THE PROSPECTS FOR HEAT

Urban heat modelling as a means for a sustainable and equitable heat transition in the historic centre of Amsterdam

MSc. Thesis MADE

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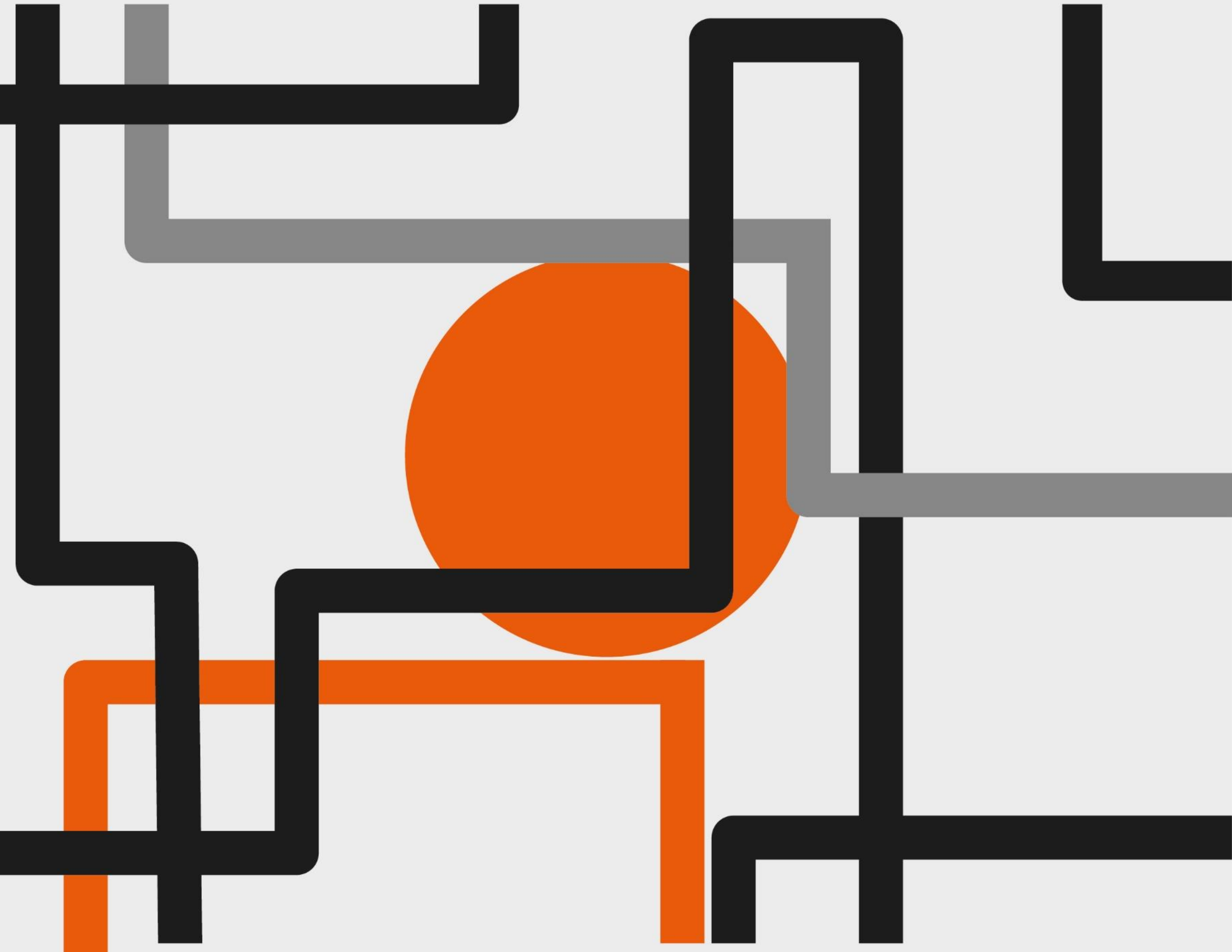

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Student

T. Miedema – MSc Metropolitan Analysis Design & Engineering – Technical University Delft and Wageningen University and Research.
Student Number Technical University Delft: 4983263
Student Number Wageningen University & Research: 941222-571-120

Graduation committee/ supervisors:

Phd candidate C. Kaandorp (daily supervisor) – Department of Water Management, faculty of Civil Engineering and Geosciences, Technical University Delft.
Dr.ir. E. Abraham (First supervisor) – Department of Water management, faculty of Civil Engineering and Geosciences, Technical University Delft.
Prof. dr. J.P. van der Hoek (Second supervisor) – Department of Water management, Professor of drinking water engineering, faculty of Civil Engineering and Geosciences, Technical University Delft.

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TU Delft Delft University of Technology Faculty of Architecture and the Built Environment

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LIST OF ABBREVIATIONS

ATES: Aquifer thermal energy system

BAG: Basic registration of addresses and buildings.

CHP: Combined heat and power plant

ECN: Energy centre of the Netherlands

ETS: Electricity transmission station

HRE: Heat Roadmap Europe

HT: Hight temperature

LT: Low temperature

MT: Middle temperature

PBL: Dutch bureau for environment and statistics

STAG: Steam and Gas plant

TCO: Total Cost of Investment

TEA: Thermal energy of wastewater

TED: Thermal energy of drinking water

TEO: Thermal energy of surface water

WIP: Waste Incineration Plant

WPW: Westpoort Warmte

ABSTRACT

As part of a nationwide energy transition, the city of Amsterdam aims to reduce CO_2 emission by 95% in 2050 relative to 1990. To achieve such an ambition, the municipality has set requirements on the implementation of a sustainable and low-carbon heat supply, and one that is both affordable and reliable, meaning that sufficient heat is always guaranteed.

The historic centre of Amsterdam has the highest heat demand density measured in peta joules (PJ) of the entire city. However, underground infrastructure and monumental buildings have postponed the development of a sustainable heat system in this area. This thesis considers the optimal mix of technology choices that can supply this areas' heat demand in the future, in a reliable, sustainable, and affordable manner. Three future heat scenarios are discussed: A High temperature (HT)-Biogas scenario, a Low temperature (LT)-Aqua thermal scenario and a Hybrid heat scenario.

Finding the most optimal scenario to implement sufficient sustainable heat sources to meet the demand at a given time, requires estimating the total heat demand, the temporal variations and generation potential of available heat sources. To do so, energy modelling is used as the leading method. Energy models can quantitatively assess different pathways and deal with energy systems under specific circumstances, hence functions as solid foundations for a heat transition. In this thesis, a bottom-up approach is employed. This form of energy modelling provides tools for a successful energy transitions under support of local entities on a small scale, such as in a city or neighbourhood.

From the spatial- temporal analysis it is concluded that 70% of the buildings are constructed before 1920, which drives up heat demand of the entire neighbourhood due to poor insulation. Moreover, building function heterogeneity is dispersed throughout the whole neighbourhood leading to different temporal heat demand peaks. This showed that heat sources must be able to supply heat throughout the entire day, and sufficient storage is essential to guarantee sufficient heat for the neighbourhood. Finally, in Felix Meritis, utility buildings especially are larger than residential buildings, and therefore drive up heat demand of the neighbourhood. The total current heat demand of the neighbourhood is estimated, using the bottom up building model, at approximately 345.000 GJ/year. Insulation measures can decrease this demand to approximately 109.000 GJ/year.

After investigating the three scenarios based on reliability, sustainability and affordability, the only scenario that can guarantee the reduced demand of 109.000 GJ/year is an HT-heat network supplied by Westpoort Warmte. This was also found to be the most affordable option for homeowners as insulation measures can be minimal. For both the hybrid and the LT-Aqua thermal scenario, insulation of historic buildings must significantly improve, as poor insulation increases costs for homeowners and consumers. However, when choosing for a HT-Biogas scenario, CO_2 emissions reduction is only 50% compared to 80% in the Hybrid scenario and 85% in the LT-Aqua thermal scenario. This complicates meeting CO_2 targets for 2050. This research does not consider the cost of infrastructure adaptations to implement scenarios in Felix Merits. However, using general cost showed that the HT-hybrid scenario carries highest infrastructure cost due to essential investment in a primary network and might therefore be presented to positive.

Using a bottom up model is a useful tool to estimate heat demand on neighbourhood level and define the right sources to meet this demand. Depending on which of the three criteria is decisive for the municipality, for each neighbourhood a local tailored heat solution can be implemented using to approach, to achieve city wide goals.

TABLE OF CONTENT

1. INTRODUCTION

This chapter introduces the subject of this thesis: A transition towards a sustainable, reliable, and affordable heat system in the historic centre of Amsterdam. Section 1.1 discusses an outline of the European context of decarbonising space heating to present the relevance of the topic on a broader scale. Thereafter, the context of the heat market in Amsterdam is assessed in section 1.2. Here, current practices in the heat market of the city are described and the importance of a heat transition to meet the goals of the municipality of Amsterdam is explained. Thereafter, a research problem is formulated in section 1.3 which describes the challenges for the city of Amsterdam.

1.1 Decarbonising space heating in Europe

Heat Roadmap Europe (HRE), a project funded by the European Commission, focuses on decarbonising heating and cooling in the built environment as vital subject to reach the energy ambitions of European countries, under the Paris agreement. Countries that signed this agreement, promise to have an economy with net-zero greenhouse gas emissions by 2050 (Connolly et al., 2014).

The latest edition of this roadmap, HRE4, claims that the expansion of thermal grids, is crucial to reach such a decarbonized heat supply (Persson et al., 2017). In this essence, a thermal grid is a network that transports heat or cold via a pipe network to the built environment. Heat in this network is supplied as combination of various low carbon heat sources, different types of excess heat and heat storage (Heat Roadmap Europe, 2019). According to the organisation, decarbonisation of heat supply via thermal grids is technically possible but is currently hindered in most countries, by ethical, political, and organisational failure to implement a right approach (Heat Roadmap Europe, 2019). One common political and organisational challenge countries face, is the adjustment of the current heat supply in existing building stock due to high renovation rates and investment, needed to improve heat efficiency in space heating for existing buildings (Heat Roadmap Europe, 2019). The city of Amsterdam is one of the European cities facing these challenges. Using this city as a case study can offer a valid approach for other cities facing the same challenges of implementing an alternative heat supply in their existing building stock to meet climate ambitions.

1.2 Current policy and practices in Amsterdam

Aligned with the national climate ambitions, Amsterdam set a local sustainability agenda to create a climate neutral city. To reach these goals, the metropolitan region aims to reduce its CO_2 emission with 50% in 2030 and 95% in 2050. Current annual CO_2 emission lies at 4437 kilotons of which the built environment makes up for 60% (3081 kilotons) (Gemeente Amsterdam, 2018). The large share of CO_2 emission in this sector is driven by the usage of natural gas for space heating. This makes up for 1270 kiloton of CO_2, which is 28% of the total city's emissions (Gemeente Amsterdam, 2019). Because of the large impact of this sector, this research focuses on space heating in the built environment.

Municipal policy documents stress that future heat supply to the built environment of Amsterdam must be: *reliable, sustainable and affordable* to create local support for strong growth of the heat networks and to maintain a fast moving transition of the energy sector (Gemeente Amsterdam, 2015) (Gemeente Amsterdam, 2019). To meet these criteria and to reduce the emissions in this sector, a widely discussed measure is gradually phasing out gas connections in neighbourhoods to eventually become free of natural gas by 2040 (Gemeente Amsterdam, 2019). Scenario's to replace gas in these neighbourhoods are discussed in the transition vision heat of Amsterdam. Examples of future heat scenarios discussed here are: aqua thermal heat energy, a hybrid variant including LT heat sources in combination with natural gas, geo thermal heat, rest heat from data centres and district heating with HT heat from waste incinerators or bio gas. Depending on the spatial implications of each neighbourhood, different scenarios might prove successful (Geldhof et al., 2020).

Currently 13% of heat demand in Amsterdam is covered by district heating (Gemeente Amsterdam, 2018). Two large high temperature heat networks exist in the city which supply heat of a minimum of 70 °C to the built environment. The location of both heat networks is shown in figure 1 and figure 2. The first is in the South East of Amsterdam and includes the neighbourhoods: Zuideramstel, Buitenveldert, Stadionbuurt, Zuid-Oost, AmstelkWartier, Ijburg, de Omval and Zeeburgereiland. This network is supplied with waste heat from the cogeneration plant in Diemer using Steam- and Gas (STAG). This is operated by Vattenfall (Segers et al., 2019) (Niessink & Rösler, 2015). In 2018 Vattenfall produced 1,8PJ of heat for 19.000 connection. The prospect is that they will produce 2.2 PJ of heat by 2020 for 25.700 connections.

Figure 1. *Heat network in the South-East of Amsterdam. The network is Operated by Vattenfall and heat is supplied by the Diemer power plant* (Segers et al., 2019)

Figure 2. *Heat networks in the North-West of Amsterdam. The network is operated by Westpoort Warmte* (Segers et al., 2019).

The second network supplies the north and west areas of Amsterdam with heat. This network carries the name Westpoort Warmte (WPW), and is a joint venture operated by the AEB and Vattenfall. Currently, all the shares of the AEB are in hands of the municipality. WPW sources its heat from four locations: two waste incinerators (AEC – WIP and HR – WIP) and the biogas central, all owned by the AEB and a biogas fermentation plant that is owned by Orgaworld (AEB, 2017). In 2017 WPW generated around 1.6 PJ heat which equals 30.000 housing equivalents. Additionally, smaller heat networks exist in the city centre that retrieve heat from small scale combined heat and power plants (CHP) controlled by Vattenfall (Segers et al., 2019).

1.3 Problem statement

Two problems arise with the current heat supply in the city of Amsterdam. Firstly, operation of heat supply does not meet the sustainability, reliability and affordability criteria set by the municipality. The main sources of the large heat networks are natural gas and (bio)waste. To meet the sustainability criteria, these sources need to be transformed into CO_2 neutral sources. The Diemer power plant shall become inoperative in 2030 and replaced with a biomass fired combined heat and power plant. However, the sustainability of bio-waste is questionable as it can only be labelled as carbon neutral when as much CO_2 is captured by newly planted trees, as there was released when burning wood to generate heat (CE Delft, 2018). Additionally, it is questionable whether in the future the Diemer powerplant and the WPW can generate sufficient heat and function as reliable heat source. The first plant is going to shut down, the latter generates heat energy via incineration of waste. However, future developments indicate a prospect where less waste is generated (CE Delft, 2018). Even at present, the AVI needs to import waste from the United Kingdom to complement national waste loads and generate sufficient heat (CE Delft, 2018). Moreover, the ambition to connect more buildings to the heat network in the future, further increases the pressure on current heat suppliers as peak demands will increase. Finally, heat tariffs for consumers are currently connected to natural gas tariffs. Because gas tariffs rose over the past year, heat tariffs equally went up. This paints district heating in a bad light in terms of affordability. In the future a new business model around heat must be presented and prices of heat might be reconsidered (ACM, 2019).

Secondly, looking at the location of the heat networks in figure 1 and figure 2, district heating is currently only available in the outskirts of Amsterdam. This is explained by the overloaded underground infrastructure of the historic centre and its UNESCO world heritage status which makes it difficult to implement an alternative for gas infrastructure in the existing building stock (CE Delft, 2018) (Van den Dobbelsteen et al., 2019). Thereby, buildings in the inner city often contain insufficient insulation making alternative, LT, or MT heat sources inadequate for heat supply. Figure 3 shows that the inner city is darker in colour, indicating a high average heat demand in the historic centre (Van den Dobbelsteen et al., 2019). Because heat demand of buildings in the historic centre of Amsterdam is currently highest, reducing CO_2 emissions from space heating, this area of the city is essential to meet the CO_2 reduction targets of 2050.

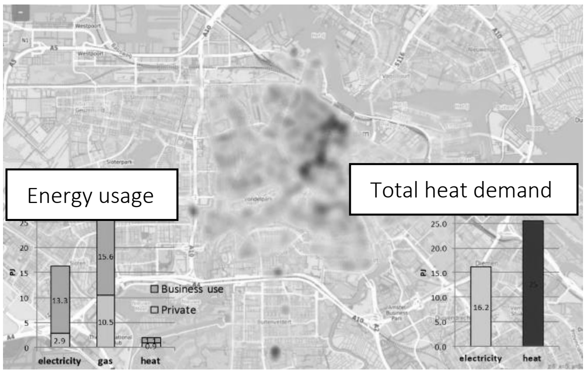


Figure 3. *Heat demand density in Amsterdam* (van den Dobbelsteen et al., 2019)

A large field of research underlines the suitability of bottom-up energy system models to support energy transitions on local scale (Allegrini et al., 2015). While the heat transition vision offers future heat scenario's it does not provide a method to assess the most sustainable, reliable, and affordable scenario. Therefore, applying a bottom-up energy system model to investigate future heat scenarios can prove to be one of the useful tools for the municipality to reach a successful heat transition in the historic centre of Amsterdam.

In conclusion, the city of Amsterdam is facing the challenge to transform their heat supply to meet the cities carbon reduction goals. In this transition, there are three principal criteria leading: reliability, sustainability, and affordability. Quantifying these criteria is part of this research and is discussed in chapter 6. Currently, no strategy exists to connect existing buildings in the historic centre of Amsterdam, which are difficult to alter due to infrastructure, age, and a monumental status to sustainable heat sources that can supply sufficient heat. However, this is essential for the city to reach their 2050 sustainability goals and to become gas free in 2040. In this research, the bottom-up building based approach is used as a strategy to model heat demand and generation. Based on heat demand estimations, three future heat scenarios are investigated: A High temperature (HT)-Biogas scenario, an Low temperature (LT)- Aqua thermal scenario and a Hybrid heat scenario and compared in terms of reliability, sustainability and affordability. This way an optimal mix for the historic centre must become clear. Moreover, findings can be interesting for other cities dealing with the same challenges.

1.4 Reading guide

The next chapter describes energy system models to deal with energy transitions. This chapter details the bottom-up building based approach within energy system models which forms the theoretical foundation on which the rest of the research is based. Thereafter, chapter 3 defines the research gaps and introduces the research question and the sub question. Chapter 4. includes a research design which holds the requirements to administer the bottom-up building based approach in the context of the historic centre of Amsterdam. An in-depth spatial analysis is performed and described in Chapter 5. This chapter guides the reader through the GIS analysis and expresses the key spatial findings. Thereby, this chapter summarizes the ready to use input data which is then used for the temporal demand analysis. Output of the temporal model includes annual, monthly, and hourly heat demand and is described in chapter 6. Chapter 7 includes a discourse analysis to clarify what the municipality understands by the three criteria: reliability, sustainability, and affordability. Thereafter, in the final chapter, three heat scenarios, chosen from the heat transition vision, that have potential to play out in the historic centre of Amsterdam are described and compared based on the three criteria. The estimated heat demand and annual and daily peak demand is used here, to indicate how each scenario scores compared to each other. Chapter 9 describes the key findings of the thesis after which the main conclusion is presented, and recommendations are given.

2. ENERGY SYSTEM MODELLING

As explained in the introduction, Amsterdam is undergoing an energy transition. The focus lies on phasing out gas and looking for alternatives for space heating. This chapter contains a theoretical exploration which aims to explain the suitability of energy system modelling and specifically the bottom up building based approach, to support an energy transition in cities. Energy system models are suitable because they help decision makers to predict pathways for the future energy supply under certain circumstances. First a context around energy system models is sketched in section 2.1. Thereafter, section 2.2 elaborates on different energy system models and explains why this research uses the bottom up approach. This approach is further explained in section 2.3, 2.4 and 2.5.

2.1 Context

A key characteristic of current energy systems, is their central and hierarchical organisation, operating at national level. In the European heat roadmap of 2050, the role of local entities such as regions and cities are established to be greater in the energy systems of the future. However, what is specifically expected of these entities on more local scales remains undefined (Voulis, 2019). Because most of the challenges related to the ongoing energy transition, arise from the informativity of decentralised, small-scale generation and storage resources, a bottom-up approach is useful. In this thesis, a bottom-up approach, is defined as ''increased guidance and tools for entities on a lower level to overcome organisational and political challenges and to establish an energy transition on city or neighbourhood level (Heat Roadmap Europe, 2019) (Voulis, 2019). Such an approach focusses on collaboration of local entities and understanding of urban planning challenges to get the wanted results. (Cajot et al., 2015) (Hopkins, 2001). This chapter describes how energy system modelling apply a bottom-up approach to help cities in their ongoing energy transition.

2.2 Energy system models

Energy models are an important tool to provide insight in the present and future practices of energy supply and demand. They can predict pathways to deal with development of energy systems under current circumstances. This helps policymakers to found their decision when they want to implement a strategy concerning the energy transition. Thereby, different energy carriers can be analysed within the same model. This makes them both suitable for modelling the transition of an entire energy system, as well as for smaller segments of the system such as a heat transition within the energy transition (Pfenninger et al., 2014).

Four established fields for energy system models exist: (1) energy planning and policy advice, (2) single-building energy use models, (3) power flow models, and (4) urban energy system models. Because this research focuses on the energy transition within a city, and because the aim is to set up a model that can be extrapolated from neighbourhood to a larger spatial area, urban energy system models form the foundation of this research. These models specifically reflect the role of cities in the energy transition (Voulis, 2019).

Figure 4 shows the pathway of an urban energy system model in dark grey. Its sub-division in bottom-up and top down approach and demand and generation is further explained in section 2.3, 2.4 and 2.5.

To use an urban energy system model as foundation for a cities transition, it is important to provide a clear definition. For this research, the definition given by Jaccard is used to define an energy system model: *''Modelling the combined processes of acquiring and using energy in a given society or economy''* (Jaccard, 2006). ***Combined processes*** in this definition considers several services that energy requires such as: resource extraction, transportation, storage, and conversion. Thereby, ***acquiring and using*** **emphasises** the importance to balance demand and generation, a phenomenon that is incredibly important in cities future energy and heat systems. Finally, a ***given society or economy*** focuses on the importance of specific tailoring of each model to local context (Keirstead et al., 2012).

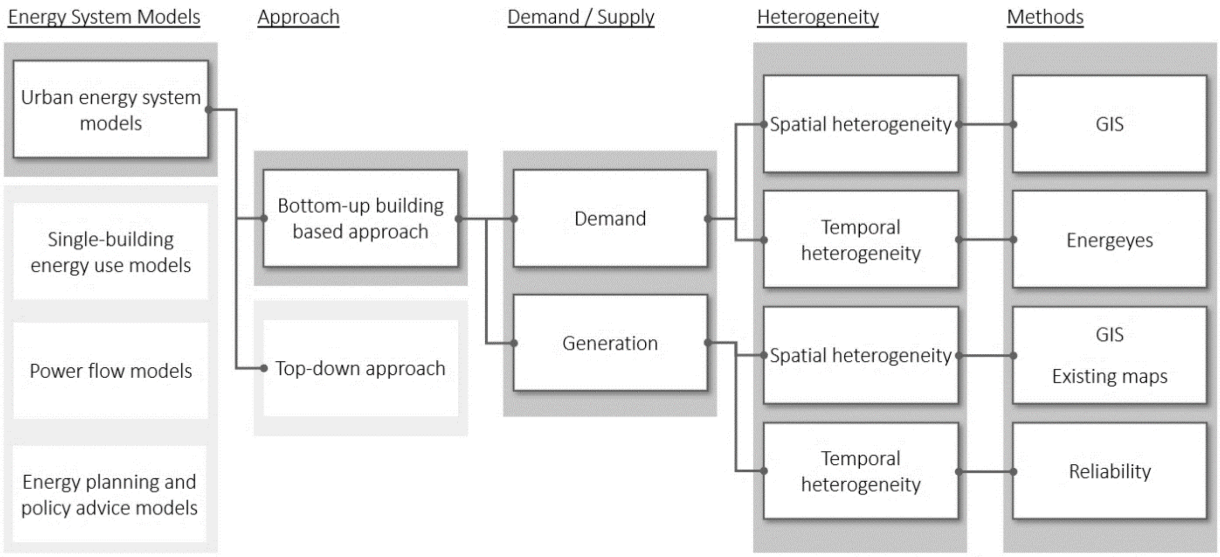


Figure 4. *Flow chart underpinning the energy model of choice in this thesis.*

2.3 The bottom-up building based approach

Top- down and bottom up are two ways to apply an urban energy system model. Top down models are specifically useful when wanting to model heat for a larger spatial area, such as a nation or a province. Within these models, energy use of buildings is attributed to sector statistics. For example, European models use a 1x1 km raster and calculate heat demand based on population density within this raster (Schneider et al., 2017) (Voulis, 2019). However, top down models are less suitable when more integrated energy supply demand scenarios are being investigated, for example for a specific neighbourhood, as it misses spatial accuracy (Reinhart & Davila, 2016).

''The bottom-up building based approach'', integrates detailed information on building level, while maintaining the potential to extrapolate its findings by generalising building specific information to a larger stock. In these models, building data and engineering data on neighbourhood level, related to heat loss surface area, function and building age, is used to estimate energy consumption. Thereafter, this data can be categorised to upscale findings of representative buildings over a larger stock (Schneider et al., 2017) (Aksoezen et al., 2015) (Voulis, 2019) (Voulis et al., 2018). Within the bottom-up building based approach, a demand-oriented and generation-oriented approaches can be combined (Delmastro et al., 2016) (Voulis, 2019).

The demand side focuses on how different building archetypes influence energy demand. The generation side focuses on energy generation in an urban area and how the demand can be fulfilled (Voulis, 2019). This offers the opportunity for local entities to ascertain the right technology option on local scale and implement sufficient sustainable heat sources to meet the demand at a given time and increases reliability of heat supply (Allegrini et al., 2015). Mapping the needed source is furthermore important to establish investment costs for both suppliers and consumers.

2.4 Demand oriented approach

2.4.1 Spatial heterogeneity

To make a representation of the real time heat demand and generation of a city or neighbourhood, a spatial analysis provides an overview of building typologies undergoing a transition. Scientific research confirms the validity of calculating demand profiles of buildings based on, age, function, and surface area (Delmastro et al., 2016) (Schneider et al., 2017) (Voulis, 2019). Therefore, these parameters are considered in the spatial analysis. Adding other spatial parameters, such as orientation to the sun, vegetation, and water surfaces etc, one can make the heat demand model even more accurate (Raji et al., 2015) (Urquizo et al., 2017). Due to time considerations, these parameters are not considered in this research. To calculate the demand profile of a complete area, single building demand profiles can simply be added up. Dispersion of buildings over metropolitan areas cause spatial heterogeneity in heat demand, meaning that different areas have a different heat demand based on the buildings in that area. How this spatial analysis is performed, is explained in chapter 5.

2.4.2 Temporal dynamics

It is relevant to map temporal variation in heat demand of physical buildings over time because it facilitates the implementation of action to reduce the building energy use and operational costs (Fumo et al., 2010). Thereby, mapping differences in peak demands for different building functions, is essential to ensure sufficient energy supply during these peaks. Temporal variation includes annual demand variation but also daily and even hourly variation. For example, heat demand in urban areas is driven by various consumers in the households and service sector (restaurant, hotel, hospital, schools etc.). Households tend to have a higher heat demand during the evening as opposed to, shops, which use more heat during the daytime (Voulis, 2019). Knowing these differences is essential when moving to the next step: implementing sufficient heat sources and ensuring a reliable heat system.

2.5 Generation oriented approach

2.5.1 Spatial heterogeneity

The demand-oriented approach explains how a demand profile is set up. Additionally, an assessment of heat generation availability, must give insight into what sources can connect to the heat network to create the right balance of demand and supply. Having a clear overview of the location specific heat sources shows if heat demand can be locally supplied or that additional non-local sources are essential to generate sufficient heat (Voulis, 2019).

2.5.2 Temporal dynamics

It is important to make a realistic assessment of heat generation and heat storage over time. The output of renewable energy sources fluctuates, depending on the season and daily weather (Obara et al., 2018). To ensure a reliable supply of heat, these fluctuations can be covered by for example heat pumps or stored thermal heat. To fill up heat generation gaps correctly, and to know how much additional heat needs to be stored to ensure a constant supply of heat, temporal dynamics of heat generation of all sources needs to be included in the model. For example, hourly energy consumption data needs to be gathered to apply the right technologies such as heating and cooling equipment, heat exchangers, solar thermal and other heat technologies to ensure sufficient supply (Fumo et al., 2010).

2.6 Conclusion

This research chose to follow a bottom-up building based approach as opposed to a top-down energy system approach because it is most suitable to provide the municipality of Amsterdam with an approach to tackle the heat transition in the historic centre. In figure 4, the dark grey outlined boxes show the pathway of this approach. Both heat demand and heat generation are modelled via spatial-temporal analysis. The reason to use this approach is twofold. Firstly, buildings have different demand profiles. Using data on building level allows policy makers to assemble a specific demand profile based on the building stock in the area they choose to transform. This is convenient for cities as it allows application of new energy systems on a desired scale (neighbourhood, district, entire city). Secondly, having building level demand profiles offers the opportunity to set up tailored solutions for specific areas within a city, which increases the chance of actual implementation and scaling up. Because the approach also takes generation into account policy makers can gain insight in the energy generation potential of a spatial area and improve reliability of the heat supply.

3. RESEARCH AIM & ACADEMIC RELEVANCE

This chapter discusses, the aim of this research is in section 3.1. Thereafter, the academic relevance is described in section 3.2. The scope and research boundaries are discussed in section 3.3. The chapter finishes off section 3.4 where the main question and four supportive sub questions to reach the research aim are given.

3.1 Research aim

In the problem statement in section 1.3 the reader is submitted with the issue that implementing a heat transition in the historic centre is complicated and current practices are not addressing the issue sufficiently. For the city to go through a successful heat transition and reach its climate goals, current practices must be reconsidered, and alternative heat scenario's must be assessed. Thereafter, chapter 2 sets out energy system models, and more specifically discusses the bottom-up building based energy model, as a key tool to assess an energy transition on neighbourhood level to help local entities to implement an alternative heat supply on a larger scale.

This research aims to experiment with the bottom-up building based approach on a representative pilot neighbourhood in the historic centre of Amsterdam. By using the bottom-up building based approach as a method for decision makers to successfully implement a heat transition that considers a reliable, sustainable, and affordable heat supply in the entire historic centre, this research must contribute to the challenge that cities face with implementing a new heat supply in the existing built environment. The research aim is defined as:

Contribute to the implementation of a reliable, sustainable and affordable heat supply in the historic centre of Amsterdam, by using a spatial temporal heat demand model, in order to asses future heat scenario's and foster the heat transition in the entire historic centre of Amsterdam.

3.2 Academic relevance

Chapter 2 showed that energy system models are a key tool in assessing future energy use, implementing better design and supporting policy and response by creating an integrated bottom-up building based spatial temporal energy model (Keirstead et al., 2012) (Voulis, 2019). Because urban energy system models are relatively new in the field, complex issues such as dealing with uncertainties, data collection issues and integration of a spatial and temporal aspect are challenges to be overcome. This research contributes to overcome these challenges by creating and applying a model to a real-life situation: heat supply in a pilot neighbourhood in the historic centre of Amsterdam. Experimenting with the model smooths out the establishes errors, difficulties, and solutions. To the authors knowledge, a spatial temporal model to assess heat demand and generation for the historic centre of Amsterdam does not exist yet. Therefore, it can be of use for policy makes to support and manage the current heat energy transition. Finally, experimenting with a bottom-up approach in an existing built environment in Amsterdam can provide useful insight for municipalities or decision makers in other cities facing the same challenges in their building stock.

3.3 Scope

This research only investigates heat demand for space heating, leaving heat demand for hot water aside. The focus on heat demand for space heating is chosen because it makes up for almost 30% of the cities CO_2 emission (EIA, 2018). Thereby, a residential energy consumption survey, conducted by the Energy Information Administration showed that that usage of natural gas for space heating in households is almost 2,75 times larger than for water heating (EIA, 2018). It can have a significant impact for the cities climate policy when reducing CO_2 emission from these practices. Entirely new heat infrastructure has an invasive spatial and financial impact on the historic centre of Amsterdam and is difficult to implement due to its UNESCO status and little available space. However, heat demand and supply are a multi-facetted issue that is larger than the discussed technical and infrastructural nature. The social implications of such a heat transition, such as the cultural value of the historic centre and societal differences in the research area is left for further research. Including these would require a different research design which does not fit within the scope and time of this research. Additionally, this research focuses on heat demand for space heating in the residential and service sector including industry. Because heat demand in the industrial sector mainly exists from large energy users, their heat demand is considerably higher and is therefore important to consider (Albadi et al., 2009). Because the heat transition vision aims to decouple neighbourhoods from natural gas, and because the bottom-up approach allows to upscale findings from neighbourhood to city level, this research investigates Felix Meritis, a representative neighbourhood in the historic centre of Amsterdam. Why this specific neighbourhood is chosen to assess the tree heat scenario's and function as example for the rest of the historic centre is further explained in chapter 5.

