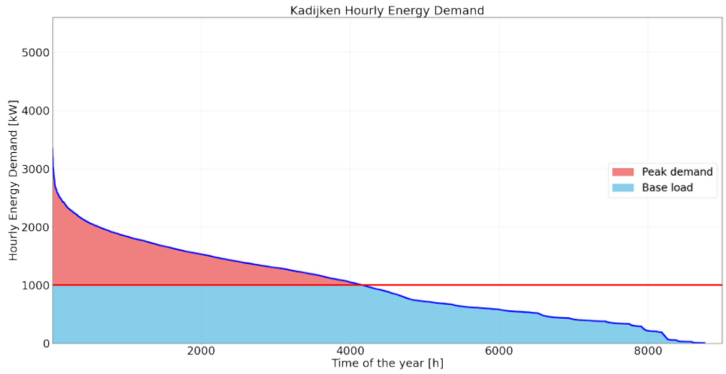

Figure 32: Determination of the base-/peak load for the second MT-2 scenario

The next step is the determination of the spatial characteristics. This was derived from Viessmann (2018) and the system that was chosen was therefore 302.D230, as was in the previous scenario.

First of all, the heating output per heat pump would be approximately 299 kW. This means a total amount of systems of 4 would be necessary to cover the base load of the annual heat demand. This resulted in approximately 5,9 x 3,6 x 2,0 metres (l x w x h) technical space needed. The total floor area for the installations in the quay walls would be approximately 50,04 m^2. Unlike the MT-1 scenario, this scenario seems to be practically feasible, given the smaller size of the TEO installation. It would therefore be plausible to integrate this scenario with the utilisation of the quay walls.

Afterward, the total CO_2 reduction of the system was determined. Approximately 6.453.704 kWh is used by the TEO system annually in this scenario. Therefore, the same system as the previous scenario, with a COP of 3,73 (Viessmann, 2018), will need roughly 1.730.216 kWh of electricity. Approximately 519 tonnes of CO_2 will be emitted in this part of the process. The peak demand that's produced by natural gas will therefore still need to be roughly 2.392.350 kWh and this translates to roughly 597 tonnes of CO_2. Therefore, approximately 49,43% of CO_2 reduction is achieved, which increases up to 72,96% when the electricity grid is completely carbon neutral. To showcase the further projected CO_2 emissions, Table 8 below summarises the prognosis.

Table 8: Prognosis of the CO_2 emissions of the MT-2 scenario

Year	Annual CO_2 emission of TEO system ($kgCO_2$)	Total annual CO_2 emission ($kgCO_2$)	Annual CO_2 emission per dwelling ($kgCO_2$)	Reduction in CO_2 emission
2020	519.065	1.115.873	837	49,43%
2025	363.345	960.154	720	56,49%
2030	155.719	752.528	565	65,90%
20xx	0	560.809	448	72,96%

After CO_2 emissions have been established, the investment costs have been incorporated and determined. These investment costs found in this scenario are presented in Figure 33 below. The same trend as in the previous MT scenario was found, where the costs are the lowest at a cluster size of 500. Per dwelling, the costs are roughly 23.999 euros. For the entire area, so a cluster size of 1333, the costs were approximately 24.455 euros per dwelling. In addition, it was found that the costs per dwelling would be higher for the MT scenarios, when compared with the LT scenarios. This is likely due to the lower COP of the systems, since the temperature of the water is to be upgraded to a higher temperature. The electricity demand is therefore relatively higher, leading to higher costs and a lower CO_2 reduction.

It is unknown whether the difference between the costs of the LT and MT scenarios can be compensated due to the retrofitting levels. Applying retrofitting measures to (monumental) buildings is expensive and can therefore lead to significantly higher costs (Dang et al., 2024). Especially given that the insulation measures can be a very significant part of the investment costs, when these would be considered (Dehens, 2022).

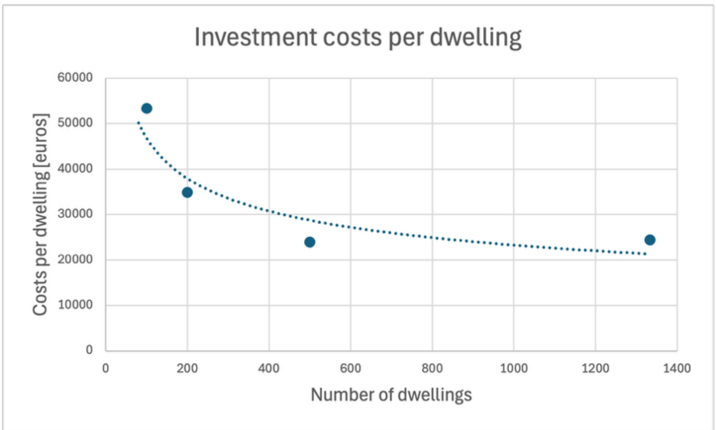

Figure 33: Investment costs of the TEO systems for the MT-2 scenario

5.1.5 All electric heating

An alternative solution to compare the aforementioned scenarios is full electrification of heating systems. An alternative approach could be found in individual installations, such as an air sourced heat pump (all electric). To do this, a rough estimate of the necessary performance of each individual installation should be assumed.

