A sustainable heating and cooling system at the district-level in Utrecht

Design and techno-economic analysis of a district heating and cooling system
with aquifer thermal energy storage (ATES) and thermal energy from surface water (TEO)

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Abstract

To meet climate change mitigation targets, more attention has to be paid to the decarbonization of the heating sector. The Dutch government decided that all residential buildings should be off gas in 2050. They expect municipalities to play a crucial role in reaching this goal. The Municipality of Utrecht aspires a gas-free energy system for two districts currently under development: Beurskwartier area and Lombokplein area. The potential of developing a collective aquifer thermal energy storage (ATES) system combined with district heating (DH) for peak supply and thermal energy from surface water (TEO) for regeneration is under discussion in this area. This research designs a sustainable heating and cooling system in the Beurskwartier and Lombokplein area by carrying out a techno-economic analysis on implementing a collective ATES system combined with DH and TEO.

Three ATES systems currently in place, owned by Jaarbeurs, Rabobank and Nederlandse Spoorwegen (NS), supply less heating and cooling compared to the maximum allowable supply according to the permits, which suggest extra heating and cooling is available for a potential collective ATES system in Beurskwartier and Lombokplein area. The future heating and cooling demand of the Beurskwartier and Lombokplein area is based on building characteristics such as the surface (m^2), construction year or level of insulation and the type of building (e.g. residential or office). Heating and cooling demand data from two datasets are used: Uniforme Maatlat Gebouwde Omgeving (UMGO) and Vesta. This results in a space heating, cooling and domestic hot water (DHW) demand of 8353 MWh, 4028 MWh and 3156 MWh respectively in the Beurskwartier area and 4058 MWh, 2208 MWh and 837 MWh respectively in the Lombokplein area. This studies shows that assumptions made regarding heating and cooling demand calculations (e.g. chosen data set) have large implications on the design and costs of the heating and cooling system, as the design of an energy systems is often based on the largest peaks. A model built in EnergyPRO compared the heating and cooling demand with the maximum heating and cooling supply of the potential collective ATES system, based on six doublets in the Beurskwartier area and three doublets in the Lombokplein area. Both collective ATES systems do not have enough capacity to supply the areas with sufficient heating and cooling throughout the whole year. Extra peak supply is needed during cold winter days and hot summer days. Four scenarios are developed: collective ATES, TEO and DH (reference), collective ATES, dry coolers and DH (scenario 1), collective ATES, TEO and biomass boiler (scenario 2) and collective ATES including existing ATES systems, TEO and DH (scenario 3). The most optimal technical performance (lowest energy input and primary energy input) is achieved by scenario 3 and the most optimal economic scenario (lowest LCOE and PBP) is achieved by scenario 1. From an investor point of view, all scenarios have a low IRR (< 8%), which makes investments from private parties less expected.

Abbreviations

ATES	Aquifer thermal energy storage
BENG	Bijna Energie Neutrale Gebouwen
CDD	Cooling degree days
COP	Coefficient of performance
DH	District heating
DHW	Domestic hot water
HDD	Heating degree days
HP	Heat pump
HT	High-temperature
IRR	Internal rate of return
LCOE	Levelized cost of energy
LT	Low-temperature
MW	Megawatt
MWh	Megawatt hour
NPV	Net present value
nZEB	Nearly Zero Energy Buildings
O&M	Operation and maintenance
PBP	Payback period
PEF	Primary energy factor
PV	Photovoltaic
TEO	Energy from surface water
UMGO	Uniforme Maatlat Gebouwde Omgeving
Vesta	Vesta MAIS model

COP_{HP}	Heat pump COP
COP_{Lor}	Lorentz COP
η_s	System efficiency
T_a	Ambient air temperature (°C)
T_{ref}	Reference temperature (°C)
$T_{H,LM}$	Logarithmic mean temperature of delivered hot water (K)
$T_{L,LM}$	Logarithmic mean temperature of heat source (K)
$T_{s,FH}$	Supply temperature floor heating (°C)
$T_{r,FH}$	Return temperature floor heating (°C)
$T_{s,DHW}$	Supply temperature DHW (°C)
$T_{well,h}$	Average temperature of hot well (°C)
$T_{well,c}$	Average temperature of cold well (°C)
$P_{doublet}$	Power output doublet (MW)
$\dot{m}$	Flow rate (m^3/h)
C_p	Specific heat capacity (kJ/kg/°C)
ΔT	Temperature difference (°C)

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1. Introduction

1.1 Background

Climate change mitigation requires countries to undertake ambitious efforts in reducing greenhouse gas emissions. The Netherlands has a national energy agenda aiming to achieve a CO_2 neutral energy supply system by 2050 (Ministerie van Economische Zaken, 2016). Researchers state that more attention has to be paid to the decarbonization of the heating sector in order to meet such climate change mitigation targets (Fleuchaus et al., 2018). A large share (32%) of the total final energy consumption in the Netherlands is for heating purposes in the built environment (Schoots et al., 2017). Natural gas is the main primary energy source for supplying heat in the built environment. At the moment, 95% of the dwellings in the Netherlands is connected to the gas grid (Natuur en Milieu, 2017). Recently the use of natural gas has given rise to public resistance, which is mainly caused by social and environmental concerns related to the gas drilling in Groningen (Boelhouwer & van der Heijden, 2018). In response to these issues, the Dutch government decided that all residential buildings should be off gas in 2050 (Ministerie van Economische Zaken, 2016). Municipalities are requested to play a crucial role in reaching this goal. In the national energy agenda it is stated that municipalities are given full responsibility to make decisions, in cooperation with the local network operator, about their local energy supply (Ministerie van Economische Zaken, 2016). In addition, the Dutch climate agreement states that municipalities must draw up a transition vision at municipal level and compose implementation plans at a district level (Sectortafel Gebouwde Omgeving, 2018). This highlights the need for sustainable heating strategies on a district level.

While sustainable heating strategies at the district level receive attention by media and public bodies, discussion about sustainable cooling often goes unnoticed. Various studies expect an increasing demand for sustainable cooling in the coming years (RVO, 2018). This is caused by multiple developments such as temperature increase due to climate change or urban heat island effects (TNO, 2012), improved insulation in buildings and higher expectations of comfort (RVO, 2018). These developments suggest to also include sustainable cooling when drawing up sustainable heating strategies.

1.2 State of current research

Sustainable heating strategies at the district level consist of demand side measures as well as supply side measures. Demand side measures are mostly energy saving measures required to reduce the heating demand of buildings. The energy performance of buildings and potential energy saving measures are extensively studied in scientific research (Aditya et al., 2017; Allouhi et al., 2015; Raji et al., 2015). Also at the district-level, researchers assessed the potential heat demand reduction by renovation measures and its associated costs (van den Wijngaart et al., 2018). Supply side strategies refer to the replacement of heat from fossil-based energy sources with heat from renewable sources. Several heat roadmaps have been proposed, either on European level (Connolly et al., 2014) or national level (Menkveld et al., 2018). At a city or district level, the majority of literature on sustainable heating concerns the optimization of operation strategies (Sameti & Haghighat, 2017; Wang et al., 2015; Weber et al., 2007).

Sustainable cooling strategies at the district level are less represented in scientific articles. At European level, the Heat Roadmap mapped the cooling potential in the EU and provided some sustainable cooling strategies (Connolly et al., 2014). More research about sustainable cooling was done at the building level, in which articles reviewed various individual sustainable cooling technologies (Hepbasli, 2012; Hughes et al., 2011; Mateus & Oliveira, 2009).

Lake et al. (2017) presented a comprehensive review on district heating and cooling systems and concluded that combined district heating and cooling systems have higher efficiencies compared to individual heating or cooling systems. Some studies in Scandinavian countries have tried to identify the optimal choice of technologies and fuels for a sustainable heating and cooling system based on technical, economic and environmental parameters (Abdurafikov et al., 2017; Amer-allam et al., 2017; Gebremedhin, 2014). This integrated research approach for combined heating and cooling systems at the district level is currently underrepresented in the Netherlands.

1.3 Case description and problem definition

The Municipality of Utrecht would serve as an interesting case for this type of research, as they are a frontrunner in terms of alternative heating. A large share (29%) of the dwellings in Utrecht is connected to a district heating (DH) system (CBS, 2017). This DH system is delivering heat to over 40.000 buildings and is currently fed by natural gas, but will partly be fed by biomass, geothermal heat and other renewable sources in the coming years (Eneco, 2018a). The Municipality of Utrecht is also planning on expanding the building stock with new residential and non-residential buildings. Two areas currently under development are the Beurskwartier area and Lombokplein area. The Municipality of Utrecht aspires a gas-free energy system for these areas. The Municipality of Utrecht plans to build new residential buildings (238,800 m^2), offices (50,000 m^2), a mix of residential buildings and offices (20,000 m^2) and buildings with cultural or recreational purposes (22,000 m^2) in the Beurskwartier and Lombokplein area (Municipality of Utrecht, 2017). The constructions will be finished around 2040. The area will become densely populated with low-rise constructions as well as high-rise constructions. Low-rise buildings will vary in height between 12, 25 or 45 meters, while high-rise buildings vary in height between 70-90 meters. Besides these planned buildings, the Beurskwartier and Lombokplein area also consists of already existing buildings such as the train station terminal, the Jaarbeurs, a theatre, a cinema, offices and dwellings from social housing corporation Mitros. Some buildings are supplied with heat via DH or a connection to the gas grid. Others are provided with heating and cooling supplied by aquifer thermal energy storage (ATES) systems combined with DH. In this case the connection to DH plays a role in meeting the peak heat demand. Figure 1 shows an overview of all buildings and their type of heat supply connection.

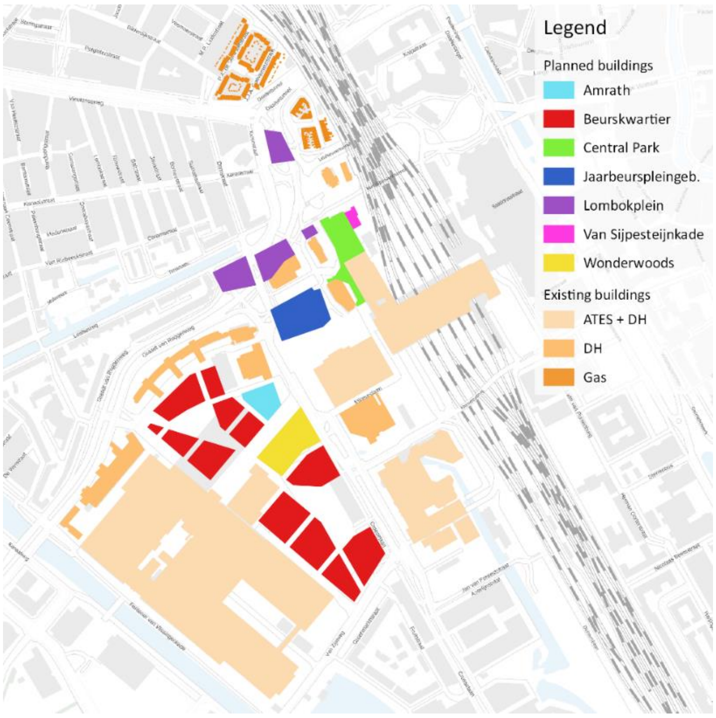


Figure 1 Map of buildings in the Beurskwartier and Lombokplein area

Currently, three ATES systems are in place in the Beurskwartier and Lombokplein area, owned by the Jaarbeurs, Rabobank and the Nederlandse Spoorwegen (NS). There are also potential sources for new ATES systems in the Beurskwartier and Lombokplein area (Schuurman et al., 2017). In addition, the Merwede and Leidsche Rijn canal, situated at the Westside of the Beurskwartier area, could serve as a potential source for thermal energy from surface water (TEO). Geographical constraints, dense existing use of ATES and stringent guidelines to allow for well distances limit the available space for new wells (Jaxa-Rozen, 2019), which makes individual use of ATES systems undesirable. Subsequently, the potential of developing a collective ATES system, possibly combined with DH and TEO, is under discussion in this area.

1.4 Objective and research questions

Based on above-mentioned discussion, the aim of this research is to *"Design a sustainable heating and cooling system in the Beurskwartier and Lombokplein area by carrying out a techno-economic analysis on implementing a collective ATES system combined with DH and TEO."*

In order to achieve the research objective, some sub-questions were formulated.

1. What are the characteristics (in terms of heating and cooling supply) of the ATES systems currently in place at the Beurskwartier and Lombokplein area?
2. What is the estimated heating and cooling demand of the Beurskwartier and Lombokplein area in 2040?
3. To what extent can a collective ATES system meet the future heating and cooling demand of the Beurskwartier or Lombokplein area?
4. What is the sustainable heating and cooling system with the most optimal techno-economic performance in the Beurskwartier and Lombokplein area?

1.5 Scientific and societal relevance

This study is expected to deliver several contributions to the state of current research. This research provides in-depth insights from a district-level perspective on the optimal use of a heating and cooling system. It attempts to further develop the existing knowledge about distributed heating and cooling systems by examining the possible configurations between ATES systems and other supply technologies such as DH and TEO. Besides sustainable heating, this research also focusses on sustainable cooling, a topic that is currently underrepresented by academia. From a more broader perspective, the outcome of this research can serve as useful tool to stimulate the decision-making process of new energy concepts at the district level. Local governmental organizations, energy suppliers or network operators could also benefit from methodological steps taken in this research, when developing heat related strategies.

2. Theoretical background

Municipalities in the Netherlands need to define heat related strategies towards a low-carbon emission built environment for each district within its borders. This chapter describes a range of possible heat transition pathways for the built environment on a district level (section 2.1). The next sections (section 2.2 and 2.3) provide a more in-depth background on the technologies considered in the Beurskwartier and Lombokplein area in Utrecht.

2.1 Heat transition strategies on a district level

Multiple heat related strategies are able to contribute to the heat transition on a district level. These strategies include energy saving measures as well as alternatives for fossil-based heating and cooling systems such as electrification or the implementation of district heating. Energy saving measures mainly refer to better insulation of buildings. Though insulation is an important first step, it is only feasible to a certain extent. Mathiesen et al. (2016) state that energy renovations should only be invested up until the point in which the cost of further renovations exceed the cost of supplying heat to the building. This research therefore focusses on alternatives for fossil-based heating and cooling systems. Various gas-free alternative heating and cooling options are available. Rijksdienst voor Ondernemend Nederland (RVO) created an overview for municipalities of technologies suited for a district-level heat transition in the built environment: biomass boiler, solar thermal collector, air or ground sourced heat pump, hybrid heat pump, ATES system, deep geothermal system, district heating and power to heat. These technologies differ in *energy source*, *temperature of heat delivered* and *system design (individual or collective)* (RVO, 2017).

Multiple energy sources can be used for energy systems. A system is appointed all-electric when the only energy source is electricity (e.g. in case of heat pumps). Heating and cooling can also be provided by biomass sources (e.g. wood pellets) or renewable gas (e.g. biogas or power to gas). In addition, shallow and deep geothermal energy sources (e.g. used for ATES or deep geothermal energy systems) have proven to be able to deliver energy. Other energy sources include waste heat (e.g. industrial waste heat or heat from data centres) or energy from water (e.g. TEO or waste water treatment plants (WWTP)).

The temperature of the heat delivered by a heating and cooling system can be divided into low-temperature (LT) heat and high temperature (HT) heat, which refers to temperature ranges of 35-70 ^{o}C and 70-90 ^{o}C respectively (Lund et al., 2014). From a system perspective, researchers have found that LT heat entails synergistic supply benefits (Averfalk & Werner, 2018; Lund et al., 2014). The utilisation of more heat becomes accessible, solar thermal collectors operate at higher efficiencies, heat pumps utilise ambient heat sources with lower demand of electricity and heat losses in DH networks decrease. In the Netherlands, the possibility to utilise old mines in Heerlen as LT resources has been tested (Verhoeven et al., 2014).

Heating and cooling systems can be designed as individual and collective systems, depending on whether energy is delivered to an individual building (e.g. in case of an individual heat pump) or a group of buildings (e.g. in case of district heating). However, it is expected that intermediate forms will arise, such as heat pumps in combination with low-temperature heat networks.

Table 1 provides an overview of the sustainable heating and cooling technologies identified by RVO, classified by energy source, temperature and system design.

Table 1 Overview of sustainable heating technologies

Technology	Temperature	System design	Energy source
Biomass boiler	HT	Individual	Biomass
Solar thermal collector	LT	Individual	Sun
Hybrid heat pump	HT	Individual	Electricity Renewable gas
Air or ground sourced heat pump	LT	Individual	Electricity
ATES	LT	Individual/Collective	Electricity
Deep geothermal system	HT	Collective	Deep geothermal energy
LT district heating	LT	Collective	Datacentre WWTP ATES TEO
HT district heating	HT	Collective	Industrial waste heat Biomass Deep geothermal heat
Power to heat	LT	Collective	Electricity

Which option is most preferable for a district also depends on the *type of buildings* and *insulation of buildings* within the district (Bruin, 2017; Over Morgen, 2017). For example, Bruin (2017) compared the costs of alternatives for natural gas in newbuild homes and concluded that heat pumps are less attractive for mid- and high-rise buildings compared to dwellings as the high initial investment costs consume a relatively larger part of the total construction costs. In addition, an older building with a higher temperature internal distribution system like radiators will require high temperature heat, while modern buildings with a low temperature internal distribution system will require low temperature heat. Furthermore, all-electric and LT heat solutions require a certain level of insulation within the a building (Over Morgen, 2017).

Leeuwen et al. (2017) distinguish two heat transition strategies that receive most attention in urban areas the Netherlands: the individual approach and the collective approach. In the individual approach, natural gas boilers for each building are replaced by a heat pumps. The electricity is supplied by renewable energy from solar PV and an increasing number of regional wind turbines. Electric and thermal storage are sometimes part of the building energy system. This approach is mostly adopted in new building projects or renovation projects. In the collective approach, buildings are connected to district heating. Currently, waste and biomass conversion are mainly used as renewable energy sources.

The Energy Protocol of the Municipality of Utrecht asks project developers to first seek heating and cooling solutions at the building site (Gemeente Utrecht, 2019). However, some sustainable heating and cooling systems are not suitable for the Beurskwartier and Lombokplein area. The area will become densely populated with many high-rise constructions. Individual solutions such as heat pumps in combination with photovoltaic (PV) panels or solar thermal systems are not straightforward solutions due noise pollution and limited space availability at roofs. The Municipality of Utrecht also excluded renewable gas and wood pellet stoves as possible solutions. Wood pellet stoves are not preferred for air quality reasons (Bäfver et al., 2011) and renewable gas is not preferred due to its limited availability (CE Delft, 2018a). As a result, other heating and cooling sources within the district, such as the existing DH system, existing and potential ATES wells and the Merwede and Leidsche Rijn canal, might serve as a solution. For these reasons, this research takes DH, ATES and TEO into account as potential components for the sustainable heating and cooling system in the Beurskwartier and Lombokplein area.

2.2 Aquifer Thermal Energy Storage (ATES)

Aquifer Thermal Energy Storage (ATES) is a form of underground thermal energy storage and is applied to provide heating and cooling to buildings. It has attracted increasing attention as it can tackle the seasonal mismatch of thermal energy demand and supply. An ATES system combines a heat pump with seasonal thermal storage in the subsurface. It uses sensible heat and cold that is temporarily stored in the subsurface through injection and withdrawal of groundwater (Fleuchaus et al., 2018). A typical ATES system consists of two groundwater wells (called a doublet): one used for the storage of cold and one for the storage of heat. In wintertime, warm groundwater is extracted from heat storage well and directed to through a heat exchanger to provide heating to a building. This cools down the groundwater, which is subsequently injected back into the aquifer through the cold storage well (Sommer, 2015). In summertime, the flow direction of this process is reversed. A schematic representation of this process is shown in Figure 2.

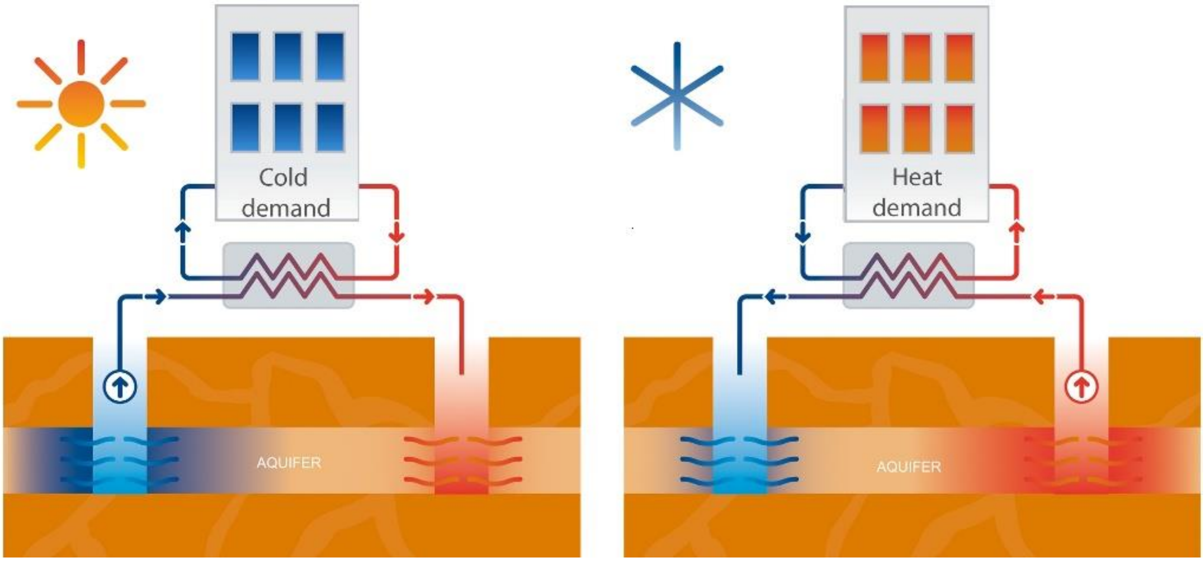


Figure 2 Schematic representation of ATES system in summer and winter time (IF Technology, 2017a)

The use of ATES systems has been rapidly growing, especially in the Netherlands were over 3000 systems are currently active in urban areas (Jaxa-Rozen et al., 2016). The Netherlands has become the largest market for ATES systems and by now the use of ATES systems has become a standard in the commercial buildings sector (IF Technology, 2017a). At the moment, scientific research is mainly focussed on the successful management of these systems. Bloemendal et al. (2014) sought solutions for the institutional hindrances to the diffusion of ATES systems and found that future governance may include self-organization or self-governance. Jaxa-Rozen et al. (2016) tried to identify an efficient trade-off between individual economic returns and collective energy-saving performance. This study showed the beneficial role of positive thermal interactions between ATES wells of similar temperatures, compared to a case which attempts to minimize any thermal interactions between systems. In addition, a case study of ATES development in the Beurskwartier area in Utrecht investigated the performance of ATES systems across different scenarios for spatial planning (Jaxa-Rozen, 2019). This study found that the scarcity of space for further development of ATES may be largely artificial considering that the guideline for thermal interference is in itself conservative. An adaptive permitting approach could allocate subsurface volume more efficiently.