3.4 Research questions

To reach the research aim and to overcome the challenge to implement a successful heat transition in an existing building stock, it is important to formulate a clear main research question. The question is posed as follows:

''*How can the municipality of Amsterdam implement the most optimal technology mix for space heating of the built environment in the historic centre of Amsterdam, to guarantee a sustainable, reliable, and affordable heat supply?''*

To be able to answer this question, four sub questions are formulated that at the same time make up for the layout of this research. The four sub-questions are:

Sub question 1. ''*What is the yearly heat demand for space heating of different building categories in Felix Meritis?*

Sub question 2. *''How do peak demands fluctuate for different building categories in Felix Meritis and how do insulation values help flattening the peak demands and supply needed?''*

Sub question 3. ''*What does the municipality mean by a sustainable, affordable, and reliable heat supply?''*

Sub question 4. ''*What future heat scenario is most optimal for the historic centre to meet the reliability, sustainability, and affordability criteria?''*

The flowchart in figure 5 shows how the sub questions are related to the flowchart visualised in chapter 2. The first sub questions focus on defining the spatial heterogeneity of the pilot neighbourhood. The second sub question uses this input, to model the heat demand of the neighbourhood and establish the temporal dynamics of buildings. To answer the final sub question and show the opportunities for local heat supply in this area, another spatial analysis is performed. However, to be able to link the future heat supply e.g. heat generation to the criteria set by the municipality, first a discourse analysis is performed that proves clear measurable definition of the three criteria: reliability, sustainability, and affordability.

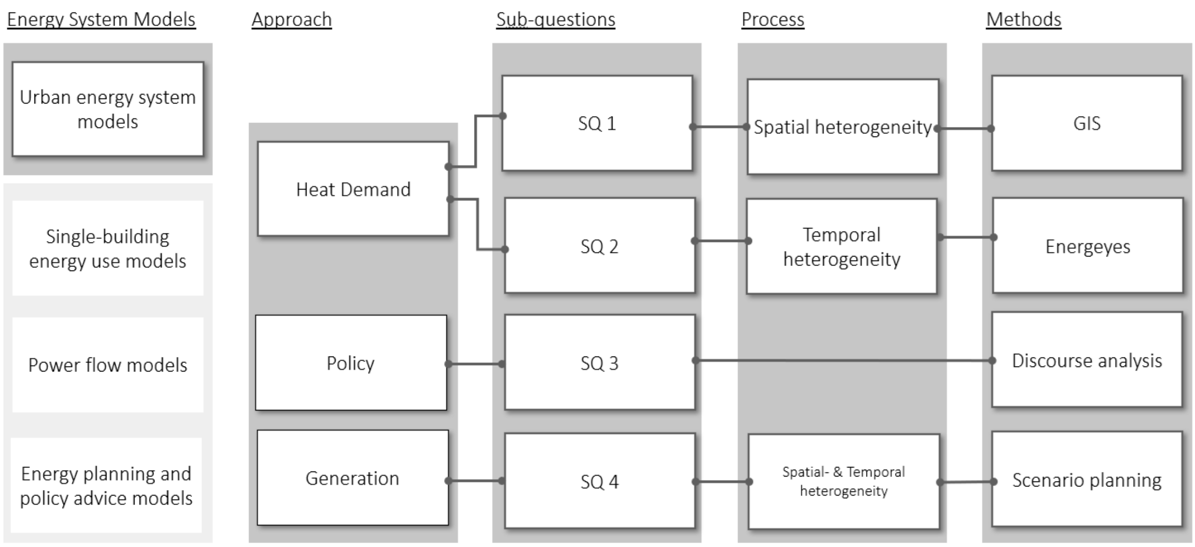


Figure 5. *Flow chart of the research design used in this thesis to answer the sub questions and the main research question.*

4. RESEARCH DESIGN

This chapter describes the methodological approach used in this research to reach the aim and answer the main questions as described in chapter 3. Both the methods to obtain data and the methods to analyse data are discussed thoroughly, because this allows policy makers to apply the method step by step.

The method applied in this research is already briefly introduced in figure 5 and further discussed in section 4.1. Based on the theoretical framework, a spatial analysis is executed with GIS to identify a representative neighbourhood and to collect sufficient data to perform a temporal demand analysis of this neighbourhood with Energeyes. Thereafter, a discourse analysis provides the opportunity to measure the 3 mentioned criteria set by the municipality. Finally, based on quantitative-analysis and a discourse analysis, three likely scenarios for the historic centre are explained and their suitability for Felix Meritis is compared based on these criteria.

4.1 Used methods

4.1.1 Spatial analysis – GIS

The most optimal technology mix, as stated in the main question, should be reliable, sustainable, and affordable. A reliable heat supply can only be guaranteed when sufficient heat is available to meet the demand. Therefore, sub question 1 and 2 focus on estimating the heat demand of Felix Meritis, and on finding the temporal peaks.

Because gas usage for space heating of companies and private users are not publicly available, this research uses a spatial analysis to estimate heat demand for space heating. Although CBS does provide average gas use for the entire neighbourhood (Statline., 2019), it is not specified per building or street. Furthermore, it is not clear what percentage of this gas is used for space heating and what is used for hot water. Therefore, the method to answer sub question 1 and 2, requires a spatial analysis of the study area (Voulis et al., 2018).

In this research, mapping spatial characteristics of Felix Meritis is carried out using GIS software. There are several Geo data sources that provide spatial visualisations such as Google Maps, Yahoo Maps or Open Street Maps. However, these do not provide free and open underlying raw data due to strict copyright restrictions (Alhamwi et al., 2017). When setting up a spatial-temporal energy model, it is of great importance that visualisation is not static and that raw data is available and adjustable to be able to realistically represent the reality.

Scientific research stresses the suitability of GIS to perform a spatial analysis that supports the spatial component of an urban energy system model (Alhamwi et al., 2017) (Delmastro et al., 2016) (Ramaswami et al., 2011). Geographic information Systems (GIS) use raw data as input not only to visualise spatial data but to create and manage input data (Gimond, 2019). When making an energy planning process of an urban settlement, integration of spatial variation is helpful to establish the demand of various buildings and to assist in mapping generation facilities and determining the optimal route for distribution and transmission network lines (Delmastro et al., 2016). Arc GIS software geo-references these features in a map, allowing it to create a detailed representation with the characteristics of the buildings and its connecting infrastructure. In short, the GIS modelling (1) manages the spatial data input (2) it transfers this data into tables, plots and maps on the urban space outputs which forms the foundation for the demand profile (Delmastro et al., 2016).

Several types of GIS software are available. The most popular are ArcGIS and QGIS (Gimond, 2019). This research uses ArcGIS pro to perform a spatial analysis due to its free availability and its ability to perform an extensive spatial analysis.

4.1.2 Data gathering for GIS

To establish the heat demand and generation potential of the neighbourhood, data related to the case study area was gathered. Table 1 and 2 show what data was used and where the data was retrieved from.

Heat demand	Opensource data	Source
Historic centre boundaries	Neighbourhoods	https://maps.amsterdam.nl/open_geodata/
Building locations	Basic Registration of Buildings (BAG)	Integrated data in ArcGIS software
Building years	BAG	Integrated data in ArcGIS software
Service sector	Function map (non-residential)	https://maps.amsterdam.nl/open_geodata/
Building height	AHN	https://downloads.pdok.nl/ahn3-downloadpage/
Average gas usage per household	Heat Atlas	https://rvo.b3p.nl/viewer/app/Warmteatlas/v2

Table 1. *Used open data sources to map heat demand in the Historic centre and the pilot neighbourhood, Felix Meritis.*

Heat generation	Opensource e data	Source
LT sources	Thermal energy from surface water (TEO)	Protected database Waternet
	Thermal energy from drinking water (TED)	Protected database Waternet
	Thermal energy from waste water (TEA)	Protected database Waternet
Heat storage	Thermal storage	https://wkotool.nl/

Table 2. *Used open data sources to map heat generation and storage in the pilot neighbourhood, Felix Meritis.*

4.1.3 Data handling GIS

For the spatial analysis, data of building age, function and surface area of the historic centre are needed. Most of the required data is available as open source data. To create the right maps that give insight in the spatial dispersion of construction years, function and heat loss surface area, several data handling steps must be performed in GIS. Because this research focuses on a neighbourhood in the historic centre of Amsterdam, a first step is to create the boundaries for this specific area. The municipality of Amsterdam offers a map where neighbourhood boundaries for the entire urban area are shown. With the selection tool in GIS we could make a separate layer which only shows the neighbourhood boundaries of the historic centre of Amsterdam. The selection tool extracts features from an input feature layer and stores them in a new output layer (Gimond, 2019). In this case, neighbourhoods that fall within the historic centre of Amsterdam are selected and form a new layer named: ´´Neighbourhood Historic´´.

A next step is to import data of basic registration of buildings (BAG), provided by the national government. This data is integrated in the ArcGIS software and includes information on building age, surface area and function. Additionally, another map of building function is imported from the open data maps provided by the municipality. This map gives more extensive details of diverse functions of buildings.

Creating ''historic'' layer in the previous step, allows to clip other layers to the same boundaries, showing only information about the historic centre. The clip tool cuts out a piece of one feature class and uses this to show it on another features layer. This way, a detailed insight is given in the buildings in het historic centre of Amsterdam and their corresponding characteristics. A conceptual image of the clipping tool is shown in figure 6.

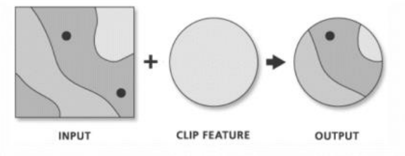


Figure 6 . *Clipping tool function in ArcGIS.*

By performing a spatial join, the point data of the functions can be joined to the vector data of the BAG. This allows to see exactly how much functions a building has and where. Performing a spatial join adds new information to a data set: functions of buildings to the BAG.

A second step of the spatial analysis is to zoom in on a selected neighbourhood. Like the function performed before, a zoom in from city scale to neighbourhood scale is performed using the selection tool. By creating a separate layer of this neighbourhood, it is now possible to clip the building age and building function maps to this layer. The clip tool cuts out a piece from the *''Historic Building clip''* layer and creates a new layer where only the historic buildings and their construction year for Felix Meritis are shown. A similar action is performed for the ''Function Historic'' layer where only the building functions of the pilot neighbourhood are shown.

A third step in the spatial analysis is to visualise the height of buildings. To do so, two elevation maps are imported from the AHN website (https://www.ahn.nl/). The first map represents the surface elevation of the terrain and is indicated with the letters dtm (digital terrain model). The second map represents the surface elevation and is indicated with the letters dsm (digital surface model). The dtm initially only includes the elevation of streets. To include the building function ''elevation void fill'' needs to be applied. This function creates pixels where holes in the data exist. Doing so creates a new layer. To calculate the height of the buildings, this new layer needs to be subtracted from the terrain model. This can be done by the ''minus'' tool. When having a layer of the actual elevation of buildings, it is important to link them to the polygons. This can be done using the ''zonal statistics as table''. With this function, the values of a raster (in our case the elevation map) are summarized within the zones of another dataset. A second action that needs to be fulfilled is to ''join functions''. Here you connect the new table to the existing buildings providing the ability to read the heights of the buildings in the dataset.

To make an analysis of heat generation and storage for the pilot neighbourhood, similar steps as described above must be followed. Raw data of wko's and energy from surface water are imported and clipped as described when creating the ´´Neighbourhood Historic´´ layer. This shows the location specific potential of heat generation and storage in the historic centre of Amsterdam. After fitting everything to the boundaries of the historic centre, the sources are connected to the buildings by performing a spatial joint. This allows to see how much sources are exactly available in or near by each building to identify potential future heat sources.

Going through these steps allows for a detailed spatial analysis of the neighbourhood. The output of this spatial analysis is discussed in depth in chapter 4.

4.1.4 Temporal analysis – Energeyes

As a follow up on the spatial analysis, heat demand of the entire neighbourhood is estimated as well as the temporal differences between buildings with different functions. To answer the main question, the impact insulation on heat demand of a neighbourhood is interesting to explain. This it allows for city planners to estimate to how much the municipality must invest in insulation to reduce heat demand and thus how affordable a heat network is. If the desire of the municipality is to connect Felix Meritis to heat generated from aqua thermal sources, they should investigate the generation potential of this source and try to steer the demand in the neighbourhood so that demand matches generation. This most likely means a high investment in insulation up to label A. Furthermore, better insulation means less heat use and therefore lower CO_2 emission which improves sustainability of the heat supply (RCE, n.d.).

To map the temporal dynamics of energy for a building, and to answer sub question 1 and 2, additional software needs to be used. This research uses Energeyes as heat modelling program. This software offers users a ready to use tool to model the heat efficiency of their home. The program gives the opportunity to develop simple building concepts by putting in several parameters such as heat loss surface area, insulation values and material usage (EnergyGO, n.d.). With this program it is also possible to compare effects of several measures such as improving insulation within a building (EnergyGO, n.d.). Having the needed parameters without having to go to deep into the construction of each separate building made this program appeared suitable to use in this research.

Initially this researched aimed to use EnergyPlus to model heat demand of several characteristic residential and service buildings. This software is a merge of two globally recognized building simulation software: DOE-2 (Crawley et al., 2001) and BLAST (Crawley et al., 2001). Both focussed on building energy simulation using a different load calculation method. In 1995, an initiative was taken to combine the two programs into the EnergyPlus program (Crawley et al., 2001), to create a 'best of' version. EnergyPlus is the official building simulation program of the United States Department of Energy and is currently widely accepted in the building energy analysis community around the world (Fumo et al. 2010). The tool can apply energy simulation, load calculation, energy performance, heat balance and mass balance (Fumo et al., 2010). However, this software was not appropriate for the following reasons: Firstly, as a detail oriented ''single-building energy use model'' the software demands a very specific input for each building including nodes, water pipes and electricity cables and plugs. Because no such data was available for the research area, this made using the program unsuitable. Secondly, although one could overcome this issue and create a more general script to model heat demand with EnergyPlus, in depth knowledge of the program is needed. Due to a time limit within the scope of this research, it was opted out to use EnergyPlus in the end.

4.1.5 Data gathering for Energeyes

As input for Energeyes, the output of the spatial analysis is used. Combing all this data and exporting it to Excel gives a clear overview of the neighbourhood's buildings and their corresponding characteristics such as construction year, surface area, and function. This allowed for a categorization of the buildings based on the level of heat demand their temporal patterns could be performed.

Scientific research (Aksoezen et al., 2015) (Ratti et al., 2005) (Rovers & Tichelaar, 2019) and technical reports (RVO, 2011) (RCE, n.d.), state that the older a building, the less insulation measures are in place, hence the higher the heat demand of the building. Dividing buildings of Felix Meritis into 7 groups of ascending construction years, created the opportunity to test these assumptions. Secondly, buildings were grouped based on their functions which resulted in 8 different function categories within the building stock of Felix Meritis: residential, social, offices, shops, industry, hotel/motel, services and medical. Finally, as in literature, we assume a relation between volume of a building and heat demand. From physical laws (Danielski et al., 2012) the larger a building, the larger the heat demand. By dividing residential buildings in groups with different volumes, it was possible to test this statement. Residential buildings are divided into groups with a similar range of volume and building envelope. These groups are (1) 0-1500 m3, (2) 1500-5000m3 and (3) >5000m3.

Appendix 2 and Appendix 3 include the ready to use output data for Energeyes. Here also the insulation values that correspond to different construction years are included.

4.1.6 Data handing Energeyes

Setting up different categories of building functions, size, and construction year, allowed to separately calculate heat demand of these categories. We created a separate project for each different building concept (function). Within this project a division is made based on construction year. For each construction year, the right insulation values were implemented in Energeyes. These insulation values relate to construction materials used over different periods of time, such as type glass for windows, brick type and additional insulation material. Furthermore, per construction year, for each function the average surface area of all heat loss surface areas is calculated, and the output of these calculations can be found in Appendix 3. Using this method allows to extrapolate findings over a larger stock of buildings for a large area. As such, this approach gives a scalable method for modelling heat demand from neighbourhood to city scale. In Chapter 5, a detailed description is given on the output of modelling heat for these different categories using Energeyes.

4.1.7 Discourse analysis

To answer the third sub question, a discourse analysis was conducted. This provides the opportunity to conceptualise reliability, sustainability, and affordability, by analysing the written language that surround these words, when written down in policy reports. Reading policy reports gives a broader idea of the context these words are implemented in and enable to find a usable definition for each (Brown et al., 1983). Eventually doing a discourse analysis must help making these concepts measurable to include them in future policy on heat provision.

4.1.8 Interviews

Additional to the previous mentioned methods, non-structured interviews were held with experts from the energy and heat sector. The interviews were used to validate decisions made throughout the research. Besides a validation purpose, interviews functioned as a guide for the progress of this research and generate a broader understanding of the spatial and political energy and heat arena of Amsterdam. Table 3 shows the interviews and the main content of each.

Number	Date	Name	Company/Institution	Content
1	09-09-2019	Evert Hassink	Milieu defensie	- Research gap - Netherlands of the gas
2	02-10-2020	Paul Voskuilen	AMS: Program developer urban energy	- Initial set up of Thesis - Alliander - Research gap
3	11-11-2019	Siebe Broersma	Tu Delft & Municipality of Amsterdam	- Municipal session about gas replacement and the future of heat supply in Amsterdam
4	17-12-2019	Harry de Brauw	Waternet	- Interactive maps for potential of TEO, TEA and TED. - Current activities of Waternet in the heat market of Amsterdam
5	08-01-2020	Laura Hakvoort	Living lab vernieuwing Municipality	- Renovation of bridges and quay walls - Energy from support poles
6	09-01-2020	Ian Minnes	Koppelkansen	- Energy scenario assessment - 9-streets as pilot area
7	27-01-2020	Veerle Valkema	Groene grachten	- Building specific implications for historic buildings in Amsterdam

8	29-01-2020	Geothermie congres		- Potential Geothermal energy NL
9	30-01-2020	Siebe Broersma	Citizen, Tu Delft	- Methodology of energy model - Current practices of Andy van den Dobbelsteen research group
10	30-01-2020	Koppelkansen meeting	Koppelkansen project	- Overview different sustainable solution posed for the 9-streets.
11	18-02-2020	Nina Voulis	CE Delft	- Usage of Energy Plus and creating temporal demand curves.
12	26-05	Stefan Mol	Waternet	- The potential and criteria of heat energy from surface water
13	05-06	Marcel Elswijk	Energeyes	- Introduction to the software and manual of Energeyes.
14	19-08	Martin Buijck	AEB/Vattenfall	- Heat supply WPW.

Table 3. *Overview of conducted interviews with experts in the heat and energy field.*

chapter 5 and chapter 6 aim to answer sub question 1: ''*What is the yearly heat demand for space heating of different building categories in Felix Meritis?* And sub question 2: *''How do peak demands fluctuate for different building categories in Felix Meritis and how do insulation values help flattening the peak demands and supply needed?''* To do so, we start off with a spatial analysis.

As explained in Chapter 2, the building-based approach takes construction year, heated surface area and function of the building as critical parameters that influence heat demand. Using these parameters enables replication of the models output between buildings (Voulis, 2019). Section 5.1 describes buildings' construction year, heated surface area and function in the context of the entire historic center of Amsterdam. Performing an analysis on district scale allows for a rough insight in the appearance and variety of each parameter. Thereby, it creates the opportunity to create logical categories, in which buildings can be grouped. Thereafter, as the aim is to create a locally applicable tool for the implementation of reliable, sustainable, and affordable heat supply, an analysis on neighborhood level is discussed in in section 5.2 In this section, it is explained why Felix Meritis is chosen as a pilot neighborhood. Additionally, a spatial analysis of all parameters in ''Felix Meritis'' is performed. Finally, some assumption that had to be made are discussed and key findings are given in section 5.3 and 5.4.

5.1 Spatial indication of the historic centre

5.1.1 Construction years

Several researches state that age of a building serves as a good indicator for the energetic state of a building, as it influences the demanded heat to create a comfortable indoor temperature (Ratti et al., 2005)(McKenna et al., 2013). A rule of thumb is: the older a building, the higher the heat demand (Aksoezen et al., 2015) (Leguit et al., 2015). During different time periods, a variation of construction materials and building techniques were used. This indirectly influences heat demand via insulation measures, type of heating, conservation measures implemented over time, evolution of construction techniques, single- or double glazing and implementation of a cavity wall (McKenna et al., 2013) (Aksoezen et al., 2015). Mapping building age reduces the risk to misinterpret heat consumption patterns and give a truthful reflection of a neighbourhoods building heat demand (Aksoezen et al., 2015). Thereby, knowing the spatial allocation of buildings with different construction years shows policy makers in which areas investment in insulation might be necessary to implement the desired heat source. This is also important when talking about the affordability of a heat transition (Dowson, 2016).

Figure 7 and Figure 8 show the dispersions of buildings with varying construction years. There are excluded values in the dataset behind the figures. Unfortunately, the BAG data contains buildings where the construction year has a value of 1005, which means the exact construction year is unknown. On the website of the municipality of Amsterdam, this issue is dealt with, by setting the construction year of these buildings at <1850. From literature, additional building years could be found and are manually added to the data set (Meijers & Bakker, 2017). However, of a large amount of buildings the construction year could not be identified yet. To complete the data, it was chosen to apply the same method as the municipality. The buildings got assigned the construction year <1850.

Transforming figure 7 into a graph, shows construction years of buildings go as far back as 1300 A.C. It also shows that most buildings are constructed around 1905. A first conclusion that can be drawn from this map, is that there are old buildings in the historic center that most likely increase the heat demand of this area (Aksoezen et al., 2015). Furthermore, the buildings of varying construction years (mainly before 1940) are dispersed randomly over the entire historic center. Insulation measure are therefore not specifically applicable to one spatial area but could essentially be needed everywhere.

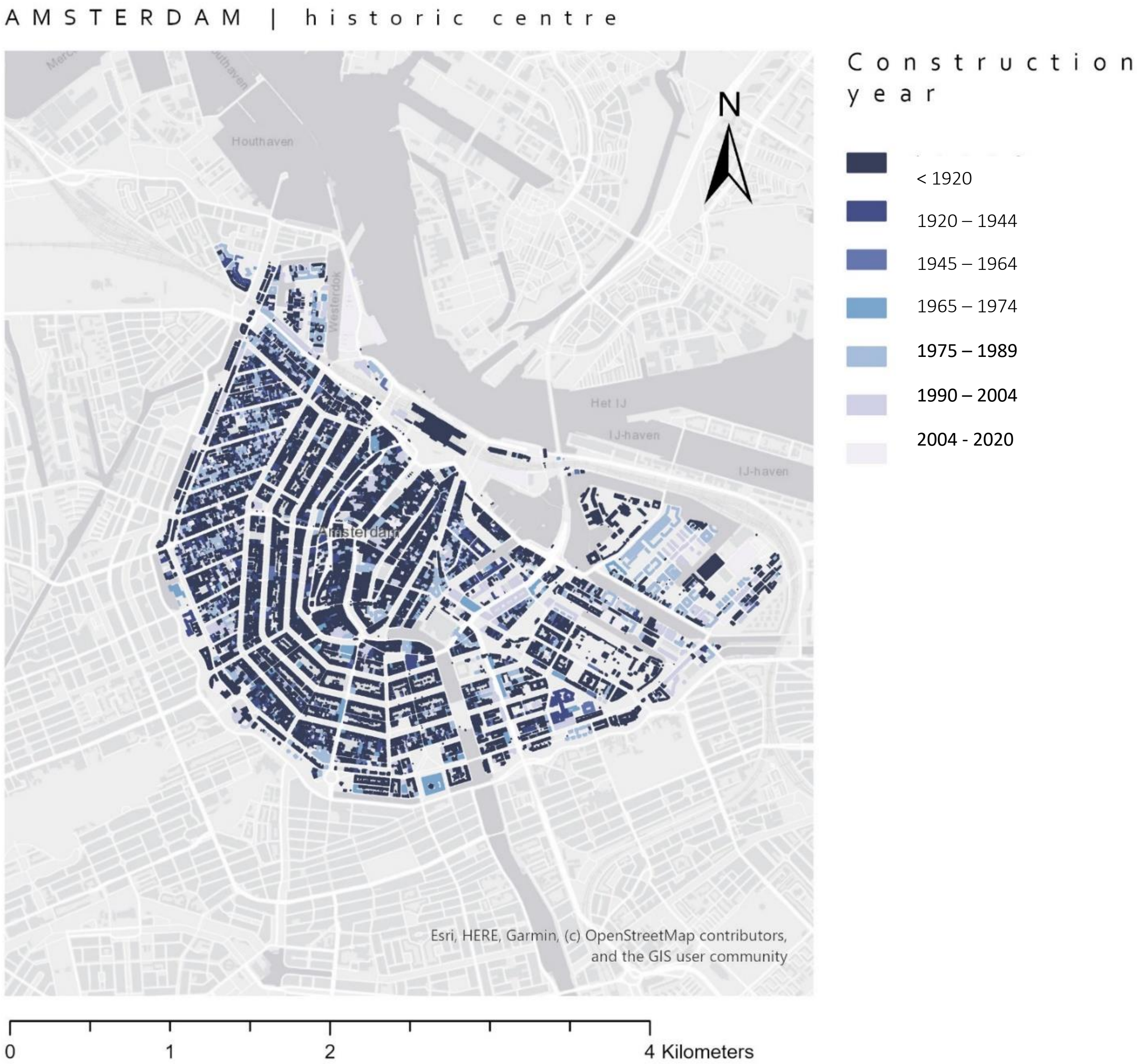


Figure 7. *Map of construction years dispersed over the historic center of Amsterdam. The darkest blue represents the oldest buildings and the less intense blue indicate newer buildings.*

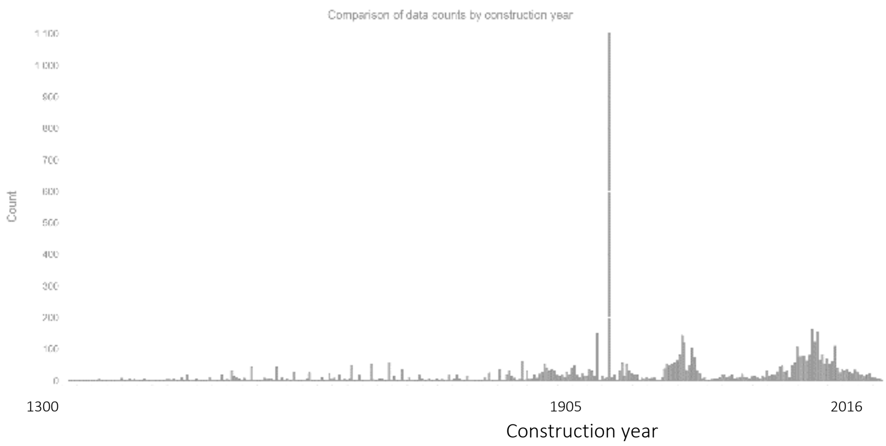


Figure 8. *Dispersion of buildings with different construction years in the historic center of Amsterdam.*

A second conclusion that can be drawn from this initial analysis is that categorization of buildings based on construction year should include categories that go relatively far back. This gives a more detailed overview of the building stock and therefore the heat demand of these buildings.

To ensure that information on insulation levels linked to construction year can be found, categorizations of other organizations are used as example. Currently, organizations concerned with analyzing heat demand of buildings from different age, apply different categories. The most common one used on national scale in the Netherlands is a categorization from AgentschapNL and shown in table 4.

Category	Construction year
1	< 1965
2	1965 - 1974
3	1975 - 1991
4	1992 - 2005

Table 4. *Construction years of residential building examples in the Netherlands (AgentschapNL, 2011).*

Table 4 scales all buildings constructed before 1965 under one denominator, taking away the possibility to differentiate insulation values of older buildings. Because old buildings are poorly insulated, this leads to under estimation of heat demand of individual buildings (AgentschapNL, 2011), which is problematic because it leads to larger errors when extrapolating findings to a larger building stock (AgentschapNL, 2011).

Table 5 shows the categorization research center TNO uses for utility buildings. Although more sub-categories are made in older construction years, still no sub-category exist before 1946.

Category	Construction year
1	< 1946
2	1946 - 1964
3	1965 - 1974
4	1975 - 1991
5	1992 - 2005
6	2006 - 2014

Table 5. *Categorization construction years utilities (TNO, 2019).*

Based on these two categorizations, an attempt is made to make a suitable categorization for this research. The main aim is to include essential groups that ensure the most realistic output of heat demand for the neighbourhood and at the same time be able to assign corresponding insulation values to these buildings. It was chosen to work with the following division of construction years. By categorising construction years before 1965, we could assign more specific insulation values and building characteristics to these buildings. This increases the accuracy of the heat estimation. Because old buildings are assumed to have lower insulation (Leguit et al., 2015), adding subcategories most likely increases the heat demand estimates of the entire neighbourhood. Table 6 shows that most buildings in the historic centre are constructed before 1920

Category	Construction year	Count	Percentage %
1	< 1920	12460	77
2	1920 - 1944	980	6
3	1945 - 1964	205	1
3	1965 - 1974	168	1
4	1975 - 1989	1048	7
5	1990 - 2004	885	5
6	2005 - 2020	352	2

Table 6. *Final categorization building construction years and division.*

Especially buildings constructed before 1920 appeared to have no or little information about insulation values. Additional information about construction of canal houses in this period was investigated. Some important findings are mentioned below:

- Most historic buildings in Amsterdam that are built before 1920 have no cavity wall. Only from the late 1920s, these walls were used on a more regular basis.
- A common way to construct the façade wall was a brick wall of one or one and a half stone in width. Additionally, a header layer was added to make the building moisture proof.
- The ground floor as well as the higher floors where constructed from wooden beam layers and panels. Ceilings where often rested with a reed layer and stucco.
- The colliding roof often consisted of a wooden framework added with water drip to resist rain.
- Most common is single glazing in these buildings surrounded by wooden window frames (Archidat, n.d.) (RES, n.d.)

Based on this information, corresponding thermal values are filled in Appendix 2. Moreover, Appendix 2. provides an overview of the insulation values for all construction materials, that belong to each construction year category. Appendix 4 gives a brief description on the meaning of these insulation values.

5.1.2 Building functions

A second parameter of the bottom up building based approach is to map and categorize buildings based on their function (Figure 9). This is important because different utility buildings have a different heat demand as well as different temporal demand profiles (Voulis et al.,2018). Predicting where and when peak demand of different buildings needs to be met is essential when planning future heat supply because it determines the minimum needed capacity of future heat sources (Ma et al., 2014).

The difference in peak demand can be explained by the energy consumption pattern (ECP) that is related to the function of a building. For example, the typical heat consumption of a household peaks during morning hours and in the evening when residents return home. At the same time, buildings in the service sector such as shops, bars, restaurants, school, hospitals have quite different energy consumption patterns. Here the day hours have a higher demand (Ma et al., 2014). Additionally, utility buildings such as hospitals and hotels often have a significant larger surface area than an average house, with correspondingly much larger heat demand compared to houses (Sipma & Rietkerk, 2016). Differentiating between residential buildings as well as service sector for their energy consumption patterns and surface area allows us to model heat demand for a spatial area more accurately (Voulis, 2019). To model heat demand of buildings with different functions, main functions were retrieved from BAG data. These brought two complication which are discussed below.

Firstly, importing the building function map from the municipality's website, led to the generation of 148 different functions of buildings within the historic center of Amsterdam. Many buildings got assigned a similar function but carry a slightly different label, resulting in a separate function created by GIS. Generating a spatial-temporal model including each of these 148 functions is not a methodology that is easy to scale and readily applicable to each neighborhood, because it would be extremely time consuming to model heat demand for all these building functions. Thereby several functions carry a different label but perform the same activities. Examples are: bar/dancing and café/bar or workshop and atelier.