First of all, it should be noted that the insulation level impacts the potential usage of the individual heat pump (Hoetz et al., 2024). It is suggested that the insulation level for all electric solutions should be minimum energy label B. This would also make the buildings suitable for LT heating solutions. Therefore, the heat demand for this solution should be taken from the scenario with LT retrofitting measures. This is then divided by the number of dwellings taken into consideration, 1333 for the area of the Kadijken.

From the heat demand load duration curve as presented in Figure 24 in Section 5.1.1, the average heat demand load duration curve for each individual dwelling can be determined. This is displayed in Figure 34 below.

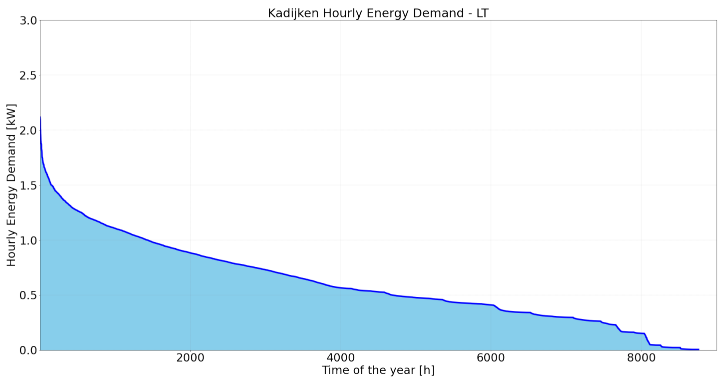

Figure 34: Average heat demand duration curve for an individual residential building, after LT retrofitting measures

The heat demand load duration curve as presented above has a peak demand (on the left of the curve, representing the coldest day of the year) of approximately 2,12 kW. To cover this demand with an individual solution, such as the individual heat pump, a brief analysis should be done to estimate the effects of it.

For a comparison for CO_2 reduction with the different scenarios, it can simply be derived from the electricity usage of the installations. As suggested by CE Delft (2021), the efficiency of the individual air sourced heat pump would be between 350% to 450%. The efficiency would be largely dictated by the temperature to be delivered to the building. With an increase of temperature, the efficiency of the installation decreases (CE Delft, 2021). Therefore, an efficiency of 350% should be taken into consideration for comparison with the previously mentioned scenarios.

The total heat demand of the area, with retrofitting measures to LT-level, was previously found to be approximately 7.083.787 kWh. With an efficiency of 350%, the amount of electricity needed would be roughly 2.023.939 kWh. This leads to an initial CO_2 reduction of approximately 65,66% and increases in time up to 100%, due to the electricity grid being greener. The projection of the CO_2 emissions is summarised in Table 9 below.

Table 9: Prognosis of the CO_2 emissions of the individual heat pumps

Year	Total annual CO_2 emission ($kgCO_2$)	Annual CO_2 emission per dwelling ($kgCO_2$)	Reduction in CO_2 emission
2020	607.181	455	65,66%
2025	425.027	319	75,92%
2030	182.155	136	89,74%
20xx	0	0	100%

The investment costs can be derived relatively easily. For comparison with the other scenarios, the investment costs for an air sourced heat pump ranges from 6.500 to 14.500 euros (CE Delft, 2021). This would make it significantly less expensive option for individual buildings when compared to the other scenarios. It should be noted that given the monumental status of the historic city centre of Amsterdam, the costs would likely be on the higher end of the spectrum.

Recent studies however, as conducted by Hoetz et al. (2024), suggests that this individual solution has different implications when compared to the collective solutions such as heat grids (with a TEO heat source). This research was done in a neighbourhood in The Hague, with similar characteristics as the area chosen in this thesis. Relatively old apartments, partially constructed before 1945. The applicability of the individual solution was often an obstacle for the houses, which is a direct consequence of the applicable insulation that could be installed. Furthermore, the study concluded that the individual installation required more space inside the dwellings as well as outside the buildings (e.g. on the rooftop). Another aspect is the potential sound pollution. The individual heat pumps would produce approximately 45 dB, which could lead to serious sound pollution in dense urban areas such as the historic city centre of Amsterdam. Finally, the study concludes that societal costs are significantly higher for the individual heat pumps in comparison to the collective heat grids. This is mainly due to the reinforcement of the electricity grid, which is necessary to install these individual heat pumps. It is expected that net congestion will persevere for the longest period of time when this solution is chosen for these types of apartments. However, the study also concludes that the space in the subsurface is significantly higher for the collective heat grids. This is due to the necessary connections to the heat pipelines. In conclusion, it should be considered to apply a collective solution, as opposed to the individual heat pumps.

5.2 Comparison of scenarios

In Section 4.4, the scenarios that should be considered have been determined. After establishing the data, preparing it for utilisation in the integration of systems, the results should be studied. The objective is to determine how thermal energy from surface water can be integrated in the existing urban energy system in Amsterdam. This implicates a comparison of the scenarios on the ratio of base load/peak demand, as well as spatial and economic impact and the reduction in CO_2 emissions. When the scenarios have been analysed, they were compared to each other. This would emphasise the importance of the different design choices, such as cluster size, retrofitting level, among others, as discussed in Chapter 4. These design choices have different consequences to CO_2 emissions, costs and spatial requirements. These alterations will be presented in this section.