2.3 Thermal energy form surface water (TEO)

Thermal energy from surface water (TEO) is a relatively new concept and is still in the development phase (Van Schaik et al., 2017). However, the concept does not involve large-scale technological innovation. The technologies used in order to utilize TEO are proven technologies such as heat exchangers, heat pumps and ATES systems. From the source (the surface water) heat or cold is extracted with a heat exchanger. The heat or cold is then distributed either directly to a building or to an ATES system. Combining these technologies in order to link surface water with an energy system makes it an innovative approach. The application of extracting heat from TEO in combination with ATES is particularly useful when the heating demand is larger than the cooling demand. In this case TEO could provide extra heat and serve as regeneration method (IF Technology, 2018). Figure 3 provides an overview of the energy flows of a TEO system combined with ATES.

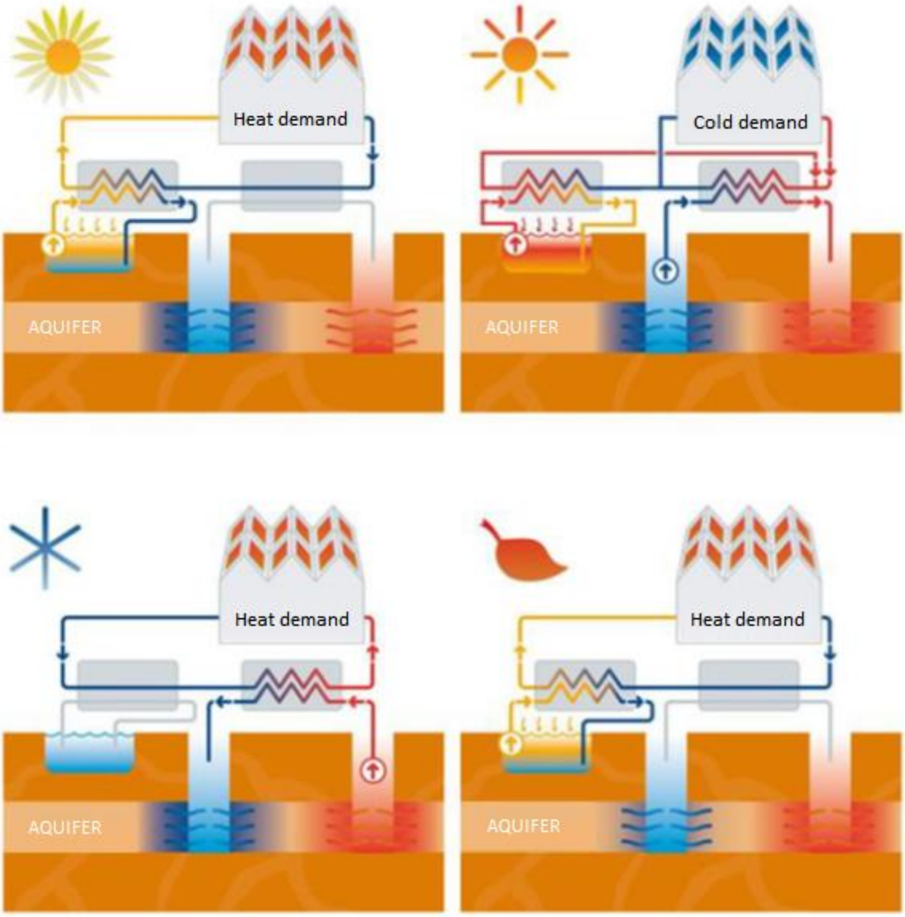


Figure 3 Schematic representation of TEO and ATES system in spring, summer, winter and fall (IF Technology, 2017c)

TEO seems to be a relatively unknown concept amongst the international scientific community. In the Netherlands, some studies have assessed the theoretical potential of TEO, either on national scale (CE Delft, 2018b) or regional scale (IF Technology, 2017b). These studies concluded TEO is particularly interesting in areas where heat is supplied with temperatures lower than 70 ºC. It was found that TEO has an economic potential of around 150 PJ per year, which is more than 40% of the total future heat demand of 350 PJ per year in the built environment (CE Delft, 2018b). Another study developed a business case to investigate the technical and financial feasibility of TEO systems (IF Technology, 2018). It showed that a heating and cooling concept including TEO is technically and financially feasible for a specific case (‘Baronie Haven’) in Alphen aan den Rijn.

3. Method

This chapter provides an overview of all steps taken to answer the research questions. The methodological steps of this research are divided in four phases. Each phase uses a different method in order to answer a sub-question. An overview is presented in Figure 4. A brief case description of the Beurskwartier and Lombokplein area is presented (section 3.1), after which all four phases are discussed (section 3.2, 3.3, 3.4 and 3.5).

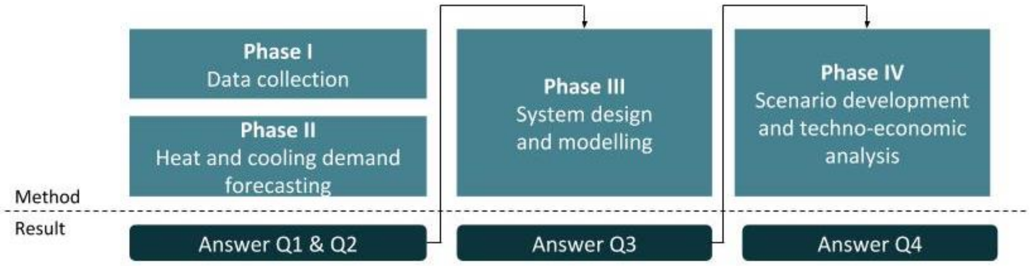


Figure 4 Overview of methodological steps

3.1 Case description

The Beurskwartier and Lombokplein area currently have three ATES systems in place: the Jaarbeurs, Rabobank and NS. Multiple consumers are connected to these ATES systems. The ATES system of the Jaarbeurs is connected to the Jaarbeurs hall, Beatrix theatre and Kinepolis cinema. The ATES system of the Rabobank is connected to all office building of the Rabobank and the ATES system of NS is connected to the train station terminal and Stadskantoor. There is also potential for new ATES systems. The maximum amount of doublets that can be established without interfering with other ATES systems is determined in a geological study commissioned by the Municipality of Utrecht. In the Beurskwartier area a maximum amount of 6 new doublets can be established and in the Lombokplein area a maximum of 3 new doublets (Schuurman et al., 2017). A more recent study within this area however found that new ATES wells can be placed closer to each other without interfering, which means that more ATES wells can be established (Jaxa-Rozen, 2019). This is not taken into account in this research, as this is currently not in accordance with the permit guidelines (Jaxa-Rozen, 2019). Figure 5 shows an overview of the current ATES systems and its consumers and the potential areas for new ATES systems and its potential consumers, which are the remaining buildings in the Beurskwartier and Lombokplein area.

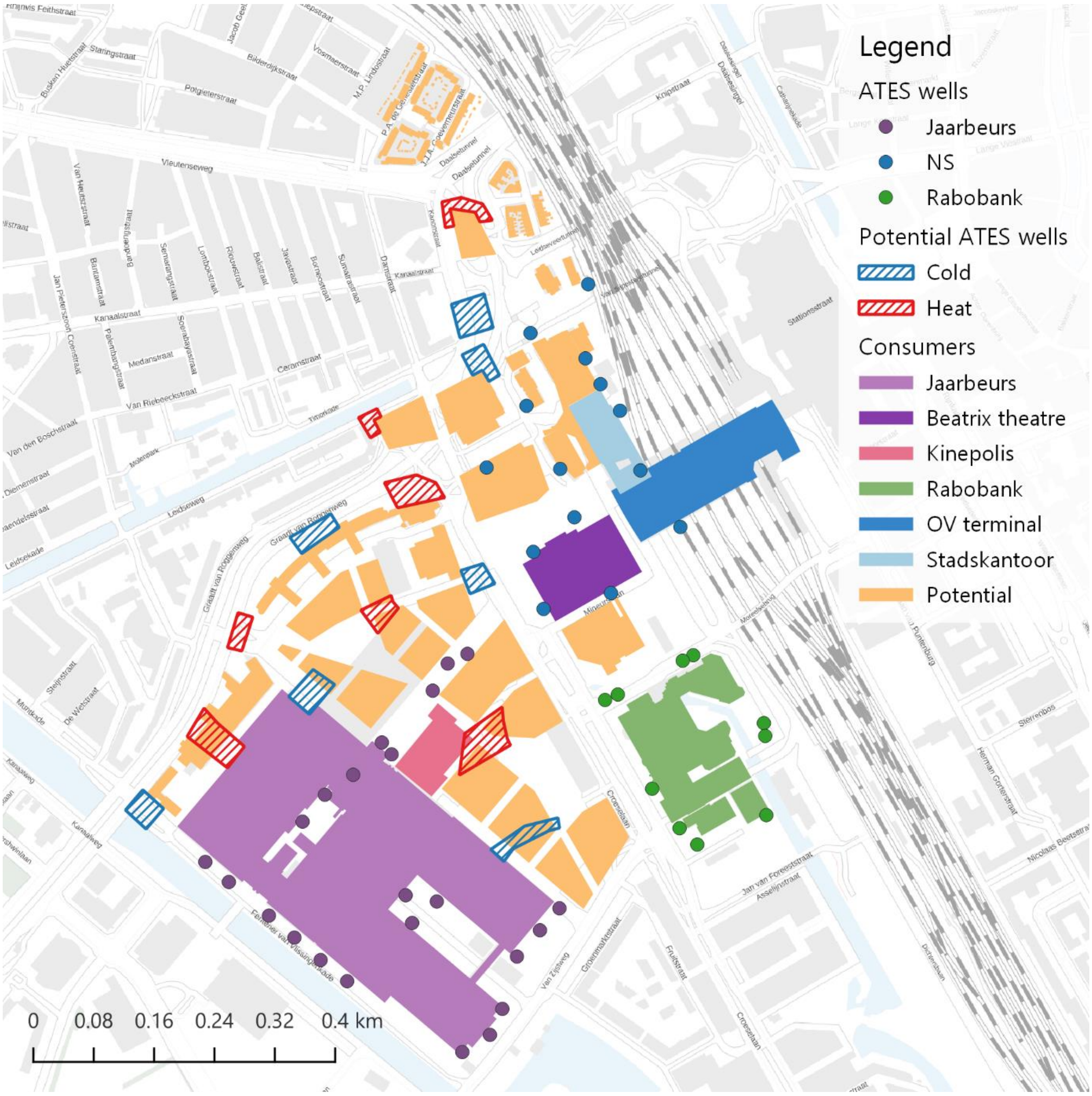


Figure 5 Existing and potential ATES systems

The potential consumers for the to be developed ATES systems are existing buildings as well as buildings planned to be built in the coming 20 years. Table 2 provides an overview of these buildings. The buildings labelled with the status 'existing' are buildings that are currently in use and have a heating (and cooling) system in place. Their energy system is currently based on DH or gas. The energy system of buildings labelled as 'planned' still have to be determined. Data on the surface (m^2), type of building and energy system was collected from the Municipality of Utrecht and Kadaster. The maps in Appendix I & II shows a more detailed overview of the exact location of each building.

Table 2 Potential consumers for new ATES system

Status	**Name**	**Surface (m^2)**	**Type**	**Energy system**
Beurskwartier				
Planned	Amrath	44900	Hotel, Residential	TBD
	Wonderwoods	44272	Office, Residential, Other*	TBD
	Building blocks	265000	Office, Residential	TBD

Existing	De Knoop	28500	Office	DH
	Graadt van Roggenweg	75631	Office	DH
	RVO	15705	Office	DH
	Volksbank	14316	Office	DH
Lombokplein				
Planned	Central Park	30000	Office	TBD
	Jaarbeurspleingebouw	57500	Office, Residential, Other*	TBD
	Van Sijpesteijnkade	40000	Office, Residential	TBD
	Building blocks	40000	Office, Residential	TBD
Existing	NH Hotel	17250	Hotel	DH
	Offices opposite to NH	8293	Office	DH
	Park Plaza Hotel	6078	Hotel	DH
	WTC	27858	Office	DH
	Mitros dwellings	17015	Residential	Gas

* Other refers to public spaces, shops or restaurants

3.2 Phase 1: data collection

The aim of this phase is to answer sub-question 1: *What are the characteristics (in terms of heating and cooling supply) of the ATES systems currently in place at the Beurskwartier and Lombokplein area?*

Data on the yearly heating and cooling supply of the ATES systems owned by Jaarbeurs, NS and Rabobank was requested from the Province of Utrecht. The following data was requested: heating supply (MWh), cooling supply (MWh), hot well extraction temperature (°C), cold well injection temperature (°C), cold well extraction temperature (°C) and hot well injection temperature (°C). Historic data was collected from the past three years (2016, 2017, 2018) in a monthly time resolution, in order to accurately reflect seasonal supply patterns. Inaccurate data due to maintenance or malfunctioning of the ATES systems is removed.

In order to compare the current supply characteristics of the ATES systems of the Jaarbeurs, NS and Rabobank to their maximum allowable supply, permits of each system were obtained from the Province of Utrecht. These permits identify the maximum allowable flow rate (m^3/h) and the maximum allowable amount of energy (MWh) or water (m^3) to be displaced.

3.3 Phase 2: Heat and cooling demand forecasting

The aim of this phase is to answer sub-question 2: *What is the estimated heating and cooling demand of the Beurskwartier and Lombokplein area in 2040?*

The final energy demand of a building can be divided in various categories based on its purpose: space heating, cooling, domestic hot water (DHW), lighting, auxiliary power (e.g. fan, pump) and electric appliances. This research focusses on the energy demand for space heating, cooling and DHW. The annual future demand for space heating and cooling is based on the surface (m^2) and the level of insulation (indicated by the construction year or the energy label) of existing and planned buildings.

Regarding existing residential buildings, it is assumed that in 2040 the insulation of these buildings has been upgraded to a minimum of energy level D, which is the lowest energy label for which a LT-network is still suitable (CE Delft, 2019). Non-residential buildings are expected to have an energy label C, which is in line with upcoming regulation that states that from 2023 onwards all offices in the Netherlands should be label C or higher (RVO, 2019).

Space heating and cooling demand key figures corresponding to the level of insulation, energy label or construction year are derived from two sources: the ‘Uniforme Maatlat Gebouwde Omgeving’ (UMGO) from RVO and the Vesta MAIS model from PBL. Both datasets are publicly available and serve as instrument for decision makers. The datasets differ in the way they treat the heating and cooling demand of new-built buildings. The Vesta datasets reasons from the most recent actual data of new-built buildings and their energy use, while the UMGO dataset defines the heating and cooling demand based on targets set by the government. For this reason, the UMGO dataset has less energy demand per square meter than the Vesta data set. In the Energy Performance of Buildings Directive (EPBD) published by the European Parliament it is stated that all new buildings should meet the nearly Zero Energy Buildings (nZEB) requirements (European Parliament, 2010). In the Netherlands these requirements are defined as Bijna Energie Neutrale Gebouwen (BENG) criteria. From 2020 onwards all new buildings should comply with the BENG-criteria. The UMGO dataset incorporates the draft version from November 2018 of these BENG requirements. However, in June 2019 the definite version of the BENG requirements were presented by the government, which are less stringent compared to the draft version (Ministry of the Interior and Kingdom Relations, 2019). In addition, designing an energy system solely based on a theoretical heating and cooling demand might be less reliable. For these two reasons, this analysis calculates the heating and cooling demand based on the Vesta dataset as well as the UMGO dataset and takes an average of Vesta and UMGO into account for the remainder of the analysis. A sensitivity analysis shows the effect of assuming either UMGO data or Vesta data (elaborated upon in section 3.6). Table 3 provides an overview of the space heating and cooling demand values.

Table 3 Key figures space heating, cooling and domestic hot water demand

				Space heating ($kWh/m^2/year$)		**Cooling ($kWh/m^2/year$)**	
Category	**Type**	**Year**	**Label**	**UMGO**	**Vesta**	**UMGO**	**Vesta**
Residential	Apartment	Planned	BENG	9.5	32.9	8.0	8.0**
	Terraced	1904 - 1980	to C	129.7	69.6	0.0	0.0
Utility	Office	Planned	BENG	12.4	40.3	11.3	22.9
		2018	A+	12.4	40.3	11.3	22.9
		1998	B	63.3	82.2	9.2	24.1
		1993	B	101.1	100.4	9.4	24.1
		1970	to C	79.1	109.2	8.3	24.1
	Hotel	Planned	BENG	12.4*	65.9	11.3*	39.3
		1970 - 1988	to C	79.1*	89.9	8.3*	43.3
	Other***	Planned	BENG	28.0	32.9	7.2	13.1

* UMGO does not include hotels, corresponding to a Techniplan study, values of offices were assumed (Techniplan, 2018)

** Vesta does not include cooling for residential buildings, the same value (8.0) as UMGO was assumed.

*** Other refers to public space, restaurants and shops.

The space heating and cooling demand of buildings, both now and in the future, can be distributed over the year in a variety of ways. Cox et al. (2015) mention the use heating degree days (HDD) and cooling degree days (CDD) as a common method utilized in scientific research to determine heating or cooling demand. It is a simplified approximate procedure that reflects the number of degrees that a day’s average ambient temperature (T_a) is above (in case of cooling) or below (in case of heating) a certain reference temperature (T_{ref}). In the Netherlands, T_{ref} for heating as well as cooling is usually chosen at 18 °C (F. Niessink et al., 2017). However, this research also deals with a building stock that must comply to BENG requirements and thus is very well insulated. It is expected that for these type of buildings T_{ref} for heating will be 11 °C (“Warmtepomp indicatie tabel,” 2019).

The annual DHW demand is based on a demand of 12.3 kWh/m^2 for residential buildings and 1.4 kWh/m^2 for utility buildings (Nuiten et al., 2019), based on the type of building. The yearly distribution of the DHW demand does not depend on outside temperatures or the level of insulation of buildings. However, a constant DHW demand throughout the day does not accurately reflect reality. In order to demonstrate the capacity needed to supply DHW, this study assumed all DHW to be consumed during a morning period (two hours) and evening period (two hours) of four hours in total.

3.4 Phase 3: system design and modelling

The aim of this phase is to answer sub-question 3: *To what extent can a collective ATES system meet the future heating and cooling demand of the Beurskwartier or Lombokplein area?*

3.4.1 System design

The Beurskwartier and Lombokplein area are considered two separate areas (Appendix II shows which buildings belong to which area) which each will have a separate collective ATES system. Figure 6 is a schematic representation of a collective ATES system, in which a number (N) of doublets are connected to a collective piping system and consumers. During winter, hot water is extracted from the ATES wells and distributed to a central heat pump, where the temperature of the water is increased to levels needed for floor heating. Water needed for DHW demand is directed to a small booster heat pump (located at each building block) to further increase the temperature needed. During summer, cooling is directly distributed from the ATES well to the consumers. Heating and cooling flows through a separate piping system. Generally, the heating demand of a building is larger compared to its cooling demand. To restore the aquifer balance, a regeneration method (such as TEO) is needed to load extra heat into the ATES wells.

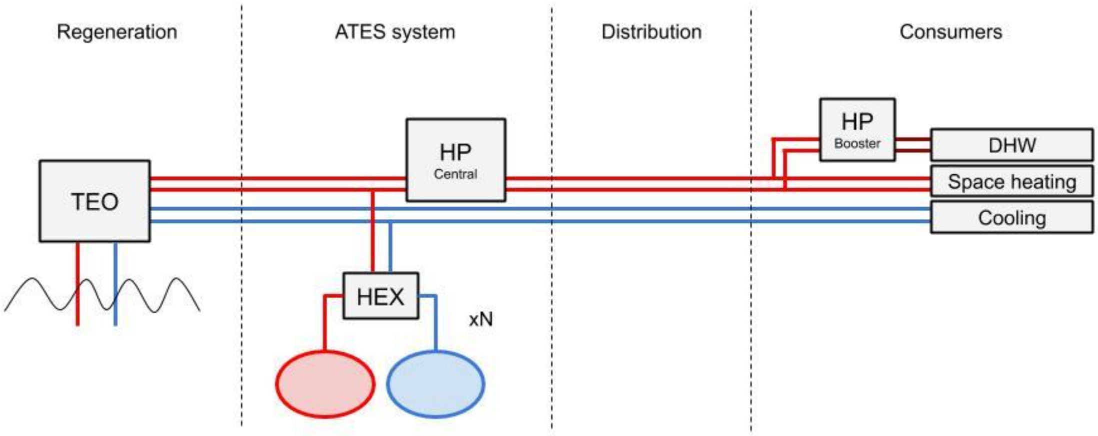


Figure 6 Design of ATES system

3.4.2 Choice of simulation model

The alignment of the future heating and cooling demand and supply is modelled in EnergyPRO. This modelling software package allows for combined techno-economic analysis and optimization of complex energy systems. The type of energy system in this research requires a more disaggregated simulation model compared to well-known simulation models like EnergyPLAN, which has been applied in over one hundred journal articles (Østergaard, 2015). EnergyPRO is a simulation model that is able to handle energy system analysis at a user-defined level of aggregation. Østergaard & Andersen (2016) show that EnergyPRO is able to cope with coefficient of performance (COP) values and DH grid losses that vary with external conditions and loads. It also allows booster heat pumps to be combined with DH. Hinojosa et al. (2007) reviewed several energy simulation models and concluded that, while a good understanding of the system and program crucial, EnergyPRO is a flexible and powerful tool.

3.4.3 Description of EnergyPRO

The use and operation of EnergyPRO can be described through its components: project identification, external conditions, model components (fuels, demands, energy conversion units, storages, transmissions and electricity markets), and output reports. The user is able to adjust project identification settings such as the number of timesteps (one-day in this study) or planning period (one year in this study). The external conditions of an energy system modelled in EnergyPRO consist of user-defined timeseries that serve as input. This analysis makes use of varying timeseries (such as ambient air temperature) and timeseries assumed to be constant (such as well temperatures). A more extensive elaboration on the input parameters of this analysis can be found in section 3.4.4. Timeseries are a fundamental object in EnergyPRO models, either directly or indirectly. This could be as input data (e.g. weather data) or as intermediate outcomes (e.g. demands, results). In addition, model units (fuels, demands, energy conversion units, storages, transmissions and electricity markets) can be added to the project. For simplicity reasons, the ATES wells are modelled as fuel units, as EnergyPRO is not equipped with standard ATES modules. Figure 7 shows a schematic overview of the chosen model units that reflect the system design as presented earlier in section 3.4.1.

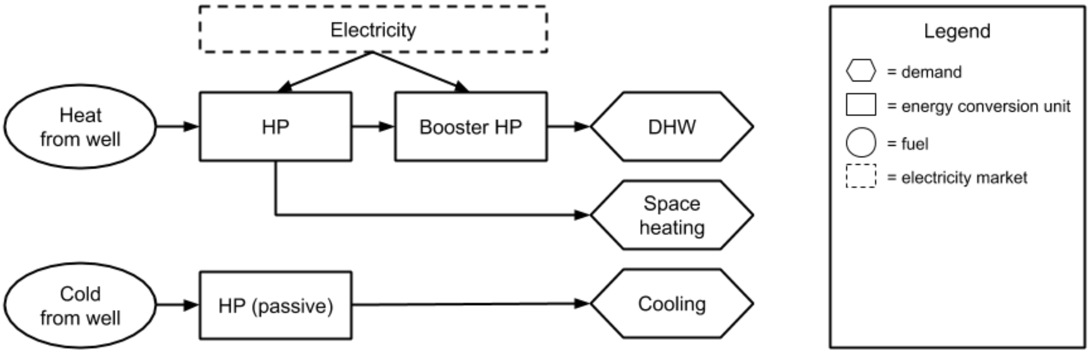


Figure 7 Model components of energy system in EnergyPRO (EMD International, 2019)

It is possible to model units with characteristics based on the momentary performance of other units or user-defined input series. For instance, the COP of a heat pump may be modelled as a function based on a required supply temperature for floor heating which in turn is a function of the ambient air temperature. In other words, all units can be in algebraic terms referring to outputs from other units or timeseries. The formulas used to model the system components in this analysis are presented in section 3.4.4. As a starting point EnergyPRO creates a matrix formed by the number of production units and the number of timesteps. It enters new productions in the matrix taking into account restrictions in energy stores and transmissions. EnergyPRO continues to the next production unit after having checked if the production is possible. Various output reports can be displayed after running the model. For this analysis, output reports considered relevant are production graphics, annual energy conversions and load duration curves.