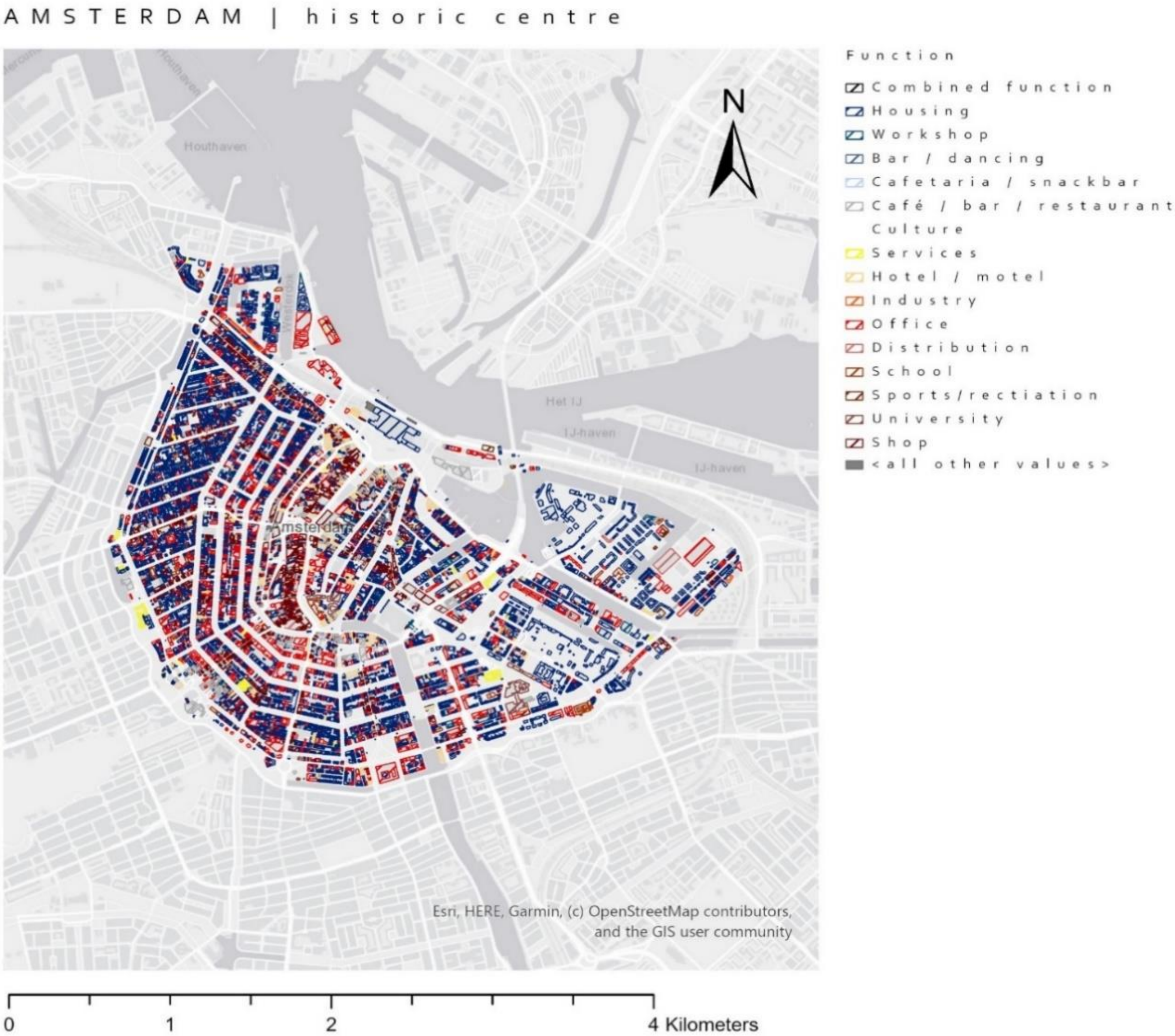


Figure 9. *Building functions in the historic center of Amsterdam. Buildings that have more than one function for example both residential as well as shop or office are scaled under the function: combined function. Buildings of which it is unclear what their function is are scaled under the function: all other values.*

Keeping in mind that the aim of this research is to create method that can be extrapolated to other neighborhoods in Amsterdam, this research chose to narrow down the functions to the main functions from the BAG data. These functions also resemble the function categories used in an ECN report of (Sipma & Rietkerk, 2016), concerned with heat estimations of utility buildings. This validates using these function categories in this thesis. Interestingly, the same report makes an extra division within offices based on their main activities (Sipma & Rietkerk, 2016). This increases accuracy of the model as office activities can be more of less energy intensive.

Figure 9 shows the different function categories and where they are located within the historic center.

Due to the large scale of the map, it is difficult to see the exact location of all functions. A zoom in to neighborhood level in section 5.2.2 provides this insight for Felix Meritis. Some buildings have a combined function. Performing a spatial analysis shows that most utility buildings (non-residential function) have residencies on higher floors. A visit to the study area confirmed this. Table 7 shows the subdivision of combined building functions in the last six rows of the table.

Building functions	Count	Percentage %
Social function	1067	6.6
Cel function	0	0
Medical care	21	0.1
Industry	761	4.7
Office	779	4.8
Hotel / Motel	156	1
Education	58	0.4
Sport / Recreation	23	0.1
Shop	1476	9.2
Services (fire station, police station, culture)	715	4.4
Housing	9063	56.3
Housing + Social function	124	0.8
Housing + Industry	52	0.3
Housing + Office	70	0.4
Housing + Education	2	0.01
Housing + Shop	255	1.6
Housing + Services	15	0.1
<Null>	1461	9.1
	16098	100%

Table 7. *Building functions in the historic center. To the main functions provided in the BAG database, a subdivision of combined functions can be added. These are buildings that have more than one function.*

Table 7 shows that only 12,3% of the entire building stock in the historic center of Amsterdam has a combined housing and utility function. Furthermore, visiting the study area confirmed that often only the bottom floor is occupied with a utility function while the remaining floors are residential. Having made these observations and considering the complexity of dividing one building unit in more building functions, it was decided to scale all buildings with a combined function under the ''residential'' function. This influences the output of the heat estimation because utility buildings often have a higher heat demand than residential buildings (Sipma & Rietkerk, 2016). This means that when utilities on the bottom floor of residential buildings would be considered, heat demand might be than when scaling them under the residential function as is done in this research.

5.1.3 Volume and heat loss surface area

Heat demand of a building is influenced by a buildings volume and its envelope. The building envelope can be described as: ''*All the elements of the outer shell, that separates between the indoor and the outdoor environment of a building and that facilitate climate control''* (Danielski et al., 2012). Together, these form the shape factor of a building, a surface to volume ratio. The value of the shape factor depends on the shape of the building for a given volume as shown in Figure 10. Even though building A and B have the same volume, they have a different shape which results in different heat loss ratios (Danielski et al., 2012). This image shows that the shape factor of a building depends on its volume (length x height x width = a3) and the thermal envelope, which is the sum of all surface areas.

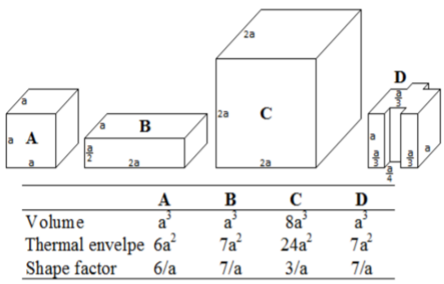


Figure 10. *A building shape factor* (Danielski et al., 2012).

After creating building categories based on function as explained in section 5.1.2, buildings are further categorized based on volume or average surface area. Because residential buildings form the largest group, only these buildings were further subdivided based on their volume. This division is shown in table 8. The volume of each building is calculated by multiplying the ground surface area of each building by its height. To be able to do so, height had to be separately imported in the BAG data as described in section 4.3. To the authors knowledge, no literature exists to provide examples on how to categorize buildings based on volume. The following categorization was created to ameliorate our heat demand estimations.

Category	Construction year
1	0 -1500
2	1501 - 5000
3	> 5000

Table 8. *Categorization of the volume of residential buildings based used in this research.*

Furthermore, the average heat loss surface area of each part of the building envelope is calculated for different function categories. To do so, we first determined what surfaces of the thermal envelope are most influential on heat loss. Reports of the PBL (Schepers et al., 2019), ECN (Sipma & Rietkerk, 2016), and TNO (Rovers & Tichelaar, 2019) are used to define these areas. Both, TNO, ECN, The Plan Bureau environment, and statistics (PBL) and CE Delft take, façade area, roof, windows, and gross floor area to calculate heat loss of buildings. Furthermore, it was found that little or no heat is lost through the side walls because most buildings in the historic centre are intricately connected (Leguit et al., 2015) (Rovers & Tigchelaar, 2019). Based on these sources, an assumption was made that the main heat loss of buildings in the historic centre of Amsterdam happens through, the façade front and back, roof windows and total floor area. Adding specific heat loss surface areas to buildings influences heat demand as the larger a heat loss surface area, the bigger the heat loss.

Appendix 1. shows the formulas that are used to calculate both the volume of buildings, as well as separate heat loss surface areas of buildings. Having these formulas allows to calculate heat loss surface area in any neighbourhood in the historic centre. Appendix 1 also describes the impact of assumptions related to heat loss surface areas, on heat demand. Examples of assumptions that influence heat demand are: height of a ceiling, gross floor area and window surface area.

5.2 Spatial analysis of Felix Meritis

This section describes the findings of the spatial analysis on neighbourhood level. By analysing a pilot neighbourhood, it becomes clear how the first step of the bottom-up building based approach (the spatial analysis) as explained in chapter 3, contributes to giving a neighbourhood specific heat advice. First a brief introduction of the chosen neighbourhood is given.

A pilot neighbourhood, is chosen based on the following two criteria:

1. It has neighbourhood boundaries that are formally defined and acknowledged by the municipality of Amsterdam.
2. Availability of data required at building and neighbourhood levels.

The municipality of Amsterdam divides Amsterdam in subareas that are identified as quarters and neighbourhoods. The city counts 481 quarters and 99 neighbourhoods. Amsterdam's historic centre is divided in 10 quarters. Within these quarters there are 61 neighbourhoods which are mapped in figure 11 (Gemeente Amsterdam, 2019). The origin of this data can be found in table 2. Investing in a new form of heat supply, will most likely cross neighbourhood boundaries by pipes, heat sources aninsd thermal storage areas (Gemeente Amsterdam, 2019). This indicates that although heat demand solutions can be found on neighbourhood scale, findings must be extrapolated to the entire historic centre in parallel to make suitable infrastructural decisions.

Figure 11. *Neighbourhood boundaries within the historic centre of Amsterdam. The orange boundaries indicate the location of Felix Meritis, the neighbourhood in which the 9-streets are located in (Gemeente Amsterdam, 2019).*

Although the second criteria might sound obvious, it is important to mention that modelling heat on neighbourhood level, requires availability of spatial and temporal data on heat demand and generation.

Spatial data on the building age, function and typology of each neighborhood of Amsterdam is quick to find and easily accessible on various websites mentioned in the methodology section. To ensure additional information can be found, it is decided to pick a neighbourhood that the municipality appointed as experimental area to integrate sustainable energy solutions with other innovative solutions. Doing so provided extra spatial information as well as an exploration of future energy scenario's in this neighbourhood.

In 2019 the ''koppelkansen project'' kicked off, which aims to combine various ambitions of the city in an integral approach for underground and above ground infrastructural development (I. Minnes, personal communication, January 9th, 20). The project focuses on 3 exemplary pilot projects in Amsterdam: Amstelstad, Havestad (west) and the 9-streets. Within these projects, the energy question, and the ambition to become gas free by 2040 are leading. The 9-streets is an area in Felix Meritis which is an exemplary neighbourhood in the historic centre of Amsterdam due to its housing typologies and mix of residencies and utility buildings (figure 11). Contrary to the other two areas, this is an already existing part of the city. Most of the buildings have an exceptionally low insulation levels and a low energy label. Thereby, the buildings in this area are all UNESCO heritage, making adjusting the cityscape complex (I. Minnes, personal communication, January 9th, 20). Additionally, chapter 5 shows that a commonality of all neighbourhoods is spatial heterogeneity of buildings in terms of functions, size, and construction year. Therefore, we assume that findings of a pilot neighbourhood in the historic centre are comparable and applicable to other neighbourhoods in the historic centre. To further answer the main question, the rest of this research focuses on data from Felix Meritis, which is an existing neighbourhood located in the 9-streets area. The following section describes an in-depth spatial analysis of this area.

5.2.1 Construction years

Figure 12 shows a map of Felix Meritis and the location of buildings with diverging construction years. Figure 13 shows count of construction years in a bar chart. The newest building in our study area is built in 2006. Most buildings stem from a year between 1905 and 1912. Thereby, a significant amount of buildings is built between 1720 and 1773.

Knowing that most buildings in the pilot neighbourhood stem from before 1920, is essential when planning future heat supply. Although additional information is needed to model exact heat demand of such buildings, it provides a first indication of the status of the buildings. In this case, heat demand of the neighbourhood is most likely high due to the large number of buildings in category 1 shown in table 9. Old buildings are less heat efficient and therefore have a higher heat demand than newly constructed buildings. Consequently, likely is that investment in insulation must proceed to connect sustainable, LT heat sources. (Aksoezen et al., 2015) (Leguit et al., 2015).

Figure 12. *Map of buildings in Felix Meritis and their corresponding construction years. The darkes blue shows all buildings constructed before or in 1920. The less intense the blue colours the later the building is constructed.*

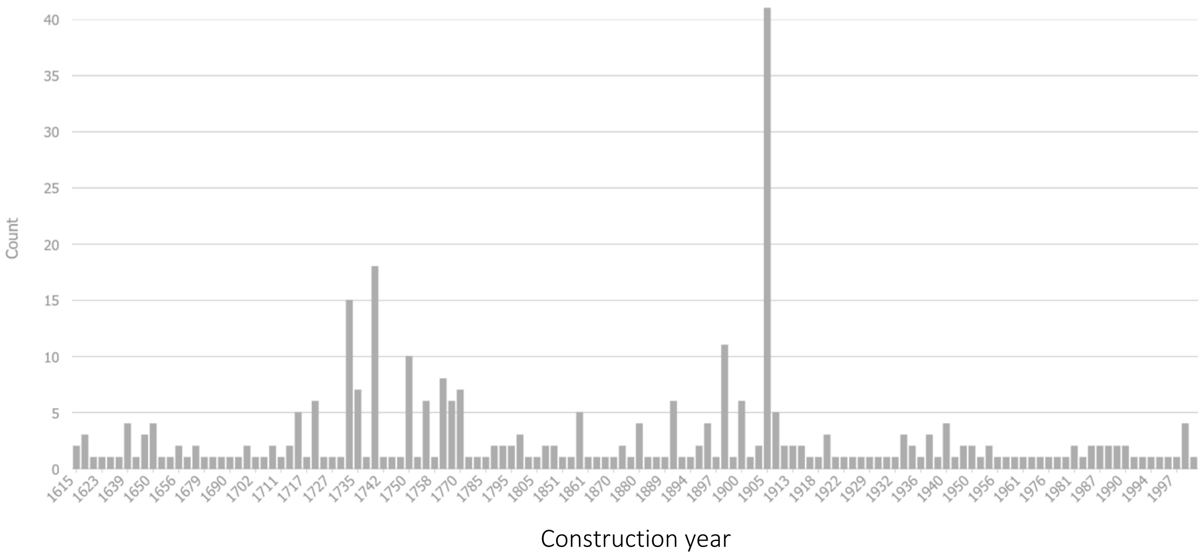


Figure 13. *Division of construction years and count of buildings Felix Meritis. Most buildings are constructed in 1905 which is like the entire historic center (figure 8).*

Category	Construction years		Number	Percentage %
1		<1920	571	89.8
2	1920	1944	27	4.2
3	1945	1964	9	1.4
4	1965	1974	2	0.3
5	1975	1989	14	2.2
6	1990	2004	8	1.3
7	2005	2020	5	0.8
			636	100

Table 9. *Division of buildings based on construction year in Felix Meritis*.

5.2.2 Building Functions

Figure 14. *Function map buildings Felix Meritis. Of some buildings the function is not registered. These carry the heading: Unknown.*

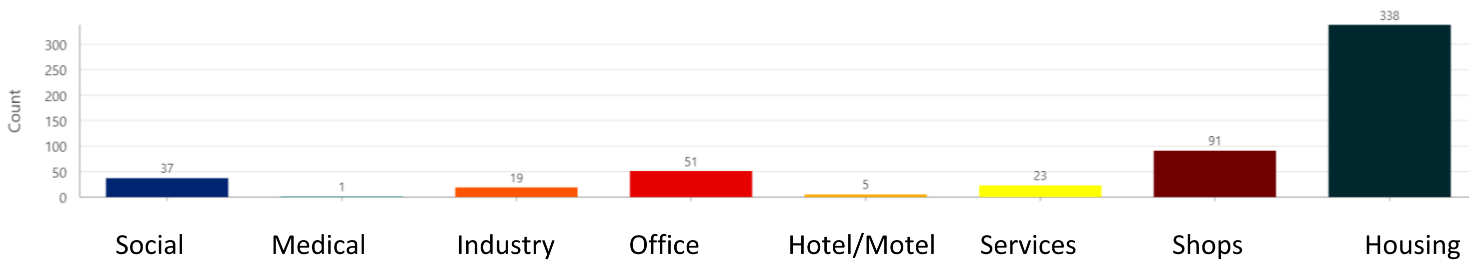


Figure 15. *Appearance and count of all functions in Felix Meritis.*

BAG Function	Count	percentage %
Social function (bar/cafe/restaurant)	37	5.8
Medical care / health	1	0.2
Industry	19	3.0
Office	51	8.0
Hotel / Motel	5	0.8
Shop	91	14.3
Services (fire station, police station, culture)	23	3.6
Housing	338	53.1
<Unknown>	71	11.2
Total	636	100

Table 10. *BAG functions and appearance in Felix Meritis.*

As mentioned before, in Amsterdam many buildings have multiple functions. The function map visualized here shows only the main functions of buildings stemming from the BAG database. From figure 14 it becomes clear that functions are spatially dispersed over the entire neighborhood. This means that different temporal demands can be expected throughout the entire neighborhood. Furthermore, looking at figure 15 and table 10, we can conclude that office spaces and shops are, besides the residential function, most widely represented.

Taking buildings with different functions into account, gives two important insights. Firstly, knowing the average yearly demand of each function allows policy makers to make a more accurate estimation of the yearly heat demand of the total neighbourhood based on these functions. Secondly, different building functions have a different temporal demand throughout the day which means that different peak demands can be seen at different moments in time. Mapping these peak demands is important to assure reliability of future heat supply sources. Whenever, the municipality wants to ensure a reliable heat demand, peak both monthly peak loads of a neighbourhood, as well as hourly peak loads of buildings with different functions need to be met.

5.2.3 Heat loss surface area

From the BAG data surface area of each separate building could be retrieved. This is visualized in figure 16.

As can be seen in figure 16, with some exceptions to the rule most buildings have a ground floor area that is smaller or equal than 300 m2. This can be contributed to the fact that initial this area was used for residential buildings (Meijers & Bakker, 2017). The smaller a building, the lower the heat loss surface areas and the volume, e.g. the smaller the heat demand. Knowing that on average the surface area of buildings is relatively small heat demand might be low. Thereby, similar as in the rest of the historic center, all buildings are intricately connected indicating that much less heat is lost through the side walls (Rovers & Tichelaar, 2019) (Sipma & Rietkerk, 2016). Additionally, calculating the height of the buildings in Felix Meritis gave the map visualized in figure 17.

Knowing different building heights, allows us to calculate volume for each individual building. Volumes and heat loss surfaces areas of building in Felix Meritis vary, because most buildings have different dimensions (figure 16 and figure 17). To be able to extrapolate findings to the entire neighborhood, we chose to take an average of heat loss surface area for different building functions, which can be found in appendix 3. Furthermore, volumes of residential buildings are categorized as described in section 4.1.3. The formulas to calculate heat loss surface areas and the implications of assumptions that had to be made, can be found in Appendix 1.

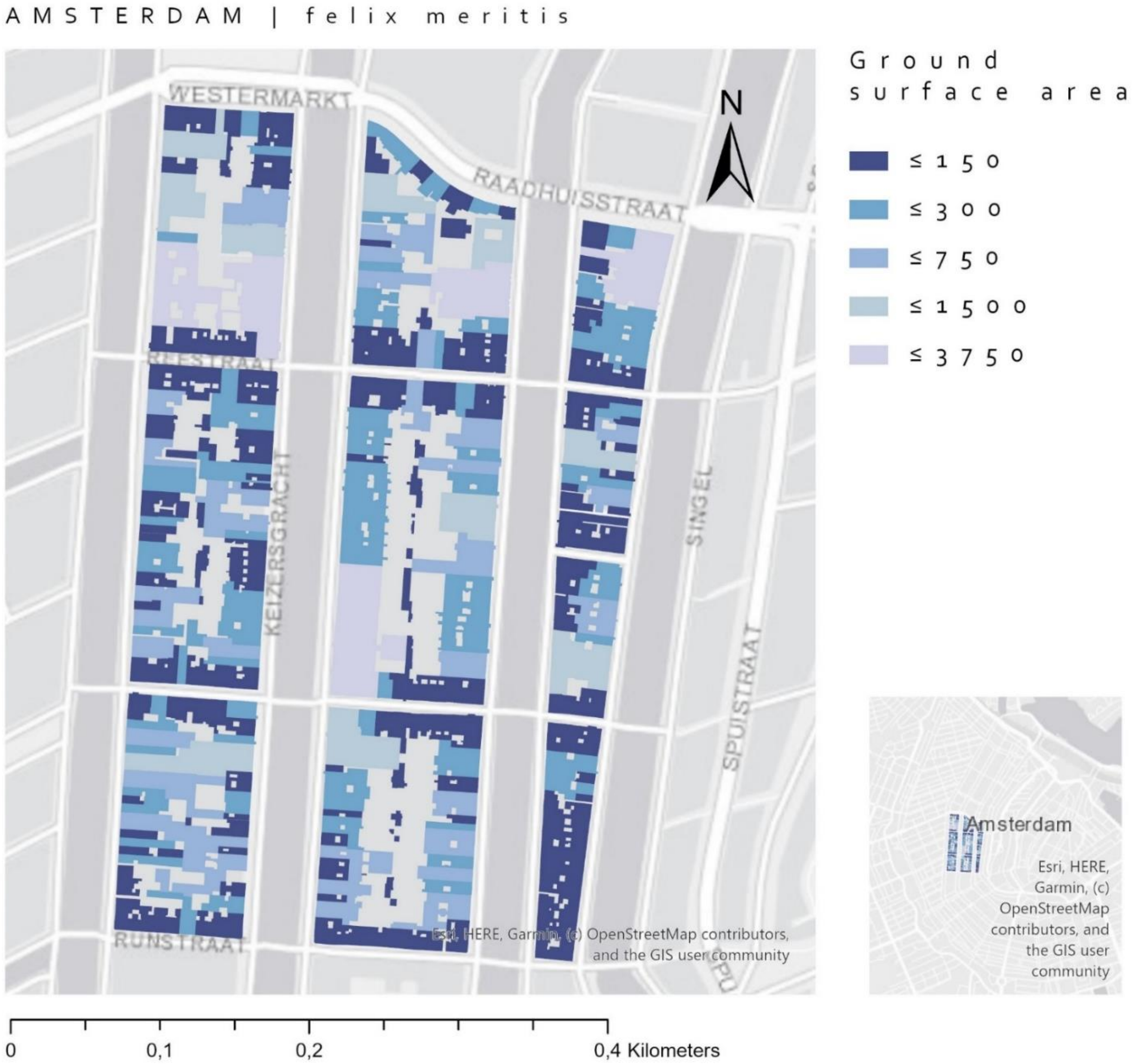


Figure 16. *Surface area buildings Felix Meritis*. *The darkest blue represents the smallest surface areas up to 150 m2. Thereafter, the less intense the color, the larger ground floor surface area of a building.*

Figure 17. *Height of buildings Felix Meritis. The darkest blue shows buildings with a height up to 10 meters. The more intense blue colors show an increasing height of buildings.*

5.3 Key findings

1) By mapping the three critical parameters: construction year, building function and heat loss surface area, we know that all three parameters are spatially dispersed over the entire historic centre and within the pilot neighbourhood. This shows that spatial heterogeneity is present in the historic centre, underpinning the possibility to extrapolate heat demand estimates and optimal technical solutions for Felix Meritis to the rest of the historic centre.

2) Table 9 shows that in Felix Meritis, almost 90 % of the buildings is constructed before 1920. The older a building the less heat efficient, indicating that a significant investment needs to proceed to improve insulation measures in this area when wanting to connect LT-heat sources.

3) The map in figure 12 shows that buildings of different construction years are dispersed over the spatial area, indicating that insulation measures cannot be targeted to one block or street.

4) Figure 14 shows that the main functions in Felix Meritis are shops, offices, and residential buildings. This insinuates that a flexible heat supply is essential as well as a sufficient storage capacity to cover different temporal peak demands. However, more clarity about this is given in chapter 5.

5.4 Discussion

Performing a spatial analysis on the historic centre and specifically on Felix Meritis created the opportunity to gain insight in the appearance of the three spatial parameters: construction year, function, and heat loss surface area. Mapping additional spatial parameters such as: vegetation cover of the area, orientation of the building towards the sun and absorption of solar radiation, the number of thermal zones and additional building functions withing one building can make the model more accurate (Raji et al., 2015) (Urquizo et al., 2018) (Schneider et al., 2017). However, finding such building specific data is time consuming and makes heat modeling for an entire neighborhood a less useful tool (Schneider et al., 2017). Although, not including these parameters can lead to underestimation of the heat demand of Felix Meritis, inputs such as window surface area and glass thickness aim to counteract this error (Urquizo et al., 2017).

6. HEAT DEMAND FELIX MERITIS – TEMPORAL ANALYIS

In chapter 5 three spatial parameters are mapped and the main outcomes are discussed. This chapter uses these results to determine the final heat demand of Felix Meritis and answer sub questions 1 and sub question 2. Section 6.1 discusses the input to estimate heat, which is a result of the spatial analysis. Section 6.2 shows, the results from modelling heat demand with Energeyes and discusses the implications of each spatial criteria. Thereafter, different temporal demand graphs are visualised and discussed, and the impact of insulation measures is shown. In section 6.3 the key findings from estimating heat for Felix Merits are discussed. Finally, to offer a perspective in the field of energy system modelling and the variable inputs and outputs that can be generated section 6.4 compares the assumption made in this research to estimate heat demand to other research using the Vesta MAIS model to estimate heat demand (Rovers & Tichelaar, 2019) (Schepers et al., 2019) (Leguit et al, 2015).

6.1 Input: modelling heat demand of Felix Meritis with Energeyes.

Energeyes is an online calculation tool that helps customers calculate detailed building energy consumption based on several building characteristics. This section contains a detailed description of how Energeyes is used for this research to model the heat demand for space heating of the buildings in Felix Meritis. This section also includes a description of several calculations and assumptions about specific building characteristics when factual data was missing.

Firstly, all building functions present in Felix Meritis are divided and for each function a separate project is created as shown in table 11. Doing so allows for an easy insight in different heat demand patterns per service sector building.

Project name
1. Felix Meritis - Hotel/Motel
2. Felix Meritis - Social
3. Felix Meritis - Industry
4. Felix Meritis - Medical
5. Felix Meritis - Offices
6. Felix Meritis – Services
7. Felix Meritis – Shops
8. Felix Meritis – Housing

Table 11. *Building projects in Energeyes.*

Secondly, for each building function, the average heat loss surface area is calculated. The output of these volumes and surface areas for buildings in Felix Meritis can be found in Appendix 3. Most buildings in Felix Meritis are residencies. Therefore, heat demand model for this function are more specific by adding, a preliminary division based on building volume for project *8. Housing*. A conceptual overview of the different building functions number of presences, and the additional subdivision of residential buildings based on volume is shown in figure 18.

Thirdly, all buildings within a project, are divided based on construction year. For residential buildings table 12 shows the sub categorisation of buildings in that project. A division of utility buildings based on construction year can be found in Appendix 3. The third and final subdivision: construction year, is essential when using Energeyes. This determines the insulation values of each representative building and allows to obtain the final heat demand output for each project.

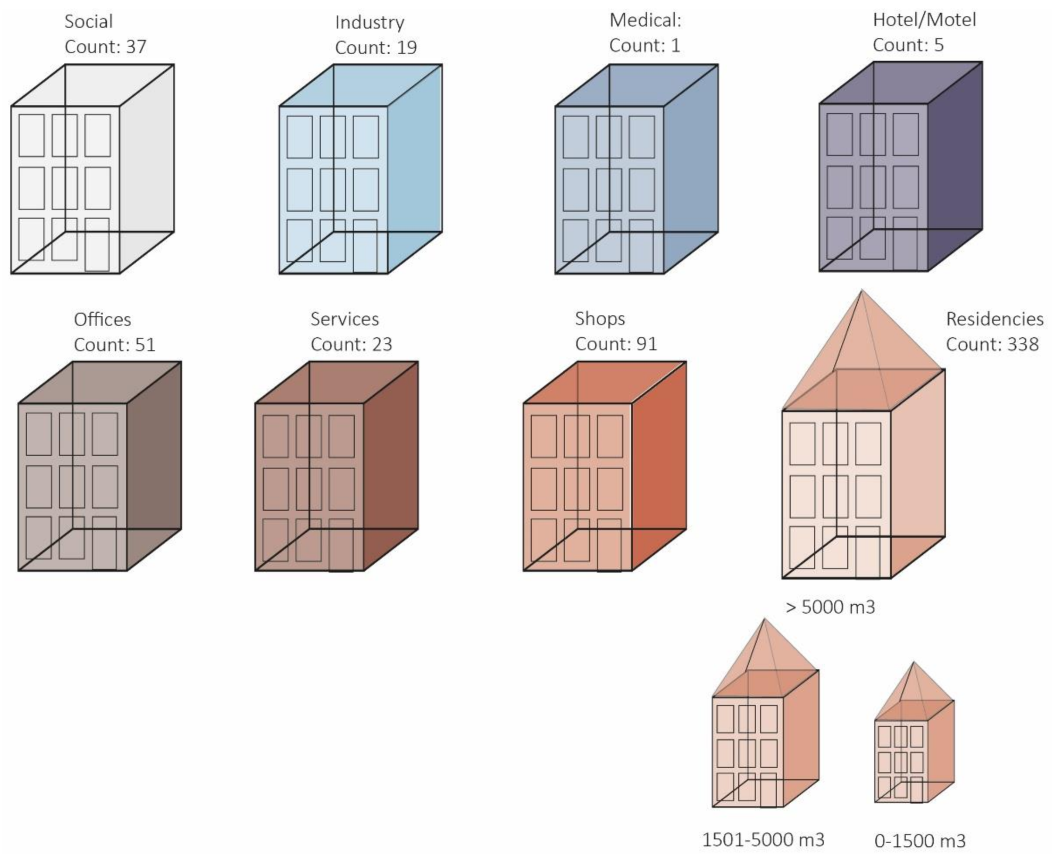


Figure 18. *Categorization and number of building functions in Felix Meritis and subdivision of residential buildings based on volume.*

Project name: **Residencies**			Description
Number	Count		Volume group 1
1.1	160	<1920	0 – 1500 m³
1.2	5	1920 – 1944	0 – 1500 m³
1.3	2	1945 - 1964	0 – 1500 m³
1.4	3	1975 – 1989	0 – 1500 m³
1.5	1	2005 – 2020	0 – 1500 m³
			Volume group 2
2.1	114	< 1920	1501 – 5000 m³
2.2	5	1920 - 1944	1501 – 5000 m³
2.3	1	1945 - 1964	1501 – 5000 m³
2.4	1	1965 - 1974	1501 – 5000 m³
2.5	7	1975 – 1989	1501 – 5000 m³
2.6	5	1990 – 2004	1501 – 5000 m³
2.7	1	2005 – 2020	1501 – 5000 m³
			Volume group 3
3.1	30	< 1920	>5000 m³
3.2	1	1920 – 1944	>5000 m³
3.3	2	1945 – 1964	>5000 m³

Table 12. *sub categorisation of buildings with a residential function based on construction year and volume.*

Below, a description of the input of parameters in Energeyes is given.

6.1.1 Energeyes input

1. Building properties
    a. Number of residencies.

Under this parameter, the number of residencies within a building must be filled in. To establish this for each building in Felix Meritis, the number of floors calculated in the spatial analysis is used (Appendix 1 & Appendix 3). Based on the presence of multiple name tags on residential buildings in the pilot neighbourhood, and registration of multiple addresses to one building, we assume that residential buildings in Felix Meritis contain multiple households within one building. The average amount of floors was used to estimate number of residencies. When a building in a group has 4 floors, three households are counted. The attic is not viewed as a separate household. What the impact of this decision is can be read in section 6.4. Table 13 shows the number of residencies set against the number of floors of a building.

Number of floors	Residencies
4	3
5	4
6	5
7	6

Table 13. *Number of floors and residences per building*

    b. Surface area of the residency
    c. Volume of the residency

For both these two parameters, an average for all the buildings that fall within a specific size group is calculated. These calculations can be found in Appendix 3.

    d. percentage of presence of people and number of people present.

This differs per building and is logically calculated based on the functions of the building. In residencies, the percentage of presence is estimated at 63% based on the following calculations: If a person is at work between 9:00 – 17:00 and uses one extra hour to get to and from the office, this person would spend 15 hours at home. 15/24 * 100 = 62.5 → 63%. For utilities, the average opening time was used to calculate the percentage of presence. After modelling in Energeyes, it showed that the larger the percentage the people are present in a building, the larger the heat demand. This is explained because if people are absent, heating is usually turned off. Furthermore, it showed that the more people are present in a building, the lower the heat demand. This is explained by the fact that people give of heat and naturally heat a space (Najjaran, 2012). For residencies, the number of people present was set at 2.