As mentioned in Section 5.1, there are multiple possibilities that alter the elements of a TEO installation. Section 5.1 showed the results of the chosen base loads for both retrofitting levels. This section will compare these results and briefly reflect on them. Table 10 will present the characteristics of the different scenarios.

The comparison will include the required space for the installations, the CO_2 reduction right after implementation and the total investment costs per dwelling. The costs per dwelling for the highest cluster size have been considered, for a clearer comparison.

Table 10: Comparison of all 5 scenarios

Year	Scenario 1 LT-1	Scenario 2 LT-2	Scenario 3 MT-1	Scenario 4 MT-2	All-electric
Space required [m^2]	50,04	50,04	63,28	50,04	-
CO_2 reduction [%]	69,81	59,39	61,16	49,43	65,66
Costs [€/WEQ]	22.907	22.487	25.273	24.455	6.500-14.500

The spatial requirements for each scenario were not found to be significantly different. The same number of units were needed for most scenarios, with the exception of the MT-1 scenario. It could therefore be concluded that the quay walls could not be utilised for this scenario. Therefore, a high base load for an MT heat grid doesn't seem practically feasible in this area. For the other heat grid scenarios, it seems feasible. In the all-electric scenario, it cannot be stated what the required space would be, although for monumental buildings in historic city centres it seems unlikely that the outside unit can be installed on the rooftops or façade of the buildings.

The CO_2 reduction for the heat grid scenarios right after installation was found to be the highest in the LT-1 scenario, closely followed by the MT-1 scenario and the LT-2 scenario, respectively. The MT-2 scenario was found to have the lowest CO_2 reduction. It could be stated that for CO_2 reduction the LT heat grids were found to be favourable. This is likely due to the change in COP of the heat pumps (Viessman, 2018). The all-electric scenario has a CO_2 reduction of approximately 65,66%. It is expected to be lower in practice, due to the decreased efficiency for hot tap water utilisation (CE Delft). Eventually, the latter scenario will further increase its CO_2 reduction to 100%, due to the larger projected share of renewable energy used for electricity. However, very significant changes would be needed for the electricity grid, which seem implausible for direct implementation. In the coming decades, these changes will likely be applied to the electricity grid, which implies that these installations could have a CO_2 reduction of 100%.

Finally, the costs were compared between all scenarios. The LT-1 and LT-2 scenarios showed a similar economic impact. The same statement could be made for the MT-1 and the MT-2 scenarios. The differences could be found in the fact that the base load was higher for the MT scenarios in absolute terms when compared to the LT scenarios. For the all-electric scenario, the economic impact (investment costs) was significantly lower when compared to the heat grid scenarios. Although not considered in this research, this is most likely due to the lack of infrastructure to be constructed in the streets. This can have a great financial impact on such collective systems. The lack thereof would therefore suggest a decrease in costs for the last scenario.

The differences between the LT scenarios and MT scenarios in terms of investment costs is also relatively low. The costs between LT-1 and MT-1 are approximately 2.366 euros per dwelling. As stated before, this is likely due to the significance of the construction of pipelines that have a large influence on the total investment costs. These costs would be approximately the same for both mentioned scenarios. However, this is in line with research as performed by Kaandorp et al. (2022), where the difference between LT heat networks and MT/HT heat networks was found to be very comparable for three different neighbourhoods in Amsterdam.

6 Reflections

This section interprets the key findings of this study in relation to the research objectives and the existing literature. Then, the results will be briefly addressed before acknowledging their limitations. The insights gained will be shared as well as the respective recommendations. If necessary, previous studies will be compared to underscore the areas of alignment and potential contributions to the field.

One of the key components of the study was to reduce the CO_2 emissions that are produced by the traditional heating installations in the residential buildings in the historic city centre of Amsterdam. Due to the temperature of the source of TEO systems, a peak facility is still necessary to come to a feasible (and affordable) heating system. This study has solely taken the (existing) natural gas boilers as the only available alternative. Other gases could be considered in future research, to investigate their respective effects on environmental performance (CO_2 emissions). Another alternative could be found in electric boilers, where the peak facility can be fueled by electricity, instead of using any form of gas. This would probably result in even lower CO_2 emissions of the system. It should be noted that electric boilers could have a negative effect on the grid congestion (Van ’t Slot, 2024). In the historic city centre of Amsterdam, it would most likely be of great difficulty to provide electricity from solar panels, to limit this grid congestion. This is due to the monumental status of a significant part of the residential buildings (Van den Dobbelsteen et al., 2019). However, this possibility should be explored in further detail in future research.