3.4.4 Modelling of system components and input parameters

The central heat pump in the energy system is modelled as a simplified HP model using a Lorentz COP. A realistic COP is then estimated by correcting the theoretical maximum Lorentz COP by an efficiency factor covering all the losses in the heat pump system (Reinholdt et al., 2018). In this analysis, the central HP efficiency is defined by the theoretical Lorentz efficiency and an empirically determined system efficiency, defined as

$$COP_{HP} = \eta_s * COP_{Lor} \tag{1}$$

Reinholdt et al. (2016) suggest a system efficiency (η_s) in the range of 50% - 60% for the maximum achievable Lorentz efficiency. In this analysis, the η_s is set at 50%, which is in line with empirical experience in a project with large HPs in DH systems (Clausen et al., 2014). In order to reflect the lower efficiency of smaller-scale HPs, the η_s of the booster HPs is set at 40%, which is in line with a theoretical case representing a LT district heating network with a central heat pump and booster heat pumps in Denmark (Østergaard & Andersen, 2016). Considering the second law of thermodynamics, the Lorentz efficiency is defined as

$$COP_{Lor} = \frac{T_{H,LM}}{T_{H,LM} - T_{L,LM}} \tag{2}$$

in which $T_{H,LM}$ is the logarithmic mean temperature (K) of the delivered hot water and $T_{L,LM}$ the logarithmic mean temperature (K) of the heat source, defined as

$$T_{LM} = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in}}{T_{out}}\right)} \tag{3}$$

Heat exchanger losses between the HP and the DH system are enclosed in η_s.

The buildings in this analysis need to be adapted for LT heating. It is therefore assumed that space heating or cooling in these buildings is supplied through floor heating or cooling. This research assumes that the supply temperature for floor heating ($T_{s,FH}$) depends linear on the ambient temperature (T_a). The $T_{s,FH}$ is based on empirically found temperature levels mentioned by Østergaard & Andersen (2016): the upper point (T_a, $T_{s,FH}$) of the linear curve is (15.5°C, 23°C) while the lower point is (-12°C, 35°C). This is defined as

$$T_{s,FH} = \frac{(35 - 23)}{(15.5 - (-12))} * \left(T_a - (-12)\right) + 23 \tag{4}$$

The return temperature for floor heating ($T_{r,FH}$) is based on empirical experience found by Østergaard & Andersen (2016). It follows the following temperature, defined as

$$T_{r,FH} = \frac{T_{s,FH} + 23}{2} \tag{5}$$

The T_a serves as input parameter to this model. This research uses daily values for T_a, which follows the distribution profile of the year 2018 at one day intervals. A realistic reference ambient temperature (T_{ref}) from which space heating is required in buildings that comply to BENG requirements is 11°C ("Warmtepomp indicatie tabel", 2019). For these buildings, floor heating switches off at ambient temperatures above 11°C. For the existing buildings in this analysis, floor heating switches off at an ambient temperature above 18°C. In total, 176 days have temperatures below 11°C and 80 days have temperatures above 18°C. Changes in T_a due to climate change are not taken into account in this analysis.

DHW production is connected to the booster HP through a heat exchanger and heat storage. The required supply temperature for DHW ($T_{s,DHW}$) in this analysis is set at 60°C. This is a mandatory temperature level set by the Dutch government in order to deal with bacteria concerns (NEN 1006).

Heating or cooling is distributed from the ATES wells to the consumers. The distribution energy loss is dependent on the insulation and the length of the pipes as well as the temperature of the water that flows through the pipes. In LT-networks, the energy loss is limited due to low temperature of the water compared to HT-networks. The distribution losses in LT-networks are estimated to be around 15% (CE Delft, 2019). In this analysis, the DH losses are set at 15% in each timestep, not depending on any external conditions.

Demand-side input parameters are the future heating and cooling demand of all planned buildings in the Beurskwartier and Lombokplein area (result from phase 2) as the projected demand. Supply-side input parameters regarding the ATES system are the maximum power outputs of each doublet based on the maximum allowable flow rate ($\dot{m}$) and a ΔT, defined as

$$P_{doublet} = \dot{m} * C_p * \Delta T \tag{6}$$

The maximum $\dot{m}$ for new doublets without negatively influencing the aquifer was determined in a geological study commissioned by the Municipality of Utrecht and set to 80 m^3/h (Schuurman et al., 2017). The maximum $\dot{m}$ of a doublet of the Rabobank and NS is 70 m^3/h and 90 m^3/h respectively. The Jaarbeurs has maximum $\dot{m}$ of 1700 m^3/h for all cold wells combined and 570 m^3/h for all hot wells combined. The specific heat capacity of water is 4.2 kJ/kg/°C. The maximum ΔT is assumed to be 7°C, which corresponds to abovementioned geological study (Schuurman et al., 2017). Table 4 provides an overview of the maximum power of all ATES systems.

Table 4 Maximum power output of ATES systems

Name	Amount	Maximum $\dot{m}$ (m^3/h)	Power output (MW)
New ATES Beurskwartier	6 doublets	480	3.91
New ATES Lombokplein	3 doublets	240	1.95
Jaarbeurs	23 wells	570 - 1700	4.64 – 13.84
Rabobank	5 doublets	350	2.85
NS	7 doublets	630	5.13

The average temperature of the hot well ($T_{well,h}$) is set at 14°C and the average temperature of the cold well ($T_{well,c}$) is set at 9°C, which results in an average ΔT of 5°C. These values show correspondence with actual measured data from the ATES systems of Jaarbeurs, Rabobank and NS. A more detailed analysis on the findings of the current ATES systems is presented in section 4.1.

A summary of all important assumptions regarding modelling components or input parameters presented in this section is shown in an overview in Table 5.

Table 5 Overview of modelling components and input parameters

Parameter	Value	Unit
Heat pump COP (COP_{HP})	See formula 1	-
System efficiency HP (η_s)	50%	-
System efficiency booster HP (η_s)	40%	-
Supply temperature for floor heating ($T_{s,FH}$)	See formula 4	°C
Return temperature for floor heating ($T_{r,FH}$)	See formula 5	°C
Reference temperature heating	11	°C
Reference temperature cooling	18	°C
Supply temperature for DHW ($T_{s,DHW}$)	60	°C
Distribution losses	15%	-
Maximum allowable flow rate ($\dot{m}$)	80	m^3/h
Maximum ΔT	7	°C

Power output doublet ($P_{doublet}$)	See formula 6	MW
Average temperature of the hot well ($T_{well,h}$)	14	°C
Average temperature of the cold well ($T_{well,c}$)	9	°C
Average ΔT	5	°C

3.5 Phase 4: scenario development and techno-economic analysis

The aim of this phase is to answer sub-question 4: *What is the sustainable heating and cooling system with the most optimal techno-economic performance in the Beurskwartier and Lombokplein area?*

3.5.1 Scenario development

In order identify suitable heating and cooling system concepts from a technical and economic perspective, multiple scenarios are formulated and compared to a reference scenario. A collective ATES system, as presented in section 3.4.1, is the central system component in the reference scenario. Other scenarios differ in the way how this ATES system is designed. They vary in terms of base load energy source (new ATES wells or combining new + existing ATES wells), regeneration method (TEO or dry cooler) or peak load supply (DH or biomass boiler). An overview of all scenarios is shown in Table 6. All scenarios are applicable to the collective ATES system in the Beurskwartier area as well as the collective ATES system in the Lombokplein area.

Table 6 Overview of all scenarios

		Scenario			
Category	**Possibility**	**Ref**	**1**	**2**	**3**
Energy Source	New ATES wells	x	x	x	
	New + existing ATES wells*				x
Regeneration	TEO	x		x	x
	Dry cooler		x		
Peak load	DH	x	x		x
	Biomass boiler			x	

* In this case the heating and cooling demand consists of the future heating and cooling demand of the planned buildings in the Beurskwartier or Lombokplein area plus the heating and cooling demand of the existing ATES system consumers.

3.5.2 Evaluation indicators

Evaluation indicators are necessary to reflect the performance of the future heating and cooling system of the Beurskwartier and Lombokplein area. This research uses two technical and three economic parameters which were identified as frequently-used technical and economic indicators for the evaluation of energy systems (Ma et al., 2018). The technical indicators are energy input and primary energy input and the economic indicators are payback period (PBP), levelized costs of energy (LCOE) and internal rate of return (IRR). An overview and description is presented in Table 7.

Table 7 Technical and economic performance indicators

Category	**Name**	**Description**
Technical indicator	Energy input	Amount of energy input of energy system
	Primary energy input	Amount of primary energy input of energy system
Economic indicator	PBP	Length of time to recover cost of investment
	LCOE	The energy price per unit of energy when NPV is zero
	IRR	The discount rate when NPV of the project is zero

3.5.3 Technical indicators

The indicators energy input and primary energy input are used to evaluate the overall energy efficiency of the heating and cooling system for each scenario presented in paragraph 3.4.

$$\boldsymbol{Energy\ input} = purchased\ heat\ or\ biomass + electricity\ consumption \tag{7}$$

The energy sources used as input in the heating and cooling system in this analysis are: (1) heat from a DH system or biomass (2) electricity for the use of HP's, (3) electricity for the use of ATES and (4) electricity for the use of TEO or dry coolers. The electricity use of the HP's is derived as a result from the EnergyPRO modelling. The auxiliary energy of the energy system consists of electricity used for ATES and TEO pumps. In NEN 7125 a fixed value for this type of energy is defined: 0.0072 GJ_e/GJ_{th} (Schepers & Scholten, 2016), which is also used in this analysis. The electricity use of dry coolers is calculated based on a COP of 20 (CE Delft, 2014) and a biomass boiler efficiency of 80% was assumed for biomass use calculations (European Biomass Association (AEBIOM), 2015). An overview of abovementioned assumptions is shown in Table 8.

Table 8 Input parameters for absolute energy input calculations

Input	Value	Unit
Electricity use HP's	Result EnergyPRO	MWh
Electricity use ATES/TEO	0.0072	GJ_e/GJ_{th}
COP dry coolers	20	-
Efficiency biomass boiler	80%	-

$$\boldsymbol{Primary\ energy} = purchased\ heat * PEF\ or\ biomass + electricity\ consumption * PEF \tag{8}$$

The primary energy factor (PEF) for the Dutch electricity generation is based on the electricity production projections for 2030 calculated in 'Nationale Energieverkenning 2017'. This study calculated a PEF of 0.77 $MJ_{primary}/MJ_{electricity}$ (Niessink & Gerdes, 2018), based on the electricity mix shown in Table 9.

Table 9 Projections of electricity production in 2030 (Schoots et al., 2017)

Energy source	Production (PJ)	Share
Natural gas	47.4	10%
Coal	83.0	17%
Fossil (other)	16.5	3%
Nuclear	14.8	3%
Renewable (wind, solar, hydro, biomass)	242.3	64%
Other	9.6	2%
Total	478.3	100%

The PEF for heat purchased from the DH grid is based on the sustainability roadmap of Eneco, in which their aspirations for the delivered heat from the Utrecht/Nieuwegein DH grid in 2030 are presented (Eneco, 2018a). The shares of energy sources shown in Table 10 resulted from this sustainability roadmap. A PEF for each source is calculated based on its energy efficiency (Eneco, 2018a; European Biomass Association (AEBIOM), 2015; GasTerra, 2008; Visser, 2014).

Table 10 Energy source of Utrecht/Nieuwegein DH system in 2030

Energy source	Share energy source	Efficiency	PEF
Natural gas	30%	50%	2.00
Sewage treatment plant	10%	COP = 4	0.19*
Biomass	40%	80%	1.25
Geothermal	20%	100%	1.00
Total	100%		1.32

* Based on COP = 4 and $PEF_{electricity}$ = 0.77

3.5.4 Economic indicators

The economic indicators are assessed from a system level perspective. The scope of the calculations is the total heating and cooling system, which includes the main energy source (ATES wells), regeneration technology (TEO or dry coolers), peak load technology (DH or biomass boiler) and the distribution of the heating and cooling. This is because a municipality often introduces a concession agreement in these type of energy projects. The owner of the concession, often a single party, receives a monopoly and is responsible for the development and operation of the entire energy system. This means that the heating and cooling system will be deployed as one system by one developing party. The economic indicators (LCOE, PBP, IRR) emphasize on perspectives of different stakeholders involved. The LCOE provides useful insights for parties like the Municipality of Utrecht as it allows for simple comparison of energy generating technologies based on overall costs per unit of energy. The PBP is helpful for project developers as it shows the time period to recover from investments. For investors, the IRR is an effective indicator of the economic viability of a project.

LCOE is a common metric for the comparison of power generating technologies (Ueckerdt et al., 2013). It is considered a useful tool as it combines both fixed and variable costs in a single measurement to simplify analysis (Namovicz, 2013). LCOE calculates the amount of money that must be made per unit of energy to regain the lifetime costs of the system.

$$\boldsymbol{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{9}$$

Where:

I_t = Investment expenditures in year t (including financing)
M_t = Operations and maintenance expenditures in year t
F_t = Fuel expenditures in year t
E_t = Heat generation in year t
r = Discount rate
n = Life of the system

The PBP is an important indicator to determine whether to undertake a project. Longer payback periods are typically not desirable. A PBP calculation is based on the flows during the lifetime of a project and is defined as

$$\boldsymbol{PBP} = \frac{initial\ investment}{annual\ cash\ inflows} \tag{10}$$

The IRR simplifies a project to a single number that executives, analysts or investors can use to determine whether a projects is economically viable, which is defined as

$$0 = NPV = \sum_{n=0}^{N} \frac{CF_n}{(1 + \boldsymbol{IRR})^n} \tag{11}$$

Where:

CF_0 = initial investment
CF_n = cash flows
n = each period
NPV = net present value
IRR = internal rate of return

Economic data is collected to serve as input for LCOE, PBP and IRR calculations. As the heating and cooling system in the Beurskwartier and Lombokplein area is assumed to be implemented around 2030-2040, economic data needs to reflect the future prices of the following expenses: capital expenditures, operation and maintenance (O&M) costs and fuel costs.

Regarding the future investments expenditures, current prices are taken into account and are not converted to future prices by means of technology learning curves. This would lead results with apparent accuracy. In addition, the building sector is known for being the least innovative sector in the Netherlands (TNO, 2007). Investment costs are gathered for each individual component of the heating and cooling system: ATES wells, central HP, booster HP, TEO installation, dry cooler, distribution (subsurface), distribution (building-related) and biomass boiler. The building-related distribution concerns all distribution up until the heating and cooling delivery set in each building. This does not include floor heating distribution pipes.

In academic research, O&M expenditures are yearly expenses commonly illustrated by a percentage of the initial investment expenditures. Generally, distribution pipes have a relatively low percentage as they are less sensitive to breakdown compared to above-ground installations. The O&M costs of distribution are set at 2.5% (Schepers & Leguijt, 2017). Above-ground installations (such as biomass boilers, small-scale heat pumps and dry coolers) tend to have higher shares, often quoted between 3.5% - 7% (PBL, 2018; Smekens et al., 2017). New sources (such as ATES wells or geothermal wells) are assumed to have O&M costs of approximately 5% (Schepers & Leguijt, 2017). These kind of shares do not apply to large-scale heat pumps, which generally have O&M costs of 1% of the initial investment costs (Boissavy, 2015; Koreneff et al., 2015).

Regarding fuel expenditures, the Heat Roadmap Europe calculated the average price for biomass in 2040 (7.9 €/GJ) (David Connolly et al., 2012), which is used as economic input for biomass fuel expenditures in this analysis. The electricity price is also assumed to change in the coming years. It is expected that the electricity price will increase until 2040. After 2040 prices will stagnate due to high feed-in from wind and PV power plants, despite the rising gas and CO_2 prices. This analysis sets the electricity price at 93 €/MWh, corresponding to the default electricity price in 2040 according to the Vesta model developed by PBL (Schepers & Leguijt, 2017). The future price of heat from the DH system in Utrecht is more complicated to forecast, as Eneco is has the ambition to make the DH system in Utrecht more sustainable by changing its energy sources (as explained in section 3.5.3). As these developments may have significant impact on the price of heat, it is challenging to accurately estimate future heat prices. For this reason, this analysis takes current heat prices into account. A sensitivity analysis shows the impact of changes in the district heating prices (presented in section 4.4.2)

Economic data is derived from literature and desktop research and is presented in Table 11. Table 12 shows which type of expenditures are taken into account in each scenario. A typical system lifetime for business case calculations of similar projects is 30 years (IF Technology, 2017c, 2018), in which the lifespan of installations such as heat pumps are typically 15 years (Li, 2015). The discount rate often used in climate and energy modelling in the Netherlands varies from 5%-9% (Ecofys, 2015). This study takes the middle value (7%) into account. Investments and re-investments are assumed to be one-time only, in year 0 and year 15 respectively. O&M and fuel costs are assumed to be constant yearly costs.

Table 11 Overview of economic input parameters

Expenditure	Economic parameters	Unit	Input (€)	Source
Investments	ATES wells	€/doublet	200,000	(STOWA, 2018)
	Central HP	€/kW$_{th}$	300	(Boissavy, 2015)
	Booster HP	€/kW$_{th}$	1,300	(PBL, 2018)
	TEO installation	€/kW$_{th}$	400	(PBL, 2018)
	Dry cooler	€/kW$_{th}$	80	(Bloemendal et al., 2018)
	Distribution (subsurface)	€/MWh	150	(Lund & Nielsen, 2017)
	Distribution (building)	€/consumer	2700	(Techniplan, 2018)
	Biomass boiler	€/kW$_{th}$	480	(Smekens et al., 2017)
O&M	ATES wells	% of investment	5.0%	(Schepers & Leguijt, 2017)
	Central HP	% of investment	1.0%	(Boissavy, 2015)
	Booster HP	% of investment	3.5%	(PBL, 2018)
	TEO installation	% of investment	9.0%	(PBL, 2018)
	Dry cooler	% of investment	3.5%	(Bloemendal et al., 2018)
	Distribution (outside)	% of investment	2.5%	(Schepers & Leguijt, 2017)
	In-house distribution	% of investment	2.5%	(Schepers & Leguijt, 2017)
	Biomass boiler	% of investment	7.0%	(Smekens et al., 2017)
Fuels	Electricity - connection	€/kW/year	35	(Techniplan, 2018)
	Electricity - use	€/MWh/year	93	(Schepers & Leguijt, 2017)
	District heating - connection	€/kW/month	variable*	(Eneco, 2018b)
	District heating - use	€/GJ/year	20	(Eneco, 2018b)
	Biomass	€/GJ/year	7.9	(Connolly et al., 2012)
Other	Discount rate	-	7.0%	(Ecofys, 2015)
	System lifetime	years	30	(IF Technology, 2018)
	Reinvestment HP/boiler	years	15	(Li, 2015)

* Connection costs are dependent on the capacity, defined by: 4*capacity$^{-0.221}$

Table 12 Expenditures of each scenario

		Scenario			
Expenditure category	**Type**	**Ref**	**Sc 1**	**Sc 2**	**Sc 3**
Investments and O&M	ATES wells	x	x	x	x
	HP's (central and booster)	x	x	x	x
	Distribution (outside and inside)	x	x	x	x
	TEO installation	x		x	x
	Dry cooler		x		
	Biomass boiler			x	
Fuels	Electricity ATES	x	x	x	x
	Electricity HP's	x	x	x	x
	Electricity TEO	x		x	x
	Electricity dry cooler		x		
	DH	x	x		x
	Biomass			x	

Besides costs, a project also receives benefits. In this analysis, the benefits of the heating and cooling system consist of a onetime connection fee (BAK), income from selling heat, income from selling cold and income from fixed costs (‘vastrecht’). Schepers & Leguijt (2017) assume a one-time connection fee of 5000 €/consumer (residential) and 75 €/kW (utility) for new-built buildings, based on an extensive market analysis. Data regarding the income of residential buildings and utility buildings is based on tariffs from Eneco and on the analysis of Schepers & Leguijt (2017) respectively. Table 13 provides an overview of the benefits taken into account.

Table 13 Overview of income parameters of heating and cooling system (Eneco, 2019; Schepers & Leguijt, 2017)

	Residential		Utility	
Benefits	**Amount**	**Unit**	**Amount**	**Unit**
Connection costs (BAK)	5000.00	€/consumer	75.00	€/kW
Heat consumption	28.47	€/GJ	20.00	€/GJ
Cold consumption	24.94	€/GJ	20.00	€/GJ
Fixed costs	284.45	€/consumer/year	96.84/capacity$^{0.22}$	€

3.6 Sensitivity analysis

To illustrate the uncertainty of modelling outcomes, a sensitivity analysis is performed. This analysis identifies input parameters whose variations have significant impact on crucial outputs and demonstrates the effect of changing these input parameters. The influence of the following parameters is examined: the future heating and cooling demand, price of DH, electricity costs, price of biomass and the discount rate.

The influence of variation the future heating and cooling demand is analysed by calculating the future heating and cooling demand based on two different datasets, UMGO (lower bound) and Vesta (upper bound). The caused effect on the yearly distribution of the energy demand, the alignment of energy supply and demand, and the LCOE is presented in section 4.2, 4.3 and 4.4.2.

The influence of variation in the price of DH, electricity costs, price of biomass and the discount rate was tested against the LCOE of all scenarios in the Beurskwartier area. The effect of a decrease (-25%) and increase (+25%) of all input parameters is analysed. The effect caused by these variations is presented in section 4.4.2.

4. Results

This chapter provides an overview of the findings arising from this research. It describes the heating and cooling supply pattern of the current ATES systems in place (section 4.1), the estimated future energy demand of the Beurskwartier and Lombokplein area (section 4.2), the (mis)match of the heating and cooling supply and demand (section 4.3) and techno-economic indicators of various scenarios (section 4.4).

4.1 Current ATES systems

The yearly heating and cooling supply pattern of the ATES systems (Rabobank, Jaarbeurs and NS) in the Beurskwartier and Lombokplein area is derived from actual data. Table 14 provides an overview of each ATES system and its average yearly heating and cooling supply and the average temperature difference between the hot and cold well for heat supply as well as cooling supply.

Table 14 Average yearly heating and cooling supply of the ATES systems

ATES	Yearly heat supply (MWh)	Yearly cooling supply (MWh)	Average ΔT heat supply (°C)	Average ΔT cooling supply (°C)
Jaarbeurs	1098	1063	4.8	4.5
Rabobank	1795	1950	5.3	4.4
NS	1731	1739	6.7	5.3

The actual supply is compared to the allowable heating and cooling supply of the ATES systems according to their permits. The Jaarbeurs is allowed to extract 3800 MWh of heat and 3200 MWh of cold from its ATES system during one year. The Rabobank is allowed to extract 4508 MWh of heat and 4508 MWh of cold and the NS is allowed to extract 5400 MWh of heat and 5400 MWh of cold. These numbers do not reflect the absolute maximum allowable heating and cooling supply. It demonstrates the allowable heating and cooling supply under standard conditions, which leaves enough margin for extreme weather conditions or the start-up period of the ATES system. The allowable heating and cooling supply mentioned in the permits is distributed over the year with a supply pattern identical to the actual heating and cooling supply. Figure 8, Figure 9 and Figure 10 provide an overview of the actual yearly heating and cooling supply of the ATES systems compared to the allowable yearly heating and cooling supply.