2. Building envelope

The building envelope allows the user to insert all different heat loss surface areas and their corresponding resistance construction value (Rc) and thermal transmittance or U-value of the specific construction materials. In this research, key values of terraced housing are used as representative values for canal houses and implemented in Energeyes (AgenschapNL, 2011). Furthermore, insulation values of specific construction materials corresponding to a construction year, such as: plasterwork, wood, brickWork and rooftiles are considered. A description of what the insulation values mean is given in Appendix 4. What the right values are corresponding to the categories of construction years can be found in Appendix 2.

    a. Surface areas of heat loss area.

In the building envelope, the surface areas of each of the heat loss areas (roof, ground floor, façade, and window area (m2) can be added. The larger the area, the more heat is lost. For each of these surface areas, the average of the building in a specific group is taken and implemented. For the façade, only the closed area had to be considered, by adding the total window areas and retracting this from the total façade, this could be calculated. The implications of all heat loss surface areas and assumptions made is stated in Appendix 1.

3. Infiltration

The infiltration value of a building is the process by which air moves uncontrolled into a building, via cracks and holes. Infiltration is exceedingly difficult to estimate and needs to be measured per building to give a good indication. However, as this research focuses on a more general method, making measures per building does not fit this approach. Therefore, a start value used by the national cultural heritage service was taken. They explain that the building decree assumes a minimum of 7 dm3/s. this can be reduced by implementing more insulation (RCE, n.d). In the oldest buildings <1920 we used the value of 7 dm3/s. Over time, as insulation improves, the infiltration values decreased, and infiltration values provided by Energeyes are used.

4. Ventilation

This parameter indicates the type of ventilation. In general, in historic buildings, natural ventilation of spaces happens through cracks and holes. Additionally, the rate on which a building is filled with fresh air needs to be added. The faster this happens, the higher the heat demand. In this research the ventilations is set at 0.4. From construction year 2004, natural ventilation is replaced by mechanical ventilation.

5. Space heating installation

Based on the construction year, the correct type of space heating installation is added. Each type of installation has a corresponding efficiency, the more efficient an installation, the lower the heat demand. Space heating corresponding to the correct construction year is given in Appendix 2. The efficiency of heating systems lies between 70% and a 100% for the building stock in Felix Meritis.

6. Solar radiation

Based on the window surface, the type of glazing and the orientation of the window surfaces, the solar radiation for a building can be estimated. Because Felix Meritis mainly has buildings with facades either pointing to the east or the west these orientations are used for either the front or the back façade of the building in which the windows are placed. How the glass service area is calculated can be found in Appendix 1. The outcome of these calculation per building function and volume category can be found in Appendix 3.

Additionally, to the window surface area, the ZTA of the glass stands for the transmission factor of solar radiations. The thicker the glass, the ZTA factor. The ZTA of single glazing lies around 0.8, for double glazing at 0.7 and for HR++ glass 0.6.

6.2 Output: heat demand of Felix Meritis

Knowing the input for Energeyes to estimate heat demand for Felix Meritis, enables us to estimate heat demand of the neighbourhood and discuss the output. In this section, the temporal heat demand of Felix Meritis is evaluated based on the three spatial parameters: construction year, building function and heat loss surface area.

6.2.1 Construction year

The total heat demand of residential buildings in Felix Meritis is estimated at 50813.9 GJ/year. The total heat demand of utilities in Felix Meritis is 291.769.8 GJ/year

For residential buildings, the older a building, the higher the heat demand. Residential buildings are divided into groups with a similar range of volume and building envelope as is shown in table 14 – 16. A more detailed effect of volume is discussed in section 5.2.2. However, when it comes to construction years, within all groups, heat demand decreases with newer buildings. For example, table 14 shows that buildings in volume group (1), constructed between 2005 and 2020, have an average heat demand of 16.8 GJ/year. This is approximately 5.5 times lower than the annual heat demand of 92 GJ/year belonging to a building built before 1920. For buildings in size group (2) heat demand of buildings constructed between 2005 – 2020 is approximately 4.5 times less than the oldest buildings in this group (table 15).

There are some exceptions to this rule. For example, table 14 shows that buildings constructed before 1920 tend to have a slightly lower heat demand then buildings constructed between 1920 and 1944. The same accounts for residential buildings constructed in 1945 – 1964 that fall within the volume group (2) (table 15). These buildings have an average heat demand of 152. 7 GJ/year whereas the buildings constructed in 1920-1944, have a heat demand of 140.2 GJ. Finally, for residential buildings in volume category (3), buildings constructed between 1920-1944 have a larger heat demand than those built before 1920. Comparing buildings based on their volume and building envelope in section 5.2.2, must prove if these differences in heat demand are related to the size of a building, or if something else influences heat demand.

Building volume 0-1500 Construction year	GJ/building/ year	count	Total heat demand GJ/year	Insulated A	Demand 2040	Insulated B	Demand 2040
<1920	92.0	160	14720.0	7.5	1192.0	15.9	118.6
1920 – 1944	103.9	5	519.5	15.5	77.3	23.3	359.6
1945 – 1964	82.8	2	165.6	14.8	29.6	24.2	358.2
1965 – 1974		0					
1975 – 1989	41.6	3	124.7	16.2	48.7	26.1	423.1
1990 – 2004		0					
2004 - 2020	16.8	1	16.8	16.8	16.8	23.8	398.1
			15546.6		**1364.3**		**1657.6**

Table 14. *Annual heat demand and number of residential buildings in Felix Meritis in volume group (1) 0 – 1500 m³.*

Building volume 1501-5000 Construction year	GJ/building/ year	count	Total heat demand GJ/year	Insulated A	Demand 2040	Insulated B	Demand 2040
<1920	171.4	114	19535.0	21.5	2448.7	34.9	3974.0
1920 – 1944	140.2	5	701.2	22.1	110.7	34.4	171.9
1945 – 1964	152.7	1	152.7	30.2	30.2	42.1	42.1
1965 – 1974	86.9	1	86.9	19.86	19.9	28.9	28.9
1975 – 1989	93.0	7	651.0	39.275	274.9	45.1	315.4
1990 – 2004	38.2	5	191.1	25.14	125.7	38.2	191.1
2004 - 2020	38.7	1	38.7	38.7	38.7	38.7	38.7
			21356.67		**3048.8**		**4762.2**

Table 15. *Annual heat demand and number of residential buildings in Felix Meritis in volume group (2) 1501 – 5000 m³.*

Building volume >5000 Construction year	GJ/building/ year	count	Total heat demand GJ/year	Insulated A	Demand 2040	Insulated B	Demand 2040
<1920	429.7	30	12890.5	71.4	2141.0	101.3	3038.5
1920 – 1944	481.8	1	481.8	83.7	83.7	116.2	116.2
1945 – 1964	269.2	2	538.4	62.7	125.3	88.2	176.4
1965 – 1974		0					
1975 – 1989		0					
1990 – 2004		0					
2004 - 2020		0					
			13910.62667		**2350.0**		**3331.1**

Table 16. *Annual heat demand and number of residential buildings in Felix Meritis in volume group (3) > 5000 m³.*

Table 17 – 23 show that heat demand utilities follows a somewhat similar pattern. Heat demand decreases for newly built utilities. However, there are more exceptions on this rule. Especially for offices, shops, and industry the rule: the older a building, the lower the heat demand does not apply. This can have several reasons which are further explored in section 6.2.2 and 6.2.3.

	UTILITIES SOCIAL							
	Construction year	**GJ/building /year**	**count**	**Total heat demand GJ/year**	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	2026.8	31	62830.8	349.1	10822.1	494.9	15341.9
1920	**1944**	1289.1	4	5156.4	200.5	802	289	1156
1945	**1964**							
1965	**1974**							
1975	**1989**							
1990	**2004**							
2005	**2020**	158.2	2	316.4	158.2	316.4	158.2	25027.24
				68303.6		**11940.5**		**41525.14**

Table 17. *Annual heat demand and number of social buildings in Felix Meritis.*

	UTILITIES OFFICES							
	Construction year	**GJ/building /year**	**count**	**Total heat demand GJ/year**	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	2171.8	44	95559.2	382.5	16830	539.2	23724.8
1920	**1944**	4067.5	1	4067.5	805.8	805.8	1101	1101
1945	**1964**	3687.3	3	11061.9	845.5	2536.5	1147	3441
1965	**1974**							
1975	**1989**	666.6	1	666.6	282.4	282.4	397.7	397.7
1990	**2004**	231.6	2	463.2	156.6	313.2	231.6	463.2
2005	**2020**							
				111818.4		**20767.9**		**29127.7**

Table 18. *Annual heat demand and number of offices in Felix Meritis.*

	UTILITIES SHOP							
								0
	Construction year	**GJ/building /year**	**count**	**Total heat demand GJ/year**	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	606.8	74	44903.2	82	6068	136	11152
1920	**1944**	596.6	9	5369.4	138	1242	151.3	1361.7
1945	**1964**	17880.3	1	17880.3	4264.9	4264.9	5591.3	5591.3
1965	**1974**	1067.5	1	1067.5	284	284	405	405
1975	**1989**	269.6	3	808.8	113	339	175.3	525.9
1990	**2004**	133.2	1	133.2	85.4	85.4	133.2	133.2
2005	**2020**	82.4	2	164.8	82.4	164.8	82.4	164.8
				70327.2		**12448.1**		**19333.9**

Table 19. *Annual heat demand and number of shops in Felix Meritis.*

	UTILITIES INDUSTRY							
	Construction year	GJ/building /year	count	Total heat demand GJ/year	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	836.7	18	15060.6	123.2	2217.6	191.8	3452.4
1920	1944	1048.9	1	1048.9	193.2	193.2	274.7	274.7
1945	1964							
1965	1974							
1975	1989							
1990	2004							
2005	2020							
				16109.5		**2410.8**		**3727.1**

Table 20. *Annual heat demand and number of industry buildings in Felix Meritis.*

	UTILITIES HOTEL/MOTEL							
	Construction year	GJ/building/year	count	Total heat demand GJ/year	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	2766.2	1	2766.2	427.4	427.4	625.8	625.8
1920	1944							
1945	1964							
1965	1974							
1975	1989							
1990	2004							
2005	2020							
				2766.2		**427.4**		**625.8**

Table 21. *Annual heat demand and number of hotels/motels in Felix Meritis.*

	UTILITIES SERVICES							
	Construction year	GJ/building/year	count	Total heat demand GJ/year	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	955.1	22	21012.2	137.3	3020.6	214.4	4716.8
1920	1944	620	1	620	101.3	101.3	152.7	152.7
1945	1964							
1965	1974							
1975	1989							
1990	2004							
2005	2020							
				21632.2		**3121.9**		**4869.5**

Table 22. *Annual heat demand and number of service buildings in Felix Meritis.*

	UTILITIES							
	MEDICAL							
	Construction year	**GJ/building/year**	**count**	**Total heat demand GJ/year**	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	812.7	1	812.7	121.9	121.9	193.6	193.6
1920	**1944**							
1945	**1964**							
1965	**1974**							
1975	**1989**							
1990	**2004**							
2005	**2020**							
				812.7		**121.9**		**193.6**

Table 23. *Annual heat demand and number of medical buildings in Felix Meritis.*

In general, most buildings in Felix Meritis are constructed before 1920. This increases heat demand of the neighbourhood due to low insulation compared to newer buildings. When concerned with implementation of sustainable and LT heat sources, insulation measures must take place throughout the entire neighbourhood to decrease the demand.

6.2.2 Volume and heat loss surface area.

Looking at table 14 – 16, the relation between volume of a building and heat demand seems to hold for residential buildings. By dividing residential buildings in groups with different volumes, it was possible to test this initial statement. The total heat demand of residential buildings in volume group 1 is approximately 4 times smaller than residencies in volume group 3. For volume group 2 these differences are around 2 times lower.

For utility buildings, no subdivision of volume groups was made. However, literature states that the volume of a building influences heat demand (Delmastro et al., 2017). The larger a building, the higher the heat demand. By looking at the average heat loss surface areas and the volume of different function buildings, as presented in Appendix 3, the impact of surface area was investigated. This is interesting especially for offices, shops and industry that did not follow the rule: ‘’the older the building, the higher the heat demand’’.

Table 18 shows that the demand of offices constructed between 1920 – 1944 lies at 4067.5 GJ/year. The demand of those built between 1945 – 1964 is 3687.3 GJ/year. This is approximately twice as much as for offices constructed before 1920. Interestingly, these buildings are also twice the volume of those offices built before 1920. The same accounts for industry. Table 24 – 26 support these findings. Industrial buildings constructed between 1920 and 1944 are around 1.3 times the volume of older industrial buildings and have a heat demand that is 1.3 times larger. This indicates that for utility buildings, an increase in the volume of a building is proportional to the increase of the heat demand. However, when looking at shops in table 19, the volume of a shop built in 1945-1964 is almost 60 times the volume of a shop built before that. However, the heat demand is only 30 times larger. Although the increase in volume of a utility does not grow proportionally with the heat demand, we can conclude that for utilities in Felix Meritis, volume of the building envelope has a larger impact on heat demand of utility buildings than construction year.

	UTILITIES		
	OFFICES	**51**	
	Construction year	**Average volume m3 building**	**GJ/building/year**
	<1920	6980	2171.8
1920	**1944**	13504	4067.5
1945	**1964**	14510	3687.3
1965	**1974**		
1975	**1989**	4302	666.6
1990	**2004**	2216	231.6
2005	**2020**		

Table 24. *Relation between volume of offices in Felix Meritis and annual heat demand*

	UTILITIES		
	SHOP	91	
	Construction year	Average volume m3 building	GJ/building/year
	<1920	1498	606.8
1920	1944	1295	596.6
1945	1964	74818	17880.3
1965	1974	4405	1067.5
1975	1989	1481	269.6
1990	2004	941	133.2
2005	2020	919	82.4

Table 25. *Relation between volume of shops in Felix Meritis and annual heat demand*

	UTILITIES		
	INDUSTRY	19	
	Construction year	Average volume m3 building	GJ/building/year
	<1920	2291	836.7
1920	1944	2880	1048.9
1945	1964		
1965	1974		
1975	1989		
1990	2004		
2005	2020		

Table 26. *Relation between volume of industrial buildings in Felix Meritis and annual heat demand*

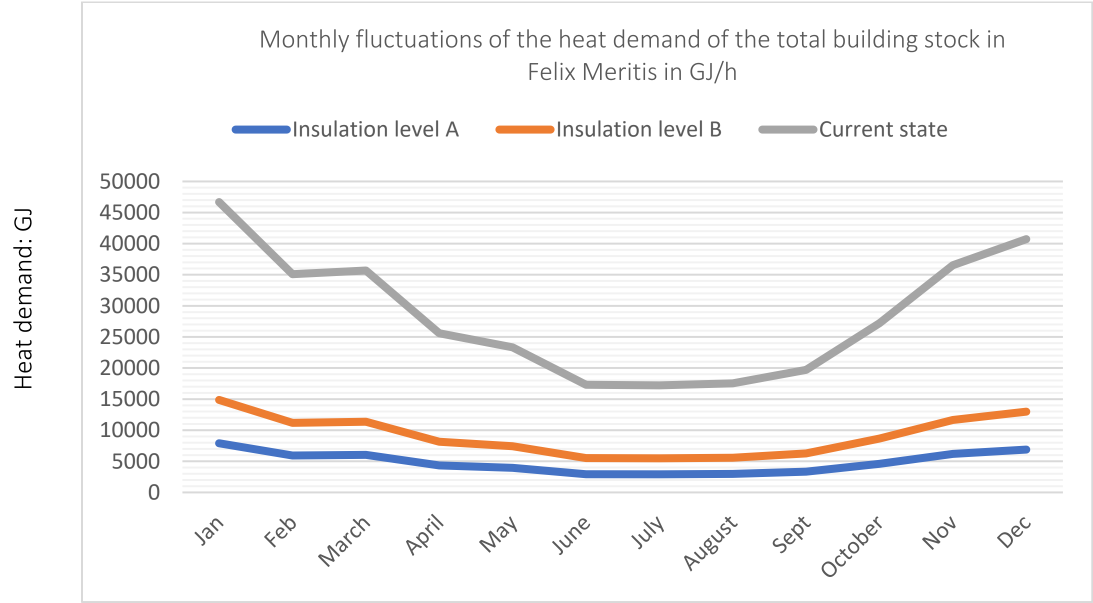
6.2.3 Building Functions

As described in section 5.2.2, taking buildings with different functions into account, gives two important insights. Firstly, it gives decision makers insight in the total needed heat capacity in the neighbourhood. Secondly it shows the different temporal demand peaks which explains the hourly peaks that need to be met. Anticipating the total demand and hourly fluctuation increases reliability of heat supply in the neighbourhood.

Knowing the average yearly demand of each function allows policy makers to make a more accurate estimation of the yearly heat demand of the total neighbourhood based on these functions. From the results, it becomes clear that additional to offices, large shops, hotels, and motels have a significantly larger heat demand than buildings with other functions. Driving up the heat demand of the area.

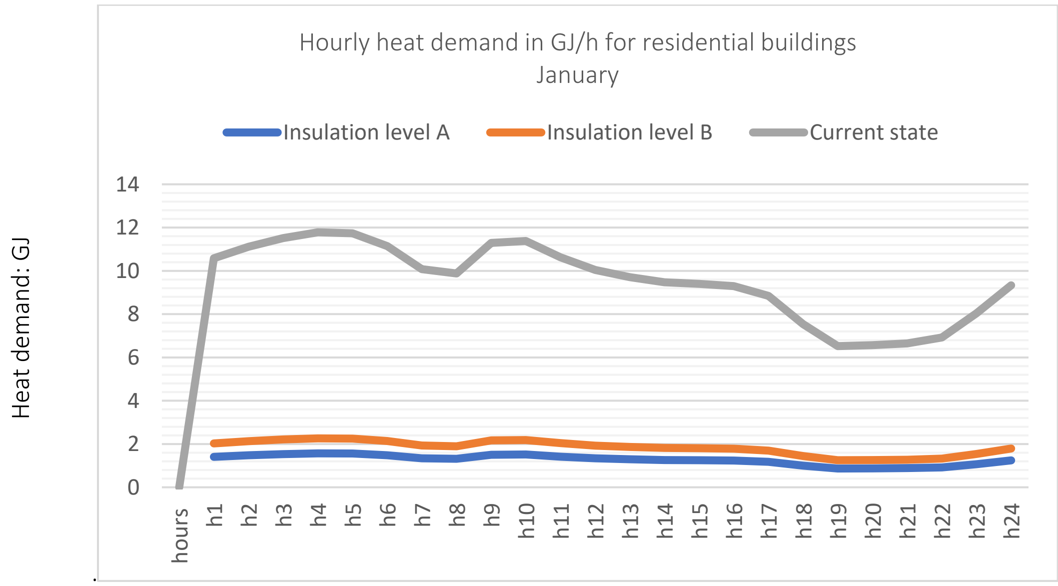
This research provided demand curves of different building functions existing in the Netherlands, over 24 hours. By dividing the monthly or hourly heat demand by the total demand, a proportion of the demand could be calculated. Multiplying this proportion with the demand data generated in this research allows for a visualisation of demand curves. The used data can be found in Appendix 6. Prior to the hourly demand of each function, an analysis on the monthly temporal differences is done. This shows during which months peaks demands are expected and thus what the minimum capacity or generation of storage and supply sources must be.

Graph 1. shows the monthly demand under current insulation levels of Felix Meritis. Thereby, it shows the demand when all buildings would be insulated up to level A and level B. Based on existing literature, the assumption is made that heat demand is highest in January and December (Amato et al., 2005) (Tronchin et al., 2019) . This allowed us to use data of Nina Voulis to calculate factors of heat demand per month. Although the actual demands differ, it becomes clear that for all insulation values, the highest peak is in January and December and that heat demand decreases during summer. The minimum supply to ensure a reliable heat demand in Felix Meritis, when no insulation measures are taken, must be 46680.4 GJ/January and 40724.9 GJ/year in December.

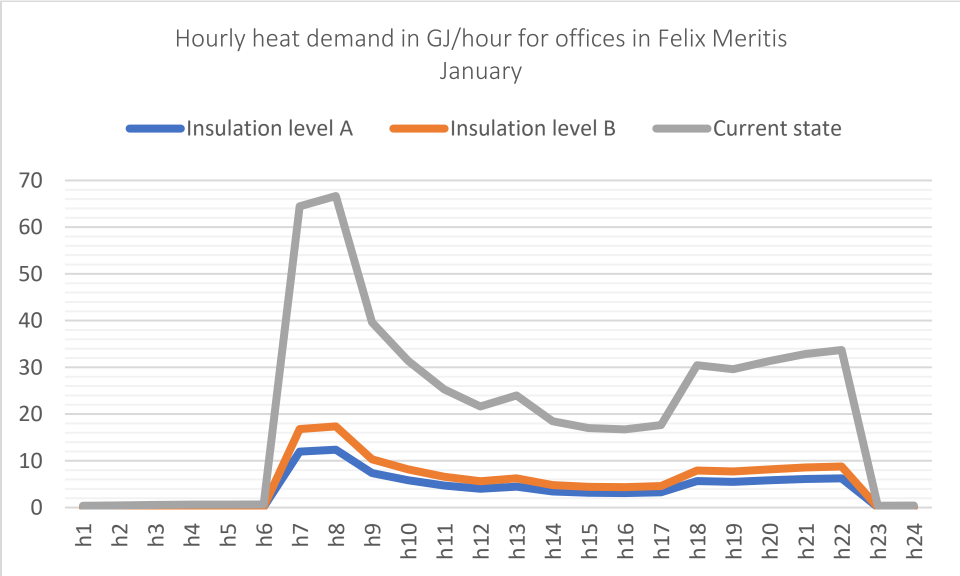


Graph 1. *Monthly fluctuations of heat demand in Felix Meritis in the current insulation state (grey) and before and after insulation to level A (Blue) and level B (Orange).*

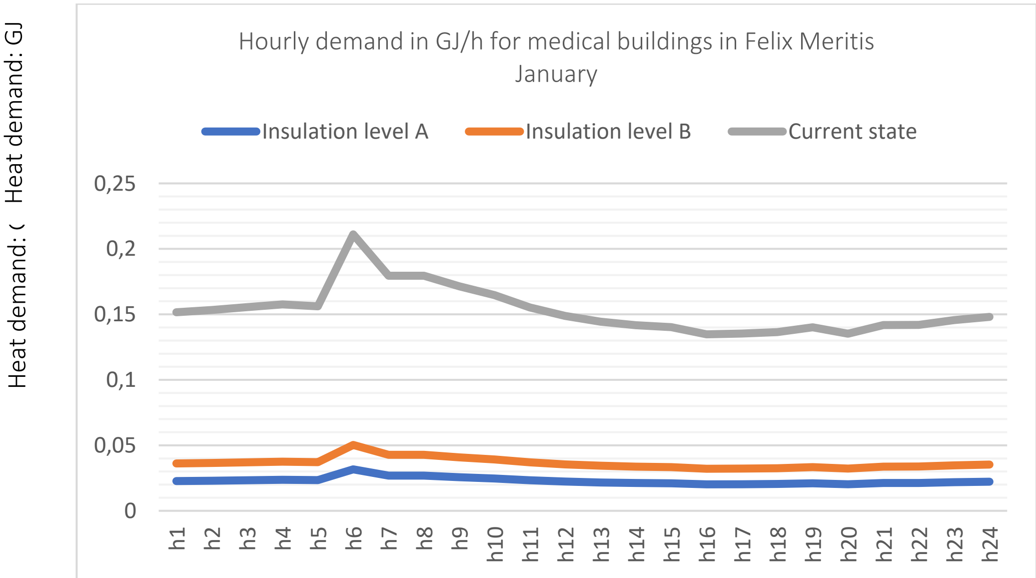
A second step was to calculate the hourly heat demand of each building function. These demand curves are visualized in graph 2 – 8. Because the highest annual heat demand lies in January and thus shows the minimum hourly heat supply that should be met, this month was chosen to base the hourly demand curves on



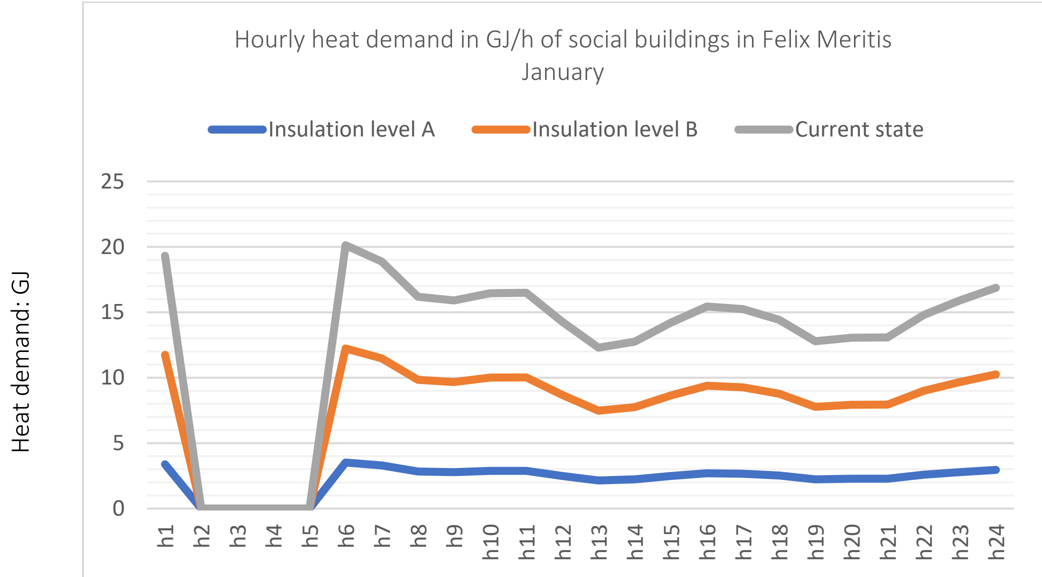
Graph 2. *Hourly temporal heat demand of residential buildings in Felix Meritis in the current insulation (grey) state and before and after insulation to level A and B.*



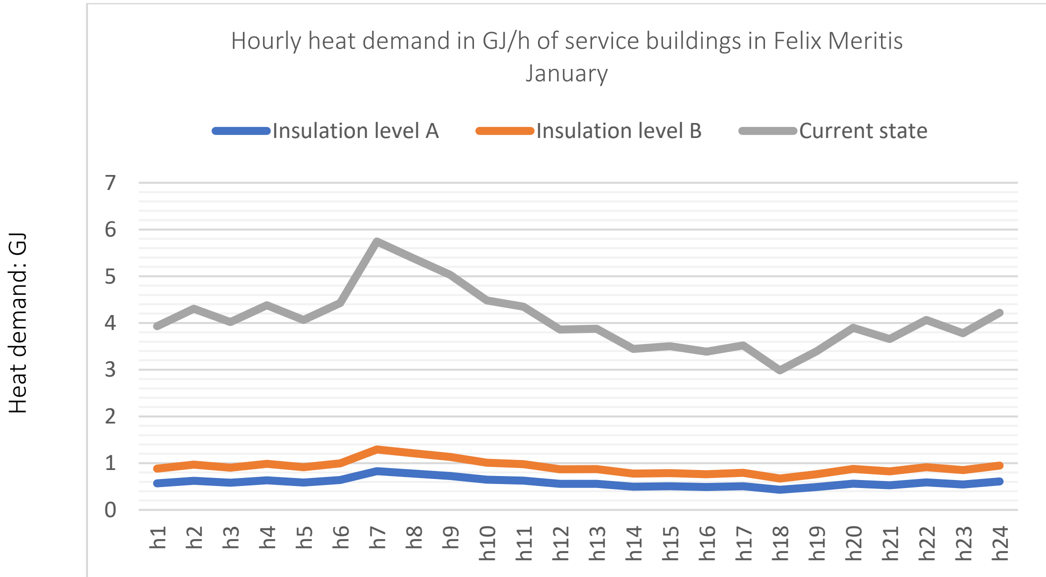
Graph 3. *Hourly temporal heat demand of offices in Felix Meritis in the current insulation state (grey) and before and after insulation to level A and B.*



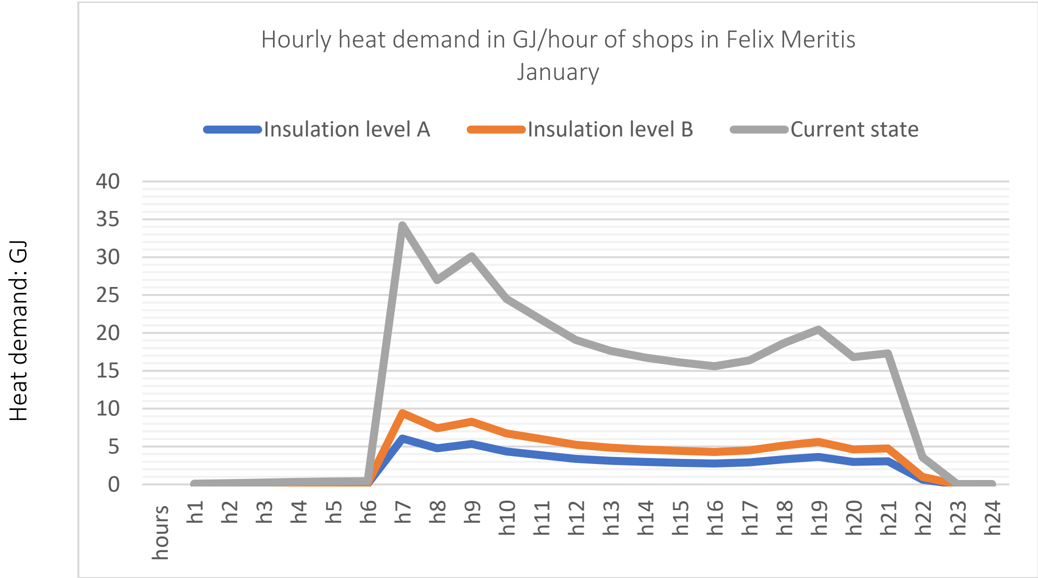
Graph 4. *Hourly temporal heat demand of medical buildings in Felix Meritis in the current insulation state (grey) and before and after insulation to level A and B.*



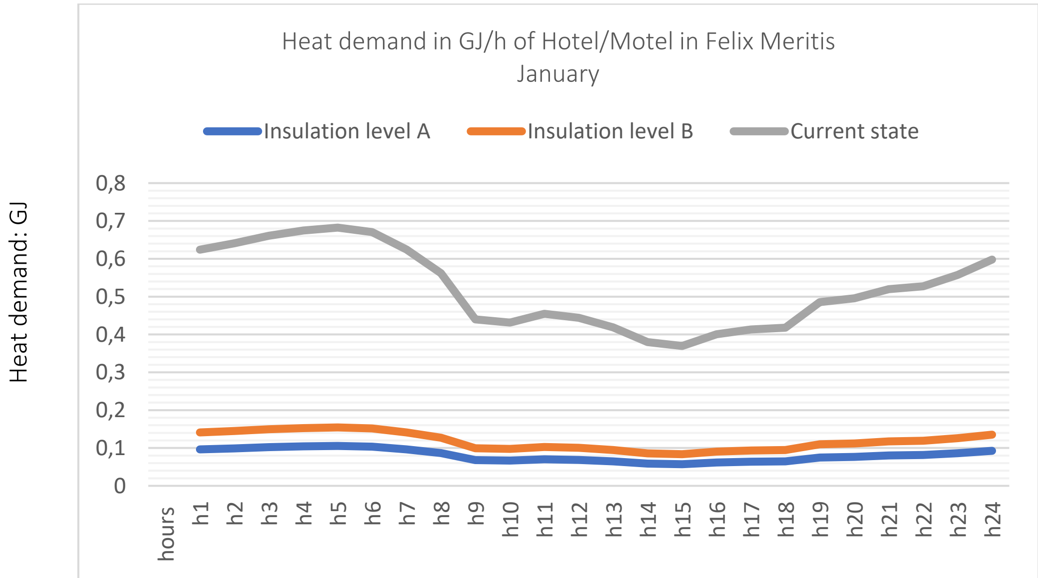
Graph 5. *Hourly temporal heat demand of social buildings in Felix Meritis in the current insulation state (grey) and before and after insulation to level A and B.*



Graph 6. *Hourly temporal heat demand of service buildings in Felix Meritis in the current insulation state (grey) and before and after insulation to level A and B.*



Graph 7. *Hourly temporal heat demand of shops in Felix Meritis in the current insulation state (grey) and before and after insulation to level A and B.*



Graph 8. *Hourly temporal heat demand of hotels and motels in Felix Meritis in the current insulation state (grey) and before and after insulation to level A and B.*

Several things can be concluded when looking at the hourly demand of different building functions in January.

Firstly, all functions, except the residential function show a peak rise in heat demand somewhere between 5:00 and 9:00. This happens because more heat energy is needed to reach a comfortable temperature within a building, after the heating was switched of during the night (Love et al., 2017). In residencies during night, the heating remains on to some extent, explaining a less abrupt peak. A future heat source must ensure a minimum heat supply that is equal to the sum of all morning peaks of a given day in January. For all functions this is 418 GJ/year between 5:00 – 9:00.