Considering the grid congestion, it is likely that a range of effects can be found throughout the different scenarios. Other than the well-known effect of the all-electric solutions on grid congestion as stated by Hoetz et al. (2024), the other scenarios will also likely have difficulties of implementation when installed on the grid. An extra impulse of electricity is needed for the TEO systems and due to the current problems regarding grid congestion, grid reinforcement would be necessary. However, the COP of current systems is likely to increase. This could result in a lower electricity demand and therefore a lower impact on grid congestion. Grid reinforcement will also be implemented over time and therefore an increase in electricity demand can then likely be covered. However, it remains unknown when these improvements will be available for implementation. Future studies could provide valuable insights into this problem.

Another element of the research was that the heating demand was relatively fixed for the different housing typologies, resulting in a certain base load that was determined for designing the TEO systems. The base load can arguably be altered, either with an increase in value, or a decrease. An increase in value will most likely lead to a system that needs more space in the subsurface and this will cause an increase in (investments)costs. A decrease in predetermined base load will likely lead to a financially more feasible system, however the CO_2 reduction will likely be less impacted.

It is very plausible for climate change to have a significant impact on the heating and cooling demand for buildings (Amonkar et al., 2023). The study conducted by Amonkar et al. (2023) argues that the heating demand will likely decrease over time. Therefore, it could be argued that the base load of TEO systems could be lower. According to Amonkar et al., the amount of space needed for such systems could therefore be lower. However, during the coldest periods through the year (peak heating demand), the heating demand could increase significantly, albeit periodically. For the cooling demand, the opposite is argued (Amonkar et al., 2023). Cooling demand (drastically) increases by the effects of climate change, with a great emphasis on the peak cooling demand.

If eventually the natural gas facilities (natural gas boilers, etc.) are deemed to be phased out and cooling measures are a key component of dwellings, the alternative (peak) facilities should eventually be sufficient for covering these more extreme peaks. When electrified (using e-boilers, for example), these facilities should be accounted for by the system operators to ensure reliability and avoiding grid congestion (Amonkar et al., 2023).

Another potentially significant addition to the models would be a further analysis of the clustering of buildings that could be connected to the suggested collective energy systems. For example, utility buildings (such as offices) have a (significantly) higher cooling demand, and this is expected to exceed their heating demand in 2050 (Senel & Kruit, 2023). This could influence the design of the TEO systems, due to the imbalance of the ATES systems that could be partially covered by the heat surplus of the utility buildings. The results of this research could therefore be more beneficial when the clusters are complemented with utility buildings. It should be noted that more connections to a collective heat grid would imply more stakeholders to take into consideration. This could greatly the organisational complexity and should therefore be deliberated beforehand.

Furthermore, it could be stated that the differences in certain results as presented in table 10 are relatively small. This could indicate certain flaws in the methodology of the research. As mentioned in the previous paragraphs in this section, certain parts are missing, such as a thorough analysis on cost effectiveness per solution. More thoroughly focused research into the financial impact of these systems (including practical samples) could create different results and potentially diversify the range of the results. For future research, a thorough sensitivity analysis of more of the design choices is advised.

A sensitivity analysis per element of assessment would be recommended as well. The required space, as well as CO_2 reduction and the financial impact per building should be further investigated with a sensitivity analysis. The financial impact of the pipelines, different materials or dimensions, etc. can then be researched in the context of historical city centres. Furthermore, the opportunity of coupling other forms of works (e.g. intensive road works) can then be taken into consideration. The latter, for example, will likely lead to a significant decrease in costs.

In addition, further and different costs analyses are advised for future research. An example of this is the “Startanalyse” as performed by PBL (2025). This method utilises the Vesta MAIS model for comparing the so called “national costs”. These “national costs” includes not only the investment costs, but also the retrofitting of building, the necessary installations in the buildings, but also the costs for grid reinforcement. The analysis however doesn’t take any dimensioning of the system into consideration and generally doesn’t allow for user-friendly changing of the parameters. For example, quay wall integration wouldn’t be part of the model, but the total yearly additional “national costs” would likely still be a relatively more accurate representation of the financial impact of TEO systems. However, it would need to be adjusted for the specific case as presented in this research, since PBL (2025) generally considers national average costs. These costs can significantly increase for historic urban environments.

These “national costs” can be significant to take into consideration. It can introduce the consideration between different design choices. For example, investment costs on a more national level (e.g. grid reinforcement) would be (more) significant for collective systems. However, decreasing the heating demand (e.g. retrofitting the buildings), would lead to more costs for homeowners and would therefore affect the individual residents. This was reflected on by Van der Roest (2023), where it was found that the costs for retrofitting the individual buildings is far higher than the national costs for grid reinforcement. However, it should be noted that the diversity of the energy systems (large collective or local collective systems) is very significant for the feasibility of the energy systems. Local renewable energy systems could provide up to 40% of the total energy demand. This would entail heating and electricity as well as transportation of both.

This research has covered aquathermal energy as the main source for heating, also known as a monovalent alternative. It should be noted that other sustainable alternatives exist as mentioned in Chapter 1. However, other forms of sustainable heating exist as well, but weren’t mentioned in this research. In reality, customisation will be necessary for all different areas that need an alternative for natural gas. For example, certain buildings will not be suitable for connecting to a collective heat grid. Pothof (2025) suggested that 80% of buildings in The Netherlands are suited for low temperature heating. This means that the remaining 20% is not suited and likely will not be eligible for low temperature heat grids, e.g. TEO sourced heat grids. For these buildings, an alternative should be found. Therefore, the ideal situation most likely will not include monovalent solutions for all neighbourhoods. When implementing alternatives for natural gas, it will likely be a mixed scenario, where aquathermal energy will be a piece of the puzzle.