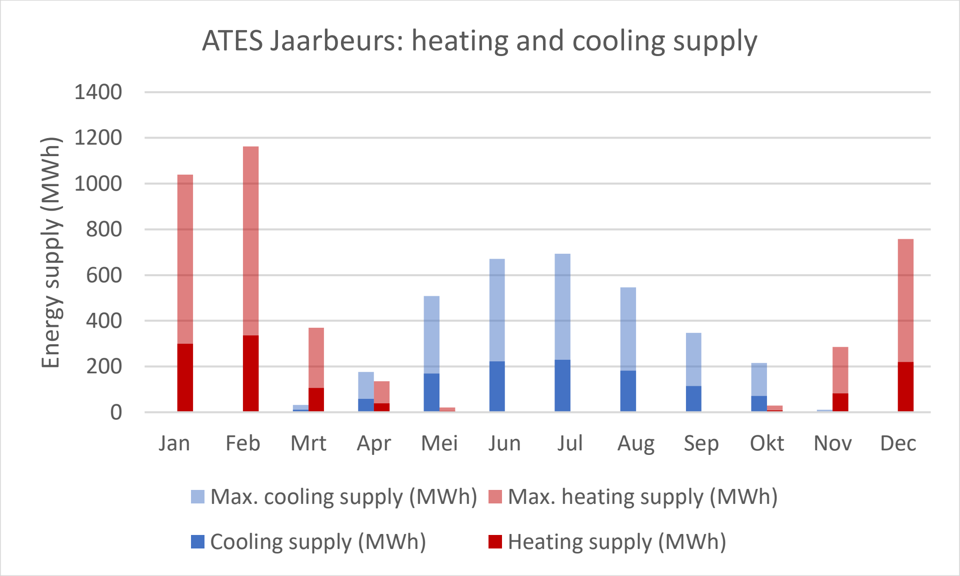


Figure 8 heating and cooling supply of ATES Jaarbeurs

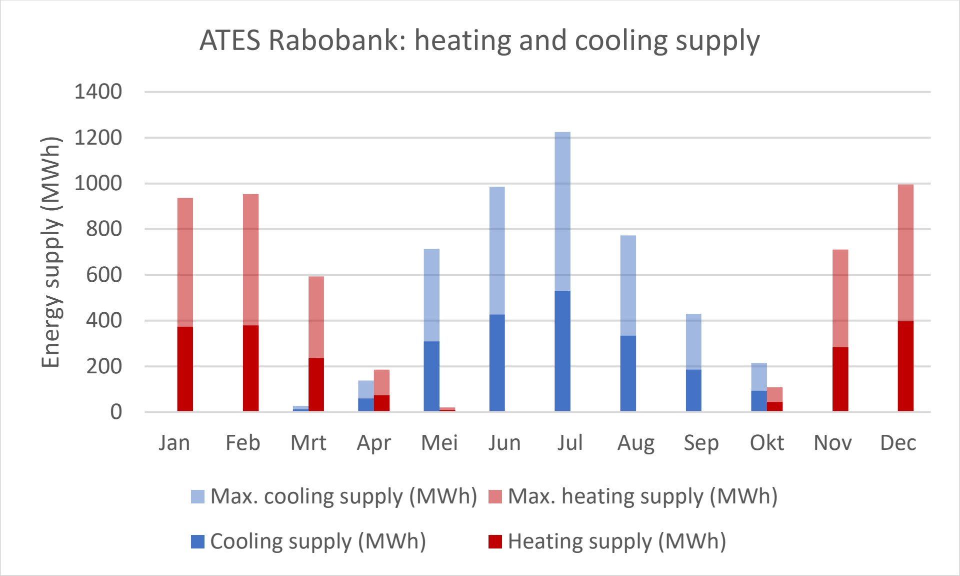


Figure 9 heating and cooling supply of ATES Rabobank

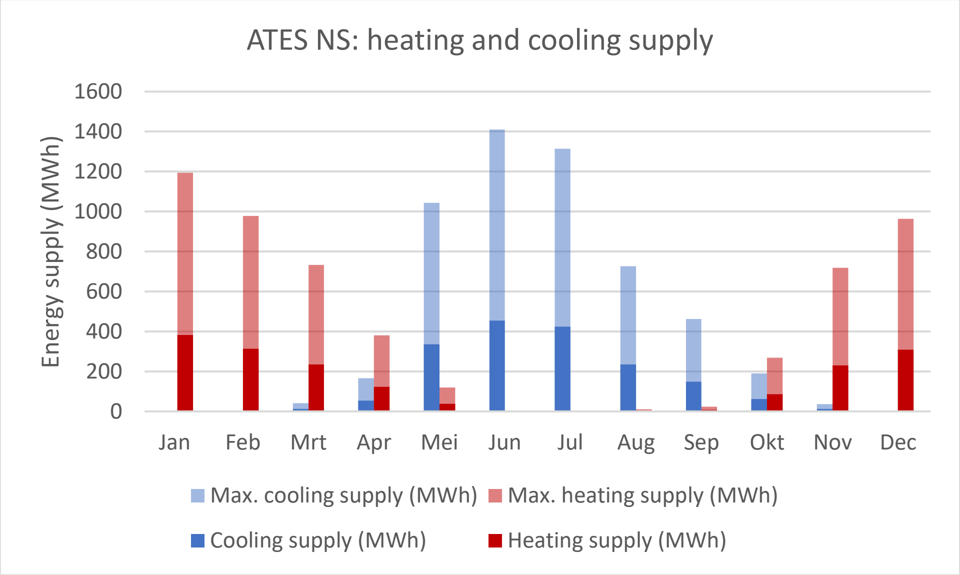


Figure 10 heating and cooling supply of ATES NS

The ATES systems (Jaarbeurs, Rabobank and NS) all operate below the allowable capacity according to their permits. Table 15 shows the yearly amount of heating and cooling surplus (MWh) that is available as heating and cooling for to the Beurskwartier and Lombokplein area. This table also includes the potential energy supply of the to be developed ATES wells in this area.

Table 15 Potential energy supply of ATES

ATES system	**Heating supply (MWh)**	**Cooling supply (MWh)**
Beurskwartier	6382 - 8476	6502 - 8596
New doublets (6)	3489 - 5583	3489 - 5583
Rabobank	1795	1950
Jaarbeurs	1098	1063
Lombokplein	3476 - 4522	3484 - 4530
New doublets (3)	1745 - 2791	1745 - 2791
NS	1731	1739

Important to note is that the result of the existing ATES supply is based on monthly supply data, the smallest time resolution available. A constant supply is assumed. However, the permits also include restrictions on the maximum allowable flow rate. In reality, the supply might be less constant and less heating and cooling surplus might be available due to this maximum flow rate restriction.

The potential energy supply of the to be developed ATES wells is based on a water displacement around 100,000 – 160,000 m^3 per season (Schuurman et al., 2017). The average difference of the temperature (ΔT) between the hot and cold well is assumed to be 5 °C, which seems accurate considering the average ΔT found in the existing ATES systems (Table 14).

4.2 Future heating and cooling demand (2040)

The future space heating and cooling demand calculations resulting from the UMGO and Vesta datasets vary significantly. Figure 11 provides an overview of the estimated space heating and cooling demand for existing and planned buildings in the Beurskwartier and Lombokplein area. It shows that the space heating demand according to the Vesta data is almost two times higher compared to the results based on the UMGO data. The discrepancy between these results can be explained by different assumptions regarding space heating and cooling values for to be developed buildings. UMGO predicts more stringent criteria for future heating and cooling demand by incorporating the latest draft version of the BENG requirements, while Vesta does not include these criteria and assumes most recent actual data. For the remainder of this research, the future heating and cooling demand is based on an average value of the Vesta and UMGO data, as earlier explained in section 3.3.

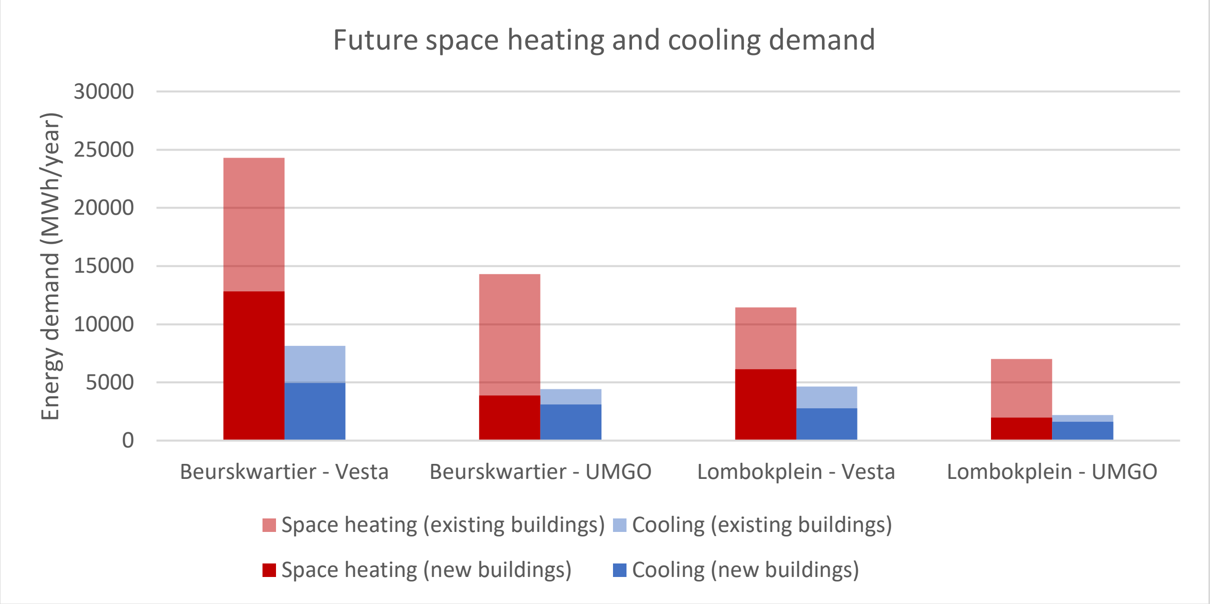


Figure 11 Future space heating and cooling demand of existing and planned buildings

Another remarkable difference is the future demand of existing buildings compared to planned buildings. A significant increase in space heating demand is found when adding existing buildings to the building stock. This increase is related to the insulation level of the existing buildings, which is worse compared to the planned buildings. This is also the reason why existing buildings need considerably less cooling, which explains why the future cooling demand increases less when adding existing buildings to the building stock. This is also driving the heating and cooling demand further apart, while ATES systems benefit from a balanced heating and cooling demand, as every five years ATES systems are required to be completely in balance according to article 3.16k of 'Activiteitenbesluit milieubeheer' (Activiteitenbesluit milieubeheer, 2019). For this reason, this research proceeds with modelling a collective ATES system in which only all planned buildings in the Beurskwartier and Lombokplein area serve as consumers. The yearly future space heating and cooling demand of the planned buildings in the Beurskwartier and Lombokplein area is presented in Table 16 and Figure 12.

Table 16 Yearly future energy demand of planned buildings in Beurskwartier and Lombokplein area

	Surface (m^2)	**Space heating (MWh)**	**Cooling (MWh)**	**DHW (MWh)**
Beurskwartier area	354172	8353	4028	3402
Residential	255772	5424	2046	3146
Hotel	13900	544	352	139
Office	70250	1852	1204	98
Other	14250	532	425	20
Lombokplein area	167500	4058	2208	969
Residential	67500	1395	540	830
Office	95000	2510	1617	132
Other	5000	152	51	7
Total	**521672**	**12411**	**6235**	**4371**

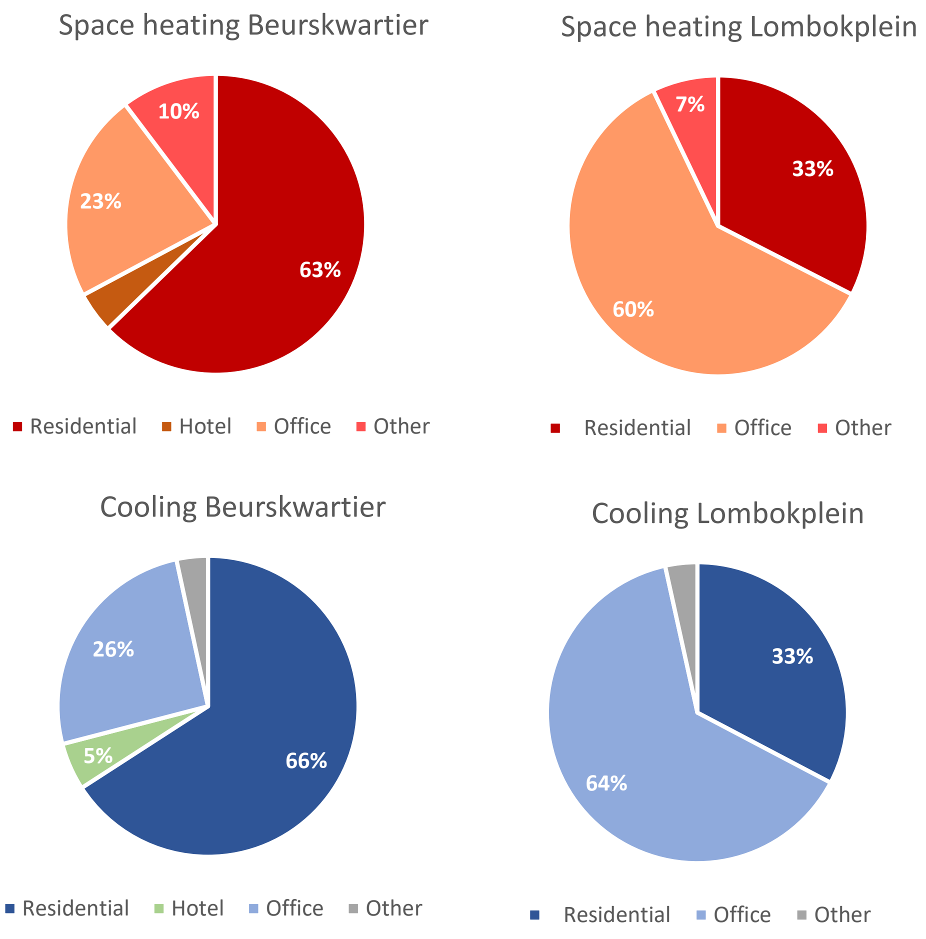


Figure 12 Share of space heating and cooling per building function

These numbers and figures show some differences between the Beurskwartier and Lombokplein area. The Beurskwartier area has a greater energy demand compared to the Lombokplein area, which is mainly due to the fact that more buildings are going to be built in the Beurskwartier area. The type of buildings also differs, the share of residential buildings is 66% in the Beurskwartier area compared to 33% in the Lombokplein area. The latter mainly consists of office buildings (64%). This influences the DHW demand, as residential buildings use significantly more hot water (e.g. for personal hygiene or kitchen) compared to offices. As a result, the DHW demand in the Beurskwartier is not only larger due to the size of the area, but also relatively larger due to the type of buildings compared to the Lombokplein area. The DHW demand during the DHW peaks in the morning and evening in the Beurskwartier and Lombokplein area is 2.8 MW and 0.8 MW respectively.

The energy demand is distributed over the duration of one year. The space heating and cooling demand is distributed based on a linear dependency on the daily ambient temperature. The distributed heating and cooling demand is presented in Figure 13 and Figure 14 in which the heating demand consists of DHW demand plus space heating demand.

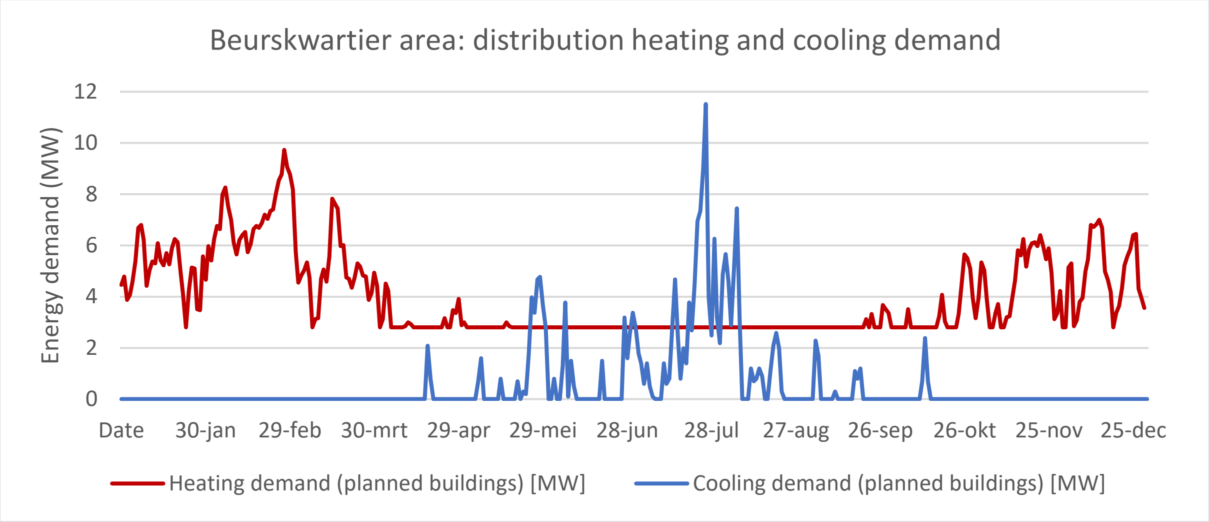


Figure 13 Heating and cooling demand of the Beurskwartier area

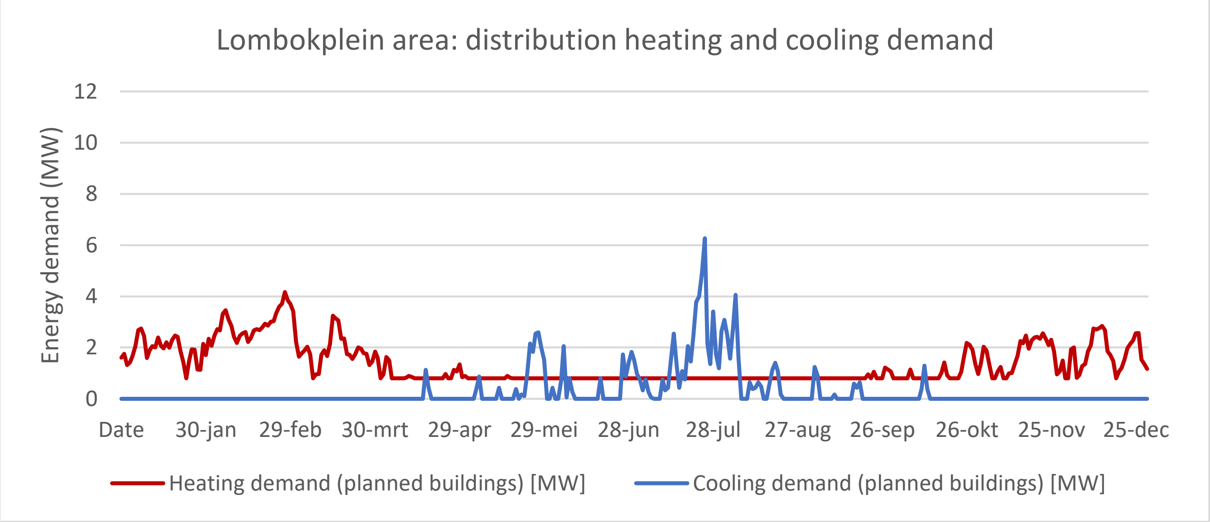
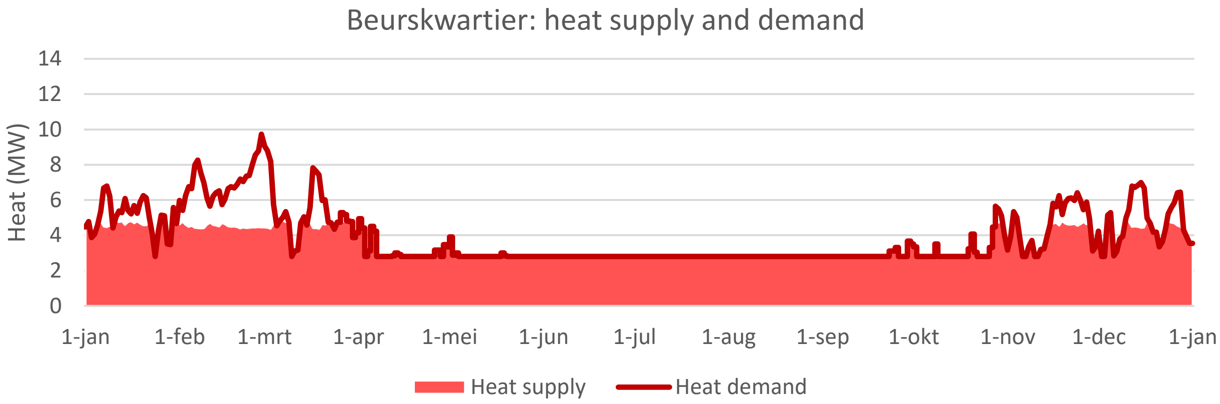


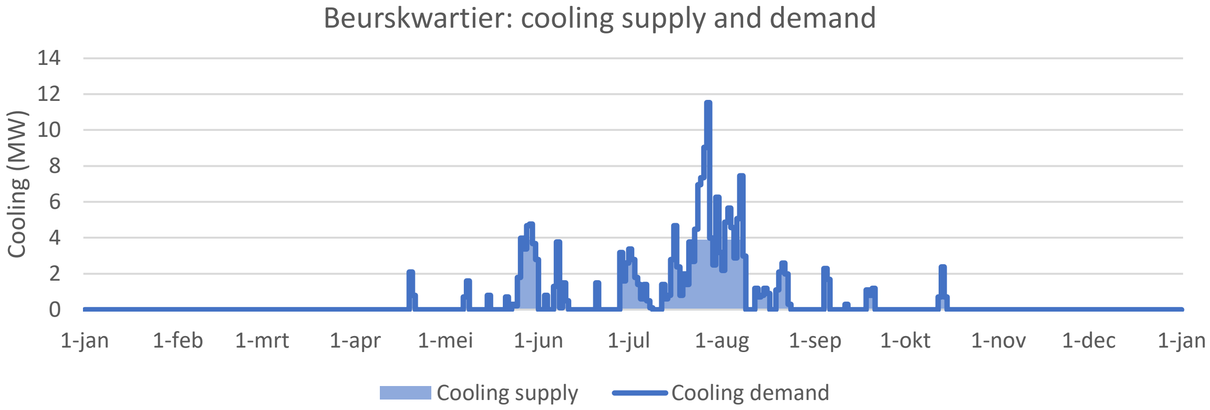
Figure 14 Heating and cooling demand of the Lombokplein area

Abovementioned graphs illustrate the heating and cooling demand based on an average of two data sources (UMGO and Vesta). A sensitivity analysis is able to identify the lower and upper bounds of the distribution of the future heating and cooling demand. The lower bound is based on the theoretical heating and cooling demand according to the BENG criteria (UMGO dataset) and the upper bound is based on actual data of the heating and cooling demand of newly built buildings (Vesta dataset). Results are visible in the graphs presented in Appendix III. The differences in the future heating and cooling demand data have large impact on the peaks during cold winter days or hot summer days. Taking the Beurskwartier area as an example, during a cold winter day the heating demand may vary from 6 MW (lower bound) to 13 MW (upper bound). This has large implications on the design and costs of the heating and cooling system, as the design of an energy systems is often based on the largest peaks. Section 4.4.2 explores the effect of variation in heating and cooling demand on the costs of the overall energy system.