Secondly, temporal demand curves can be placed in three groups:

1. A steep peak demand in the morning and evening hours
2. A constant heat demand throughout the day
3. A fluctuating heat demand throughout the day.

Looking at graph 3 and 7, both offices and shops fall in the first group. For offices, the steep peaks can be explained by the fact that people arrive in the morning and want to create an amiable work temperature. Consequence, heat demand goes up. During the day, more people arrive and as explained in section 6.1.1, people naturally heat the building, explaining a lower heat demand (Najjaran, 2012). During the evening when most people leave the temperature of the building lowers. It is assumed that those remaining want to maintain a comfortable indoor temperature. To do so, heating is increased. For shops, the small peak in the evening remains unclear.

Besides a small peak in the morning, residencies and buildings with a medical function show a constant heat demand (graph 2 and 4). In Hospitals, people are present during the entire day explaining a constant need of heat to maintain a comfortable temperature. Based on literature, a more distinct evening peak was expected for residential buildings (Arnaudo et al., 2019) (NEDU, 2020). Its absence can be explained by the usage of reference data that does not consider the specific characteristics of historic buildings. When using reference data of separate homes, most likely a more distinct morning and evening peak is identified. Furthermore, the small dip after 9:00 can be explained by the fact that once a space reaches a certain temperature, the thermal mass of building can keep a constant temperature throughout the day reducing the need for mechanical heating (Arnaudo et al., 2019).

Services, social and hotel/motel have a fluctuating heat demand as shown in graph 5,6 and 8. This can be related to the peak in heat demand during breakfast, lunch, and dinner (Voulis, 2019).

Thirdly, the difference in absolute heat demand per hour between utilities as shown in graph 3 - 8 is explained by the difference in numbers of these functions. For example, absolute hourly heat demand of hotels/motels and medical buildings is lowest because of both functions only one building is present in Felix Meritis. Absolute hourly heat demand of offices is largest because these are most present in the neighbourhood.

Additional to the impact on heat demand based on the three spatial criteria, the impact of insulation measures is considered.

6.2.4 Heat demand of Felix Meritis after insulation measures

Literature shows that insulation reduces heat demand and is therefore a condition for more sustainable and affordable heat supply (Aksoezen et al., 2015) (Leguit et al., 2015) (Dowson, 2016). Therefore, this research estimated heat demand when all buildings would be insulated to label A and label B. For all projects, the insulation values were adjusted to a correlating construction year. For label B this is construction year 1990-2004 and for label A this is year 2005-2020. These values can be found in Appendix 5.

Looking at table 14 – 16, insulation to label A, decreases the total heat demand of residential buildings between 85-90%. For utilities, with the following functions: social, shops, industry, hotel/motel, services and medical, insulating to label A shows a heat demand reduction lies a little lower between 80 – 85%. Additionally, the decrease in heat demand when all buildings are insulated to label B was measured (table 17 -23). In graph 1 – 8 its visible that even insulating buildings up to level B has a significant impact on the heat demand of all buildings. For residential buildings, the decrease in heat demand for space heating lies between 80-85%, for all utilities, total heat demand decreases by around 75%.

The next chapter focuses on the generation potential of several heat sources their CO_2 reduction compared to natural gas and the corresponding cost. Based on the results it is discussed what sources are potential for future heat supply in Felix Meritis.

6.3 Key findings

Having explained both the spatial as well as the temporal analysis on Felix Meritis, we can now answer the first two sub-questions as posed in the methodology section. This sections briefly restates these sub questions and provides an answer to both. Additionally, some related key findings are stated.

The first sub-question is:

What is the yearly heat demand for space heating of different building categories in Felix Meritis?

The total yearly heat demand of utilities is approximately 290.000 GJ/year. For residence is this is approximately 51.000 GJ/year. The yearly heat demand for buildings with different functions and different construction years is shown in table 14 – 23. The total heat demand of each functions is shown in table 27. Additional key- findings related to heat demand of different building functions are:

1) Only with a few exceptions, residential buildings in Felix Merits, are in line with existing literature that older buildings have higher heat demand. This is summarised in table 14 – 16. Knowing this is essential for future planning of sustainable heat sources. When a neighbourhood solely exists from historic buildings built before 1920 or between 1920-1944, this means more heat must be generated to meet the heat demand of this neighbourhood or a larger investment in insulation must be made to improve heat efficiency of these buildings. For utilities, the rule that older buildings demand more heat, is less appropriate.

2) The building envelope has a larger impact on heat demand of utilities, than construction year has on utility buildings in Felix Meritis. The larger the building envelope, the larger the heat demand of utility buildings in Felix Meritis especially for offices, shops, and industrial buildings. These findings are supported in table 24 – 26.

Furthermore, the insights from literature that volume of a building increases heat demand was confirmed. (Delmastro et al., 2017).

Function	Heat demand (GJ/year)
Residential	50813.9
Social	68303.6
Offices	111818.4
Shops	70327.2
Industry	16109.5
Hotel/Motel	2766.2
Services	21632.2
Medical	812.7

Table 27. *Annual heat demand per function Felix Meritis.*

The second sub question posed in the methodology sections is:

How do peak demands fluctuate for different annual periods and between different building functions in Felix Meritis?

Peak demands of different buildings fluctuate both annually and hourly as shown in graph 1-8. By using the data of Voulis, and confirming other scientific literature, it is estimated that the highest peak demand is in the coldest months (January and December) (Amato et al., 2005) (Tronchin et al., 2019). On an hourly base, peaks vary per function, but three main categories could be distinguished:

1. A steep peak demand in the morning and evening hours
2. A constant heat demand throughout the day
3. A fluctuating heat demand throughout the day.

Additional key-findings about hourly fluctuations of heat demand for buildings with different functions are pointed out below:

3) All building functions except residences have a peak demand between 5:00 and 9:00

4) Because all different functions have a different hourly peak demand, heat supply in Felix Meritis must be flexible to ensure sufficient heat demand and guarantee a reliable heat demand.

5) Insulation measures to label A decrease heat demand with approximately 80-90%

6) Insulation measures to label B decrease heat demand with approximately 75 – 85%

6.4 Discussion

Some assumption had to be made when applying the bottom up building model. Consequently, heat demand of residential buildings is estimated higher for residencies of all volumes and all construction years, when modelling heat demand with Energeyes compared to vesta MAIS, another model used to estimate heat demand in for space heating (Leguit e al., 2015) (Sipma & Rietkerk, 2016). The same accounts for utilities. For example, for hotels/motels heat demand is estimated 25% higher. For services it is estimated 300% higher. Accuracy of both models lies in different parameters, making it difficult to say which model is better.

On the one hand, Vesta MAIS include some important parameters. In a research by EPN, (Sipma & Rietkerk, 2016), heat demand of utilities is estimated using the Vesta MAIS model. In this research vacancy of utility buildings is considered which improves accuracy of the heat model and most likely decreases heat estimations of a neighbourhood. Vacant buildings house no people and therefore heat demand estimations are zero or low (Sipma & Rietkerk, 2016). In this research, assumptions on both the number of people and percentage of presence in buildings, influences the outcome of our model. The higher the number of people estimated in a building, the lower the heat demand. Additionally, the same EPN research estimates heat demand based on specific functions per floor using address registration. In this research, number of floors and functions related to these floors are estimated. For residencies, the consequences are that the higher a floor is estimated, the less residencies fit in a building, the higher the heat demand of one residency (Appendix 1). This is because the total heat demand of a residential building is divided by the number of residencies to estimate heat demand of residential buildings. Finally, for utility buildings, only appearing once or twice, the average surface areas or volumes for these buildings have a strong influence on the heat demand of this building and the entire neighbourhood. For example, Felix Meritis has one shop constructed in 1964 which happens to be an extremely large building. Modelled heat demand of this shop lies at 17.880 GJ/year, which is most likely not a representative annual heat demand for an average shop. Calculating heat demand for this shop using the ECN method, gave a yearly heat demand of around 8000 GJ/year (Appendix 3). It is likely that ECN has a much more accurate estimation because they work with a larger data base of 400.000 objects, avoiding the issue of having only one building of a specific function present.

On the other hand, modelling with Energeyes provided the opportunity to add extra details to the model that improved the accuracy of the heat estimations compared to other heat estimations. For example, research by PBL (Folker en van den Wijngaart, 2012) uses the same heating system for all buildings when modelling heat. This system has a heat efficiency of 107%. This affects the accuracy of their model as it reduces heat demand of a neighbourhood. In Energeyes, different heat systems with varying efficiency are added driving up heat demand of the neighbourhood.

Additionally, adding a categorisation of heat loss surface areas for residential buildings, increased heat demand estimated with Energeyes, as opposed to the PBL research (Folkert & van den Wijngaart, 2012). In this research heat demand for canal houses is estimated at 66 GJ/year, using an average ground surface area for all buildings between 60-67 m². Doing a spatial analysis gave us more accurate ground surface areas which are all larger than 60-67 m² and thus increase heat demand for residential buildings (Appendix 3). The difference in estimated heat demand of varies between 17GJ/year and 37 GJ/year compared to our estimations. This refers only to residencies in the smaller volume group. For the larger residencies heat demand differs more as is visible in table 15 and 16. AgentschapNL mentions that the 66GJ/year varies too much from the real values of individual canal homes and can therefore not be used as an example for individual buildings (AgentschapNL, 2011). These findings indicate that sub-dividing construction year, specifying construction materials and insulation values makes the bottom-up building based approach more accurate.

Finally, using Energeyes allowed to not only estimate total yearly heat demand but also monthly and hourly fluctuations. To create both the monthly and the hourly demand graphs, data of the Phd research of Nina Voulis (2019) is used. Local demand profiles, representing temporal heat demand of the Dutch service sector, are gathered using reference buildings from the U.S. These buildings represent the demand of similar Dutch service sector buildings. Building equivalents are calculated based on the service area of a service sector building from the

Netherlands and the corresponding U.S. reference buildings from a US database (Voulis, 2019). Consequently, a deviation from real demand profiles in our study area could originate, due to the use of U.S buildings in the Dutch context, and more specifically the Amsterdam context. However, from a study of Perez-Lombard (2008), where energy use in the US, Spain, and the UK, is compared, no larger difference between European countries and US countries are detected. Thereby, comparing energy use consumption of the entire service sector of the U.S with European countries did not show large differences, suggesting that no large errors should exist when using U.S. data (Voulis, 2019). Translating the data directly to Amsterdam context reduces the accuracy of the temporal demand outcome because specific spatial parameters that are characteristic for the historic centre Amsterdam are left out (Echevarría Icaza et al., 2016). However, this error is partly recovered when construction years and average heat loss surface areas of the utility buildings are added in Energeyes.

7. A RELIABLE, SUSTAINABLE AND AFFORDABLE HEAT DEMAND

Chapter 4 and 5 provided us with outputs to estimate the heat demand of Felix Meritis and gave the answers to sub question 1 and sub question 2. The aim of these chapters was to show how modelling heat demand helps policy makers to implement a sustainable, reliable, and affordable heat supply. To complete this aim, an additional clear definition of the three concepts should be set. In this chapter a discourse analysis is performed to substantiate these three concepts from municipal perspective. Additionally, this enables us to answer sub question 3: *''What does the municipality mean by a reliable, sustainable, and affordable heat supply?''*

7.1 Discourse analysis: making the criteria measurable

7.1.1 Reliability

In most policy documents, reliability is seen as a natural consequence when heat networks are implemented. According to the sustainability agenda of Amsterdam, reliability of heat supply is guaranteed on the long term when the heat network is open for various sources. A combination of sources makes the network more robust and enables accommodation of peak demands (Gemeente Amsterdam, 2015).

Additionally, the MRA states that, due to a limited availability of large-scale regional heat infrastructure, several local networks are more likely to create a reliable heat supply (WarmteKoude, 2018). Integrating local actors that can be both consumers and producers, allows for more and diverse sources added to the network. When one source fails to deliver and meet demand, other sources can cover for this shortage. Thereby, storage covers for seasonal variation of sources. The latest heat law states that heat companies must investigate the availability of heat sources in the heat lot to ensure a sufficient heat supply during times of peak demand. Thereby, the companies must hand in a yearly overview of their life security. A back-up plan must be in place to guarantee security to the consumers (Wiebes, 2019).

Reliability in this sense can be defined as : ***''An open source heat network with a diversity of local heat sources for supply that is able to accommodate peak demands and that can meet de heat demand of the city of Amsterdam''***

Reliability is practically measured by comparing the heat demand of the neighbourhood to the potential to meet this demand for each scenario e.g. the different proposed heat sources. If a source cannot supply the demand, the potential of storage is considered. Thereby, the peak demands are considered. This means that each source must not only be sufficient for the average annual heat demand of the neighbourhood, but also for the peak demands to be reliable. When the demand cannot be met, the scenario is noted as insufficient or unreliable. Calculations of reliability vary for each scenario and are described in detail in chapter 8.

7.1.2 Sustainability

To use sustainability as one of the pillars for the implementation of a heat network, a more specific definition of the concept is needed. Over time, the political arena around the energy transition was dynamic. This influenced the meaning of sustainability in the energy market. To show the dynamic nature of the concept, a discourse analysis of the terminology of sustainable heat within policy documents over time is performed.

Until 2005, a clear definition of sustainability in heat networks lacks (RMA, 2019). The first-time sustainable heat is described is in the: *''action plan air quality Amsterdam of 2006''*. This report described sustainability in terms of reducing carbon dioxide (CO_2), nitrogen oxides (NOx) and particulate matter (PMx). The main aim of the report was to prove the impact of extended heat networks on air quality. At this time, individual heating of households with natural gas made up for 0.5 - 4 kg of NOx yearly. Connecting 130.000 households and using waste heat of the AVI of the AEB instead, should lead to a reduction of 1.5 mg/m3 NOx. Interestingly, in this report, CO_2 did not serve as an indicator of measuring air quality (van Bergen et al., 2006).

In 2008 a second report came out describing the importance to upscale the cities heat networks and create one large network (RMA, 2019). This report gathered the following requirements under the definition of sustainability: a CO_2 reduction of 50% relative to 1990, an increase of 38.000 connections in 2008 to 100.000 in 2025, energy saving by using rest heat and the implementation of a closed ring pipeline to prevent a must run situation where electricity plants have to keep running to provide sufficient heat (Alliander 2016). The municipality of Amsterdam opted to have complete control over this new largescale network to be able to secure these sustainability ambitions.

In 2010 Climate Bureau Amsterdam published the energy strategy Amsterdam 2040. The main goals in this strategy was again reduction of CO_2, but this time with 75% in 2025 as opposed to 1990. This had to be reached by increasing the connections of new and existing buildings from 100.000 connections in 2025 to 200.000 connections in 2040. The current heat sources (Nuon and AEB) were described as means to reduce CO_2 and could foresee the whole city of heat in the future.

Since 2013 the implementation of the heat networks started actively including existing buildings. Investigation by Nuon and the AEB confirmed that especially amongst neighbourhoods with buildings constructed after 1950 a potential of an extra 170.000 connections lied ahead. This could lead to a CO_2 reduction of 170.000 tonnes yearly. Based on these conclusions, the municipal ambitions shifted from 200.000 connections in 2040 to 230.000. Additionally, connection to the heat network needed to be more area specific, and open source heat networks and sustainability of heat sources were emphasised. The central council wanted more space for individual innovations or decentral heat sources that offered an equal or even more sustainable alternative for heat supply (Gemeente Amsterdam, 2010).

When in 2015 the Agenda Sustainable Amsterdam came out, the sustainability of heat sources was emphasized, as well as the importance to phase out fossil energy for heat supply. Potential heat sources that are mentioned in this report are thermal solar energy, geothermal energy and thermal heat storage from the water cycle and datacentres (Gemeente Amsterdam, 2015).

In 2016, a strategy of Amsterdam without natural gas, became the central incentive to change heat supply in the built environment. The focus was no longer the infinite growth of connections but disconnections of buildings from gas, regardless of what technology replaces heat (RMA, 2019).

This strategy must contribute to reaching the 95% CO_2 emission reduction goal of the city, relative to 1990 (Gemeente Amsterdam, 2016). Within this new strategy, building and neighbourhood characteristics e.g. local analysis, must define the optimal heat system for each separate spatial area. High temperature networks are still seen as the most efficient form of heat supply. However, having a gas driven electricity plant as one of the main sources for this HT heat supply created the necessity to focus on alternatives (Gemeente Amsterdam, 2018). LT and MT networks are now seen as equivalent alternatives. In order to achieve more local oriented heat networks the municipality is looking for cooperation with all parties involved including: consumers; housing corporations and house owners; network distributor Alliander; heat suppliers Nuon and WPW and MRA (HeatCold program) (RMA, 2019).

Finally, the most recent heat law emphasizes the compulsory nature of carbon neutral heat supply for all heat companies that offer their product. Thereby, collecting ''waste heat'' from data centres and large industries is highly encouraged (Wiebes, 2019).

Executing a discourse analysis on the concept of sustainability in heat supply gave the following definition of sustainable heat:

'' A non-natural gas driven heat system that connects high temperature heat sources with a low CO_2 ***footprint with medium and low temperature heat sources such as water energy, thermal solar energy and heat from data centres, to an open source heat network, with the main aim to reduce*** CO_2 ***emission with 95% in 2050 as opposed to 1990 ''***

To make sustainability measurable in practice, this research chose to focus on the reduction of CO_2 emission in kg. The following formula is used to do so:

$$\Delta Mco2 = (Ecurrent * a) - (Enew * a)$$

ΔM CO_2 = CO_2 emission reduction (kg/year)

E current = current energy usage (kWh/year and/or m3/year)

E new = new energy usage (kWh/year) / COP (*when scenario is using a heat pump*)

a = emission factor (kg/kWh)

Having this formula allows us to calculate how much CO_2 emission is saved yearly by implementing a specific measure. These calculations are performed in the next section.

7.1.3 Affordability

Transitioning to a heat network requires a significant investment. The Energy Strategy Amsterdam 2040 estimates investment cost of between 5 and 6 billion euros until 2050 (RMA, 2019). This affects consumers, real estate owners and energy suppliers. To find sufficient support under all parties, the municipality aims to set up an affordable construction supporting the heat transition (Gemeente Amsterdam, 2019).

1. Consumer affordability

The municipality of Amsterdam aims to protect its consumers via the Not-more-than-before (NBDA) principle. This means that consumers should not pay more than their current gas bill. The Authority Consume and Market organisation has the task to guarantee this principle (ACM, 2019). Currently, the heat price is automatically linked to the price of gas. However, a current increase of the gas price means an increase in the heat price which causes a negative attitude of consumers towards a heat transition (Wiebes, 2019). In the future, the aim is to set up a new business case for different heat sources to supply consumer with heat. Fixing these business cases is largely depending on a yearly fee consumer pay, meaning that affordability of different heat sources will differ. Because these business cases are non-existing and ask for an extensive study into investment cost of infrastructure, on site adaptations and large technical implementations (S. Mol, personal communication, May 27th, 2020), consumer affordability is not considered in this research.

2. Affordability for heat suppliers and network operators

Both heat suppliers and network operators focus on their return on investment by looking into the security of heat demand in a spatial area. A profitable heat network is dependent on a high heat demand and a high demand density (Kruit et al., 2018). Table 28 shows the key numbers needed to make a heat network affordable for heat supplier and network operators (Kruit et al., 2018).

Requirement for collective heat	Criteria
Enough heat demand for potential feasible project	Heat demand neighbourhood > 2000 GJ
Heat network possible	Heat demand density > 600 GJ/ha

Table 28. *Essential heat demand and demand density to make collective heat affordable (Kruijt et al., 2018).*

Additional to security of demand, heat suppliers and network operators deal with the investment cost of new infrastructure and technical installations. The historic centre has an overcrowded underground infrastructure. Currently the municipality is working on a 3D model to map the exact situation of the underground infrastructure of the city. In general, the scenario that guarantees the least underground space uptake or adaptation could prove to be most feasible. Especially implementation of a district heat network running from WPW to the city centre demands huge infrastructural adaptations and is therefore costly (M. Buijck, personal communication, August 19th, 2020) (S. Mol, personal communication, May 27th, 2020). Because research to the underground infrastructure in the historic centre is difficult due to limited available data and maps, affordability could not be assessed for this specific area. However, to address the cost of implementing a new heat infrastructure for network operators, cost indications are taken from personal communication and from the Clingendael international energy program (Klip, 2017)). This report discusses general cost of main infrastructural and technical adaptations such as a central heat pump, cost of intensifying the electricity grid and replacement of a gas network (Klip, 2017).

3. Homeowners affordability

For homeowners, the main cost lies in renovation and insulation measures insulation and technical adaptions (RMA, 2019).

Assessing affordability based on municipal documents gave the following definition:

''An affordable future heat supply considers low or equal cost for consumers compared to the current cost for space heating. Furthermore, heat demand and heat demand density must be sufficient and investment cost in new infrastructure and technical

adaptation in the public space must be as low as possible. Finally, an affordable heat network concerns the lowest possible inhouse investment cost for homeowners''.

In practice, the next chapter measures affordability of each scenario based on, four parameters. 1) heat demand security. This means that heat demand of Felix Meritis must be higher than 2000 GJ/year and 2) heat demand density must lie above 600 GJ/ha. 3) Investment cost in a new heat infrastructure and additional technical installations, using general cost from the Clingendael report (Klip, 2017). 4) investment cost for homeowners are considered in the form of insulation costs and cost for inhouse investment.

7.2 Key findings

After analysing several policy document and reports supported by the municipality in section 6.1, it is now possible to answer sub-question 3.

''What does the municipality understand by a reliable, sustainable, and affordable heat supply?''

By setting these criteria the municipality aims to install a future heat supply that can supply the city with sufficient heat and that has enough storage capacity in place to cover for annual, monthly, and hourly peaks. Furthermore, its Carbon footprint must be minimal meaning they strive to a CO_2 reduction that is equal to the reduction aim for the entire city: 95% compared to 1990. Finally, future heat supply for the city must be affordable in terms of consumer cost, investment cost for the network operators and investment cost for homeowners.

7.3 Discussion

Although one can assume that a sufficient heat supply is most important (e.g. a reliable heat source), it is not clear from the discourse analysis which of the three criteria is most valued by the municipality. Recognising the trade-off, the municipality makes between CO_2 reduction, affordability and reliability is not further discussed in this thesis but could be interesting for future research to establish the most optimal scenario.

Additionally, to measure affordability specifically, this research does not consider consumer cost, because busines cases around heat scenarios are not fixed yet. Once a new heat source is implemented and business cases are fixed, further research can investigate the increasing or decreasing energy bills of consumers to measure affordability for this group. Moreover, investment cost in infrastructure and technical installations in the public space are not measured based on the spatial area we investigate Felix Meritis. Although general investment costs of infrastructure and technical installations are considered, a better picture is given when underground infrastructural maps of the exact site are investigated and exact cost and time of transition is researched.

8. HEAT SCENARIOS FOR THE HISTOIRC CENTRE OF AMSTERDAM

The main aim of this research is to provide an approach for the municipality of Amsterdam to design a reliable, sustainable, and affordable heat supply for the historic centre of Amsterdam. Having explained a method to model heat demand and applying it to a pilot neighbourhood was the first step in achieving this aim. It is important to do so because implementing local solutions asks for a local analysis of the heat demand to ensure sufficient heat generation in the neighbourhood (Voulis, 2019) (Allegrini et al., 2015). Thereafter, the discourse analysis provided insight in the criteria the municipality desires of future heat supply. This chapter uses the outcomes of the previous chapters to explain three potential scenario's that are feasible to play out in the historic centre of Amsterdam. Section 8.1 discusses the chosen scenarios. Section 8.2, 8.3 and 8.4 perform a spatial analysis of all three scenarios. In section 8.5 key findings are discussed and the chapter is ended with a short discussion of the taken approach.

8.1 Scenario selection

In this research, a scenario is a selection of the most optional technologies to supply heat in Felix Meritis. In the heat transition vision 2020, the municipality expresses several scenario's which they deem likely for a future heat supply of Amsterdam. These are shown in figure 19. Three scenarios were selected and explored based information of experts that expressed the likelihood of implementation of these heat sources in the historic centre (S. Mol, personal communication, 2020) (H. de Brauw, personal communication, 2020) (S. Broersma, personal communication, 2020).

The three chosen scenarios are:

1. Aqua thermal energy
2. HT- heat district heating (WPW)
3. Hybrid (Aqua thermal energy & Conventional gas)

No all electric individual options are selected due to the spatial characteristics of the building stock in Felix Merits. With an all-electric solution, all energy is supplied via electricity. With the relatively high energy demand of this spatial area, the electricity network needs reinforcement of the grid, which is extremely costly and might not fit in the underground especially in the historic centre (H. de Brauw, personal communication January 17th, 2020) (V. Valkema, personal communication, January 27th, 2020). Although the hybrid scenario does include natural gas, which does not align with the sustainability criteria, this scenario is included because it can pose a feasible route into a transition to a desired CO_2 neutral scenario.

In section 8.2, 8.3 and 8.4 existing infrastructure of all scenarios is spatially analysed. Thereafter, section 8.5 provides key findings.

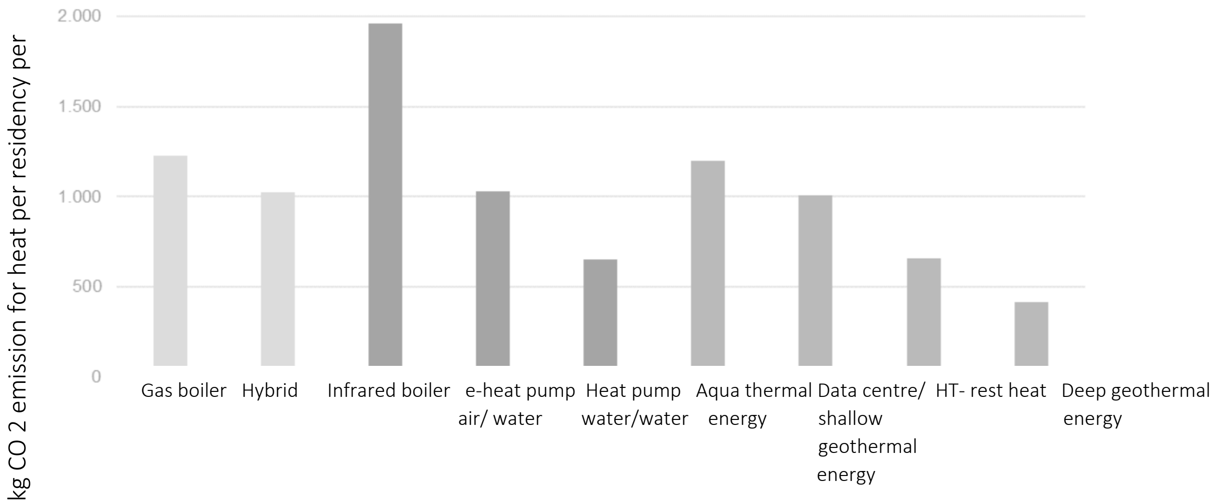


Figure 19. *Heat scenarios presented in the heat transition vision* (Geldhof et al., 2020).

8.2 Spatial indication of aqua thermal energy (Scenario I)

Three forms of aqua thermal energy are currently investigated on national level:

1. Thermal energy of drinking water (TED) is generated by heat release during process of creating drinking water. No intensive research to this technology has been executed so far. Studies state that TED will always play a minor role in the energy transition and its potential is estimated at 4 -6 PJ/year (Kruit et al., 2018).
2. Thermal energy of wastewater (TEA) is gained from wastewater on household level via influent and effluent of pressure lines and sewer pumping stations. Its potential is estimated at 56 PJ per year (Kruit et al., 2018).
3. Thermal energy from surface water (TEO) is a form of generating energy from open water bodies. This heat can either go straight to the source (the build environment) or it can be stored in an aquifer thermal energy system (ATES) system (M. Bloemendal, personal communication, 2020).

Research shows, that TEO has the highest potential to contribute to meeting future heat demand in a sustainable manner. The national potential of TEO is estimated around 150 PJ yearly (Deltares, 2018) (Kruit et al., 2018) (Waternet, 2020). Currently 40% of the national heat demand could be covered by TEO and in 2050 this can be 43%. The images below show the technical potential of TEO as well as the potential of supplying TEO via a heat network in the Netherlands. Especially for a city like Amsterdam, with its large numbers of canals, and open water it could be a feasible alternative for gas (Kleiwegt & de Coo, 2018). Due to its large potential and existing field of research, it is decided to take aqua thermal energy from TEO as a likely scenario to cover for the heat demand in the historic centre of Amsterdam.

8.2.1 Heat source: water systems

Thermal energy from surface water can be gained from all types of open water sources, such as:

- Watercourses and puddles
- Deep puddles
- Smart polders
- Sea water
- Canals (Kruit et al., 2018)

At the centre of Amsterdam, the main waters suitable for thermal energy are the IJ and the canals running through the entire city centre. The map in figure 20 shows the opportunities of heat supply from surface water in the historic centre of Amsterdam (Waternet, 2020). From this figure it becomes clear that spatially, Amsterdam offers great opportunity to gain energy from surface water.

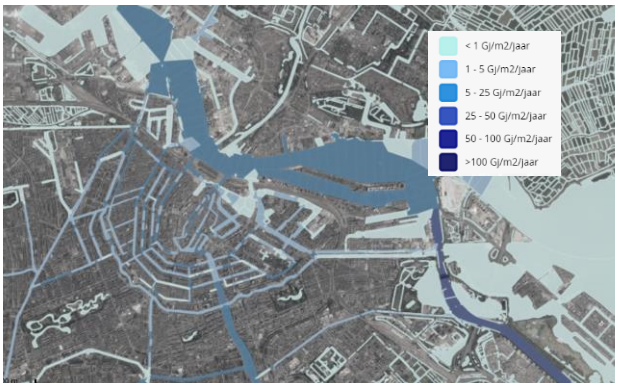


Figure 20. *Potential of TEO in GJ/m²/year. The lightest blue shows the lowest potential and the more intense blue represents the highest potential of energy from surface water* (Waternet, 2020).

8.2.2 Heat network

Zooming in to the needed heat network explains via which type of network energy from surface water can be transported. There are three possibilities:

1. Low temperature network (LT) operating at temperatures around 15 °C, where each building connection has an individual heat pump to increase heat to the desired temperature (decentral).
2. A central heat pump that increases the temperature to around 40-50 °C. Individual households can implement an additional heat pump to increase temperatures to 60 °C (hybrid or MT heat network).
3. A central heat pump that increases temperatures to 70 °C. Here there is a significant loss of efficiency for the heat pumps but less adaptation for individual buildings is required (Deltares, 2018).

In the historic centre type 2 seems the most obvious, as most homeowners are not in favour of installing a local heat pump (H. de Brauw, personal communication, December 17th, 2020. The temperature to which heat must be upgraded depends on the insulation level of individual buildings. The consequences of insulation measures on the reliability, sustainability and affordability criteria are further discussed in chapter 9.

8.2.3 Technical installations in the public space

The infrastructure for a LT heat network with a collective heat pump is shown in figure 21. In this simplified representation of the reality, there are three main installations in this network:

- Aquifer thermal energy system (ATES)
- The electricity grid and transmission stations
- A collective heat pump / heat transmission station

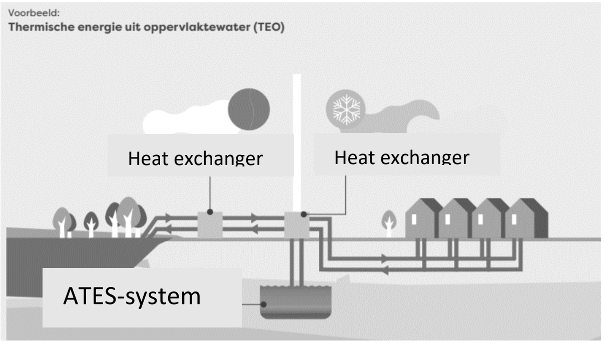


Figure 21. *Needed infrastructure for the implementation of TEO* (Nationaal programma RES, 2020)

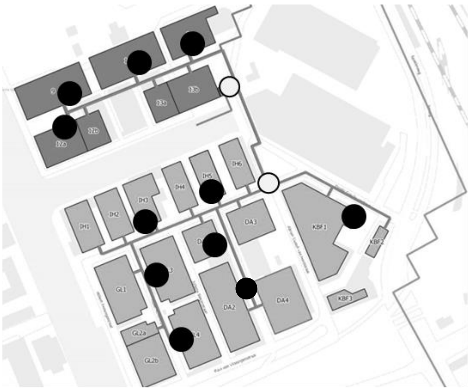
Heat from surface water is extracted with an average temperature between 7 -25 °C depending on the season (Kruit et al., 2018). This extraction happens via a heat exchanger. Heat is transported via a pipe network, either directly into the building or to the ATES system. The implementation of an ATES increases the potential of TEO due to storage of heat in times of surplus and extraction in times of shortage (Kruit et al., 2018). With the use of a central heat pump, heat can be upgraded to 40 - 50 °C and serve as space heating during cold periods (Deltares, 2018). In many occasions, existing build environment needs to be adapted to the low temperature heat in the form of insulation.