7 Conclusion

This chapter relates the key findings of this research to the previously mentioned research questions that are mentioned in chapter 3. Firstly, all sub research questions will be reflected on. This chapter will conclude with final and overall remarks.

What are spatial and retrofitting requirements for different levels of TEO use?

The spatial and retrofitting requirements have been found for TEO use in the historic city centre of Amsterdam. Retrofitting to LT level was found to be slightly more favourable than retrofitting the buildings to MT level. The costs were lower, and the CO_2 reduction was higher for the LT scenarios, and the LT retrofitting level corresponded with a decrease in heat demand of approximately 56,8%. Retrofitting to LT level requires more adaptations to buildings and will bring significantly more investment costs, however.

The space needed for the different scenarios were not too different in value. However, it could be said that to reduce the space needed for TEO systems further, it would be necessary to decrease the heating demand through higher retrofitting levels of buildings.

How could quay walls be used for TEO installations?

Depending on the available space in the subsurface, quay walls could be utilised for TEO installations as well as parts of their necessary infrastructure. In cases where the base load of the overall heating demand was be lowered, the space needed for a TEO systems would generally decrease. For example, for the MT-1 scenario, approximately 63,28 m^2 was needed to cover a base load of approximately 1.480 kW. When retrofitting the same dwellings to approximately LT level, approximately 50,04 m^2 was needed to cover a base load of 1.194 kW. In both scenarios, approximately 90% of the total annual heat demand was to be covered by the TEO system.

Therefore, it was found that the LT-1, LT-2 and MT-2 scenarios could utilise the quay walls for thermal energy recovery. In terms of amount of space needed for the installations, it could be possible for the quay walls to be used. However, a more thorough analysis would be necessary to validate this.

How do different design choices affect energy delivery?

First of all, the design choice of the base load was found to affect the energy delivery and the efficiency thereof. The scenarios with a higher base load to be delivered by the TEO system (LT-1 and MT-1), the CO_2 reduction was found to be the highest. This effect was underlined by the retrofitting measures. The scenarios where LT retrofitting measures were taken (the LT-1 and LT-2 scenarios) were found to have an increased effect on CO_2 emission reduction after installation, when compared to the other scenarios (the MT-1 and MT-2 scenarios).

Furthermore, the costs were found to be impacted by the number of dwellings that would utilise a collective TEO system to cover the base load of the heat demand. The highest costs were found by the smallest cluster of buildings, whereas the lowest costs per dwelling was found with the highest number of dwellings per cluster (1.333). The optimal cluster size, for financial feasibility, is likely between 500 and 1.333. However, for the MT heat grids it was found that the lowest costs were found for a cluster size of 500. Although the costs would very slightly increase for the cluster size of 1.333, the optimal cluster size for these grids would also likely be between 500 and 1.333.

How much CO_2 can be reduced in different scenarios?

Although highly dependent on availability of the network (grid congestion) and the emission factor of electricity, it was found that the CO_2 reduction was quite significant for TEO systems. Thermal energy recovery and utilisation from surface water in the city centre of Amsterdam therefore seems to be a sustainable alternative for natural gas. Depending on the level of insulation as well as the determined base load carried by the TEO systems and the space availability, the usage of TEO with a natural gas peak facility can save up to approximately 69,81% directly after implementation. This would be achieved with a relatively higher base load determination and an LT heat grid. This would require retrofitting measures to a LT level.

This leads to an overall conclusion, which is that thermal energy recovery and utilisation is likely possible after the right considerations. Insulation levels, as a result of retrofitting the buildings, are of great influence for assessing the applicability of TEO systems in historic city centres.

The results as shown in table 10 are relatively close in value, except the CO_2 reduction. The closeness in available space suggests that a more careful spatial analysis would be necessary for more accurate results. LT systems seem slightly more favourable, due to the amount of kW to be delivered by the TEO system.

The costs were also relatively close in value for all different scenarios. The overall investment costs are mainly determined by the construction and installation of pipelines. Therefore, it is advised to couple these construction with other works, e.g. road works, to reduce the costs of construction.

For the reduction of CO_2, the retrofitting levels were found to have a relatively larger impact. When the base load was then increased, the CO_2 reduction would then be reduced an extra 10%. However, more electricity would be required and this could create difficulties, due to the required grid reinforcement.

Furthermore, the cluster size was found to be most effective between 500 and 1.333 dwellings for installing TEO systems in historic city centres. It would lead to the optimal financial impact per dwelling. This would need to be studied further, because it could not be generalised. However, this research suggests that the optimal number of dwellings per system would be between 500 and 1.333 dwellings.

Finally, it is recommended that more case studies would be done to demonstrate the performance of the used models as well as a more accurate analysis of said availability of space. This research showed a first order estimation of the boundary conditions for TEO to be utilised in the historic city centre of Amsterdam, including integration in the quay walls.