4.3 Matching demand and supply

The planned buildings within the Beurskwartier area are supplied with heating and cooling from a collective ATES system which is connected to 6 (to be developed) doublets. The planned buildings in the Lombokplein area are supplied with heating and cooling from a collective ATES system which is connected to 3 (to be developed) doublets. The corresponding heating and cooling demand and supply curves are shown in Figure 15.





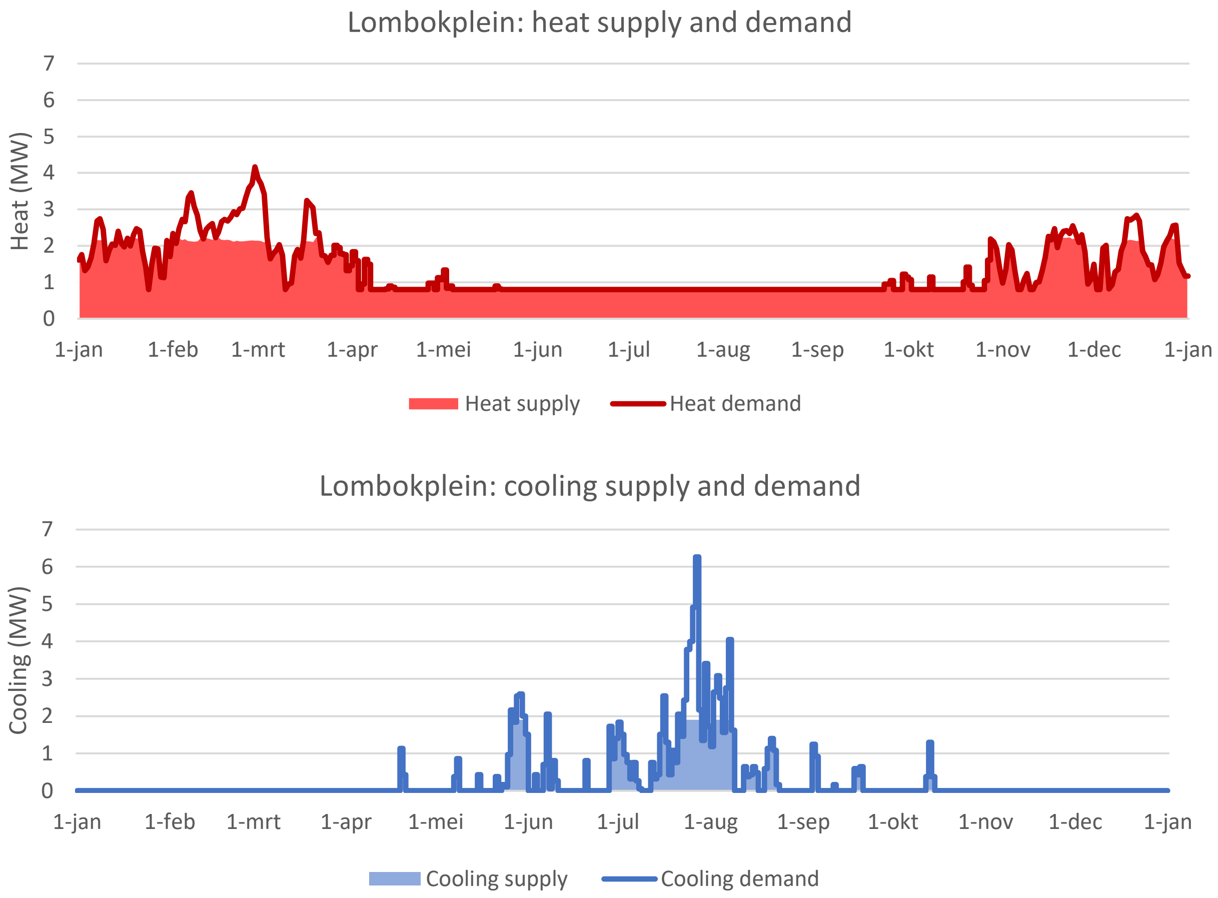


Figure 15 Alignment of heating and cooling supply and demand in 2040 (reference and scenario 1 & 2)

The figure shows that a collective ATES system (reference, scenario 1 and scenario 2) does not have enough peak capacity to supply the Beurskwartier or Lombokplein area with sufficient heating and cooling throughout a whole year. This means that extra peak supply is needed during cold winter days or hot summer days. In the Beurskwartier area, 92% of the heating demand (45% of peak capacity) and 80% of the cooling demand (34% of peak capacity) can be supplied by the ATES doublets. In the Lombokplein area, 94% of the heating demand (52% of peak capacity) and 76% of the cooling demand (30% of peak capacity) can be supplied by the ATES doublets. It must also be noted that, when comparing the area under the curve, the total amount of heat supplied is larger than the total amount of cooling supplied. This means that regeneration of the wells is needed, as an ATES system needs to be in balance. The alignment of supply and demand is different in case the new collective ATES system is connected to the existing ATES systems (scenario 3). The graphs that present this results are shown in Appendix IV. Regeneration is still needed in this case, but adding extra peak supply is only needed for cooling in the Lombokplein area. Table 17 shows an overview of the amount of peak supply and regeneration that is needed in the Beurskwartier area as well as the Lombokplein area.

Table 17 Amount of regeneration and peak supply needed

		Regeneration	Peak supply (MWh)		Capacity peak supply (MW)	
Area	**Sc.**	**(MWh)**	**Heating**	**Cooling**	**Heating**	**Cooling**
Beurskwartier	Ref, 1, 2	6232	902	788	5.3	7.6
	3	8442	0	0	0.0	0.0
Lombokplein	Ref, 1, 2	3089	267	524	2.0	4.4
	3	3386	0	153	0.0	4.2

Aforementioned results are different when varying the heating and cooling demand. This effect is studied in a sensitivity analysis. Appendix V shows the graphs of matching of energy demand and supply by taking the lower and upper bounds of the future heating and cooling demand into account. The tables in Appendix VI show an overview of the amount of regeneration and peak supply that would be needed in these cases. Obviously, more peak supply is needed in case of a higher heating and cooling demand and less (to almost no) peak supply is needed in case of a lower heating and cooling demand. In case of the reference scenario, scenario 1 and scenario 2 there is always a need for extra peak capacity (e.g. DH or biomass boiler). In case of scenario 3 there is only need for extra peak capacity (e.g. DH or biomass boiler) supposing a heating and cooling demand close to the upper bound (based on Vesta data). Interesting to note is that the amount of regeneration needed is relatively lower in case of a heating and cooling demand based on the UMGO dataset, as it has a more balanced heating and cooling demand. For example, in the Beurskwartier (scenario: ref, 1, 2) the amount of regeneration needed is 66% of the total heat demand in case of a heating and cooling demand based on UMGO data. In case of a heating and cooling demand based on Vesta, this share is 74%.

4.4 Techno-economic results

4.4.1 Energy input and primary energy input

The absolute energy input in the heating and cooling system in each scenario in the Beurskwartier and Lombokplein area is presented in Figure 16. In each scenario the largest share of energy input is allocated to electricity. The heating and cooling system of the Lombokplein area requires relatively less energy input. This is caused by a significantly lower electricity use for the booster heat pump, as the Lombokplein area uses less DHW due to the type of buildings (less residential buildings). In addition, the collective ATES system of the Lombokplein area is able to cover a larger part of the heating and cooling demand compared to the Beurskwartier area (as presented in section 4.3). As a result, less heat (or biomass) is needed from a DH (or biomass) supplier.

Observing the differences between the scenarios, it can be concluded that scenario 3 has the lowest overall energy input, which is due to the fact that no extra peak supply is needed, as the existing ATES systems from the Jaarbeurs, NS and Rabobank are able to provide this part. In addition, scenario 1 and 2 have a higher energy input compared to the reference scenario due to electricity needed for dry coolers and biomass needed for peak supply.

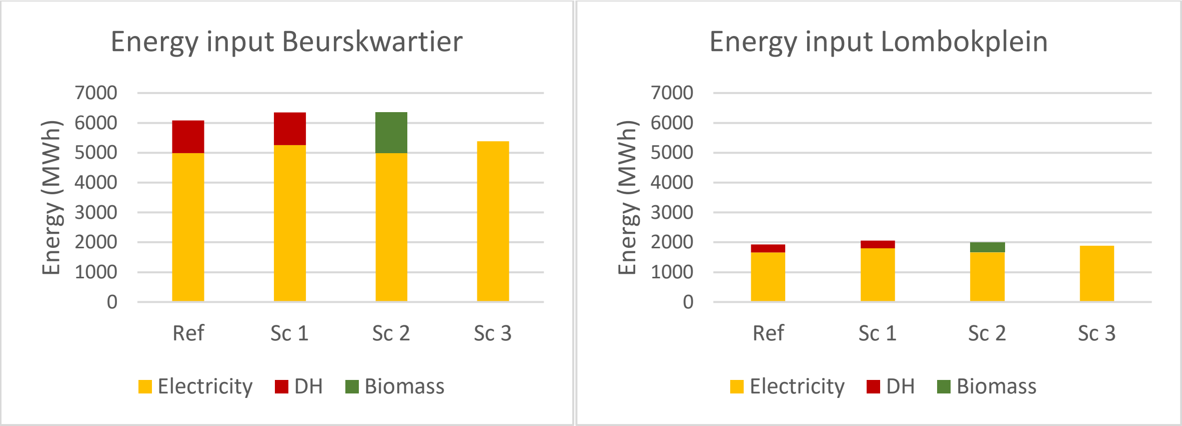


Figure 16 Energy input of heating and cooling system in Beurskwartier and Lombokplein area

The primary energy input of the heating and cooling system in each scenario in the Beurskwartier and Lombokplein area is presented in Figure 17. While the largest part of the primary energy input is also allocated to electricity, the share of primary energy input allocated to DH or biomass increased compared to the absolute energy input (Figure 16). This causes different results regarding the differences between the scenarios. Looking at the primary energy input, scenario 2 is more favourable compared to scenarios including DH. However, scenario 3 still has the lowest primary energy input.

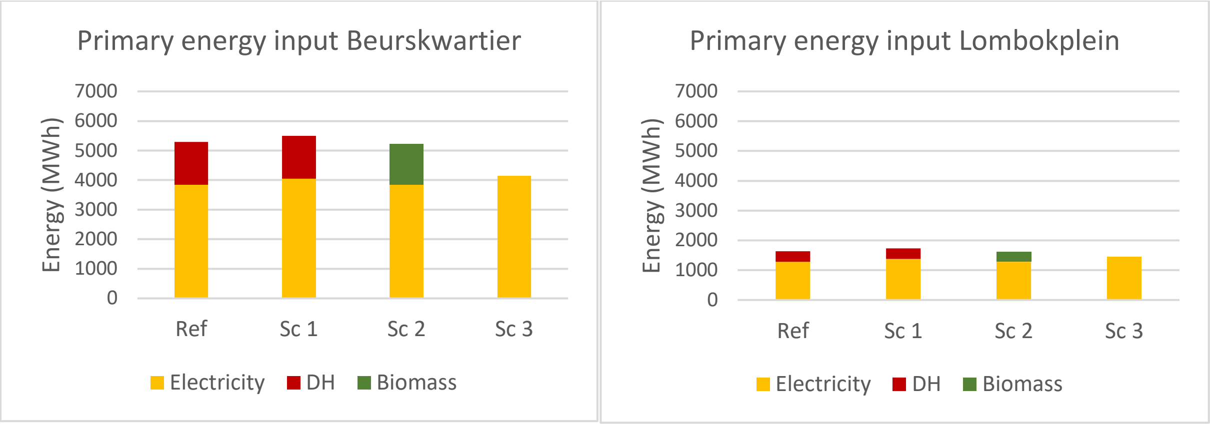


Figure 17 Primary energy input of heating and cooling system in Beurskwartier and Lombokplein area

4.4.2 Levelized cost of energy (LCOE)

This section presents the LCOE for each scenario (reference and scenario 1, 2 and 3) for the Beurskwartier area as well as the Lombokplein area. Figure 18 shows the LCOE for each scenario, also illustrating the share of the type of expenditures (investments, O&M and fuel costs).

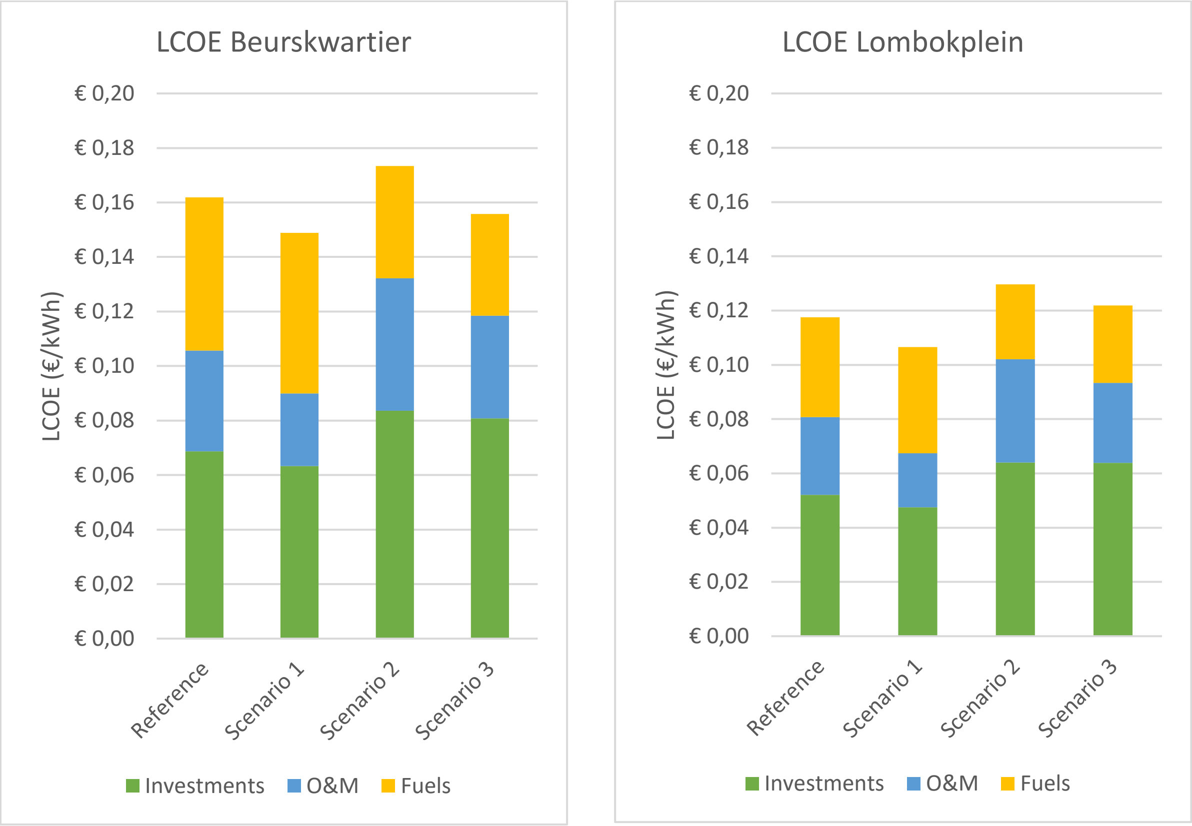


Figure 18 LCOE of Beurskwartier area and Lombokplein area

Comparing the LCOE of Beurskwartier and the LCOE of Lombokplein, the figure demonstrates that the overall the overall costs (of each scenario) are lower for the Lombokplein area. As the investment and O&M costs (in €/kWh) are nearly equal, the difference between the LCOE of the Beurskwartier and

Lombokplein area is caused by the fuel costs. This is explained by two causes. The Beurskwartier area has a relatively larger DHW demand due to the type of buildings (as explained in section 4.2), which means that it also needs relatively more electricity for its HP's. Another reason is that the peak supply needed by the Beurskwartier area is relatively larger compared to the Lombokplein area, which has effect on the amount of DH (or biomass) needed.

Regarding investment expenditures, investments in distribution systems (subsurface-related and building-related) cover the largest share of the total investment costs, varying from 52%-72%, depending on the scenario. This also translates in high O&M costs for distribution systems, making up for 33%-67% of the total O&M costs, depending on the scenario. Regarding the fuel costs, electricity and district heating require connection costs (depending on the capacity) as wells as costs for the actual use. This does not apply for biomass, which only requires costs for the biomass itself. The electricity costs for HP's and dry coolers are higher compared to the electricity costs for the ATES wells and a TEO installation, as these only require auxiliary power.

In addition, a couple of remarks can be made by analysing the differences between the scenarios. Scenario 1 makes use of a dry cooler as regeneration method (instead of TEO). The investment and O&M costs of dry coolers are significantly lower compared to a TEO installation. However, the fuel costs are larger due to an increasing electricity demand because of the use of dry coolers. This effect minimizes the overall difference. As a result, the LCOE of scenario 1 is slightly lower compared to the reference scenario. Scenario 2 makes use of a biomass boiler instead of district heating as peak supply. This brings extra investment and O&M expenditures, as a district heating system is already present in the surrounding area, whilst a biomass boiler is not. On the other hand, fuel costs for heat from biomass are significantly lower compared to heat bought from a DH supplier. However, this cannot outweigh the extra investment costs of the biomass boiler, which results in the LCOE of scenario 2 being slightly higher compared to the reference scenario. In scenario 3 the ATES systems of Jaarbeurs, NS and Rabobank are connected to the collective ATES systems of the Beurskwartier or Lombokplein area. As a results, peak supply from DH is not needed, which reduces the fuel costs. However, as the capacity of this combined ATES system is larger, more or bigger heat pumps are needed to upgrade the water to higher temperatures. This results in a significant increase in HP investment, O&M and electricity costs. However, the overall LCOE of scenario 3 is still slightly lower than the reference scenario.

Abovementioned results are different when varying the heating and cooling demand. This effect is studied in a sensitivity analysis. Figure 19 and Figure 20 show the LCOE based on the lower and upper bounds of the future heating and cooling demand. Assuming the lower bound of the future heating and cooling demand (based on UMGO) results in a maximum LCOE, while assuming the upper bound of the future heating and cooling demand (based on Vesta) results in a minimum LCOE. A larger energy demand results in a lower price per kWh, as not all type of expenditures are dependent on the size of the energy demand. Interesting to note is that the LCOE of scenario 3 is noticeably sensitive to changes in the heating and cooling demand. When assuming the lower bound of the heating and cooling demand (based on UMGO), the LCOE of scenario 3 is the largest of all scenarios, while it was one of the cheaper options in case of a higher heating and cooling demand. This is due to the fact that the LCOE is mainly driven by investment expenditures (and less by fuel costs for example) in case of a lower heating and cooling demand. Scenario 3 has large HP investment expenditures, due to the large HP capacity that is needed, as DH is not needed for peak supply.

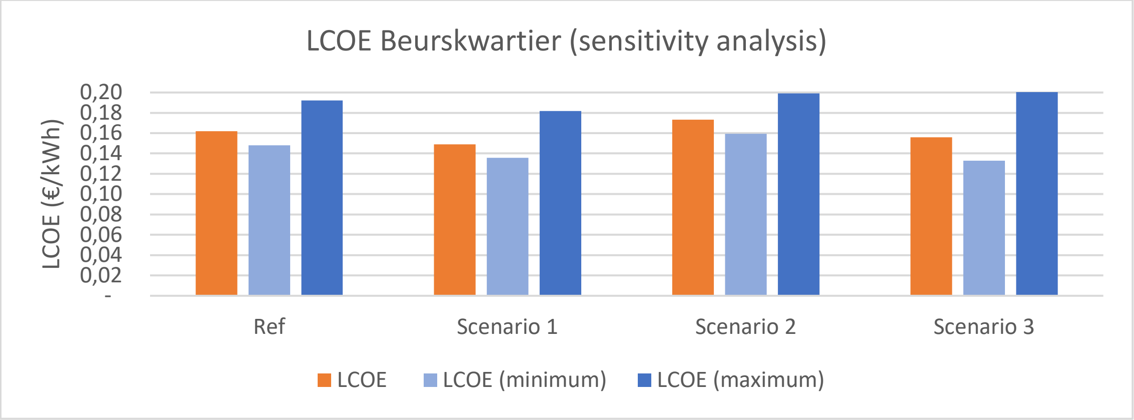


Figure 19 LCOE Beurskwartier (sensitivity analysis)