An important spatial implication of the energy from surface water is the availability of ATES systems (S. Mol, personal communication, 2020). To analyse the presence of ATES systems in the historic centre, a GIS analysis was performed on the presence of these systems in the pilot neighbourhood. Data was retrieved from www.wkotool.nl. A map of ATES systems is shown in figure 22.

Figure 22. *ATES systems currently present in the historic centre of Amsterdam*.

It was chosen to set a buffer of 500 m around Felix Meritis because for an LT heat source to be efficient, the maximum distance is 500 m (Kruit et al., 2018). Both open and closed ATES systems are available within the buffer zone. This indicates that storage potential in Felix Meritis is not an issue. For each of the storage sources, data on the maximum capacity is available which will be further explored in chapter 9. The grey dots represent installation via which water is extracted or pumped into the soil.

Another spatial implication of installing an LT heat network, supplied with aqua thermal energy, is the necessity to intensify the electricity grid. The spatial implications of underground infrastructure, such as electricity cables are not further discussed due its complex nature and limited open source data on the matter. However, above ground additional electricity transmission station (ETS) within the neighbourhood are needed. Such a transmissions station on take up approximately 4m2 (Liander, 2018). From a study of Liander it was found that on average 10 ETS stations can supply 1800 connections. An example is shown in figure 23.



11 ETS systems for 1800 residencies

+ 2 ETS systems with AC5 connections > 13 total

Figure 23. *Explorative study in ETS capacity in a pilot neighbourhood chosen by Liander* (Liander, 2018)

If each building in Felix Meritis needs at least one connection, this means that a minimum of 1800/ 637 = 3 electricity transmission station are needed to cover the current electricity demand. For an all-electric scenario, Liander estimates an increase of 2-3 ETS' per neighbourhood. Because aqua thermal energy does not suggest an all-electric scenario, this research worked with an increase of 1.5 ETS which means that above ground a minimum of 6m2 must be available to construct these.

Finally, heat transmissions stations or central heat pumps need to be installed in the neighbourhood. These stations cover a similar surface area of 4m2 (Liander, 2018). Currently no such installations are in place in the historic centre. This means that additional free space is needed for these stations (Liander, 2018).

8.3 Spatial indication of HT- district heating (Scenario II)

Heat source: Westpoort Warmte

Currently, an existing heat network owned by Vattenfall and Westpoort Warmte is in place around the historic centre of Amsterdam but not within the centre. This is shown in figure 24.

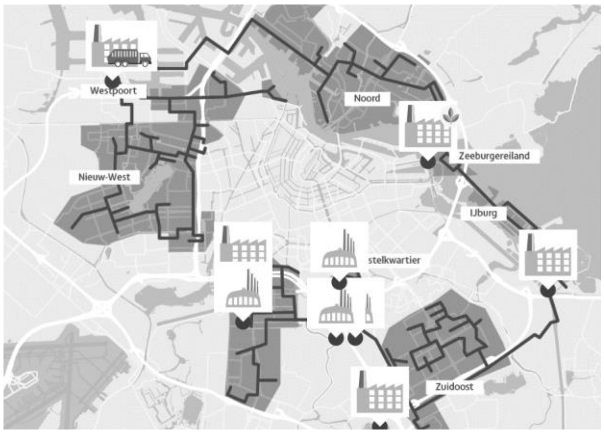


Figure 24. *Existing heat network in Amsterdam. Two networks from Vattenfall (South-East) and Westpoor Warmte (North-West) are now connected.*

Although no buildings in the historic centre are currently connected to the existing heat network, spatial analysis explores the opportunities to expand the heat network towards the centre of the city. Figure 25 shows that a pipeline towards the historic centre could be placed in the south west of the city. This location is favourable due to planned renovations of bridges which forms the perfect opportunity to implement new infrastructure at the same time. The fictive network can be divided into the primary network which is directly connected to the heat source and a sub network which is connected to a heat delivery station and the neighbourhood (Ruijs, 2020).

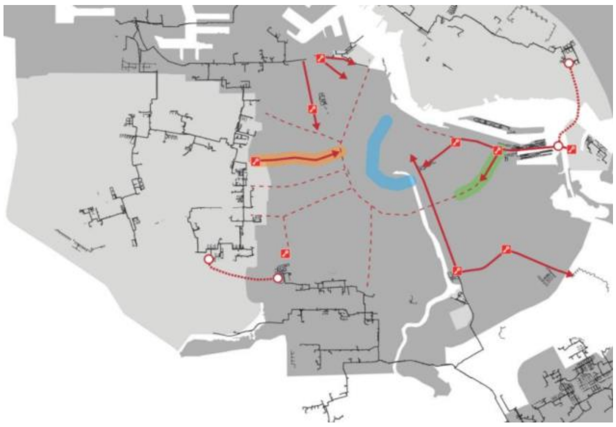


Figure 25. *A fictional heat network in the historic centre of Amsterdam* (Ruijs, 2020).

8.3.1 Technical installations in the public space

A heat network is a collective form of heat supply, where heat is transported from the source via an underground pipe network to a heat transmission station. Such a heat pump doses the right amount of water and brings it to the desired temperature before sending it off to the built environment. Amsterdam has two large scale collective heat pumps in the south east of the city. Additionally, over 200 small collective heat pumps are in place to supply neighbourhoods with the right amount of water at the right temperature (Ruijs, 2020). A collective heat pump on neighbourhood level covers an average surface area of 4m² which is much larger than a gas-district station (Liander, 2018). Again, the demand of the neighbourhood determines the number needed of pumps. Unfortunately, no open data was found to show the capacity of existing collective heat pumps. However, figure 26, gives an indication of where small collective heat pump systems are currently located. None are currently present in Felix Meritis.

8.4 Spatial indication of a hybrid system (Scenario III)

Old canal buildings need HT heat (70-90 °C) to create an amiable indoor temperature. Taking insulation measures to reach such temperatures is usually expensive and an economically unprofitable option, (H. de Brauw, personal communication, December 17th 2020). Therefore, the hybrid scenario, suggest the combination of a conventional boiler with a collective heat pump. In this research aqua thermal energy and a collective heat pump is used as heat source for the baseload and biogas for the peaks. The heat pump as described in the aqua thermal scenario uses 30-40% of its capacity, while 60-70% of the boiler's capacity is used (H. de Brauw & S. Mol, personal communication, 2020). This boiler heats water to higher temperatures on extremely cold days. Although the thermal storage and the heat pump run on full capacity, the peak load is covered by the biogas boiler. This creates a situation where 75- 80% of the heat demand is generated by the heat pump and in the coldest week the bio-gas boiler forms a buffer (H. de Brauw & S. Mol, personal communication, 2020). Because the sources, the infrastructure and technical installations for aqua thermal energy are discussed in the aqua thermal and the current gas-infrastructure is already in place, no further spatial analysis is performed here.

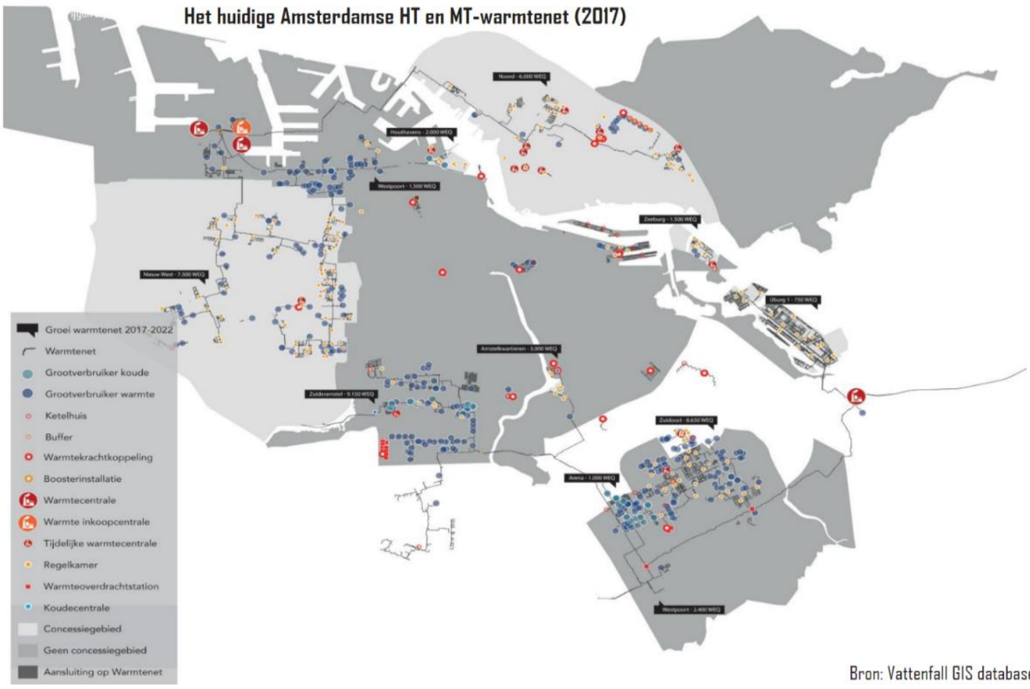


Figure 26. *Heat transmission systems are indicated by the small red dots. These are especially visible in the south east of the city where many large energy consumers are located* (Ruijs, 2020

8.5 Key findings

1) Surface water is widely available throughout the city and thus offers the potential to be a heat source for the historic centre.

2) Both open and closed ATES systems are present in Felix Meritis

3) Above ground space is needed for ETS stations (at least 6 m2)

4) Above ground space is needed to install a collective heat pump (at least 4m2)

5) No heat network is existing in the historic centre yet

6) Collective heat pumps are not present in Felix Meritis and take up around 4m2 per installation

7) ATES storage capacity in Felix Meritis is dependent on the heat demand of the neighbourhood

8) Potential lower spatial uptake because peaks are covered by existing gas infrastructure

9) Gas distribution stations take up less space than collective heat pumps (Liander, 2018).

8.6 Discussion

In this chapter, three potential sources for heat that can supply space heating to Felix Meritis are chosen. However, insecurity about potential of different heat sources and ongoing innovation and research to other future heat sources must be considered in further research to ensure no options are prematurely excluded. Furthermore, this research takes Felix Meritis as representative neighbourhood for other neighbourhoods in the historic centre, due to its spatial characteristics and spatial heterogeneity (section 5.2). Doing so gives an insight in what technology mix is potentially interesting for the entire historic centre. However, a neighbourhood approach is useful because it allows for locally tailored solution. Therefore, when wanting to assess the best scenario for each neighbourhood, further research can apply the bottom-up approach separately to each neighbourhood or to a cluster of neighbourhoods to identify the best technology mix.

9. SCENARIO ASSESEMENT

This chapter compares the three scenarios as explained in chapter 8, on reliability, sustainability, and affordability.

Section 9.1 discusses reliability. Thereafter sustainability and affordability for each scenario are discussed in section 9.2 and 9.3. Section 9.4 shows bar chart to represent how each scenario ''scores'' on the three criteria and how they relate to one another this is complemented with the main key findings. Thereafter question 4 is answered: *''What future heat scenario is most optimal to meet the reliability, sustainability, and affordability criteria?*

Before reading this section, it is recommended to read Appendix 7. In this appendix, a description is given on key-numbers that are essential to make calculations for each scenario.

9.1 Reliability

Implementation of Aqua thermal energy requires insulation measures that are minimal to label B to reach a comfortable indoor temperature (Rovers & Tichelaar, 2019). Moreover, Insulation to label A for buildings constructed before 1920 is so expensive that this is not regarded as a feasible option (H. de Brouw, personal communication, January 17th, 2020) (V. Valkema, personal communication, January 27th, 2020). The total current annual heat demand of Felix Meritis is modelled at approximately 342.500 GJ/year. Assuming that the entire neighbourhood would be insulated to label B, heat demand of the neighbourhood can be reduced by around 68 %, to 109.150 GJ/year (Appendix 5).

To supply buildings with a temperature of 40-50 degrees heat, a collective heat pump needs to have a COP of 3,5. This means that 1 MWh electricity is converted into 3,5 MWh heat. From calculations in Appendix 8, it becomes clear that in this case, the TEO system annually needs to generate 77.964 GJ/year. The availability of TEO in this neighbourhood is approximately 16.400 GJ/year (Waternet, 2020). This means that there a shortage of 61.564 GJ/year should be covered by storage from the ATES system. In the hottest months of the year, most likely, no heat from storage is needed. Based on this given, a more specific calculation can be made on the needed capacity and shortage of the TEO system.

Within a year, the rule of thumb is, that there are 100 days where water temperature lies above 16 degrees. At this temperature heat energy can be extracted. This means that the ATES systems in Felix Meritis must have a capacity to store 61.564 GJ which must be supplied by the TEO system within these 100 days. For simplicity, this research assumes that infiltration of hot water in the ATES systems happens during the three warmest moths of the year: June, July, and August. This means that there is 92 days to refill the ATES system.

Heat demand in these three months in Felix Meritis lies at 17.269 GJ in total. Having the same central heat pump with a COP of 3.5 means that the TEO system needs to supply 4.934 GJ during these months. This means that the TEO system can infiltrate 12.335 GJ/heat to the ATES system. However, for the remaining months, a heat demand of 65.629 GJ remains. This means that the ATES system has a shortage of 60.695 GJ to cover heat demand for the other colder months in Felix Merits. From these calculations, it can be concluded that the aqua thermal scenario is not feasible, as the total heat demand of the neighbourhood cannot be met and storage capacity is insufficient.

When assessing the reliability of scenario II, the HT district heating scenario, table 29 shows the heat generation of WPW was 918.786 GJ in 2017. In 2018 this was increased to 1.2 million GJ. and currently, heat generation lies around 1.3 million GJ (M. Buijck, personal communication, 19th of August 2020).

Heat Mix WPW	Substance	Heat generation (2017) [GJ] (aeb, 2017)	Emission factors
AEB	Total	918.786	
Waste incineration AEC-AVI	household waste, business waste, sewage sludge	735.583	0.0314 (over 47%)
Waste incineration HR-AVI	household waste, business waste, sewage sludge	137.487	0.0314 (over 47%)
Biogas installation	Low-grade pruning and waste wood, + Biogas Waternet	45.716	0
Orgaworld	Bio fermentation gas	**75.000**	**0**

Table 29. *The heat mix of WPW.*

In this scenario, heat is generated at HT making insulation unnecessary. When undertaking no insulation measures, heat demand remains at 342.500 GJ/year.

Currently, the boundary of heat supply by the AEB is set by the peak heat demand. The base load heat demand of 40.000 residencies connected to WPW, is covered with bio-gas while a natural gas driven heat central is used to supply the peaks. Investment in larger capacity for biogas is only feasible when the baseload heat demand is high enough (M. Buijck, personal communication, 19th of August 2020). In theory, Felix Meritis has a relatively high heat demand compared to currently connected neighbourhoods of WPW. This indicates it is feasible to invest in a HT heat network at this location. However, the main obstacle for expansion of the heat network to the historic lies in the investment cost in expensive infrastructure in the historic centre (M. Buijck, personal communication, 19th of August 2020). Because it was chosen to measure reliability of a technology by the opportunity to supply sufficient heat, a HT- district heating scenario, with heat from WPW is seen as a reliable scenario as it generates a 1.3GJ/year.

Finally, looking at the reliability of the hybrid scenario, it must first be established what part of heat demand is covered by the central heat pump (aqua thermal energy) and what part is covered by a conventional boiler. In this research, the following rule of thumb is used:

40% of the total needed capacity of the ATES system, the base load, is covered by an expensive heat pump, and that these heat pumps can deliver 80% of the heat demand. 60% of the total needed capacity, the peak load, is covered by a cheaper gas boiler which delivers 20% of the heat demand (S. Mol, personal communication, 2020). A Schematic overview of this situation is given in figure 27.

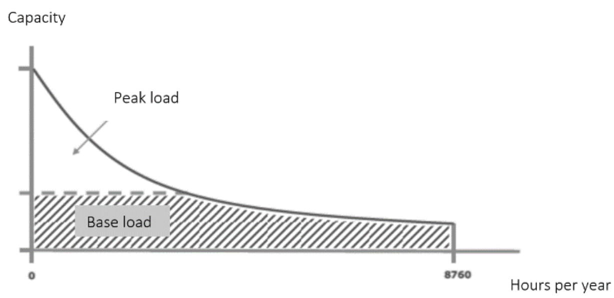


Figure 27. *Division of coverage heat demand (S.Mol, personal communication, 2020).*

It is assumed that the peak demand in Felix Meritis lies within the coldest months January and December. Because the rule of thumb assumes 20% of the peaks is covered by a conventional boiler this means that also a part of Novembers heat demand should be included (Appendix 8). The total heat demand of Felix Meritis within these 2.5 months lies at 33.669 GJ.

This leaves heat demand in other 80% of the year at 75.481 GJ. According to the rule of thumb, this 80% should be covered by a TEO installation. Whit the same collective heat pump as in the aqua thermal scenario, this means that TEO should be able to generate 53.915 GJ/year for space heating. The potential of 16.400 GJ is not enough. Another 37.515 GJ must come from storage. This means the ATES system would have to have a storage capacity of 70% filled by aqua thermal energy, as opposed to the 40% suggested. This means that the hybrid scenario, when following the rule of thumb is not sufficient and is therefore not a reliable heat source for Felix Meritis.

NB: A reason to implement a hybrid heat pump is that it allows for a more gradual heat transition. The current gas infrastructure is used to supply capacity that lies outside that of aqua thermal heat, while the hybrid pump is steered as such that it only uses electricity when the networks allows this. The hybrid pump then fills a heat buffer. In this case, the electrical heat pump optimally uses the sustainable electricity, while the gas driven boiler efficiently covers the rest of the demand. Improvement of the efficiency of aqua thermal energy in the future could then increase the share of the hybrid heat pump to fill the heat buffer and slowly phase out the uses of the gas driven boiler (C. Boonstra, personal communication, 2020). Although this scenario is marked as unfeasible because it cannot meet the demand when following the rule of thumb, in practice, the share of natural gas used for space heating can be bigger at the beginning and slowly decrease while other sustainable options present themselves (C. Boonstra, personal communication, 2020).

9.2 Sustainability

Sustainability	Unit	*Electricity*	Gas
kWh/year		1	
m3/ year			1
COP		3.5	
Emission factor NEN7210	kg CO_2/kWh (m3)	0.5649	1.884
Emission factor NTA8800	kg CO_2/kWh	0.34	
CO_2 emission NEN7210	kg CO_2/kWh	0.5649	1.884
Current CO_2 emission	kg CO_2/kWh	0.34	
New CO_2 emission	kg CO_2/kWh	0.1614	

Table 30. *Emission factor of electricity and gas.*

Table 30 shows the emission factors of different heat sources used. To calculate how sustainable each scenario is, current CO_2 emissions are subtracted from the CO_2 emission predicted at the future scenario.

The CO_2 emission of Felix Meritis under current heat supply circumstances was calculated by multiplying the energy demand times the emission factor of gas. 1 GJ is equal to 31.6 m³. Converting 342.500 GJ heat to gas gives an annual demand of 10.8 million m3 gas which when used for space heating emits 20.4 million kg CO_2/year.

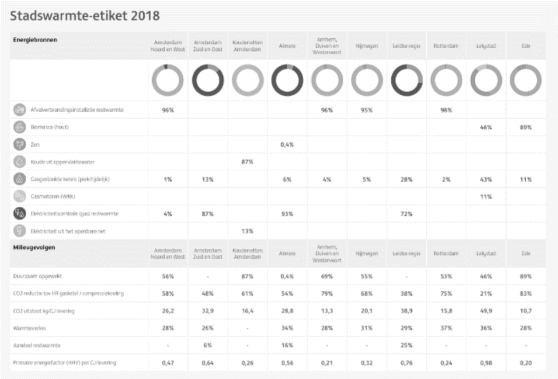
Starting off with the aqua thermal scenario, 77.964 GJ/year is equal to 8.7 million kWh electricity needed to run the central heat pump. The emission factor of electricity was 0.5649 kg CO_2/kWh. However, the future electricity mix is assumed to include more sustainable sources. Therefore, the new heat law (Wiebes, 2019), sets this emission factor at 0,34 kg CO_2/kWh. This research uses this emission factor to calculate CO_2 emission of electricity. When implementing aqua thermal energy in the neighbourhood, a CO_2 emission of 3 million kg/year (Appendix 8). This means that a reduction of 17.4 million kg CO_2/year is possible when implementing heat energy from surface water in the historic centre of Amsterdam.

Comparing the CO_2 emission of the aqua thermal scenario with the HT-district heating scenario is a complex matter as the heat source in this scenario is covering a much larger area, automatically leading to a higher CO_2 emission. To be able to make a comparison, the CO_2 emission per GJ from WPW is established. This allows for a CO_2 emission calculation based on the heat demand of Felix Meritis rather than on the entire system.

Under the latest climate treaty, the emission factor of biomass to calculate CO_2 emission is set at 0. Although, companies that generate heat via biomass are obliged to report the emission of biomass and their corresponding emission factors in their yearly report, they may use a CO_2 emission factor of 0 when calculation the annual emission of CO_2 (Zijlema, 2019). The value of this emission factor is questioned by researchers as they state that the reasoning behind this emission factor is invalid. Politics state that a factor of 0 may be used because newly planted trees can take up the CO_2 emission that is released when burning biomass (Zijlema, 2019). Looking back at able 12, this means that for 5% of the energy supplied by AEB and for all the energy supplied by Orgawold, no emission factor is in place.

For the AVIs, other rules must be followed. The national government yearly states the percentage of electricity and heat generated by an AVIS, which are classified as sustainable. In 2019 this was 53% (H. Rödel, personal communication, April 4th, 2020). Over the rest 47% heat from the AVIs an emission factor of 0,0314 kg/MJ must be used which is set in the NEN7125.

Additionally, the emission of the heat generation during peaks, usage of back up kettles and CO_2 emission from electricity use of heat pumps must be considered. Eventually the CO_2 emission of the entire system is reported in the heat label shown in figure 28. The CO_2 emission of WPW lies at 26,2 kg/GJ heat delivery (H. Rödel, personal communication, April 4th, 2020).



Stadswarmte-etiket 2018

Energiebronnen	Amsterdam Noord en West	Amsterdam Zuid en Oost	Koudenetten Amsterdam	Almere	Arnhem, Duiven en Westervoort	Nijmegen	Leidse regio	Rotterdam	Lelystad	Ede
Afvalverbrandingsinstallatie restwarmte	96%				96%	95%		98%		
Biomassa (hout)									46%	89%
Zon				0,4%						
Koude uit oppervlaktewater			87%							
Gasgestookte ketels (piek/tijdelijk)	1%	13%		6%	4%	5%	28%	2%	43%	11%
Gasmotoren (WKK)									11%	
Elektriciteitscentrale (gas) restwarmte	4%	87%		93%			72%			
Elektriciteit uit het openbare net			13%							

Milieugevolgen	Amsterdam Noord en West	Amsterdam Zuid en Oost	Koudenetten Amsterdam	Almere	Arnhem, Duiven en Westervoort	Nijmegen	Leidse regio	Rotterdam	Lelystad	Ede
Duurzaam opgewekt	56%	-	87%	0,4%	69%	55%	-	53%	46%	89%
CO2-reductie tov HR gasketel / compressiekoeling	58%	48%	61%	54%	79%	68%	38%	75%	21%	83%
CO2 uitstoot kg/GJ levering	26,2	32,9	16,4	28,8	13,3	20,1	38,9	15,8	49,9	10,7
Warmteverlies	28%	26%	-	34%	28%	31%	29%	37%	36%	28%
Aandeel restwarmte	-	6%	-	16%	-	-	25%	-	-	-
Primaire energiefactor (HHV) per GJ levering	0,47	0,64	0,26	0,56	0,21	0,32	0,76	0,24	0,98	0,20

Figure 28. *District heating label WPW (Vattenfall,2018).*

If Felix Merits would be entirely connected to the HT heat network of WPW, no insulation measures must be taken. This means that the heat demand lies at 342.500 GJ/year which induces a CO_2 emission of 9 million kg annually when multiplying it with the CO_2 emissions per GJ of WPW. This means, for the HT-district heating scenario, a CO_2 emission reduction of 11.4 million kg/year is possible.

CO_2 emission reduction in the hybrid scenario is again depended on the rule of thumb mentioned before. Of the total heat demand, 53.915 GJ is covered by the TEO system. This gives a CO_2 emission of 2 million kg CO_2 from electricity. Furthermore, the remaining 20% of the heat demand (33.669 GJ), that is covered by conventional gas leads to a CO_2 emission of 1.98 million kg CO_2/year. Together this is 6.8kg CO_2/year. A CO_2 emission reduction of 16.4 million kg CO_2/year in Felix Meritis can be achieved when implementing the hybrid scenario.

9.3 Affordability

To make it economically feasible to implement a new heat source, the heat demand of a neighbourhood should be above 2000GJ/year (Kruijt et al., 2018). Even if Felix Meritis would be insulated up to label A, its total heat demand is estimated at 58.001GJ/year and thus well above this minimum. Furthermore, heat demand density should be over 600GJ/ha. The built surface of Felix Meritis is 9.3 ha. Assuming that for the aqua thermal scenario and the hybrid scenario, heat demand is 109.150 GJ/year, the neighbourhoods heat demand density would lie at 11.737/ha which is again well above the needed. For the HT-district heating scenario, no insulation is needed meaning the heat demand density would be 36.828/ha. Based on heat demand and heat demand density, all scenarios are affordable.

Considering investment cost of infrastructure and technical installations the following cost are shown in table 31 – 33 for each scenario. These numbers are not specifically based on the spatial area of Felix Meritis and might not be readily applicable.

Aquathermal energy	Unit	
Technical installations		
Collective heat pump	€	8000-15000
ATES station	€/KW	530
TEO installation	€/KW	175
ETS system	€/KW	220
Infrastructure		
Decoupling from gas network	€	722.72
electricity cables	€/m	55
distribution network	€/m	1288

Table 31. *Gross overview of investment cost in infrastructure and technical installations essential to implement aqua thermal heat energy (S. Mol, personal communication, 2020) (Klip, 2017).*

HT-distribution network	Unit	
Technical installations		
Large collective heat pump	€/MW	125000
Transmission station	€/KW	55000
Ifrastructure		
Decoupling from gas network	€	722.72
Primairy network	€/m	1700
Distribution network	€/m	950

Table 32. *Gross overview of investment cost in infrastructure and technical installations essential to implement an HT- district heat network with heat supplied from WPW (S. Mol, personal communication, 2020) (Klip, 2017).*

Hybrid	Unit	
Technical installations		
hybrid heat pump	€	5000
ATES station	€/KW	530
TEO installation	€/KW	175
ETS system	€/KW	220
Infrastructure		
electricity cables	€/m	55
distribution network	€/m	1288

Table 33. *Gross overview of investment cost in infrastructure and technical installations essential to implement A hybrid heat solution (S. Mol, personal communication, 2020) (Klip, 2017).*

For the aqua thermal scenario, the investment cost to reinforce the electricity net are most likely highest. For the hybrid scenario, these costs are considered but are not essential, as potential congestion at the electricity net can be covered by natural gas (Klip, 2017). For the HT- district heating, no reinforcement of the electricity net in the neighbourhood is considered as the temperature of heat is high enough and small-scale collective heat pumps are neglected.

For the HT-district heating, especially the cost of the transmission station and the cost of the large collective heat pump are 125.000 and 55.000, respectively. However, the large collective heat pump covers a spatial area larger than neighbourhood level meaning cost can be spread over a larger spatial area. The smaller heat pump is 55.000 of which some are already in place. Additional cost for this scenario are the cost to decouple homes from gas and the cost of the primary network that runs from the source (WPW) down to the historic centre. Especially implementing a primary network drives up the cost of this scenario. For the aqua thermal scenario, the heat source is locally available in the neighbourhood. This means that only a small distribution network is needed. For the hybrid network the same accounts including the use of the existing gas network (Klip, 2017).

For the hybrid scenario, investment cost of infrastructure and technical installations are similar except the cost of the hybrid pump are slightly lower (Klip, 2017). Furthermore, complementing the heat demand with natural gas allows for a more natural replacement of technical installations and infrastructure when they are due for replacement. Moreover, when renovation of other underground infrastructure is already planned, this task can be performed in combination avoiding having to open up the street twice. The cost of doing so are calculated around 2000 €/m and therefore wisely to save (S. Mol, personal communication).

Lastly, considering investment cost for insulation in the aqua thermal scenario, it is important to set the average heat loss surface area, based on which prices of insulation can be estimated. This can be found in Appendix 7. Based on these average heat loss surface areas and knowing that a minimum insulation to level B is essential, insulation cost could be calculated. A list of the cost can be found in Appendix 9. To insulate homes to label B and to implement the right inhouse installations, cost for homeowners for the aqua thermal scenario add up to €53.625.

Because the HT-district scenario describes a HT heat source, no insulation measures must be taken. However, to receive heat from district heating, some inhouse technical need to be in place. The total inhouse investment cost in this scenario add up to €10.050.

As discussed above, heat demand and heat demand density are sufficient to guarantee affordability of the hybrid scenario. Furthermore, similar insulation levels as in the aqua thermal scenario are demanded. However, natural gas can fulfil the peak demands. Therefore, the cost of induction cooking and low temperature radiators are not included. The total inhouse investment cost of the hybrid scenario is estimated at €49.325.

NB: As mentioned in chapter 6, cost for infrastructure are not considered. However, for the hybrid scenario, the existing capacity of natural gas system is used. Furthermore, locally generated heat energy must be transported on neighbourhood level, requiring a collective heat pump and a small heat network, taking a way the necessity to invest in a large-scale district heat network in the historic centre. Although no exact costs are calculated, comparing implementation cost a new HT- heat district network from a source outside the city centre into Felix Meritis, versus the cost of a collective heat pump, a local small-scale heat network and the existing gas infrastructure, affordability is most likely much more positive for the hybrid and LT-network (C. Boonstra, personal communication, 2020).

9.4 Key findings

Scenario's	Reliability GJ/year	Heat demand GJ/year	Heat demand density GJ/ha	Infrastructure & Technical cost	Inhouse investment [€]	Sustainability ΔMCO2 [kgCO2]
Aqua thermic scenario	-60.695	109.150	11.737	12.99	53.625	17.4
Ht- disctric heating	1.3	342.500	36.828	58.372	10.050	11.4
Hybrid scenario	-37.515	109.150	11.373	7.265	49.325	16.4

Table 34. *Comparing the criteria for each proposed heat scenario in the historic centre of Amsterdam. The reliability column indicates the shortage of heat generation by the given source. For the aqua thermal scenario this is a shortage of 60.695 GJ/year, for the hybrid scenario this shortage lies at 37.515 GJ/year. The HT-district heating by WPW currently generates 1.3 million GJ/year. For the infrastructure and technical cost, the sum of all cost is taken. When the price was given in €/kW or €/m the cost of 1 kW or 1 metre is considered.*

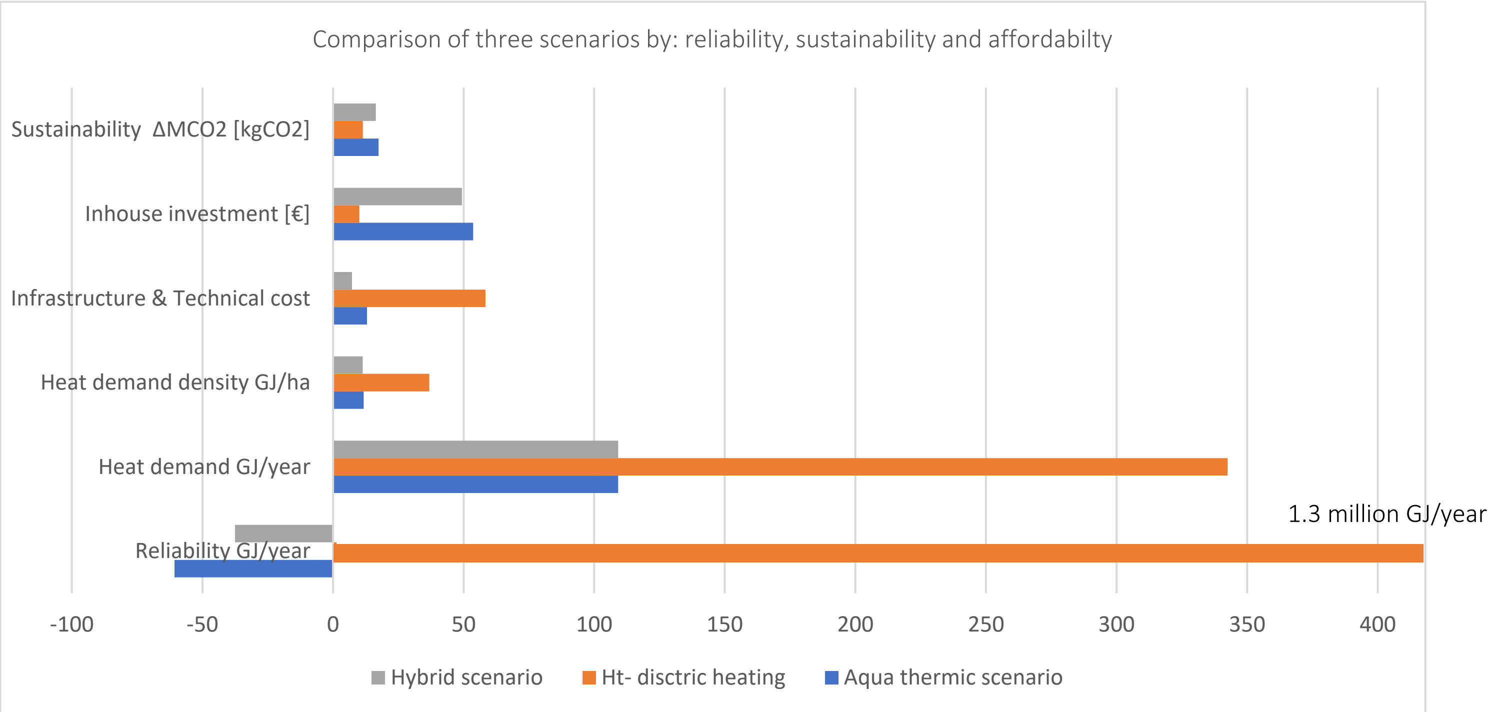


Figure 29. *Chart comparison of the three scenarios by criteria to assess if the scenario can supply enough heat, how sustainable they are and what the cost are for each scenario.*

Figure 29 and table 34 show how the scenarios perform compared to each other. This gave the following key-findings:

1) Even after taking insulation measures, both the aqua thermal scenario and the hybrid scenario prove to be unreliable to supply sufficient heat for Felix Meritis.