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Appendices

Appendix A. Tree rooting calculations

Licentiehouder — **Blad 1 van 2**

Projectgegevens

Project	Voorbeeld groeivolume bomengranulaat
Projectcode	
Projectomschrijving	
Gebruiker	Joeri Faas
Plaats	
Datum (aanmaak)	28-08-2023

Boomsoort (boomgrootte)

Invoer *Automatisch (boomsoort)*

Boomsoort

Ulmus 'Dodoens' I 1e grootte

H20m, cultivar, opgaande takstructuur met donker glanzende bladeren, weinig gevoelig voor iepziekte

Stand- en groeiplaats

Maaiveld bodemtype	*Verharding (zware belasting 'rijweg' I ...*
Profieltype	*Grondwater (direct contact GWST)*
Doorwortelbare diepte	*1.2 m -m.v.*

Boominfo

Omloop (cyclus)

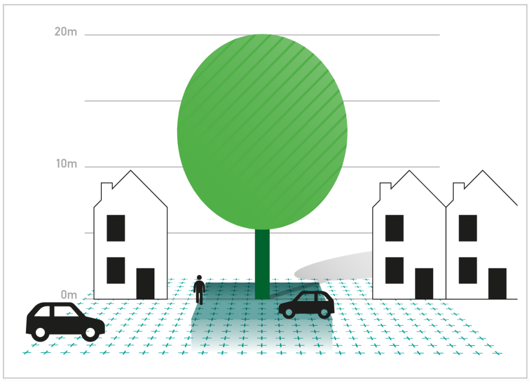
Regulier (duurzaam groeiend)	20	40	60	80	jaar

Benodigde doorwortelbare ruimte (m³) en grondvlak (m²)

(ambitieniveau) Optimaal	19.2	33	41.2	49.5	m³
	16	27.5	34.3	41.2	m²
(ambitieniveau) Redelijk	15.4	26.4	33	39.6	m³
	12.8	22	27.5	33	m²
(minimum niveau) Marginaal	11.5	19.8	24.7	29.7	m³
	9.6	16.5	20.6	24.7	m²

Doorwortelbare diepte	1.2	1.2	1.2	1.2	m
Bovengronds opstakelvrij	4.2	7.2	9	10.8	m
Ondergronds obstakelvrij = minimale graafafstand	1.5	1.7	2.1	2.6	m
Kroonbreedte (verloop) = plantafstand	7	12	15	18	m
Plantspiegel	1.5 x 1.5	1.7 x 1.7	2.1 x 2.1	2.6 x 2.6	m

Opmerkingen:

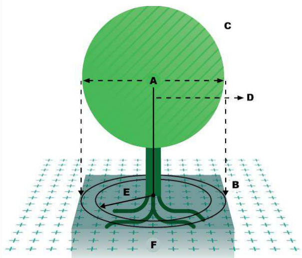


Soortkeuze

Ulmus 'Dodoens' I 1e grootte

Boomkroonvolume = BKV

Boomgrootte	1e grootte (eindhoogte > 15m) I Normale kroon				
Boomkroondiameter	7	12	15	18	m
Boomkroonprojectie	38	113	177	254	m²
Boomkroonvolume (BKV)	150	800	2.000	4.000	m³



Maatvoeringen:

Bovengronds:
A. Kroondiameter (m)
B. Kroonprojectie (m²)
C. Boomkroonvolume BKV (m³)
D. Obstakelvrije zone bovengronds (m)

Ondergronds:
E. Obstakelvrije zone ondergronds (m) = minimale graafafstand
F. Doorwortelbare ruimte (m³)

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Licentiehouder

Boommonitor: Bomenontwerp (uitgangspunten)

Samengevat:

Boomgrootte	1e grootte
Kroonbreedte	Normale kroon
Ambitieniveau	Redelijk
Omloop	40 jaar

Bovengronds:

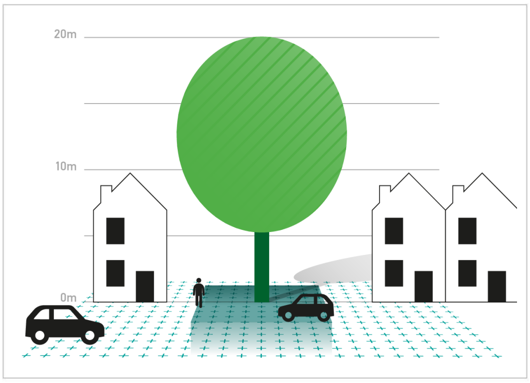
A. Kroondiameter = indicatie plantafstand	12 m
B. Kroonprojectie	113 m²
C. Boomkroonvolume (BKV)	800 m³
D. Obstakelvrije zone (bovengronds)	7.2 m

Ondergronds:

E. Obstakelvrije zone (ondergronds) = minimale graafafstand	1.7 m
F. Doorwortelbare ruimte	26.4 m³

Groeiplaats:

Profieltype	Grondwater
Doorwortelbare diepte	1.2 m -m.v.
Inhoud (m³)	26.4 m³
Grondvlak (m²)	22 m²
Minimale breedte groeiplaats ter hoogte van standplaats boom	3.4 m
(Open)boomspiegel	1.7 x 1.7 m
Voorbeeld afmetingen (l x b x d)	4.7 x 4.7 x 1.2 m



Soortkeuze

Ulmus 'Dodoens' I 1e grootte

Verharding (zware belasting 'rijweg' I skeletbouw bomengranulaat (breuksteen)

Grondwater (direct contact GWST) 1.2 meter -m.v.