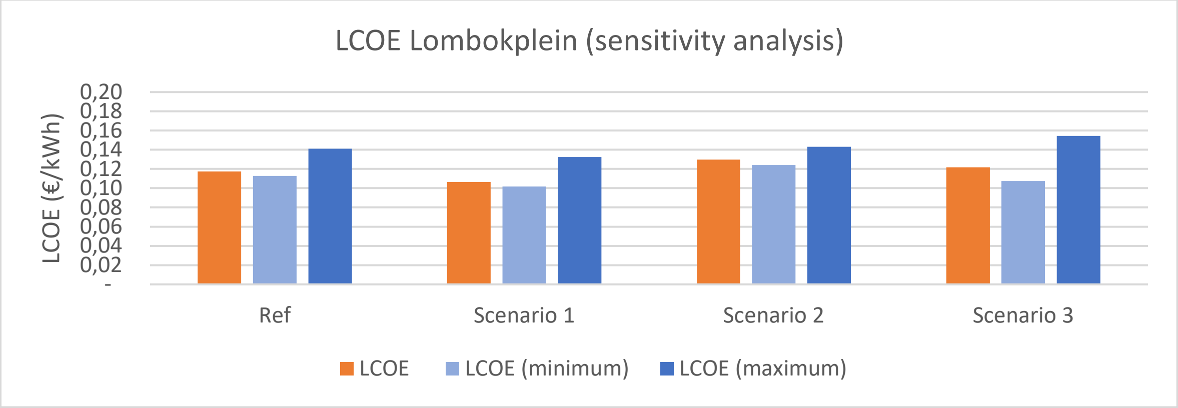
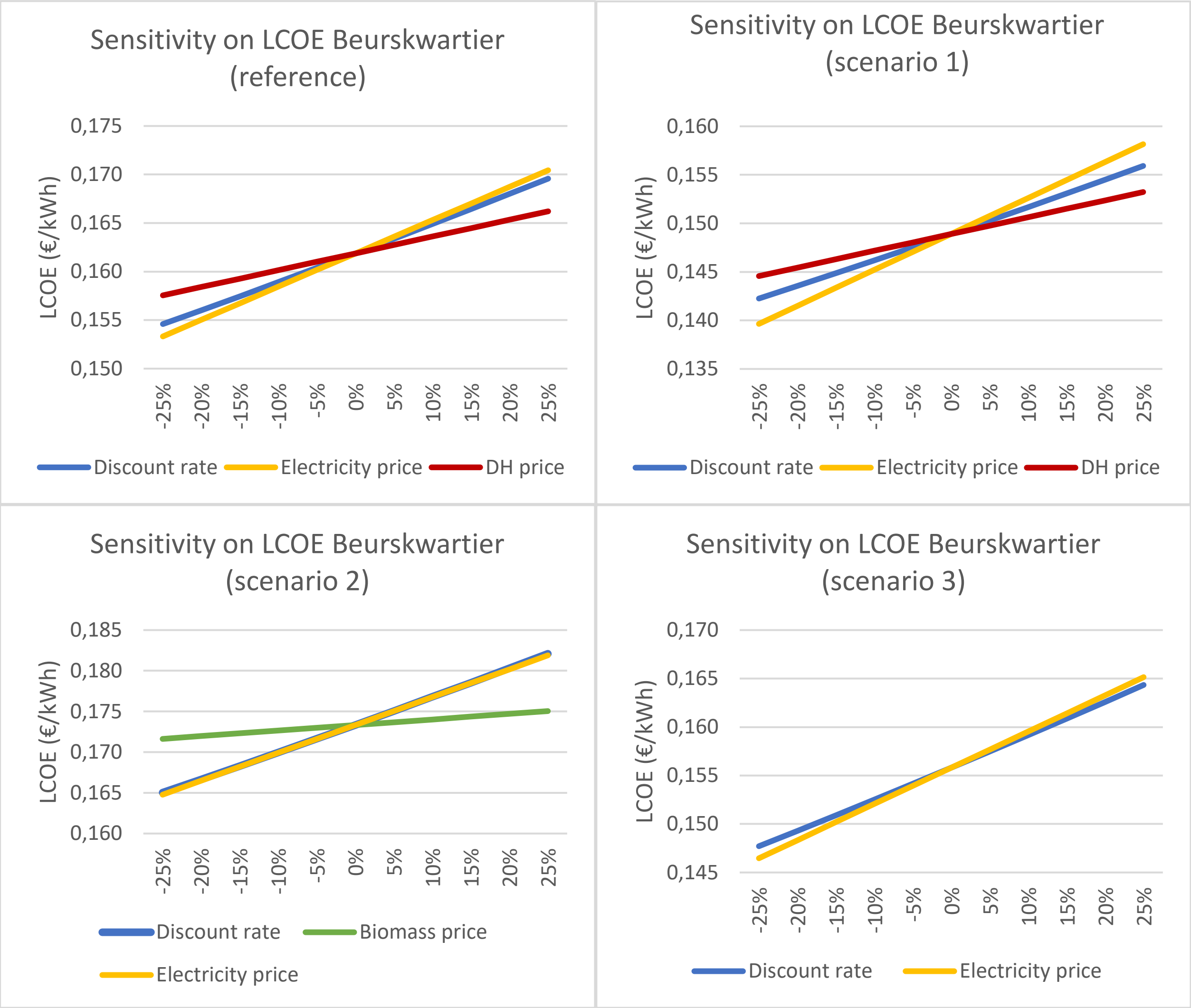


Figure 20 LCOE Lombokplein (sensitivity analysis)

Uncertainty regarding an increasing or decreasing DH price, electricity price, biomass price and discount rate and its effect on the LCOE is also tested for all scenarios in the Beurskwartier area. Figure 21 shows the effect on the LCOE when increasing (until 25%) or decreasing (until -25%) the DH price, electricity price, biomass price and discount rate. It shows that changes in the biomass price hardly has any influence on the LCOE, while changes in the electricity price, DH price and discount rate have more effect. Still the changes in the LCOE do not affect the outcome of this research. Changes in none of the input parameters (DH price, electricity price, biomass price and discount rate) led to a different ranking of the LCOE among the scenarios (e.g. in terms of being most expensive). This only happens when the costs of purchased DH increase with at least 70%. At this point the LCOE of scenario 2 becomes cheaper than the reference scenario. In other words, peak supply provided by a biomass boiler becomes more favourable (from an economic point of view) compared to purchasing DH.


Sensitivity on LCOE Beurskwartier (reference)

Sensitivity on LCOE Beurskwartier (scenario 1)

Sensitivity on LCOE Beurskwartier (scenario 2)

Sensitivity on LCOE Beurskwartier (scenario 3)

Figure 21 Effect of DH price, electricity price, biomass price and discount rate on the LCOE of all scenarios in Beurskwartier

4.4.3 Payback period

The time period needed for the return on the investment to equal the sum of the first investment varies for each scenario. Figure 22 and Figure 23 show the balance of each scenario for the Beurskwartier and Lombokplein area. The PBP refers to the year in which the balance turns positive. The one-time contribution at the start of the project (BAK) and the re-investment of the HP's (and biomass boiler) after fifteen years can also be observed in the chart. At the Beurskwartier area, the reference scenario has a PBP of 17 years, while scenario 1 and 3 have a shorter PBP: 12 and 14 years respectively. Scenario 2 on the other hand has a longer PBP: 21 years. At the Lombokplein area, the reference scenario has a PBP of 20 years, while scenario 1 has a shorter PBP: 17 years. Scenario 2 and 3 have a longer PBP periods: 24 and 22 years. The Lombokplein area deals with overall longer PBPs compared to the Beurskwartier area. This is explained by the type of buildings in this area (less residential buildings). The income from heating and cooling (consisting of connection costs (BAK), a fixed charge, and the sale of heat and cold) is relatively higher for residential buildings than for utility buildings.

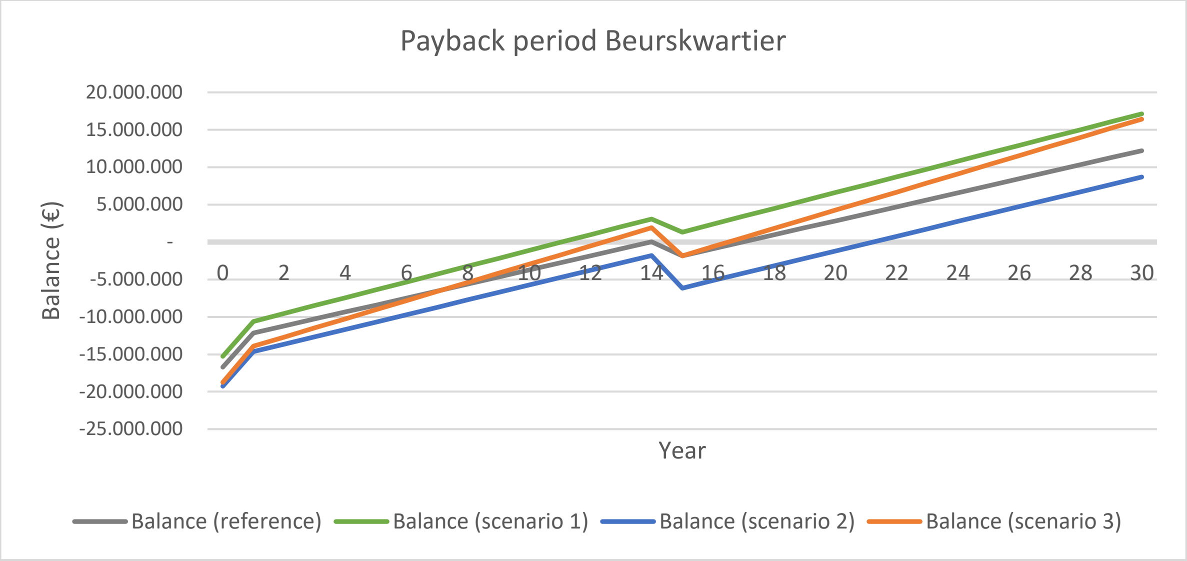


Figure 22 PBP Beurskwartier

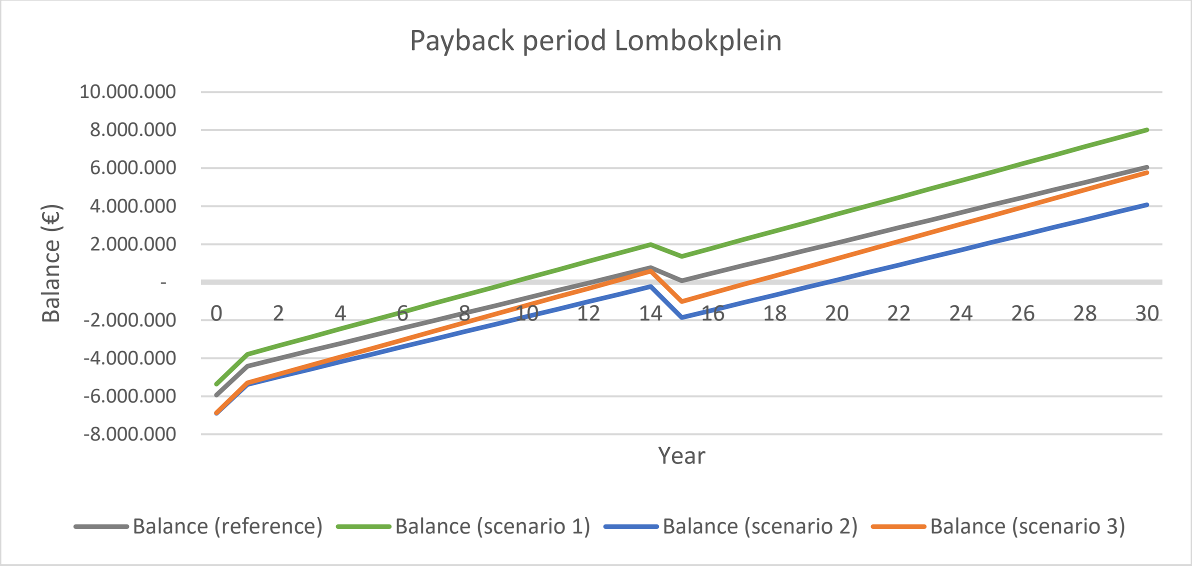


Figure 23 PBP Lombokplein

4.4.4 Internal rate of return (IRR)

Table 18 shows the IRR of each scenario in the Beurskwartier and Lombokplein area. When a project has a low IRR, typically in range of 2-6%, cities generally develop such projects via the public utility, and the low returns are spread across other projects with higher IRRs (UN Environment, 2016). The numbers show that only scenario 1 in the Beurskwartier area has an IRR above 6%. This means that from a private sector investor point of view, it is most likely to develop an energy system in the Beurskwartier area that combines a collective ATES system with DH for peak supply and dry coolers as regeneration method. In the Lombokplein area none of the scenarios are likely to be developed by a private sector investor.

Table 18 Internal rate of return (IRR) of each scenario in the Beurskwartier and Lombokplein area

Area	Reference	Scenario 1	Scenario 2	Scenario 3
Beurskwartier	5%	7%	3%	5%
Lombokplein	3%	5%	2%	3%

5. Discussion

This chapter elaborates on the limitations and uncertainties of this research (section 5.1). It also explains how this research extends current theoretical insights and provides avenues for further research (section 5.2). Policy and managerial advice resulting from this research is presented (section 5.3).

5.1 Limitations and uncertainties

The use of EnergyPRO software for modelling the collective ATES system brings some advantages as well as limitations. EnergyPRO facilitates the calculation of the energy demand, COP values, supply and return temperatures and the energy supply that vary with external conditions such as the daily ambient air temperature. However, its application in this particular subject is not ideal. EnergyPRO is mainly used for optimization of combined heat and power production rather than heating and cooling supplied by ATES systems. EnergyPRO does not include standard ATES units within its modelling package. This research deals with this drawback by designing a collective ATES system based on user defined system components. This model is able to solve the matching of the future heating and cooling demand with the heating and cooling supplied by the ATES system. More detailed analysis about the regeneration and peak supply technologies, total energy input and costs cannot be solved within this model. For this reason, this study only uses EnergyPRO for the purpose of solving research question 2: "To what extent can a collective ATES system meet the future heating and cooling demand of the Beurskwartier or Lombokplein area?"

Another limitation is that this research looks at the collective ATES system in its final state. It assumes all planned buildings to be built and the ATES system to be fully deployed. In reality, the planned buildings will not be built at the same time. This research could better deal with planning by including a scenario in which multiple small ATES clusters are developed throughout time, instead of two large collective ATES systems. It is expected that the costs of this type of system are higher. More capacity needs to be installed, as smaller clusters benefit less from simultaneousness advantages. The costs of connections to TEO of DH also increase, as multiple connections are needed instead of one.

Out of all input parameters within this research, the data used to forecast the future heating and cooling demand seems to have the largest uncertainty. There is a large discrepancy in heating and cooling demand numbers, depending on assumptions made (e.g. reasoning from actual data or BENG requirements). For this reason, a sensitivity analysis is performed to show the impact of these differences on the alignment of the heating and cooling demand and supply (presented in section 4.3) and the LCOE of each scenario (presented in section 4.4.2). A larger heating and cooling demand results in a lower price per kWh. Variation in the heating and cooling demand also causes different results when comparing the LCOE of all scenarios. For example, the LCOE of scenario 3 is the largest when assuming a low heating and cooling demand, while it is one of the cheaper options when assuming a high heating and cooling demand.

An uncertainty in estimating the future space heating and cooling demand is that the distribution of this demand was calculated in daily intervals, solely based on the average daily ambient air temperature. It does not show variations within the day, such as morning and evening peaks. The purpose of this research is however not to create an optimal technical design of an ATES system, but to estimate to what extent a collective ATES system could provide a certain district with heating and cooling. It must be noted that, as a result of this approach, the chosen reference temperature (T_{ref}) at which space heating or cooling is needed, becomes an important determinant.

Another uncertainty is the way this research deals with the estimation of future investments expenditures and future fuel costs. Regarding the future investments expenditures, current prices are taken into account and are not converted to future prices by means of technology learning curves. This would lead results with apparent accuracy. In addition, the building sector is known for being the least innovative sector in the Netherlands (TNO, 2007). Regarding the future fuel costs, a future price is assumed for electricity and biomass and a current price for DH. It is challenging to accurately forecast the price of DH, as Eneco has planned developments regarding the fuel use of the Utrecht/Nieuwegein DH system. For this reason a sensitivity analysis was performed (presented in section 4.4.2). This analysis showed that this research is still of added value as the price of purchased DH has to increase with at least 70% in order to be less favourable (from an economic point of view) compared to a biomass boiler.

5.2 Theoretical implications

This research adds insights from a district-level perspective to current research about the optimal techno-economic use of a sustainable district heating and cooling system. In this research, the Beurskwartier and Lombokplein area in Utrecht served as case. Each district in the Netherlands is defined by different characteristics and restrictions, such as the heating and cooling demand of the consumers in a district. This research showed that the estimation of the heating and cooling demand of a district has a large bandwidth, caused by large differences in key figures published by various research institutes (as explained in section 3.3). This research also showed that variations in characteristics such as the future heating and cooling demand result in different optimal techno-economic outcomes (as explained in section 4.4.2.). This highlights the need for further research into the heating and cooling demand of the built environment (specified per type of building) and comparison of existing studies and datasets in order to make more accurate estimates.

This research also extended existing knowledge on the configuration of ATES systems and other technologies. The use of DH or a biomass boiler as peak supply and TEO or dry coolers as regeneration method were examined. These configurations require a different role from DH suppliers such as Eneco, as DH is only supplied at peak times. This might however not be beneficial for the overall district heating system in Utrecht, as extra demand is added to the peak demand. An avenue for further research would be to explore an option where DH is used as regeneration method. In this way, DH is used in summer when the demand for heat from the DH system is low.

Besides sustainable heating, this research also focussed on sustainable cooling, a topic that is currently underrepresented by academia. However, this study did not take multiple type of cooling technologies into account. Today’s developments such as better insulated buildings, temperature increase caused by climate change and heat island effects in urban areas provide reason for more in-depth research in different type of sustainable cooling options.

5.3 Managerial implications

This study mentioned that individual heating and cooling solutions (e.g. HPs with PV panels) are not always straightforward solutions for districts such as the Beurskwartier and Lombokplein area, as it will become densely populated with many high-rise constructions. A collective heating and cooling system, making use of DH, ATES and TEO, is more suitable to this area. This is not entirely in accordance with the guidelines in the Energy Protocol written by the Municipality of Utrecht. This protocol asks project developers to first seek heating and cooling solutions at the building site (Gemeente Utrecht, 2019). The Municipality of Utrecht could consider to revise the Energy Protocol for areas identical to the Beurskwartier and Lombokplein area.

An analysis of the current ATES systems of the Jaarbeurs, Rabobank and NS compared the actual supply and the maximum allowable supply according to their permits. This research showed all systems operate below their permits and a heating and cooling surplus (MWh) might be available for a collective ATES system in the Beurskwartier and Lombokplein area. Important to note is that this result is based on monthly supply data, the smallest time resolution available. A constant supply is assumed. However, the permits also include restrictions on the maximum allowable flow rate. In reality, the supply might be less constant and less heating and cooling surplus might be available due to this maximum flow rate restriction. Additional in-depth research on the supply characteristics of the ATES systems of Jaarbeurs, Rabobank and NS in a smaller time resolution is recommended.

This research found that adding existing buildings as consumers to a collective ATES system is driving the future heating and cooling demand further apart, compared to a system in which only planned buildings serve as consumers (presented in section 4.2). As an ATES system benefits from a balanced heating and cooling demand, it seems more favourable to connect the planned buildings to a collective ATES system and seek other solutions for the existing building stock in the Beurskwartier and Lombokplein area.

When matching the supply and demand of a collective ATES system in the Beurskwartier and Lombokplein area, it becomes clear that the potential ATES wells cannot provide enough capacity to provide heating or cooling during cold winter days or hot summer days. Unless the potential ATES wells are combined with the existing wells of the Jaarbeurs, Rabobank and NS. In this case, no extra peak supply is needed in the Beurskwartier area and a small amount of extra cooling is needed in the Lombokplein area. However, one cannot conclude that the existing ATES wells should be connected to the collective ATES systems in the Beurskwartier and Lombokplein area solely based on these findings. Bivalent ATES systems (peak capacity (e.g. 30%) is not supplied by ATES) might be more favourable from an economic point of view compared to monovalent systems (100% of the capacity is supplied by ATES). There is an economic trade-off in providing more capacity from ATES wells (when connecting to the existing ATES wells) and lowering the share of extra peak capacity needed from other sources (e.g. DH). The costs for HP's will increase, while the costs for purchased heat form another source decrease. Additional studies are recommended needed to find the most optimal division.

The PBP of the collective heating and cooling system varies between 12 and 24 year, depending on the scenario or area. This reflects the time period investors need for their return on investment to equal the sum of the first investment. The Municipality of Utrecht can take this PBP into account when determining the duration of a concession period, as investors are only willing to invest when this period is longer than the PBP.

The most optimal configuration of the collective ATES system depends on which type of indicators are considered more relevant: technical (energy input) or economic. Looking at the total (primary) energy input, a scenario in which a collective ATES system is connected to existing ATES systems is recommended, as it has the lowest overall energy input. In addition, a scenario in which TEO is used as regeneration method and DH is used for peak supply, is more favourable in terms of energy input, compared to dry coolers or biomass boilers. Looking at the economic indicators, a collective ATES system in which peak demand is supplied by DH and regeneration is supplied by dry coolers seems most likely to invest in, as the LCOE and PBP are lowest for this scenario (scenario 1). It is however not likely that private investors will invest in the collective ATES system, as the IRR for all scenarios is rather low (<8%). The Municipality of Utrecht is recommended to explore non-private investment options. In addition, it is recommended to question which criteria (low overall energy input or low costs) is most relevant and to act accordingly.

As this research only looks at the collective ATES system in its final state, the Municipality of Utrecht still needs to overcome hurdles regarding planning and temporary solutions. In reality, some buildings will already be finished before the collective ATES system. These buildings will need temporary individual solutions (such as the individual use of doublet). It is expected that this will raise the costs, as for example extra piping is needed to first connect to an individual ATES system and later to a collective ATES system. In addition, extra space in the subsurface needs to be reserved. This also raises the question on when to start developing the collective ATES system and connection buildings to this system, while making sure that the temporary individual solution and the collective ATES system both experience a positive business case. Furthermore, the switch from an individual solution towards the collective ATES system needs to be organized and planned. It is recommended to think about the responsibilities of all parties involved and about timing (e.g. during winter or summer does not seem ideal).

6. Conclusion

The aim of this research was to *"design a sustainable heating and cooling system in the Beurskwartier and Lombokplein area by carrying out a techno-economic analysis on implementing a collective ATES system combined with DH and TEO."* Four research questions were formulated in contribution towards this goal. Below follows a short description of the method used and an answer to each research question.

1. What are the characteristics (in terms of heating and cooling supply) of the ATES systems currently in place at the Beurskwartier and Lombokplein area?

The heating and cooling supply characteristics of the ATES systems of Jaarbeurs, Rabobank and NS were compared to the maximum allowable supply according to their permits. The three ATES systems combined could theoretically supply 4624 MWh of extra heating and 4752 MWh of extra cooling each year. In practice, this amount might be less as the maximum allowable flow rate is not taken into account.

2. What is the heating and cooling demand of the Beurskwartier and Lombokplein area in 2040?

The heating and cooling demand is calculated based on building characteristics such as the surface (m^2), construction year or level of insulation and the type of building (e.g. residential or office). The calculated demand is based on the average of two data sources: the theoretical heating and cooling demand according to the BENG criteria (UMGO dataset) and the heating and cooling demand based on actual data of newly built buildings (Vesta dataset). This results in a space heating, cooling and DHW demand of 8353 MWh, 4028 MWh and 3156 MWh respectively for all planned buildings in the Beurskwartier area. All planned buildings in the Lombokplein area have a space heating, cooling and DHW demand of 4058 MWh, 2208 MWh and 837 MWh respectively. The Beurskwartier area has a greater energy demand compared to the Lombokplein area, as it contains more consumers. The DHW demand in the Beurskwartier is not only larger due to the size of the area, but also relatively larger due to the type of buildings (more residential) compared to the Lombokplein area.

The space heating and cooling demand was distributed over the year based on the ambient air temperature. This results in a maximum heating and cooling peak capacity of 9.7 MW and 11.5 MW respectively in the Beurskwartier area and a maximum heating and cooling peak capacity of 4.2 and 6.3 respectively in the Lombokplein area. A sensitivity analysis is able to identify the lower and upper bounds of the maximum heating and cooling capacity. The lower bound is based on the UMGO dataset and the upper bound is based on the Vesta dataset. Taking the Beurskwartier area as an example, during a cold winter day the maximum heating capacity may vary from 6 MW (lower bound) to 13 MW (upper bound). This shows that assumptions made regarding heating and cooling demand calculations have large implications on the design and costs of the heating and cooling system, as the design of an energy systems is often based on the largest peaks.

3. To what extent can a collective ATES system meet the future heating and cooling demand of the Beurskwartier or Lombokplein area?

A model built in EnergyPRO compared the heating and cooling demand with the maximum heating and cooling supply of the collective ATES system, based on six doublets in the Beurskwartier area and three doublets in the Lombokplein area. Both collective ATES systems do not have enough capacity to supply the areas with sufficient heating and cooling throughout the whole year. In the Beurskwartier area, 92% of the heating demand (45% of peak capacity) and 80% of the cooling demand (34% of peak capacity) can be supplied by the ATES doublets. In the Lombokplein area, 94% of the heating demand (52% of peak capacity) and 76% of the cooling demand (30% of peak capacity) can be supplied by the

ATES doublets. Extra peak supply is needed during cold winter days and hot summer days. In addition, regeneration of the wells is needed as the total amount of heat supplied is larger compared to the total amount of cooling.