2) If the share of natural gas in the Hybrid scenario may be increased, this scenario can be a reliable scenario.

3) Looking at table 29, in theory, WPW can supply enough heat to Felix Meritis.

4) From table 30 and figure 28, and calculations in Appendix 8, HT-district network is least sustainable as CO_2 reduction is lowest. The most sustainable option is the aqua thermal scenario. When expanding a given heat source to the entire city centre, CO_2 emission reduction is of even more impact.

5) Heat demand and heat demand density in Felix Meritis is enough to make implementation of all scenario's cost efficient.

6) Implementing an HT-heat networks drives up cost due to distance of the lines that run from the source to Felix Meritis (table 31). Neighbourhoods that lie closer to the source might have a cheaper investment cost in infrastructure.

7) Aqua thermal energy is the most sensitive for a large investment in the electricity grid (table 30). Depending on the neighbourhood, finding place for an extra ETS station might be difficult.

8) For the hybrid scenario, less investment in the electricity grid is needed because congestion from high demand of heat pumps can be prevented by using natural gas.

9) The hybrid scenario allows for a more natural replacement of infrastructure. For example, when renovation measures of other infrastructure are planned or when renovation is necessary. This allows for the municipality to pick any neighbourhood in the historic centre that is due for renovation.

10) Appendix 9 shows that implementing an HT-district heating network, demands a significantly lower insulation investment cost for homeowners and is therefore most affordable for this group. The other two scenario demand a much higher similar investment because improvement of insulation is essential. If there is any neighbourhood in the historic centre where insulation measures are farfetched, LT scenarios are cheaper for homeowners.

We can now answer the final sub question: *''What future heat scenario is most optimal to meet the reliability, sustainability, and affordability criteria?*

Assuming that the most important aspect is the supply of enough heat to meet the demand for space heating, the only option under the set measures is the HT-district heating in Felix Meritis. However, when looking at the chart in figure, 19, the aqua thermal scenario scores best on CO_2 emission reduction. This is important for the municipality to reach their CO_2 emission reduction goals, furthermore, implementation of a hybrid scenario seems to be cheapest in terms of investment in infrastructure as a more natural transition is possible. On the other hand, for homeowners, the HT-district heating network is cheaper. The future heat scenario is therefore dependent on the pecking order of the criteria and no optimal technology that scores highest on all criteria exists.

In this chapter, the three scenarios are compared using heat demand estimations for Felix Meritis. However, the aim of this research is to upscale the most optimal technology to the entire historic centre. Because Felix Meritis is representative for other neighbourhoods in the historic centre, it is assumed that findings for this neighbourhood can be extrapolated to the rest of the historic centre. Looking at the key findings it becomes clear that estimating heat for each neighbourhood and looking into renovation measures separately, gives a better understanding of local solutions. For example, when a neighbourhood's demand is lower than that of Felix Meritis, the hybrid scenario might be reliable. Thereby, when a neighbourhood is due to renovation, this could be the perfect combination to implement a new district network. Although the bottom-up approach can be used to extrapolate findings between buildings, it is better to not extrapolate findings between neighbourhoods but make heat demand estimations separately using the bottom up approach and adjust solutions accordingly.

9.5 Discussion

Because the weight of the three criteria, reliability, sustainability, and affordability in relation to each other is not considered, it is difficult to establish the optimal scenario for Felix Meritis, let alone for the entire city centre. Further research could focus on investigation which criteria is most important for the municipality. When taking this approach on neighbourhood level, future heat scenario's might score different in different neighbourhoods depending on specific spatial criteria and their weight in that spatial area. Taking this approach really pins down the essence of the bottom up approach by implementing local tailored heat solutions.

10. CONCLUSIONS

This chapter concludes the research by summarising the answers to the sub questions, adding up to answering the main question. The main aim of this research is: **Contribute to the implementation of a reliable, sustainable and affordable heat supply in the historic centre of Amsterdam, by using a spatial temporal heat demand model, in order to asses future heat scenario's and foster the heat transition in the entire historic centre of Amsterdam**.

To reach this aim, the main research question is: *How can the municipality of Amsterdam implement the most optimal technology mix for space heating of the built environment in the historic centre of Amsterdam, to guarantee a sustainable, reliable, and affordable heat supply?*

First, four sub questions are answered.

10.1 Sub Question 1

''What is the yearly heat demand for space heating of different building categories in Felix Meritis?''

In the applied detailed spatial temporal heat demand model, the building stock in Felix Meritis was subdivided based on construction year, building function and heat loss surface area. Detailed key-numbers such as insulation values, heating technologies, infiltration values and ventilation measures led to constructing a detailed local heat demand which is often missed by more national or regional crude models. Comparing heat estimations in this research to national research showed that heat demand of residencies is estimated 135% higher with Energeyes. Heat demand for utilities is estimated 62% higher in Felix Meritis. The total neighbourhood specific heat demand of Felix Meritis is estimated at 343000 GJ/year. The total heat demand of residential buildings in the neighbourhood is 51000 GJ/year and of utilities is 292000 GJ/year. Additional to these numbers, sub question two takes the different peak demands of each function into account.

10.2 Sub Question 2

''How do peak demands fluctuate for different building categories in Felix Meritis and how do insulation values help flattening the peak demands and supply needed?''

Usually measurement can be used to identify monthly and daily heat demand variations. Because this data is not openly accessible, estimated seasonal peaks in heat demand are based on research for the Netherland. In Felix Meritis these peaks are estimated in January and November and December despite different insulation levels. Heat generation in these months should either be higher compared to warm months, or storage capacity must be sufficient to cover a potential shortage in heat generation during these months. When no insulation measures are in place, heat capacity must be able to cover for a monthly demand of 47000 GJ/January, 36500GJ/November and 40700 GJ/December. When the neighbourhood is insulated up to level B, heat sources must be able to cover the peak demand of 15000 GJ/January, 11600 GJ/November and 13000 GJ/December, which is a decrease of 68%. For label A, this is 7900 GJ/January, 6185GJ/November and 6900 GJ/December which is equal to a decrease of 83%. However, insulation up to level A for old canal homes is seen as economically infeasible and is therefore not further considered.

In addition to the annual demand curves, hourly demand curves for each function except for residencies show a peak heat demand in the morning between 5:00 – 9:00 AM. This can be attributed to the fact that, after being turned off during night, a large heat influx via radiators must bring a space back to a comfortable temperature. Adding the morning peaks of all function together shows that future heat supply in Felix Meritis must be able to cover a morning peak of 418 GJ between 5:00 – 9:00 in January.

Besides a similar peak in heat demand during morning hours, functions have different demand curves throughout the day. For Felix Meritis, peak demands can be grouped in three categories: high morning and evening peak which include, offices and shops. Constant demand, which include residencies and medical building functions and the fluctuating peaks which include buildings with a service function, a social function and hotels and motels. Having different heat demand peaks, leads to the conclusion that heat supply must be flexible, to be able to cover for different peaks throughout the day. For each neighbourhood in the historic centre it is possible to visualise peak demands of buildings within that neighbourhood. This is essential because the hight and time of these peaks determine the needed capacity of the future heat source and storage opportunities in a specific neighbourhood.

10.3 Sub Question 3

''What does the municipality mean by a reliable, sustainable, and affordable heat supply?''

With a reliable heat supply, the municipality means that the proposed heat source can guarantee sufficient heat to meet the demand of the neighbourhood. Furthermore, storage must accommodate monthly and hourly peaks that cannot be supplied by the base load. It is expected that this is most likely to happen in an MT or LT heat network where several heat sources are connected which complement each other in times of peak demand.

A sustainable heat supply is interpreted by the municipality as a non-natural gas driven heat supply that can guarantee a low CO_2 footprint and that can reduce CO_2 emission from space heating with 95% as opposed to 1990.

For an affordable heat network different groups in the heat context should be considered. For consumers, an affordable heat supply, means that their heat bill is lower or the same as their current expenses on heat. For investors and network suppliers in the Netherlands, an affordable collective heat supply with alternative heat sources means that heat demand needs to be at least 2000 GJ/year for the covered area and heat demand density needs to be a minimum of 600 GJ/ha. Furthermore, the strive is to keep investment cost in new infrastructure and technical adaptations in the public space as low as possible. For homeowners, a heat network is more affordable when the insulation cost and inhouse adaptation costs are kept low.

10.4 Sub Question 4

''What future heat scenario is most optimal to meet the reliability, sustainability, and affordability criteria?

Three optional scenarios are assessed for Felix Meritis. Because this is a representative neighbourhood, this research claims that findings can be extrapolated to the rest of the historic centre. A selection of three scenarios that are discussed in this thesis is based on future heat scenarios as proposed in Amsterdam's heat transition vision (Geldhof et al., 2020). Scenario I: the aqua thermal scenario proposes a situation where space heating is provided with energy from surface water. Scenario II: the HT-district heating scenario proposes heat supply at high temperature via a district heat system. The heat source in this scenario is WPW. The final scenario offers a hybrid solution where 80% of the heat demand is supplied with energy from surface water and 20% is supplied with conventional gas. Each scenario was scored based on the three criteria. Based on the analysis, a conclusion can be drawn that supplying the historic centre with heat via an HT-district network is the only scenario that can guarantee sufficient heat. Furthermore, it is most affordable for homeowners. However, this scenario is the least sustainable in terms of CO_2 reduction. Current CO_2 emission lies at 20.4 million kg/year. Where scenario I realises a CO_2 reduction of 17.4 million kg CO_2/year which is equal to 85% less CO_2 emission and scenario III realises a reduction of 16.4 million kg CO_2/year equal to 80% CO_2 emission reduction, this scenario reduces CO_2 emission with 11.4 kg CO_2/year which is only a reduction of 50%. Scenario I come closest to reaching the CO_2 emission reduction goals of 95% in 2050. Furthermore, in scenario II a question mark must be placed by the number that is used to calculate CO_2 emissions. Currently, emission from burning biogas may be set at 0 which is questions by researchers that state that the net CO_2 emission is much higher and an emission factor of 0 is misleading.

10.5 Main research question

''How can the municipality of Amsterdam implement the most optimal technology mix for space heating of the built environment in the historic centre of Amsterdam, to guarantee a sustainable, reliable, and affordable heat supply?''

It can be concluded that a sustainable, reliable, and affordable heat supply can be implemented by using a locally applicable energy system model: the bottom-up building based approach. Where national and regional models usually miss the details for local energy demand, this model allows to implement buildings specific details such as insulation values and heat loss surface areas but retains the potential to extrapolate findings to a larger building stock. Furthermore, different functions can be considered which allows to model different temporal peak demands.

Gathering demand data via this method gives insight in the minimum heat generation that needs to be in place and the additional needed storage capacity that can meet peak demand. In conclusion, the bottom-up building based approach allows policy makers to make a complicated energy transition in the historic centre manageable and take a step by step approach by modelling heat per neighbourhood. In addition, it provides the opportunity to thoroughly assess several options for the historic centre that are locally tailored to the spatial implication. An example of such is given chapter 7 of this research. In this research it was opted to investigate one pilot neighbourhood and use this to give insight to the rest of the city centre. However, the bottom-up approach is even better used when heat demand for all neighbourhoods is separately estimated and local solutions are applied on site.

Finally, having done this research gives insight to other cities facing similar challenges. By explaining how the bottom-up approach can be used to incentivise a heat transition for an existing building stock on neighbourhood scale, other cities can apply this method and overcome similar issues. The outcome of the transition is most likely different for each city and even neighbourhood because varying spatial temporal characteristics influence heat demand and thus needed heat generation.

11. RECOMMENDATIONS

11.1 Recommendations for further research

This research starts off by describing existing technological solutions for space heating. Optional is to connect a variety of different LT heat sources, with a low carbon footprint to one network to guarantee reliability and sustainability. Although this research investigated the opportunities of having a reliable, sustainable, and affordable heat network using three scenarios, no further research was done into such an open heat network with several sources. In this thesis, it was opted to research the potential of heat scenario's that are currently under discussion in the heat transition vision. However, to give a more complete insight in the reliable, sustainable, and affordable options for space heating the historic centre of Amsterdam, further research should be done into scenarios that go beyond what policy documents currently suggest. This means that not only the spatial and temporal indications of aqua thermal energy within the historic centre must be mapped, but also the opportunities of solar panels, geothermal energy, wind mills, residual heat from data centres and any other form of LT- heat source. Doing so would further underpin the essence of the bottom-up building based approach. This approach suggests using bottom up modelling to estimate heat and apply local solutions. By expanding the bottom up approach and estimating heat for other neighbourhoods using the same method, and thereby, investigation more LT heat sources, local tailored solution for each neighbourhood can be implemented.

In the spatial analysis, the difficulty to link more functions to one building is discussed. Because the main aim of this research is to generate a method that can be extrapolated to other neighbourhoods, it was opted to only visualise the main functions of each building and its corresponding heat demand. However, for a more detailed perspective of the heat demand of an area, mapping the division of functions within one building is interesting. For example, in Felix Meritis, most buildings have both a residential function as well as a utility function. This does not only influence the total demand, but also hourly the peak demands of that building. Future research could use a method that can map these different functions within buildings without losing the possibility to extrapolate findings to a larger scale. A proposition is to link the number of floors separately to building functions rather than linking the entire building to a function. This way, for each floor heat demand could be modelled. Doing so allows policy makers to gain an even better understanding of the heat sources and storage capacity that must be implemented on neighbourhood level to supply sufficient heat.

During the temporal modelling phase, missing data led to, assumptions being made especially concerning building characteristics. Examples of characteristics that contain well-founded estimations are: number of windows for each building, assignment of buildings that were given the value ''1005'' to category < 1920, and width of the facades which determines the volume of buildings. Doing so influences the final output of the energy demand model. Future research should focus on completing BAG data especially for older buildings in the historic centre of Amsterdam. Furthermore, input data should be refined and grouped in one data base so that performing a spatial analysis on neighbourhood level becomes easier. This allows policy makers to use the bottom-up building based approach to model heat demand and creates the opportunity to plan future heat supply, tailored to spatial implications of each neighbourhood.

When proposing scenarios of future heat supply, several options to measure affordability are presented. The selected measures included in this thesis are investment cost for homeowners, heat demand and heat demand density. Affordability for consumers is not measured since not all scenarios have a fixed business case, based on which consumer costs can be calculated. Furthermore, total cost of investment (TCO) is not included because important information about cost of infrastructure and pipelines require an extensive a study to the underground infrastructure of the historic centre. In the future, building complete business cases, must lead to a clear overview of consumer cost over variable scenarios. From personal communication, (M. Buijck, personal communication, 19th of August) (S. Mol, personal communication, 2020), we know that especially implementation of new infrastructure is extremely costly. This means that installing an HT-district network such as proposed in scenario II can turn out to be less positive than given now, due to its high costs, compared to installing local LT heat sources or a combination with current natural gas in the hybrid scenario.

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13. APPENDICES

13.1 Appendix 1: output table and calculation of heat loss surface areas

This appendix gives the output table of the spatial data of all buildings in Felix Meritis. Moreover, it describes which formulas are used to calculate the heat loss surface areas of the building envelope of buildings in Felix Meritis. These descriptions also include which assumptions are made and what the impacts are of these assumptions on estimated heat demand.

13.1.1 Number of floors

The height of the buildings in the BAG data is indicated under the column MAX. Data from the 3D Geo-information group was used to validate the correctness of the height of our buildings. Currently this data is no longer openly available. Making this comparison showed that the height generated in the used GIS file represents the height of a building from ridge to roof. Figure 30 shows different manners to interpret the height of a building. The column MAX in calculated from the AHN data, corresponds to percentile 99.

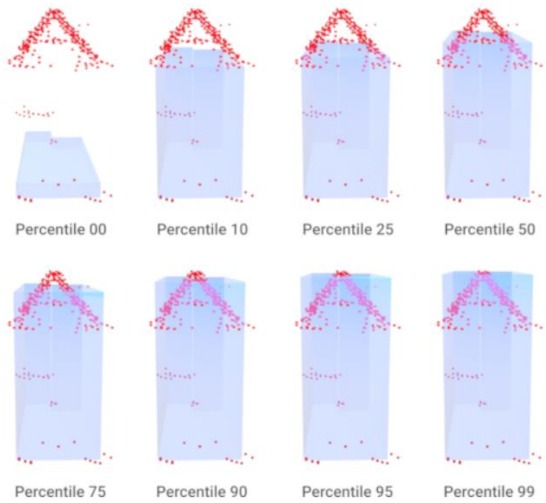

Figure 30. *Comparing the column MAX imported via BAG data with 3D Geo-information showed that the height of the buildings corresponds to the 99th percentile (Balázs, 2018).*

A rule of thumb in construction is that that the height of a floor lies around 3 meters (Ratti et al., 2005). Online research into canal homes in the historic center that are for sale confirmed the rule that most floors have a height between 2.5 and 3.5 meters (funda.nl). Therefore, it is decided to work with an average ceiling height of 3 meters. Setting this directive allows to establish the number of floors for each building. Initially, heat demand was calculated with a ceiling height of 4 meters. This influenced the demand the number of floors is dependent on the height of the ceiling and the total height of the building. Furthermore, the assumption is made that the number of floors is related to the number of residencies as shown in table 13. Because the total heat demand of a residential building is divided by the number of residencies to estimate heat demand of residential buildings, any assumption made on the height of a building influences heat demand. The higher a floor is estimated, the less residencies fit in a building, the higher the heat demand of one residency. Therefore, assuming that floor are 3 metres high reduces heat demand as opposed to floor of for example 4 metres.

The following formula is used to calculate the number of floors of each building:

$$Number\ of\ floors = MAX\ /\ 3$$

Note : all answers are rounded up. When an outcome would be 2,1 for example, the house has 3 floors.

13.1.2 Gross floor area
The gross floor area is the total surface areas of all the floors in a building. Shape_area is a given from the BAG data (table 2) and represents the ground floor of an individual building. Using the output of the previous calculation, calculating the total floor area can be done using the following formula:

$$Gross\ floor\ area = \ Shape\_Area\ x\ Numbers\ of\ floors$$

Again, the height of a ceiling influences the gross floor area and increases heat demand. The lower the ceilings, the more floors there are in one building, the larger the gross floor area. After using Energeyes, it showed that the larger the gross floor area of a building, the larger the heat demand.

13.1.3 Roof surface area.
The angle of each individual roof of buildings in the historic centre and in our pilot area, are unknow. Figure 31 shows reoccurring slope angels when looking at various parties that are interested in calculating the roof surface(houses.be). For this research it is decided to take the average of the given angles (45°) because some buildings have a very steep roofs whereas other roofs in the historic centre have a small angle or even a flat roof (own observation). When the actual slope of the roof is known, this can be added to the calculation and the roof area can be calculated in more detail which increases accuracy of the heat demand estimation.

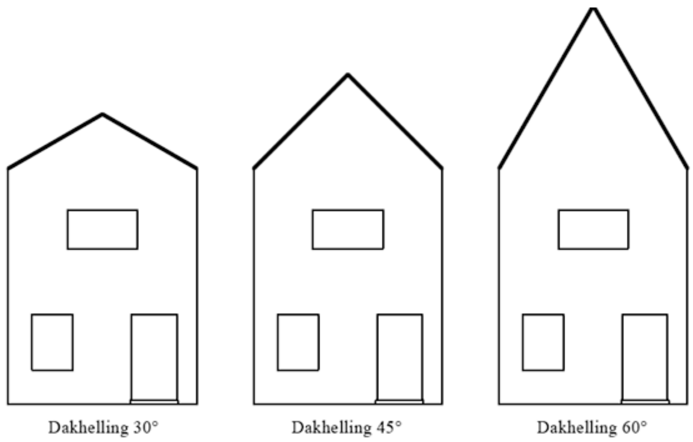

Figure 31. *Three different roof slopes. This research decided to take a slope of 45 degrees to calculate the roof surface area.*

Knowing the degree of the slope, we can calculate the roof area using the following formula

$$Surface\ Roof\ [m2] = Shape\_Area\ /\ cos(45°)$$

13.1.4 Window surface area
The exact glass surface areas of the buildings in Felix Meritis or in the historic centre in general are not know for each building. However, including glass surface area is extremely important when wanting to model heat demand for a building. Therefor the assumption was made that on average, a window in a canal house has a surface area of 1 x 2 m. For each window, a surface area of 2m2 was used to calculate the total glass area. For the ground floor, the assumption was made that besides the door, two windows are placed. On the floors above, there are three windows. Because it differs per building if the attic has a window, this was not considered. When a building has three floors, this means that only two floors of windows are considered. Finally, to calculate the total window surface area of a building, the average number of floors of a building within a specific group was used. The image below shows how the window surface area per building was estimated.

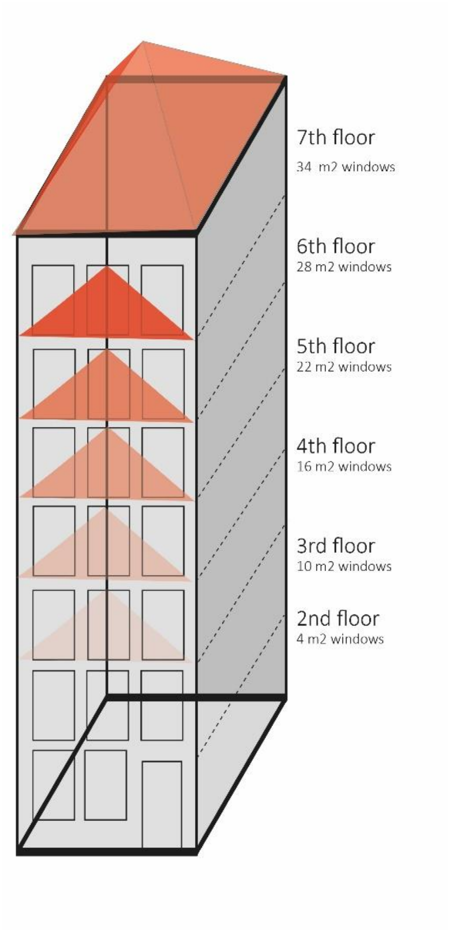

Figure 32. *The window surface area of the frond façade of a building. For a building with three floors the first and second floor are calculated with windows and the 3rd floor is the roof with no windows.*

Figure 32 shows that a building with 5 floors, has a glass surface area of 44 m² (22 m2 on both sides) the fifth floor is considered as being the attic, which does not have windows.

The assumptions made on the height of the building influences the number of windows that a building has. Furthermore, the assumption that all windows are 2m² influences heat demand. Modelling with Energeyes, shows that the larger the window surface area of a building, the higher the heat demand. This impact of window surface area is largest for buildings constructed in earlier years (<1920-1974). For buildings constructed after 1974, with better window quality (double glass or HR++), the impact of window surface area on heat demand is negligible.

13.1.5 Façade front & back

Although BAG data contains the shape area and the perimeter of each shape, no differentiation is made between the width and the length of the shapes. This makes it increasingly difficult to calculate the surface area of the façade. One option is to generate the x and y coordinates lie from 0. However, this is extremely time consuming and does not fit the nature of the methodology of this research. To overcome this issue, an easier but therefore less exact method was applied.

For each street in Felix Merits, the length of the street was measured using google maps. This length is divided by the number of buildings, which then gives an average width of the buildings in that street. The length of each street and the average width of the buildings placed in that street is visualised in figure 33.

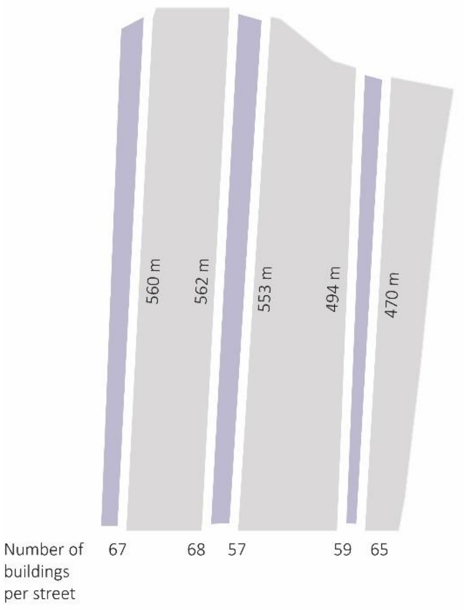

Figure 33. *Length of the streets in Felix Meritis and the number of buildings withing each street. Dividing the length of the street by the number of buildings gave us the average façade width of the buildings in Felix Meritis.*

Adding the average width of the building in each street and dividing this by the number of streets gave an average width of each building in Felix Merits of 8.1 metres. This number is used to calculate the façade area. Additionally, the window surface area had to be retracted rom the brick wall area ensures an over estimation of the façade heat loss surface area is calculated. This gave us the following formula:

$$Facade\ surface\ area = 8.1 * MAX \text{ - } window\ surface\ area$$

Estimating façade width influences accuracy of the model. By taking an average for all buildings we hope to minimize this error.

13.2 Appendix 2: insulation values for different construction years

Appendix 2 gives an insight in heat loss values corresponding to specific construction years. These numbers are imported in Energeyes and contribute to estimating heat demand more accurately based on a mix of old and new buildings in Felix Meritis.

Table 35. *Insulation values <1920*

>1919		Rc	U-value	d	λ - value
Floor surface					
Wood		0.05			
Insulation					
Air		0.17			
Total		**0.22**			
Colliding roof					
Rooftile		0.0115		0.015	1.3
Wood		0.05		0.01	0.2
Insulation					
Air		0.17			
Total		**0.23**			
Front/back facade					
Brickwork		0.19		0.15	0.8
Plaster		0.04		0.01	0.25
Cavity wall					
Insulation					
Air		0.17			
Total		**0.4**			
Windows					
Single glazing			5.2		0.8
Double glazing					
HR++ glazing					
Heating technology	local oil/gas	0.7			

Table 36. *Insulation values 1920 - 1944*

1920-1944		Rc	U-value	d	λ - value
Floor surface					
Wood		0.05			
Insulation					
Air		0.17			
Total		**0.22**			
Colliding roof					
Rooftile		0.0115		0.015	1.3
Wood		0.05		0.01	0.2
Insulation					
Air		0.17			
Total		**0.23**			
Front/back facade					
Brickwork		0.19		0.15	0.8
Plaster		0.04		0.01	0.25
Cavity wall		0.15			
Insulation					
Air		0.17			
Total		**0.55**			
Windows					
Single glazing			5.2		0.8
Double glazing					
HR++ glazing					
Heating technology	local oil/gas	0.7			

Table 37. *Insulation values 1945 – 1964*

1945-1964		Rc	U-value	d	λ - value
Floor surface					
Wood		0.05			
Insulation		0.1			
Air		0.17			
Total		**0.32**			
Colliding roof					
Rooftile		0.0115		0.015	1.3
Wood		0.05		0.01	0.2
Insulation		0.16			
Air		0.17			
Total		**0.39**			
Front/back facade					
Brickwork		0.19		0.15	0.8
Plaster		0.04		0.01	0.25
Cavity wall		0.15			
Insulation		0.36			
Air		0.17			
Total		**0.91**			
Windows					
Single glazing			5.2		0.8
Double glazing					
HR++ glazing					
Heating technology	CR-boiler	0.75			

Table 38. *Insulation values 1965 - 1974*

1965 - 1974		Rc	U-value	d	λ - value
Floor surface					
Wood		0.05			
Insulation					
Air		0.17			
Total		**0.22**			
Colliding roof					
Rooftile		0.0115		0.015	1.3
Wood		0.05		0.01	0.2
Insulation		0.63			
Air		0.17			
Total		**0.86**			
Front/back facade					
Brickwork		0.19		0.15	0.8
Plaster		0.04		0.01	0.25
Cavity wall		0.15			
Insulation		0.43			
Air		0.17			
Total		**0.98**			
Windows					
Single glazing			5.2		0.8
Double glazing					
HR++ glazing					
Heating technology	CR boiler	0			

1975 - 1989		Rc	U-value	d	λ - value
Floor surface					
Wood		0.05			
Insulation		1.08			
Air		0.17			
Total		**1.3**			
Colliding roof					
Rooftile		0.0115		0.015	1.3
Wood		0.05		0.01	0.2
Insulation		1.07			
Air		0.17			
Total		**1.30**			
Front/back facade					
Brickwork		0.19		0.15	0.8
Plaster		0.04		0.01	0.25
Cavity wall		0.15			
Insulation		1.3			
Air		0.17			
Total		**1.85**			
Windows					
Single glazing					
Double glazing			3.4		0.7
HR++ glazing					
Heating technology	VR- Kettle				

Table 39. *Insulation values 1975 – 1989.*

1990 - 2004		Rc	U-value	d	λ - value
Floor surface					
Wood		0.05			
Insulation		2.31			
Air		0.17			
Total		**2.53**			
Colliding roof					
Rooftile		0.0115		0.015	1.3
Wood		0.05		0.01	0.2
Insulation		2.3			
Air		0.17			
Total		**2.53**			
Front/back facade					
Brickwork		0.19		0.15	0.8
Plaster		0.04		0.01	0.25
Cavity wall		0.15			
Insulation		2.53			
Air		0.17			
Total		**3.08**			
Windows					
Single glazing					
Double glazing			3.4		0.7
HR++ glazing					
Heating technology	VR- Kettle				

Table 40. *Insulation values 1990 – 2004.*

2005 -2020		Rc	U-value	d	λ - value
Floor surface					
Wood		0.05			
Insulation		2.78			
Air		0.17			
Total		**3**			
Colliding roof					
Rooftile		0.0115		0.015	1.3
Wood		0.05		0.01	0.2
Insulation		4.25			
Air		0.17			
Total		**4.48**			
Front/back facade					
Brickwork		0.19		0.15	0.8
Plaster		0.04		0.01	0.25
Cavity wall		0.15			
Insulation		3.65			
Air		0.17			
Total		**4.2**			
Windows					
Single glazing					
Double glazing					
HR++ glazing			1.2		0.6
Heating technology	HR - 107				

Table 41. *Insulation values 2005-2020 (A*gentschap NL, 2011) (Archidat, n.d) (Archidat, 2010) & (RVO, 2012)

13.3 Appendix 3: heat loss surface areas

Below, a division of buildings with different functions and corresponding volume and heat loss surface areas is given. These heat loss surface areas are essential as input for Energeyes because the larger a heat loss surface area, the larger the heat demand. For each function, an average of the window surface area, the façade, the floor and the roof surface area is calculated and used in Energeyes.