Uitgangspunten:

Doorwortelbare diepte: indien het profiel grondwater gerelateerd is kies dan GHG (Gemiddeld Hoogste Grondwaterstand) voor de doorwortelingsdiepte.

Bij een doorwortelbare diepte van < 0.60 m dient de reguliere aanplant van bomen in de verharding (zeer) terughoudend te worden benaderd, zie [Handboek Bomen I H1 I Bomenontwerp].

Obstakelvrije zones, plantafstand en minimale graafafstanden gelden vanuit het hart van de boom (stamvoet). Minimale graafafstand is mede afhankelijk van bewortelbare diepte, wortelontwikkeling en lokale windbelasting. Beperkte bewortelingsdiepte (< 75 cm), eenzijdige wortelontwikkeling (specifiek wortels trekzijde) en hoge (lokale) windbelasting noodzaken tot een eventuele verruiming van de minimum graafafstand (zie Handboek Bomen I H2 I Werken rond Bomen).

Voor aanvullende detailgegevens wordt verwezen naar het tabblad 'Boominfo' en het Handboek Bomen I H1 I Bomenontwerp.

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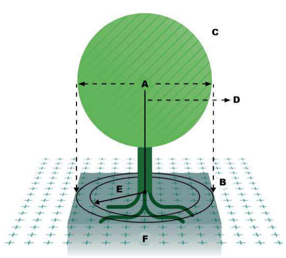
Projectgegevens

Project	Voorbeeld groeivolume bomengranulaat
Projectcode	
Projectomschrijving	
Gebruiker	Joeri Faas
Plaats	
Datum (aanmaak)	Maandag 28 Augustus 2023



Maatvoeringen:

Bovengronds:
A. Kroondiameter (m)
B. Kroonprojectie (m²)
C. Boomkroonvolume BKV (m³)
D. Obstakelvrije zone bovengronds (m)

Ondergronds:
E. Obstakelvrije zone ondergronds (m) = minimale graafafstand
F. Doorwortelbare ruimte (m³)

Figure 1: Tree rooting example, without rooting control measures taken (J. Faas, personal communication, August 28, 2023)

Licentiehouder

Projectgegevens

Project	Voorbeeld groeivolume boombunker
Projectcode	
Projectomschrijving	
Gebruiker	Joeri Faas
Plaats	
Datum (aanmaak)	28-08-2023

Boomsoort (boomgrootte)

Invoer *Automatisch (boomsoort)*

Boomsoort

Ulmus 'Dodoens' I 1e grootte

H20m, cultivar, opgaande takstructuur met donker glanzende bladeren, weinig gevoelig voor iepziekte

Stand- en groeiplaats

Maaiveld bodemtype	*Verharding (zware belasting, zelfdragen...*
Profieltype	*Grondwater (direct contact GWST)*
Doorwortelbare diepte	*1.2 m -m.v.*

Boominfo

Omloop (cyclus)

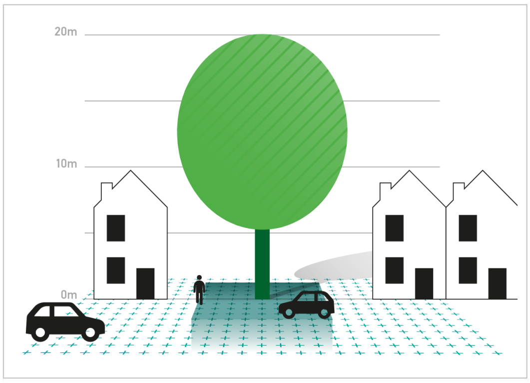
Regulier (duurzaam groeiend)	20	40	60	80	jaar

Benodigde doorwortelbare ruimte (m³) en grondvlak (m²)

(ambitieniveau) Optimaal	8.2	14.1	17.7	21.2	m³
	6.9	11.8	14.7	17.7	m²
(ambitieniveau) Redelijk	6.6	11.3	14.1	17	m³
	5.5	9.4	11.8	14.1	m²
(minimum niveau) Marginaal	4.9	8.5	10.6	12.7	m³
	4.1	7.1	8.8	10.6	m²

Doorwortelbare diepte	1.2	1.2	1.2	1.2	m
Bovengronds opstakelvrij	4.2	7.2	9	10.8	m
Ondergronds obstakelvrij = minimale graafafstand	1.5	1.7	2.1	2.6	m
Kroonbreedte (verloop) = plantafstand	7	12	15	18	m
Plantspiegel	1.5 x 1.5	1.7 x 1.7	2.1 x 2.1	2.6 x 2.6	m

Opmerkingen:

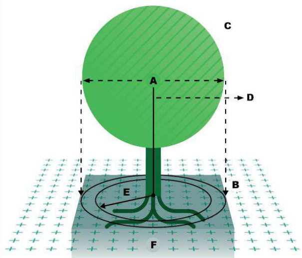


Soortkeuze

Ulmus 'Dodoens' I 1e grootte

Boomkroonvolume = BKV

Boomgrootte	1e grootte (eindhoogte > 15m) I Normale kroon				
Boomkroondiameter	7	12	15	18	m
Boomkroonprojectie	38	113	177	254	m²
Boomkroonvolume (BKV)	150	800	2.000	4.000	m³



Maatvoeringen:

Bovengronds:
A. Kroondiameter (m)
B. Kroonprojectie (m²)
C. Boomkroonvolume BKV (m³)
D. Obstakelvrije zone bovengronds (m)

Ondergronds:
E. Obstakelvrije zone ondergronds (m) = minimale graafafstand
F. Doorwortelbare ruimte (m³)

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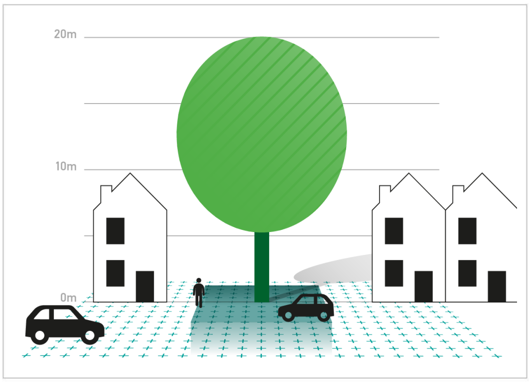
Licentiehouder — Blad 2 van 2

Boommonitor: Bomenontwerp (uitgangspunten)

Samengevat:

Boomgrootte	1e grootte
Kroonbreedte	Normale kroon
Ambitieniveau	Redelijk
Omloop	40 jaar
Bovengronds:	
A. Kroondiameter = indicatie plantafstand	12 m
B. Kroonprojectie	113 m²
C. Boomkroonvolume (BKV)	800 m³
D. Obstakelvrije zone (bovengronds)	7.2 m
Ondergronds:	
E. Obstakelvrije zone (ondergronds) = minimale graafafstand	1.7 m
F. Doorwortelbare ruimte	11.3 m³
Groeiplaats:	
Profieltype	Grondwater
Doorwortelbare diepte	1.2 m -m.v.
Inhoud (m³)	11.3 m³
Grondvlak (m²)	9.4 m²
Minimale breedte groeiplaats ter hoogte van standplaats boom	3.4 m
(Open)boomspiegel	1.7 x 1.7 m
Voorbeeld afmetingen (l x b x d)	3.1 x 3.1 x 1.2 m



Soortkeuze

Ulmus 'Dodoens' I 1e grootte

Verharding (zware belasting, zelfdragende wortelbunker invulling met bomengrond 7-10% org.)

Grondwater (direct contact GWST) 1.2 meter -m.v.

Uitgangspunten:

Doorwortelbare diepte: indien het profiel grondwater gerelateerd is kies dan GHG (Gemiddeld Hoogste Grondwaterstand) voor de doorwortelingsdiepte.

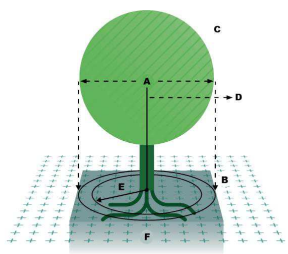
Bij een doorwortelbare diepte van < 0.60 m dient de reguliere aanplant van bomen in de verharding (zeer) terughoudend te worden benaderd, zie [Handboek Bomen I H1 I Bomenontwerp].

Obstakelvrije zones, plantafstand en minimale graafafstanden gelden vanuit het hart van de boom (stamvoet). Minimale graafafstand is mede afhankelijk van bewortelbare diepte, wortelontwikkeling en lokale windbelasting. Beperkte bewortelingsdiepte (< 75 cm), eenzijdige wortelontwikkeling (specifiek wortels trekzijde) en hoge (lokale) windbelasting noodzaken tot een eventuele verruiming van de minimum graafafstand (zie Handboek Bomen I H2 I Werken rond Bomen).

Voor aanvullende detailgegevens wordt verwezen naar het tabblad 'Boominfo' en het Handboek Bomen I H1 I Bomenontwerp.

Projectgegevens

Project	Voorbeeld groeivolume boombunker
Projectcode	
Projectomschrijving	
Gebruiker	Joeri Faas
Plaats	
Datum (aanmaak)	Maandag 28 Augustus 2023



Maatvoeringen:

Bovengronds:
- A. Kroondiameter (m)
- B. Kroonprojectie (m²)
- C. Boomkroonvolume BKV (m³)
- D. Obstakelvrije zone bovengronds (m)

Ondergronds:
- E. Obstakelvrije zone ondergronds (m) = minimale graafafstand
- F. Doorwortelbare ruimte (m³)

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Figure 2: Tree rooting example, with rooting control measures (boombunker) taken (J. Faas, personal communication, August 28, 2023)