4. What is the sustainable heating and cooling system with the most optimal techno-economic performance in the Beurskwartier and Lombokplein area?

Four scenarios are developed: collective ATES, TEO and DH (reference), collective ATES, dry coolers and DH (scenario 1), collective ATES, TEO and biomass boiler (scenario 2) and collective ATES including existing ATES systems, TEO and DH (scenario 3). These scenarios are scored on technical indicators (energy input and primary energy input) and economic indicators (LCOE, PBP and IRR). The most optimal technical performance (lowest energy input and primary energy input) is achieved by scenario 3 and the most optimal economic scenario (lowest LCOE and PBP) is achieved by scenario 1. From an investor point of view, all scenarios have a low IRR (< 8%), which makes investments from private parties less expected.

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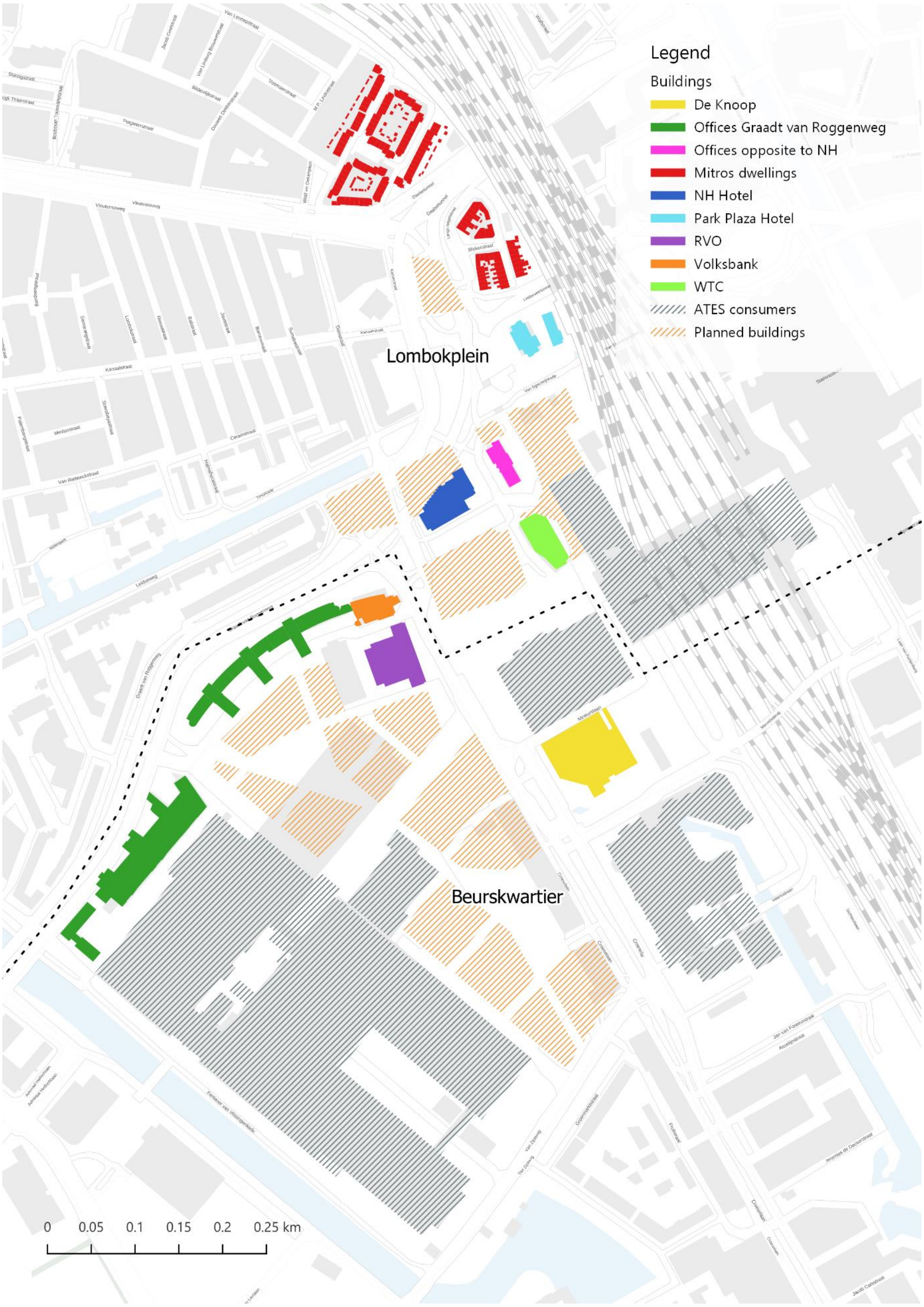
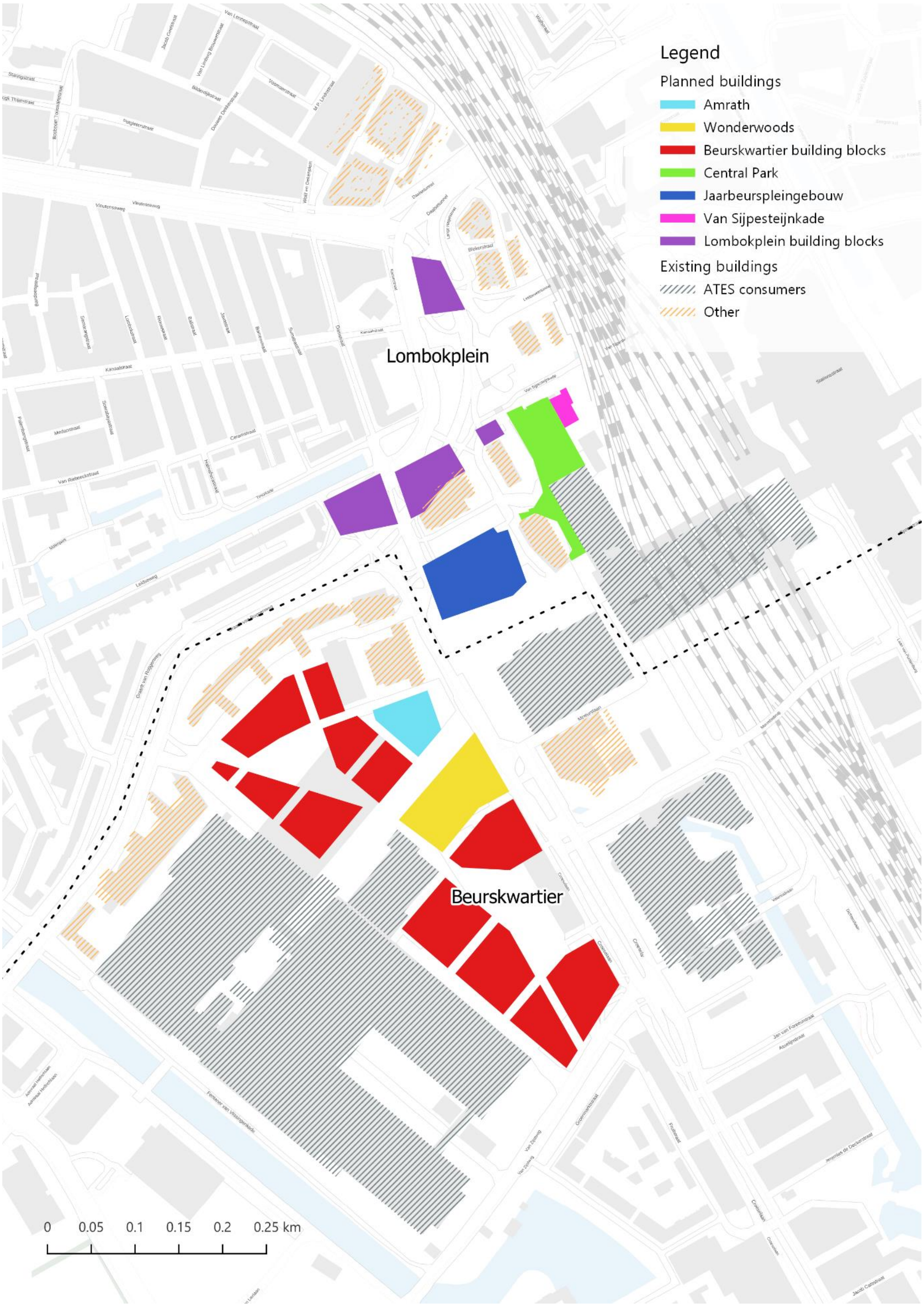
Appendix I: map existing buildings



Appendix II: map planned buildings



Appendix III: heating and cooling demand (sensitivity analysis)

Figure 24 and Figure 25 show the variation in heating and cooling demand in the Beurskwartier and Lombokplein area. The lower and upper bounds of the future energy demand are identified by the theoretical heating and cooling demand according to the BENG criteria (UMGO dataset) and actual data of the heating and cooling demand of newly built buildings (Vesta dataset).

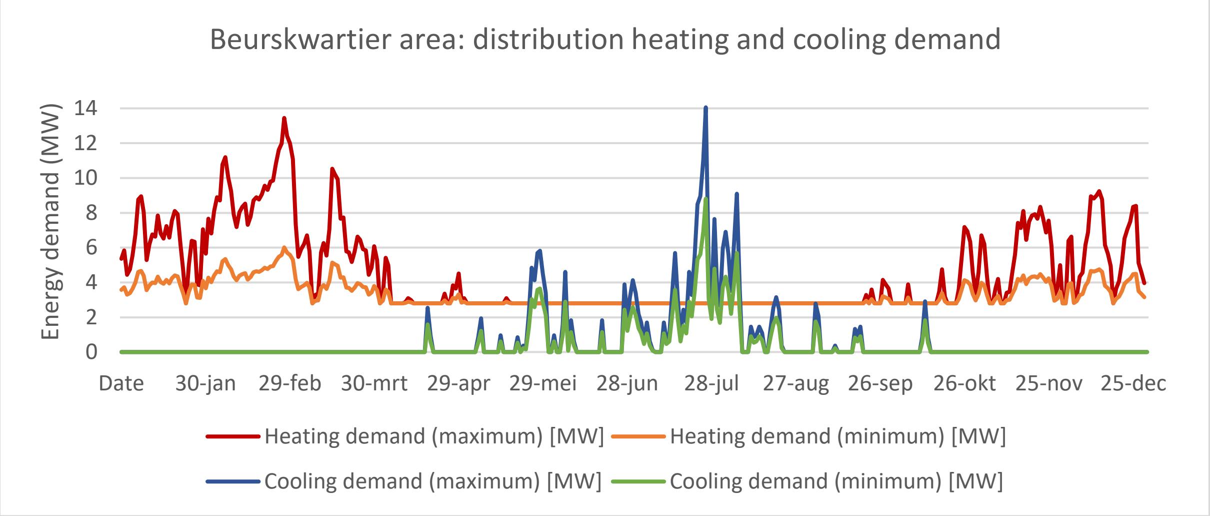


Figure 24 Heating and cooling demand Beurskwartier (sensitivity analysis)

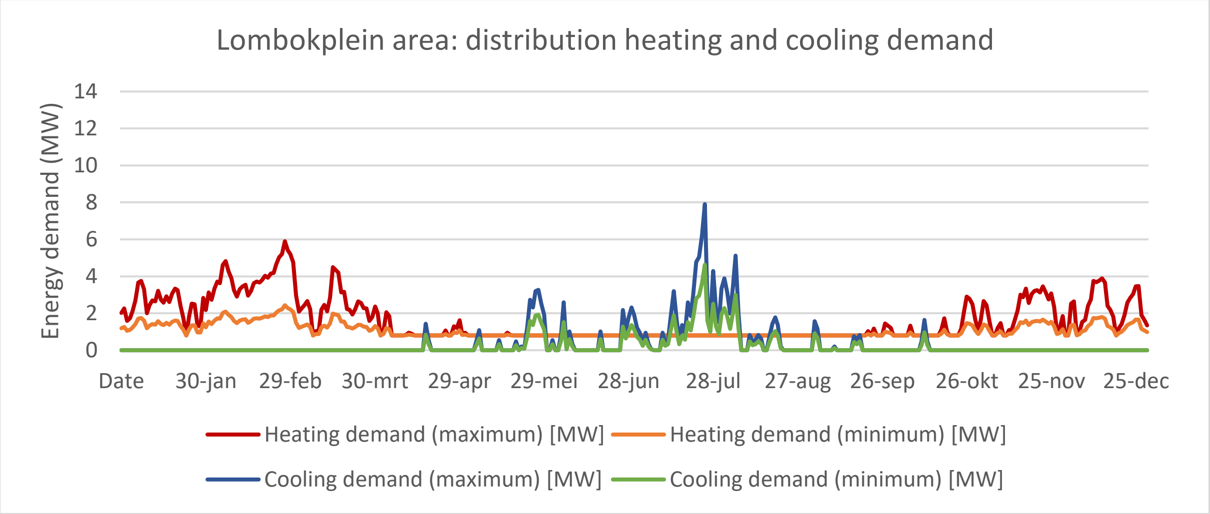
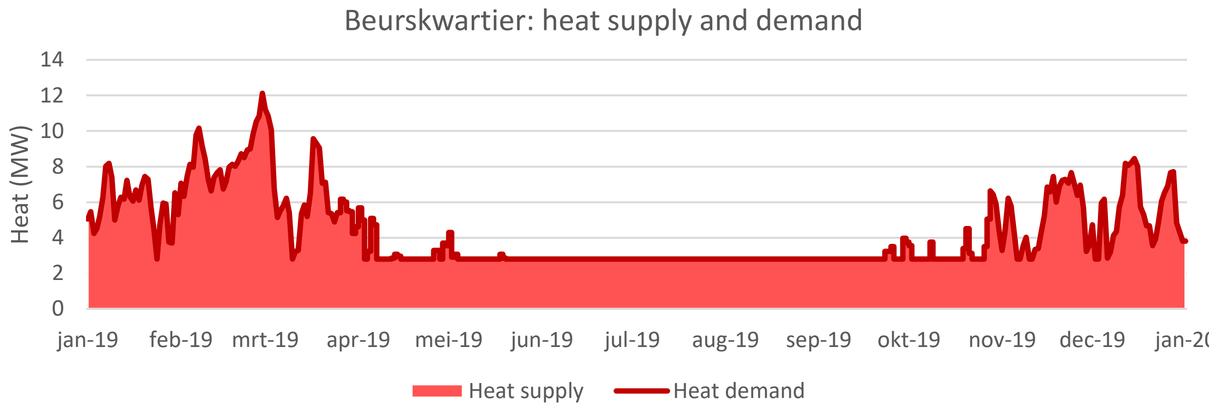
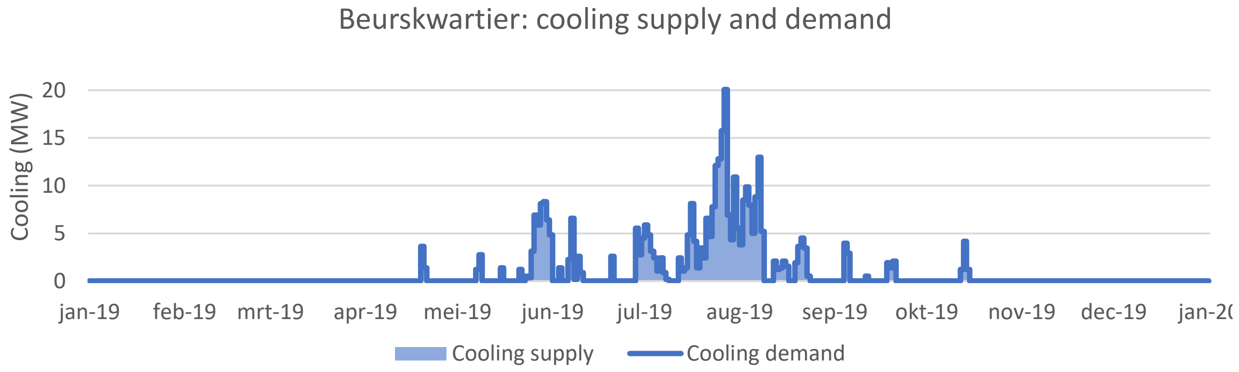


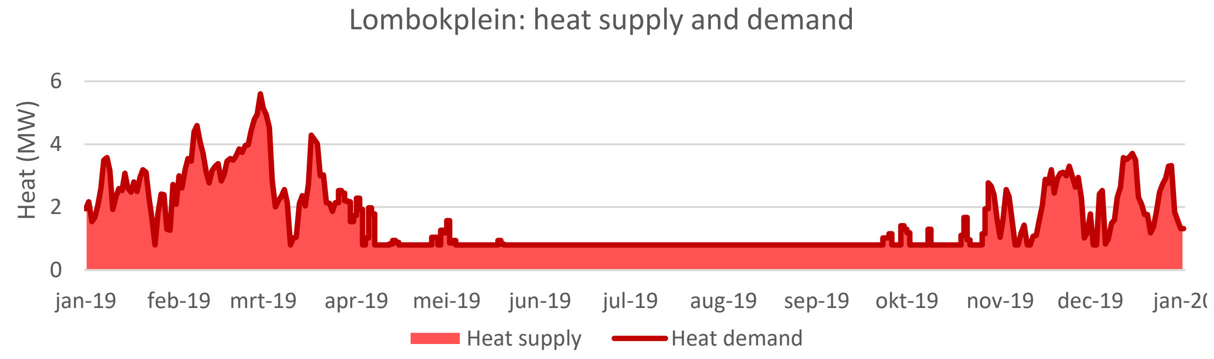
Figure 25 Heating and cooling demand Lombokplein (sensitivity analysis)

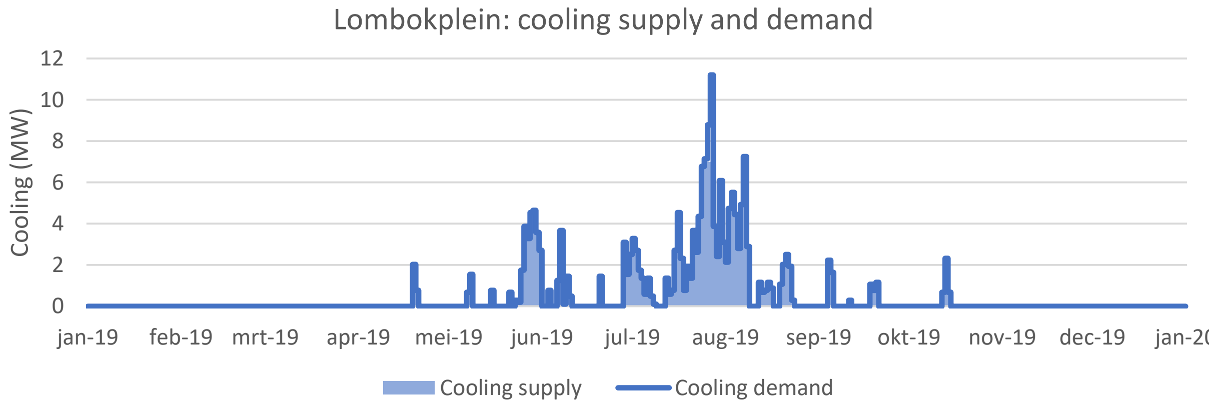
Appendix IV: matching supply and demand (scenario 3)

The figures show the alignment of heating and cooling supply and demand in case of scenario 3.



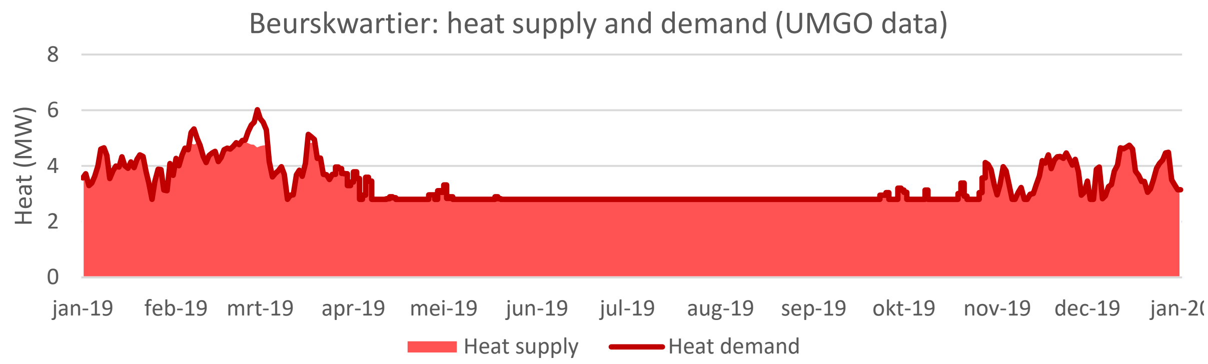


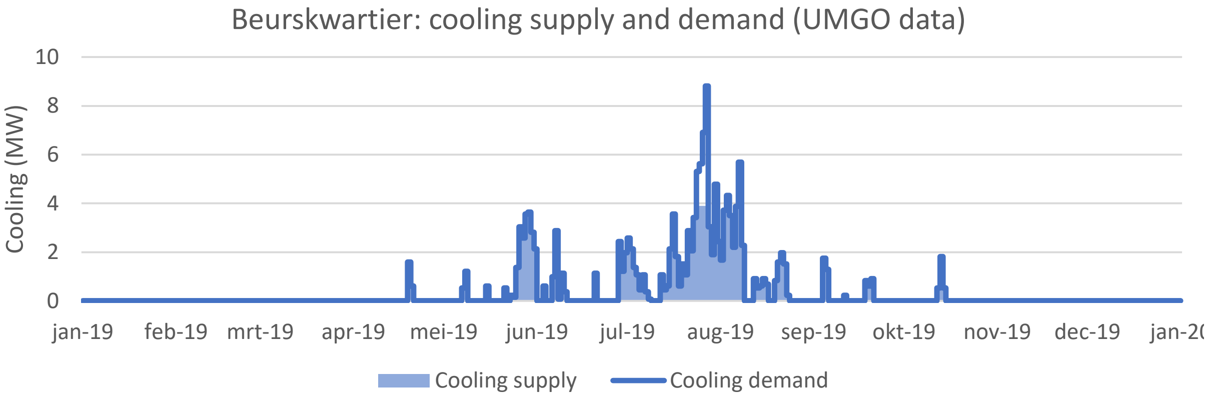


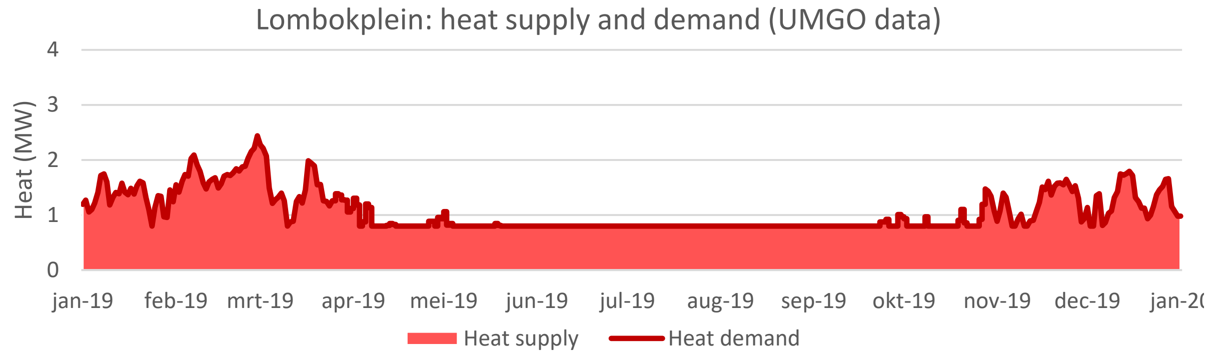


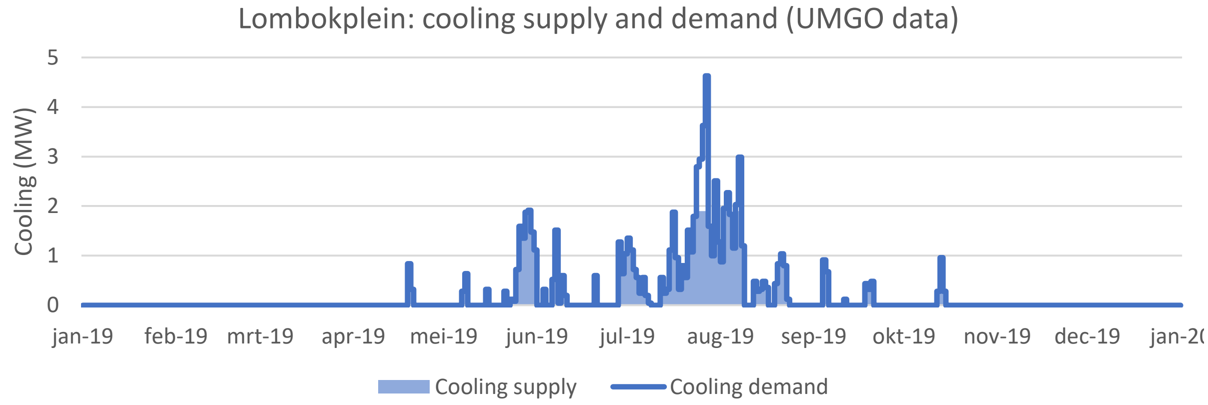
Appendix V: matching supply and demand (sensitivity analysis)

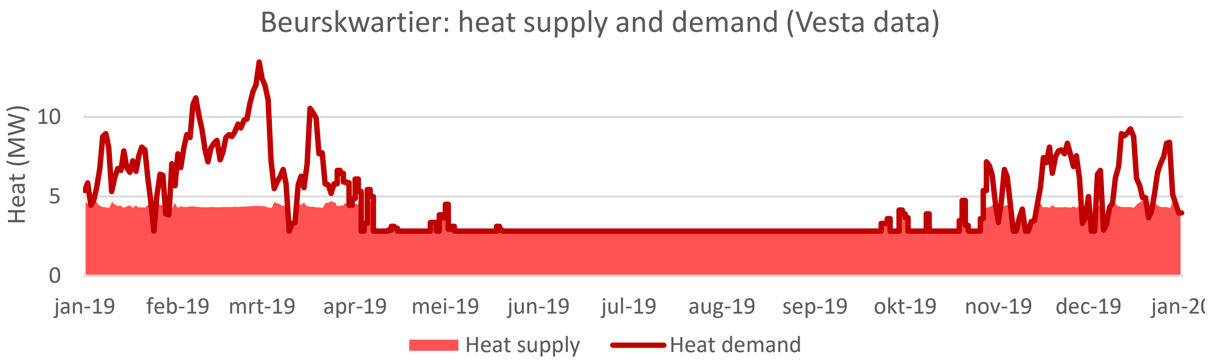
The figures below show the alignment supply and demand for the UMGO and Vesta datasets.