13.3.1 Residencies

	HOUSING	338						
	Building volume	0-1500						
	Construction year	Average volume m3 building	Average volume house m3	Average floor area m2	Average window area m2	Average facade surface area m2	Average roof surface m2	count
	<1920	848	174	58	44	196	82	160
1920	1944	878	173	58	44	202	81	5
1945	1964	845	181	60	44	182	85	2
1965	1974							0
1975	1989	968	194	65	44	194	91	3
1990	2004							0
2005	2020	992	198	66	44	200	93	1
								171
						97		
		1501-5000						
	Construction year	Average volume m3 building m3	Average volume house m3 m3	Average floor area m2 m2	Average window area m2	Average facade surface area m2	Average roof surface m2	count count
	<1920	2620	443	148	56	234	208	114
1920	1944	2187	360	120	68	224	170	5
1945	1964	3334	476	159	68	272	225	1
1965	1974	1610	284	95	56	220	134	1
1975	1989	2789	457	152	56	240	215	7
1990	2004	2257	365	122	56	242	172	5
2005	2020	3649	608	202	56	236	287	1
								134
		>5000						
	Construction year	Average volume m3 building m3	Average volume house m3 m3	Average floor area m2 m2	Average window area m2	Average facade surface area m2	Average roof surface m2	count
	<1920	9315	1323	441	68	270	624	30
1920	1944	7768	1370	457	56	220	646	1
1945	1964	6509	1065	355	68	232	502	2
1965	1974							0
1975	1989							0
1990	2004							0
2005	2020							0
								33

Table 42. *Division of residential buildings per volume and their corresponding average heat loss surface areas.*

13.3.2 Utilities

UTILITIES SOCIAL **37**

	Construction year	Average volume m3 building	Average gross floor area m2	Average floor area m2	Window surface area	Average facade area	Average roof area	count
	<1920	6462	2275	296	56	212	418	31
1920	**1944**	3085	1106	144	56	224	203	4
1945	**1964**							
1965	**1974**							
1975	**1989**							
1990	**2004**							
2005	**2020**	2340	841	164	56	204	232	2
								37

UTILITIES OFFICES **51**

	Construction year	Average volume m3 building	Average gross floor area m2	Average floor area m2	Window surface area	Average facade area	Average roof area	count
	<1920	6980	2432	326	68	230	461	44
1920	**1944**	13504	4861	540	80	326	764	1
1945	**1964**	14510	5203	569	68	230	805	3
1965	**1974**							0
1975	**1989**	4302	1613	269	56	204	380	1
1990	**2004**	2216	749	111	68	240	157	2
2005	**2020**							0
								51

UTILITIES SHOP **91**

	Construction year	Average volume m3 building	Average gross floor area m2	Average floor area m2	Window surface area	Average facade area	Average roof area	count
	<1920	1498	534	89	56	198	125	74
1920	**1944**	1295	467.4	83	56	198	117	9
1945	**1964**	74818	25899	2878	80	342	4070	1
1965	**1974**	4405	1602	200	80	276	283	1
1975	**1989**	1481	550	110	44	178	156	3
1990	**2004**	941	353	59	56	204	83	1
2005	**2020**	919	322	60	56	196	84	2
								91

UTILITIES INDUSTRY **19**

	Construction year	Average volume m3 building	Average gross floor area m2	Average floor area m2	Window surface area	Average facade area	Average roof area	count
	<1920	2291	813	133	56	194	188	18
1920	**1944**	2880	960	160	56	236	226	1
1945	**1964**							
1965	**1974**							
1975	**1989**							
1990	**2004**							
2005	**2020**							
								19

	UTILITIES HOTEL/MOTEL	**5**						
	Construction year	**Average volume m3 building**	**Average gross floor area m2**	**Average floor area m2**	**Window surface area**	**Average facade area**	**Average roof area**	**count**
	<1920	8156	2933	403	68	234	570	5
1920	**1944**							
1945	**1964**							
1965	**1974**							
1975	**1989**							
1990	**2004**							
2005	**2020**							
								5

	UTILITIES SERVICES	**23**						
	Construction year	**Average volume m3 building**	**Average gross floor area m2**	**Average floor area m2**	**Window surface area**	**Average facade area**	**Average roof area**	**count**
	<1920	2702	952	142	56	214	202	22
1920	**1944**	1333	444	89	44	200	126	1
1945	**1964**							
1965	**1974**							
1975	**1989**							
1990	**2004**							
2005	**2020**							
								23

	UTILITIES MEDICAL	**1**						
	Construction year	**Average volume m3 building**	**Average gross floor area m2**	**Average floor area m2**	**Window surface area**	**Average facade area**	**Average roof area**	**count**
	<1920	2121	707	118	56	236	167	1
1920	**1944**							
1945	**1964**							
1965	**1974**							
1975	**1989**							
1990	**2004**							
2005	**2020**							
								1

Table 43. *Division of utility buildings and their corresponding average heat loss surface areas.*

13.4 Appendix 4: description of insulation values

The building envelope allows the user to insert all different heat loss surface areas and their corresponding Rc Values and U values of the specific construction materials. Below a short description of what these values mean is given.

13.4.1 The U-value

The U-value shows how much heat is lost per second per square meter when the temperature difference is 1 C° (W/m_2K). The U-value is determined by adding the thickness and the lambda value of each material of the construction. The lower the U-value, the better the insulation of the material thus the less heat is lost.

13.4.2 The Lambda-value λ (k-value)

The lambda value entails the thermal conductivity of a material. This is expressed in W/mK. The higher the value, the better heat is conducted, the lower the material insulates. However, a low lambada value can be compensated with the thickness of the material.

13.4.3 Rc-value

The Rc value explains the insulating capacity or the heat resistance of a material layer. It is mainly used to explain the capacity of double glazing, walls, floor and roofs of a building. The R-value is expressed in m_2K/W. The larger R, the better the material insulates. The following formula belongs to the rc-value.

13.4.4 R = d/λ

R= thermal resistance in m_2K/W
d = thickness of material in m
Λ = thermal conductivity of a material in W/m

13.4.5 ZTA Value

Additionally, to the window surface area, the ZTA of the glass stands for the transmission factor of solar radiations. The thicker the glass, the ZTA factor. The ZTA of single glazing lies around 0.8, for double glazing at 0.7 and for HR++ glas this is set at 0.6.

(Archidat, n.d.) (Archidat, 2010) (RVO, 2011) (Tronchin, 2019)

13.5 Appendix 5: heat demand categorized by construction year, surface area and building function

Below an overview of the heat demand per building function is given, as well as the total heat demand for buildings in that function. The total heat demand under current circumstances is shown in the middle column and the right columns show the heat demand of these buildings when insulated up to label A or label B. Furthermore, the most left columns show the estimated heat demand by another commonly used mode: Vestas Mais.

13.5.1 Heat demand residential buildings

WOONFUNCTIE									
Building volume	**0-1500 m3**								
Construction year	**Heat demand GJ/building/year Vestas Mais**	**Total heat demand GJ/year Vestas Mais**	**GJ/building/year**	**count**	**Total heat demand GJ/year**	**Insulated A**	**Demand 2040**	**Insulated B**	**Demand 2040**
<1920	66	10560	92.0	160	14720.0	7.5	1192.0	15.9	118.6
1944	66	330	103.9	5	519.5	15.5	77.3	23.3	359.6
1964	66	132	82.8	2	165.6	14.8	29.6	24.2	358.2
1974	57	0		0					
1989	32	96	41.6	3	124.7	16.2	48.7	26.1	423.1
2004	24	0		0					
2020	16	16	16.8	1	16.8	16.8	16.8	23.8	398.1
		11134			**15546.6**		**1364.3**		**1657.6**
Building volume	**1501 - 5000 m3**								
Construction year	**Heat demand GJ/building/year Vestas Mais**	**Total heat demand GJ/year Vestas Mais**	**GJ/building/year**	**count**	**Total heat demand GJ/year**	**Insulated A**	**Demand 2040**	**Insulated B**	**Demand 2040**
<1920	66	7524	171.4	114	19535.0	21.5	2448.7	34.9	3974.0
1944	66	330	140.2	5	701.2	22.1	110.7	34.4	171.9
1964	66	66	152.7	1	152.7	30.2	30.2	42.1	42.1
1974	57	57	86.9	1	86.9	19.86	19.9	28.9	28.9
1989	32	224	93.0	7	651.0	39.275	274.9	45.1	315.4
2004	24	120	38.2	5	191.1	25.14	125.7	38.2	191.1
2020	16	16	38.7	1	38.7	38.7	38.7	38.7	38.7
		8337			**21356.67**		**3048.8**		**4762.2**
Building volume	**> 5000 m3**								
Construction year	**Heat demand GJ/building/year Vestas Mais**	**Total heat demand GJ/year Vestas Mais**	**GJ/building/year**	**count**	**Total heat demand GJ/year**	**Insulated A**	**Demand 2040**	**Insulated B**	**Demand 2040**
<1920	66	1980	429.683333	30	12890.5	71.4	2141.0	101.3	3038.5
1944	66	66	481.76	1	481.76	83.66	83.7	116.2	116.2
1964	66	132	269.183333	2	538.3666667	62.66666667	125.3	88.2	176.4
1974	57			0					
1989	32			0					
2004	24			0					
2020	16			0					
		2178			**13910.62667**		**2350.0**		**3331.1**

Table 44. *The estimated heat demand of residencies per construction year using Energeyes and from Vesta Mais.*

13.5.2 Heat demand utility buildings

UTILITIES SOCIAL

	Construction year	Vestas Mais GJ/year/m2 bvo	Heat demand GJ/building/year Vestas Mais	Total heat demand GJ/year Vestas Mais	GJ/building /year	count	Total heat demand GJ/year	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	0.579	1317.225	40833.975	2026.8	31	62830.8	349.1	10822.1	494.9	15341.9
1920	**1944**	0.833	921.298	3685.192	1289.1	4	5156.4	200.5	802	289	1156
1945	**1964**	0.833									
1965	**1974**	0.833									
1975	**1989**	0.63									
1990	**2004**	0.639									
2005	**2020**	0.45	378.45	756.9	158.2	2	316.4	158.2	316.4	158.2	25027.24
				45276.067			**68303.6**		**11940.5**		**41525.14**

UTILITIES OFFICES

	Construction year	Vestas Mais GJ/year/m2 bvo	Heat demand GJ/building/year Vestas Mais	Total heat demand GJ/year Vestas Mais	GJ/building /year	count	Total heat demand GJ/year	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	1.013	2463.616	108399.104	2171.8	44	95559.2	382.5	16830	539.2	23724.8
1920	**1944**	0.796	4861	4861	4067.5	1	4067.5	805.8	805.8	1101	1101
1945	**1964**	0.796	5203	15609	3687.3	3	11061.9	845.5	2536.5	1147	3441
1965	**1974**	0.796									
1975	**1989**	0.406	1613	1613	666.6	1	666.6	282.4	282.4	397.7	397.7
1990	**2004**	0.373	749	1498	231.6	2	463.2	156.6	313.2	231.6	463.2
2005	**2020**	0.306									
			VM	**131980.104**			**111818.4**		**20767.9**		**29127.7**

UTILITIES SHOP

	Construction year	Vestas Mais GJ/year/m2 bvo	Heat demand GJ/building/year Vestas Mais	Total heat demand GJ/year Vestas Mais	GJ/building /year	count	Total heat demand GJ/year	Insulated A	demand 2040	Insulated B	demand 2040
											0
	<1920	0.511	272.874	20192.676	606.8	74	44903.2	82	6068	136	11152
1920	**1944**	0.405	189.297	1703.673	596.6	9	5369.4	138	1242	151.3	1361.7
1945	**1964**	0.405	10489.095	10489.095	17880.3	1	17880.3	4264.9	4264.9	5591.3	5591.3
1965	**1974**	0.405	648.81	648.81	1067.5	1	1067.5	284	284	405	405
1975	**1989**	0.208	114.4	343.2	269.6	3	808.8	113	339	175.3	525.9
1990	**2004**	0.197	69.541	69.541	133.2	1	133.2	85.4	85.4	133.2	133.2
2005	**2020**	0.154	49.588	99.176	82.4	2	164.8	82.4	164.8	82.4	164.8
				33546.171			**70327.2**		**12448.1**		**19333.9**

UTILITIES INDUSTRY

	Construction year	Vestas Mais GJ/year/m2 bvo	Heat demand GJ/building/year Vestas Mais	Total heat demand GJ/year Vestas Mais	GJ/building /year	count	Total heat demand GJ/year	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	0.429	348.777	6277.986	836.7	18	15060.6	123.2	2217.6	191.8	3452.4
1920	**1944**	0.334	320.64	320.64	1048.9	1	1048.9	193.2	193.2	274.7	274.7
1945	**1964**	0.334									
1965	**1974**	0.334									
1975	**1989**	0.173									
1990	**2004**	0.159									
2005	**2020**	0.131									
				6598.626			**16109.5**		**2410.8**		**3727.1**

	UTILITIES HOTEL/MOTEL										
	Construction year	**Vestas Mais GJ/year/m2 bvo**	**Heat demand GJ/building/year Vestas Mais**	**Total heat demand GJ/year Vestas Mais**	**GJ/building/year**	**count**	**Total heat demand GJ/year**	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	0.748	2193.884	2193.884	2766.2	1	2766.2	427.4	427.4	625.8	625.8
1920	**1944**	0.602									
1945	**1964**	0.602									
1965	**1974**	0.602									
1975	**1989**	0.334									
1990	**2004**	0.312									
2005	**2020**	0.268									
				2193.884			**2766.2**		**427.4**		**625.8**

	UTILITIES SERVICES										
	Construction year	**Vestas Mais GJ/year/m2 bvo**	**Heat demand GJ/building/year Vestas Mais**	**Total heat demand GJ/year Vestas Mais**	**GJ/building/year**	**count**	**Total heat demand GJ/year**	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	0.235	223.72	4921.84	955.1	22	21012.2	137.3	3020.6	214.4	4716.8
1920	**1944**	0.171	75.924	75.924	620	1	620	101.3	101.3	152.7	152.7
1945	**1964**	0.171									
1965	**1974**	0.171									
1975	**1989**	0.092									
1990	**2004**	0.089									
2005	**2020**	0.071									
				4997.764			**21632.2**		**3121.9**		**4869.5**

	UTILITIES MEDICAL										
	Construction year	**Vestas Mais GJ/year/m2 bvo**	**Heat demand GJ/building/year Vestas Mais**	**Total heat demand GJ/year Vestas Mais**	**GJ/building/year**	**count**	**Total heat demand GJ/year**	Insulated A	demand 2040	Insulated B	demand 2040
	<1920	1.153	815.171	815.171	812.7	1	812.7	121.9	121.9	193.6	193.6
1920	**1944**	0.845									
1945	**1964**	0.845									
1965	**1974**	0.845									
1975	**1989**	0.476									
1990	**2004**	0.468									
2005	**2020**	0.39									
				815.171			**812.7**		**121.9**		**193.6**

Total heat demand Utilities GJ/year Vestas Mais	Total heat demand Utilities Energeyes	Total heat demand Utilities label A	Total heat demand Utilities label B
180131.72	**291769.8**	**51238.5**	**99402.74**

Table 45. *The estimated heat demand of utility buildings per construction year using Energeyes and from Vesta Mais.*

13.6 Appendix 6: monthly temporal heat demand Felix Meritis

Using data of Nina Voulis allowed us to calculate the heat demand factor for each month. Using this, graph 1 was produced that show total heat demand fluctuation for each month in Felix Meritis. Furthermore, this data was used to calculate the factor by which the hourly demand of each building function in Felix Meritis is multiplied. these are given in table 46.

13.6.1 Estimated monthly total heat demand in Felix Meritis

Month	Total	Electricity plants & large companies	Small end users	factor	%		Heat demand Felix Meritis	Residential	Utilities	Total	Insulation A	Insulation B
	mln/m3						GJ/year	50813.87167	291769.8	342584		
							GJ/year (A)	6763.1	51238.5	58001.6		
							GJ/year (B)	9750.8	99402.74	109154		
Jan	5315	957	4358	0.136	13.6		Jan			46680.4	7903.291524	14873.24914
Feb	4163	887	3276	0.102	10.2		Feb			35090.6	5941.069993	11180.53332
March	4160	829	3331	0.104	10.4		March			35679.8	6040.813232	11368.24068
April	3050	660	2390	0.075	7.5		April			25600.3	4334.297095	8156.738286
May	3062	884	2178	0.068	6.8		May			23329.5	3949.832248	7433.21171
June	2394	779	1615	0.050	5.0		June			17299	2928.824188	5511.77085
July	2517	910	1607	0.050	5.0		July			17213.3	2914.31608	5484.46796
August	2556	919	1637	0.051	5.1		August			17534.6	2968.721483	5586.853797
Sept	2785	947	1838	0.057	5.7		Sept			19687.6	3333.237683	6272.838899
October	3578	1038	2540	0.079	7.9		October			27207	4606.32411	8668.667467
Nov	4355	944	3411	0.107	10.7		Nov			36536.7	6185.894306	11641.26958
Dec	4567	765	3802	0.119	11.9		Dec			40724.9	6894.978057	12975.69831
Total	**42502**		**31983**		**100.0**					**342584**	**58001.6**	**109153.54**

Table 46. *The average heat demand factor per month, calculated with the data of (Voulis, 2019). The right columns show the heat demand in Felix Meritis per month under the current insulation values, when insulated to label A and when insulated to label B.*

13.6.2 Hourly temporal heat demand factor for different building functions in Felix Meritis

Hours	J/h	Average demand/h	Factor
h1	3770997936	121645094.7	0.04611
h2	3960910501	127771306.5	0.048432
h3	4103710378	132377754.1	0.050178
h4	4199209926	135458384.7	0.051346
h5	4183176769	134941186.1	0.05115
h6	3971384257	128109169.6	0.04856
h7	3591579401	115857400	0.043916
h8	3521362920	113592352.3	0.043057
h9	4024394349	129819172.6	0.049208
h10	4055642021	130827162	0.04959
h11	3786942005	122159419.5	0.046305
h12	3579067141	115453778.7	0.043763
h13	3459980406	111612271.1	0.042307
h14	3375992549	108902985.5	0.04128
h15	3349793698	108057861.2	0.04096
h16	3313243918	106878836.1	0.040513
h17	3153482852	101725253.3	0.038559
h18	2686073670	86647537.73	0.032844
h19	2325529483	75017080.11	0.028435
h20	2341596698	75535377.34	0.028632
h21	2370851077	76479067.01	0.02899
h22	2467123752	79584637.17	0.030167
h23	2864558428	92405110.57	0.035026
h24	3326387591	107302825.5	0.040673
Total		2638161023	1

Table 47. *Hourly heat demand of residencies*

Hours	J/h	Average demand/h	Factor
h1	7403009912	238806771.3	0.06264
h2	0	0	0
h3	0	0	0
h4	0	0	0
h5	0	0	0
h6	7710916482	248739241.4	0.065245
h7	7234246711	233362797.1	0.061212
h8	6201965559	200063405.1	0.052477
h9	6095686859	196635060	0.051578
h10	6305561402	203405206.5	0.053354
h11	6318002577	203806534.7	0.053459
h12	5465433694	176304312.7	0.046245
h13	4711356122	151979229.7	0.039864
h14	4883877364	157544431.1	0.041324
h15	5442403968	175561418.3	0.04605
h16	5915190500	190812596.8	0.050051
h17	5840636895	188407641.8	0.04942
h18	5526575600	178276632.3	0.046762
h19	4897165841	157973091.6	0.041437
h20	5000767830	161315091.3	0.042313
h21	5009003761	161580766.5	0.042383
h22	5667177535	182812178.6	0.047952
h23	6091694572	196506276.5	0.051544
h24	6463646360	208504721.3	0.054691
Total		3812397405	1

Table 48. *Hourly heat demand of buildings with a social function*

Hours	J/h	Average demand/h	Factor
h1	8569643.847	276440.1241	0.000756
h2	10684085.93	344647.9332	0.000943
h3	12306573.86	396986.2536	0.001086
h4	14046403.39	453109.7869	0.00124
h5	13832372.44	446205.5626	0.001221
h6	14752512.78	475887.509	0.001302
h7	1446355196	46656619.21	0.12765
h8	1495539450	48243208.07	0.131991
h9	889383358.7	28689785.76	0.078494
h10	704119720.8	22713539.38	0.062143
h11	567363930.6	18302062.28	0.050074
h12	484946186.9	15643425.38	0.0428
h13	538333211.2	17365587.46	0.047511
h14	414646717.9	13375700.58	0.036595
h15	381353026	12301710.51	0.033657
h16	374969423.3	12095787.85	0.033094
h17	395770394.5	12766786.92	0.034929
h18	683748095.5	22056390.18	0.060345
h19	664403206	21432361.48	0.058638
h20	703677082	22699260.71	0.062104
h21	737357378.5	23785721.89	0.065077
h22	756114675.9	24390796	0.066732
h23	8688117.76	280261.8632	0.000767
h24	9643270.756	311073.2502	0.000851
Total		365503355.9	1

Table 49. *Hourly heat demand of offices*

Hours	J/h	Average demand/h	Factor
h1	45298311.56	1461235.857	0.000299
h2	81151590.9	2617793.255	0.000536
h3	121889846.3	3931930.526	0.000806
h4	159074414.8	5131432.737	0.001051
h5	186754177.7	6024328.312	0.001234
h6	207838397.8	6704464.444	0.001374
h7	16296677781	525699283.2	0.107709
h8	12844784942	414347901.3	0.084895
h9	14345807516	462767984.4	0.094816
h10	11668011271	376387460.3	0.077117
h11	10366350957	334398418	0.068514
h12	9083076170	293002457.1	0.060033
h13	8403270785	271073251.1	0.05554
h14	7972320503	257171629.1	0.052691
h15	7675136332	247585043	0.050727
h16	7429670025	239666775	0.049105
h17	7797369700	251528054.8	0.051535
h18	8882774126	286541100.8	0.058709
h19	9736043298	314065912.8	0.064348
h20	8007170170	258295811.9	0.052922
h21	8239036535	265775372.1	0.054454
h22	1708278581	55105760.69	0.011291
h23	19348032.81	624130.0905	0.000128
h24	25102250.77	809750.025	0.000166
Total		4880717281	1

Table 50. *Hourly heat demand of shops.*

Hours	J/h	Average demand/h	Factor
h1	3078566869	99308608.69	0.049953
h2	3163069057	102034485.7	0.051324
h3	3259408075	105142196	0.052887
h4	3328070879	107357125.1	0.054001
h5	3366325855	108591156.6	0.054622
h6	3308562985	106727838.2	0.053685
h7	3080470566	99370018.25	0.049984
h8	2771570710	89405506.79	0.044972
h9	2169297316	69977332.78	0.035199
h10	2127262117	68621358.6	0.034517
h11	2243156444	72359885.3	0.036397
h12	2191247356	70685398.59	0.035555
h13	2066151309	66650042.23	0.033525
h14	1874491678	60467473.49	0.030416
h15	1823035609	58807600.3	0.029581
h16	1976056664	63743763.36	0.032064
h17	2038422759	65755572.87	0.033075
h18	2060689663	66473860.1	0.033437
h19	2394193806	77232058.27	0.038848
h20	2445624279	78891105.78	0.039683
h21	2563714490	82700467.42	0.041599
h22	2600490591	83886793.25	0.042196
h23	2749378197	88689619.24	0.044611
h24	2950216362	95168269.75	0.04787
Total			1

Table 51. *Hourly heat demand of Hotel/motels*

Hours	J/h	Average demand/h	Factor
h1	6780793639	218735278.7	0.040224
h2	7427121720	239584571.6	0.044058
h3	6937958438	223805110.9	0.041157
h4	7556401959	243754901.9	0.044825
h5	7013206724	226232475	0.041603
h6	7637948378	246385431.6	0.045309
h7	9911391756	319722314.7	0.058795
h8	9288845393	299640174	0.055102
h9	8680151741	280004894.9	0.051491
h10	7735575996	249534709.6	0.045888
h11	7502952385	242030722.1	0.044508
h12	6657556112	214759874.6	0.039493
h13	6685689190	215667393.2	0.03966
h14	5945447479	191788628.4	0.035269
h15	6044984408	194999497	0.035859
h16	5840010035	188387420.5	0.034643
h17	6072781064	195896163.3	0.036024
h18	5151279957	166170321.2	0.030558
h19	5854816852	188865059.7	0.034731
h20	6721443716	216820765	0.039872
h21	6312268203	203621554.9	0.037445
h22	7014998744	226290282.1	0.041614
h23	6523254567	210427566.7	0.038696
h24	7278117906	234777997	0.043174
Total		5437903108	1

Table 52. *Hourly heat demand of buildings with a service function.*

Hours	J/h	Average demand/h	Factor
h1	36677112800	1183132671	0.041324
h2	37082493466	1196209467	0.041781
h3	37616676908	1213441191	0.042383
h4	38114567543	1229502179	0.042944
h5	37765486086	1218241487	0.04255
h6	51048190394	1646715819	0.057516
h7	43402869365	1400092560	0.048902
h8	43401201524	1400038759	0.0489
h9	41445281326	1336944559	0.046697
h10	39830349134	1284849972	0.044877
h11	37564646858	1211762802	0.042324
h12	35971853539	1160382372	0.04053
h13	34913959536	1126256759	0.039338
h14	34278652199	1105762974	0.038622
h15	33918285742	1094138250	0.038216
h16	32587037921	1051194772	0.036716
h17	32739649810	1056117736	0.036888
h18	32984651387	1064021012	0.037164
h19	33868902303	1092545236	0.03816
h20	32698522038	1054791033	0.036842
h21	34291686220	1106183426	0.038637
h22	34327688544	1107344792	0.038677
h23	35213010372	1135903560	0.039675
h24	35802413661	1154916570	0.040339
Total		28630489957	1

Table 53. *Hourly heat demand of buildings with a medical function.*

13.7 APPENDIX 7: key-numbers for all future heat scenario's

To estimate the most optimal heat supply in Felix Meritis, some key numbers are taken. Below a short description of each is explained.

13.7.1 COP of a heat pump

The COP determines the efficiency of a heat pump. A heat pump with a COP of 3 for example, needs 1 kWh electricity to produce 3 kWh heat. The higher the COP the more efficient the pump works. The type of heat pump and its corresponding COP depends on the heat source (different scenario's) and the target temperature (Bouw, 2019). For the historic centre, this temperature lies at 70-90 °C meaning that a COP around 3.5 is needed (H. de Brauw, personal communication December 17th, 2020).

The heat efficiency of pumps is of large influence on the yearly cost and thus on the affordability of all scenarios. The more efficient the pump, the less electricity is needed which means lower energy bills. Thereby its efficiency influences CO_2 emission. The more efficient a heat pump, the less electricity use and thus the lower the CO_2 emission.

13.7.2 Insulation measures.

Insulation is of great importance when wanting to connect to an LT heat source.

Below, a description is given for the insulation measures essential for an LT heat network.

a. To heat a house on LT (30-50 C), a high level of insulation is essential. It is recommended to strive for an Rc-value of 3,5 m_2K/W for the floors, roof and the façade and the lowest U-value in W/m_2K possible for windows.
b. The majority of the houses in this neighbourhood are built before 1920 (90%) it is assumed that no insulation is in place meaning that Rc-values of each of the aforementioned surfaces lie around 0.2 $_2$K/W m (Appendix 2).
c. A house can be connected to an LT heat network when it has at least and Rc-value of 3,5 m_2K/W which is equal to energy label C or B, depending on additional measures such as solar panels and other sustainable measures (V. Valkema, personal communication, January 27th, 2020) (Rovers & Tichelaar, 2019).

13.7.3 Average heat loss surface area

Calculating insulation cost of a building with the online tool provided by the Groene Grachten, is only possible with estimated surface areas. Therefore, an average of all heat loss surface areas of the total building stock of Felix Meritis is provided in table 54. This allows for a rough estimation of insulation costs.

Heat loss surface area	gross surface area [m2]	area [m2]	height [m]	number
Floor (ground)	642	145.7		4.5
Roof		206		
Facade		82	16	
Windows				13

Table 54. *Average heat loss surface areas of total building stock in Felix Meritis*.

13.7.4 Insulation costs

When calculating the affordability of a scenario, the insulation cost makes up a significant share of the investment cost. However, these costs are difficult to estimate as many factors play a role and each old building is unique (V. Valkema, personal communication, Januari 27th, 2020).

The costs are related to:

a. The surface area of the building: a building has several surface areas that can be insulated to increase its heat efficiency. The larger these surfaces, the higher the insulation costs (GroeneGrachten, 2020).

b. Its construction year. The older the building, the more insulation is needed to increase the heat efficiency
c. The level of insulation. There is large difference in cost between insulating from label G to A+ or insulating from G to label D (GroeneGrachten, 2020).

Because we use an example building, the costs are possible to calculate but cannot be extrapolated to every home.

Insulation cost are dependent on the average surface area that need to be insulated. With the average surface area provided in Appendix 3, the cost of insulation could be calculated using the online tool ''the groene menukaart''. This online tool provides a range of costs given a certain surface area. Therefore, the average of this range is taken (GroeneGrachten, 2020).

13.8 Appendix 8: calculations reliability, sustainability & affordability

Chapter 7 compares the three scenarios based on their reliability, sustainability, and affordability. Corresponding calculations to make these comparisons are given below.

13.8.1 Reliability – Aqua thermal energy

Annual heat needed from TEO:

COP heat pump: 3.5

109.150 / 3.5 = 31.186

109.150 – 31.186 = 77.964 GJ/year

Needed capacity of ATES system

77.964 GJ/year – 16400 GJ/year = 61.564 GJ/year

Needed peak loads ATES system (monthly)

100 days >16 °C

Heat demand:

June: 5511.8 GJ/30 days

July: 5484.5 GJ/ 31 days

August: 5586.9 GJ/31 days

Total: 17.269 /92 days

Needed heat from TEO system during June, July & August:

17.269 / 3.5 = 4.934 GJ/92 days

17.269 – 4.934 = 12.335

TEO capacity 16.400 GJ/92 days

17.269 GJ – 12.335 GJ = 4.934 remaining to go to storage in ATES system.

Shortage of cool months:

Heat demand rest of the year:

109.150 – 17.269 = 91.881 GJ/273 days

91.881 /3.5 = 26.252

91.881 – 26.252 = 65.629 GJ/ 273 days

Shortage ATES

65.629 – 4.934 = 60.695 GJ

11.8.2 Reliability- Hybrid

Heat demand covered by conventional boiler

January: 14873 GJ

November: 0.5 * 11641 = 5820 GJ

December: 12976 GJ

Total: 33.669 GJ

Heat demand covered by TEO in warmer months

109.150 – 33.669 = 75.481 GJ

TEO demand

75.481 / 3.5 = 21.566 GJ

75.481 – 21.566 = 53.915

TEO potential 16.400

53.915 – 16.400 = 37.515

Capacity covered by TEO system

37.515 / 53.915 = 70 %

11.8.3 Sustainability – Aqua thermal energy

Current CO_2 emission in kg

1.884 * 10.8 million m3 gas = 20.4 kg CO_2/year.

CO_2 emission from electricity

0.34 * 8.700.000 = 3 million kg/ CO_2

CO_2 emission reduction

20.4 – 3 = 17.4 million kg CO_2/year

12.8.4 Sustainability- HT- heat network

CO_2 emission from WPW

26.2 * 342.500 GJ = 9 million

CO_2 emission reduction

20.4 – 9 = 11.4 million kg CO_2/year

Sustainability - Hybrid

CO_2 emission

5.990.555 * 0.34 = 2 million kg CO_2/kWh/year

33.669/0.032 = 1.052.156,25 m3 gas

1.052.156,25 * 1.884 = 1.982.262,4 kg CO_2/year

Total: 3.982.262 kg CO_2/year

CO_2 emission reduction

20.4 - 4 = 16.4 million kg CO_2/year

13.9 Appendix 9: Insulation costs

Table 55 , 56 and 57 show the cost that homeowners must make to insulate their buildings accordingly to a heat scenario. The cost for the aqua thermal scenario and the hybrid scenario is estimated higher because heat of lower temperatures is delivered to the building, demanding a better heat efficiency.

Building installations	unit	investment cost
Insulation from G - B		
Insulation facade	€	8250
Insert double glazing	€	11375
Insulation colliding roof	€	15350
Insulation ground floor	€	5800
Low temp radiators	€	2800
Building installations		
Induction cooker	€/apiece	1500
Heat delivery set (residential)	€/apiece	1100
Heat delivery set (utilities)	€/apiece	2000
Cost of installation	€	2000
Control systems and monitoring	€	3450
Total inhouse investment cost	**€**	**53625**

Table 55. *Investment cost for homeowners for the Aqua thermal energy*

Building installations	unit	investment cost
Induction cooker	€/apiece	1500
Heat delivery set (residential)	€/apiece	1100
Heat delivery set (utilities)	€/apiece	2000
Cost of installation	€	2000
Control systems and monitoring	€	3450
Total cost		**10050**

Table 56. *Investment cost for homeowners for the HT-heat network scenario.*

Building installations	unit	nvestment cost	variable cost
Insulation from G - B			
Insulation facade	€	8250	8250
Insert double glazing	€	11375	11375
Insulation colliding roof	€	15350	15350
Insulation ground floor	€	5800	5800
Low temp radiators	€	0	0
Building installations			
Induction cooker	€/apiece	0	0
Heat delivery set (residential)	€/apiece	1100	1100
Heat delivery set (utilities)	€/apiece	2000	2000
Cost of installation	€	2000	2000
Control systems and monitoring	€	3450	3450
Total inhouse investment cost	**€**	**49325**	

Table 57. *Investment cost for homeowners for the Hybrid scenario.*

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