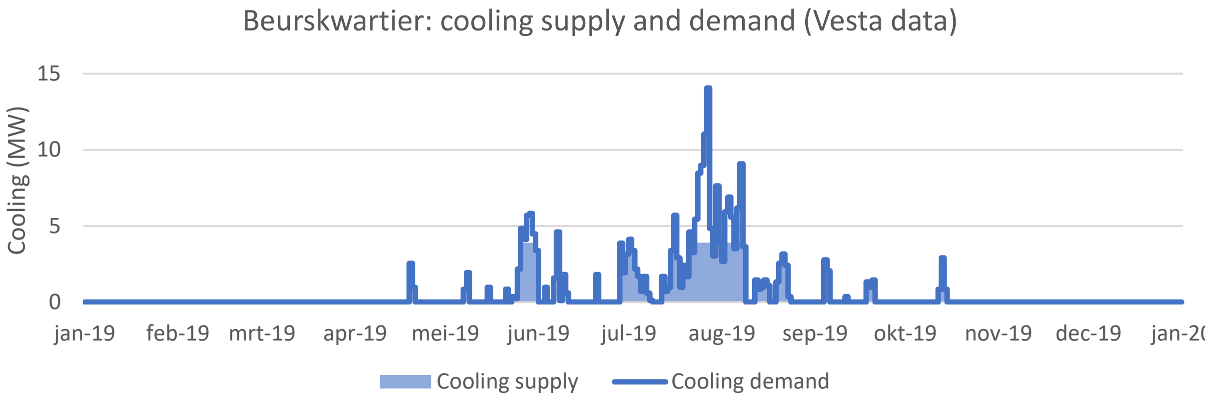


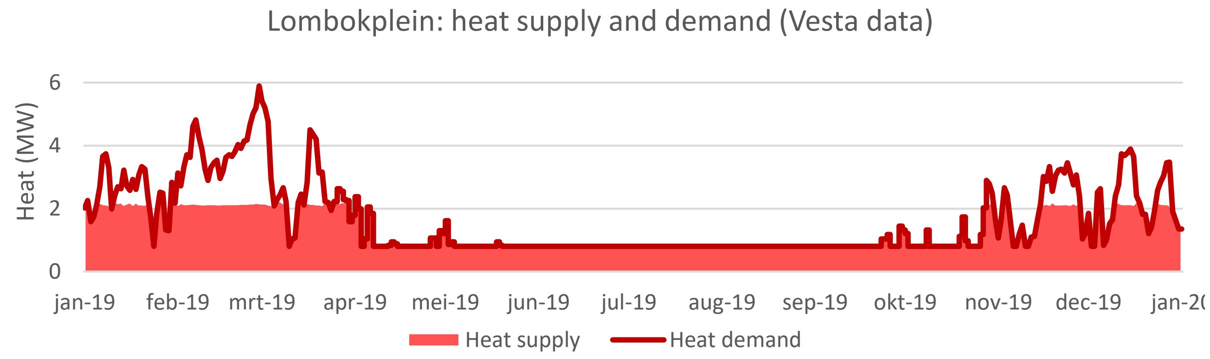


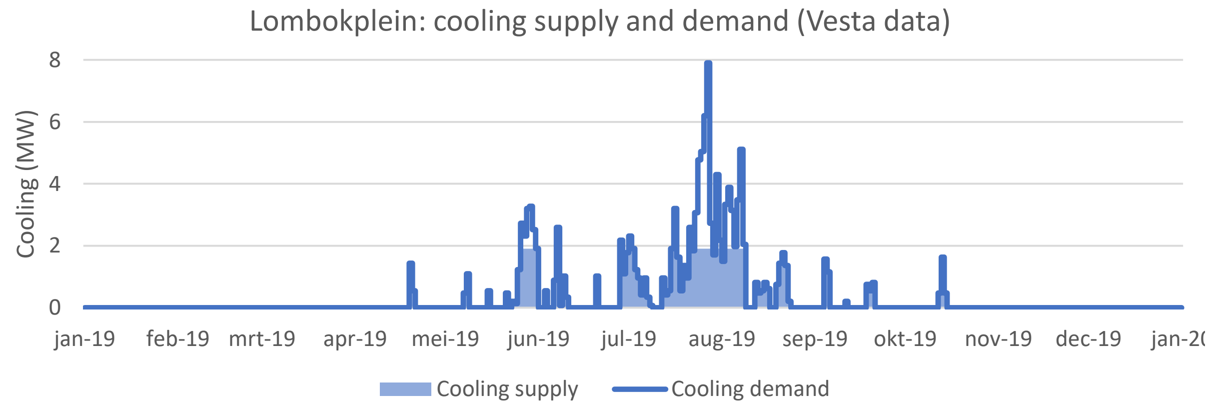


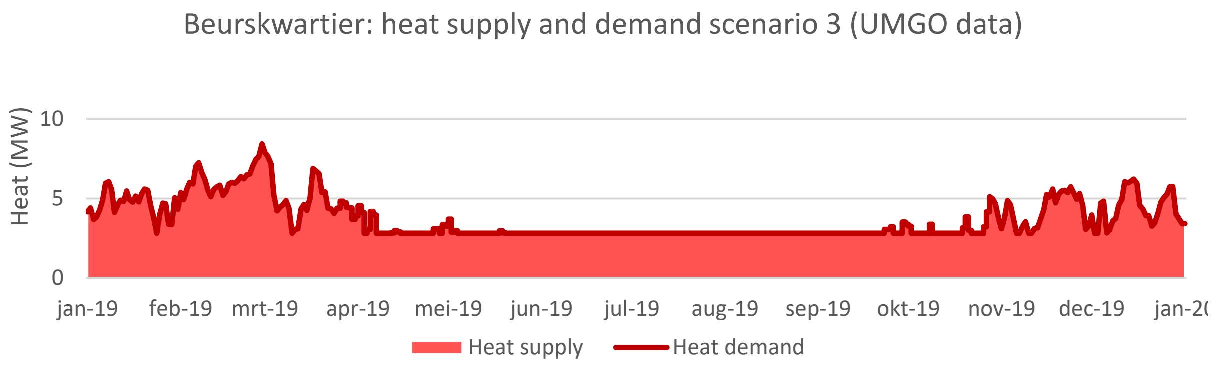


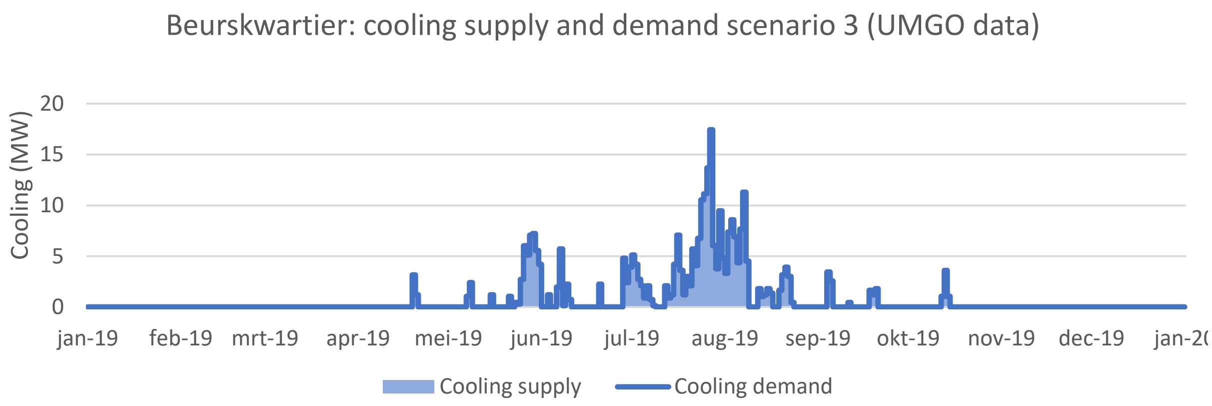

Beurskwartier: heat supply and demand (Vesta data)
Heat (MW)
0
5
10
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Heat supply
Heat demand

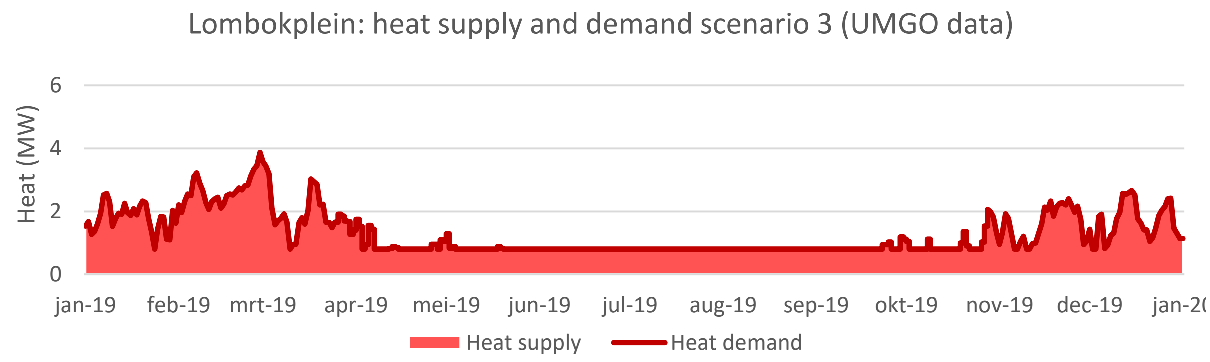

Beurskwartier: cooling supply and demand (Vesta data)
Cooling (MW)
0
5
10
15
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Cooling supply
Cooling demand

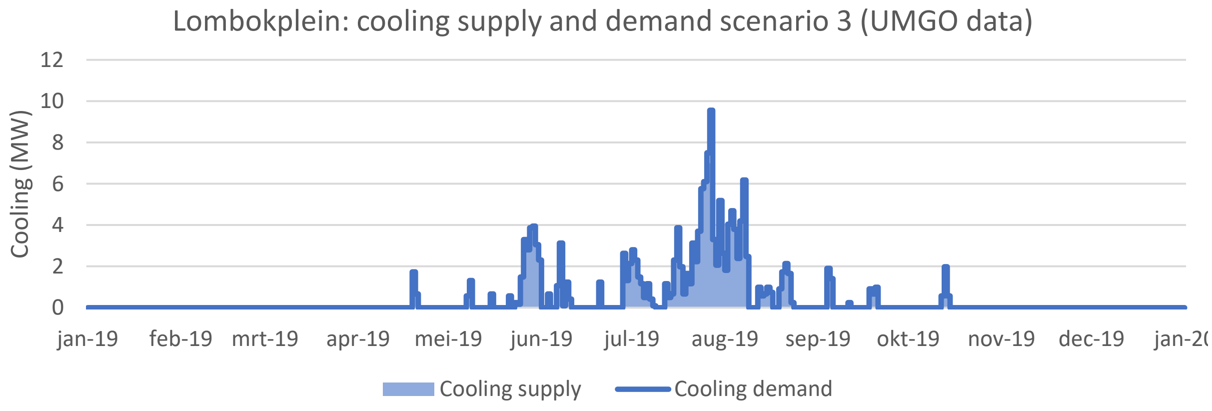

Lombokplein: heat supply and demand (Vesta data)
Heat (MW)
0
2
4
6
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Heat supply
Heat demand

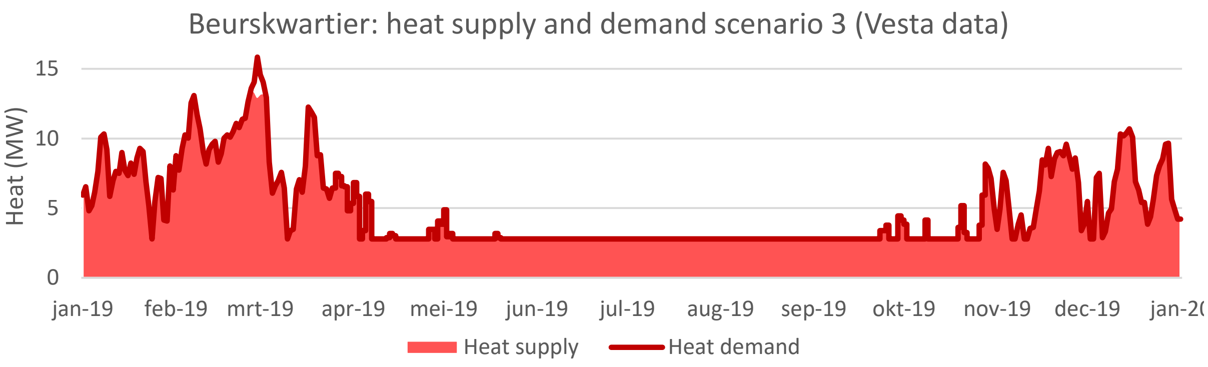

Lombokplein: cooling supply and demand (Vesta data)
Cooling (MW)
0
2
4
6
8
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Cooling supply
Cooling demand

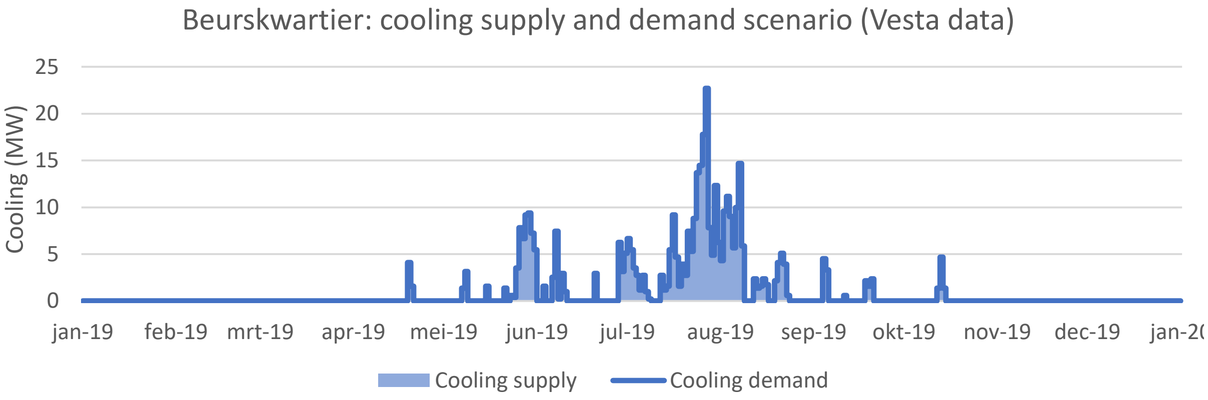

Beurskwartier: heat supply and demand scenario 3 (UMGO data)
Heat (MW)
10
5
0
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Heat supply
Heat demand

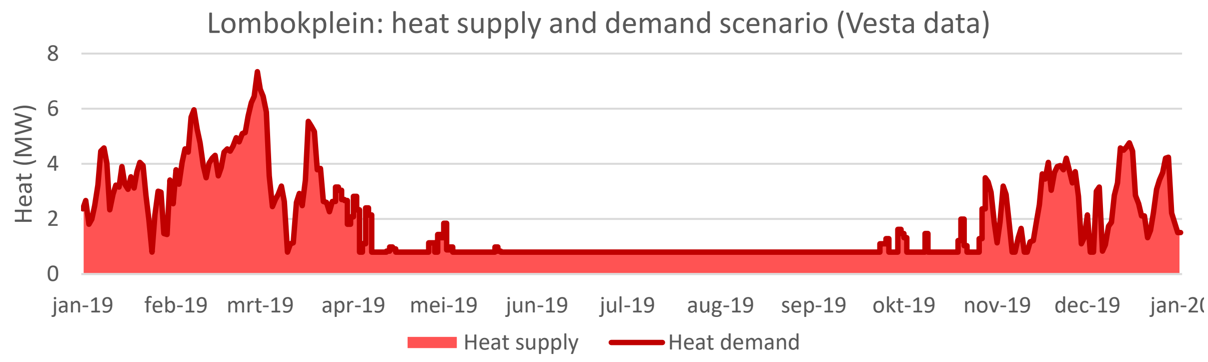

Beurskwartier: cooling supply and demand scenario 3 (UMGO data)
Cooling (MW)
20
15
10
5
0
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Cooling supply
Cooling demand

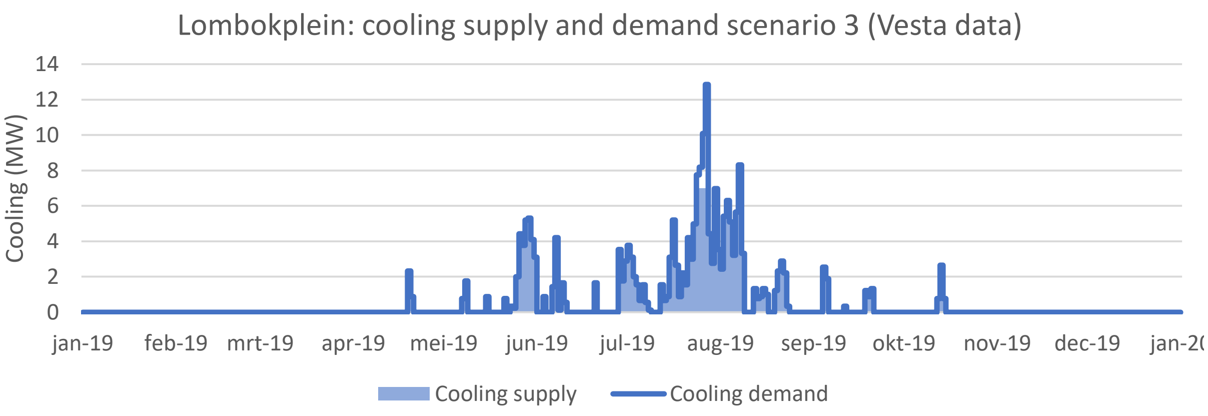

Lombokplein: heat supply and demand scenario 3 (UMGO data)
Heat (MW)
6
4
2
0
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Heat supply
Heat demand


Lombokplein: cooling supply and demand scenario 3 (UMGO data)
Cooling (MW)
12
10
8
6
4
2
0
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Cooling supply
Cooling demand


Beurskwartier: heat supply and demand scenario 3 (Vesta data)
Heat (MW)
15
10
5
0
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Heat supply
Heat demand


Beurskwartier: cooling supply and demand scenario (Vesta data)
Cooling (MW)
25
20
15
10
5
0
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Cooling supply
Cooling demand


Lombokplein: heat supply and demand scenario (Vesta data)
Heat (MW)
8
6
4
2
0
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Heat supply
Heat demand


Lombokplein: cooling supply and demand scenario 3 (Vesta data)
Cooling (MW)
14
12
10
8
6
4
2
0
jan-19
feb-19
mrt-19
apr-19
mei-19
jun-19
jul-19
aug-19
sep-19
okt-19
nov-19
dec-19
jan-2(
Cooling supply
Cooling demand

Appendix VI: regeneration and peak supply (sensitivity analysis)

The tables below show the amount of regeneration and peak supply needed in each scenario in the Beurskwartier and Lombokplein area, based on the lower (Table 19) and upper (Table 20) bounds of the heating and cooling demand.

Table 19 Amount of regeneration and peak supply needed (UMGO data)

		Regeneration	**Peak supply (MWh)**		**Capacity peak supply (MW)**	
Area	**Sc.**	**(MWh)**	**Heating**	**Cooling**	**Heating**	**Cooling**
Beurskwartier	Ref, 1, 2	4774	28	340	1.3	4.9
	3	4259	0	0	0	0
Lombokplein	Ref, 1, 2	1778	1	208	0.2	2.7
	3	1633	0	74	0	2.6

Table 20 Amount of regeneration and peak supply needed (Vesta data)

		Regeneration	**Peak supply (MWh)**		**Capacity peak supply (MW)**	
Area	**Sc.**	**(MWh)**	**Heating**	**Cooling**	**Heating**	**Cooling**
Beurskwartier	Ref, 1, 2	11618	3593	788	9.0	10.2
	3	12674	141	51	2.9	2.1
Lombokplein	Ref, 1, 2	4888	2682	927	3.7	6.0
	3	5404	0	192	0	5.8