UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA

Refurbishment measures versus geothermal district heating for residential buildings in the Netherlands

João Francisco Andrade da Silva Pinto

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Professor Doutor Guilherme Carrilho da Graça (FCUL)

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Resumo

Com a descoberta do maior reservatório de gás natural da Europa nos anos 60, a Holanda tornou-se desde então um dos maiores produtores e exportadores europeus deste recurso. Hoje, mais de metade do gás natural dessa fonte foi utilizado e a necessidade de redução energética torna-se cada vez mais aparente.

A área dos edifícios residenciais é das que mais consome gás natural. Actualmente, 96% de todas as habitações estão conectadas à rede de gás natural, mais de 60% da electricidade provém de fontes de produção a gás e praticamente todos os edifícios residenciais com aquecimento central utilizam gás natural. Devido a esses factores, o interesse numa transição energética para um recurso mais sustentável tem vindo a crescer, nomeadamente usando energia geotérmica.

Neste trabalho, o recurso à geotermia é comparado com a aplicação de medidas de eficiência energética em habitações na cidade de Groningen, onde se insere um dos maiores projetos para o desenvolvimento de uma rede de distribuição de calor geotérmico.

Assim, procedeu-se à simulação térmica de dois edifícios residenciais típicos da cidade antes e depois de serem remodelados, de forma a igualar o atual consumo dos mesmos ao valor simulado, e de modo a saber-se que poupança energética resultaria das medidas de eficiência energética aplicadas. Esta abordagem é então comparada ao recurso à geotermia não só do ponto de vista de energia poupada mas também dos custos associados a cada uma das metodologias para redução de consumo de gás natural.

Palavras-Chave: Simulação térmica, eficiência energética, energia geotérmica, remodelação de edifícios.

Abstract

With the discovery of the largest natural gas reservoir in Europe in the 60s, the Netherlands has become one of the leading natural gas exporters and producers in the continent. Today, more than half of the natural gas from that source is depleted and the need for an energy reduction approach becomes more and more necessary.

The residential buildings sector is responsible for one of the highest natural gas consumption shares. Currently, 96% of all households are connected to a natural gas grid, over 60% of electricity comes from gas-fired generation and almost all space heating comes from natural gas. Thus, interest in an energy transition to a more sustainable resource has been increasing, particularly with the use of geothermal energy.

In this work, the use of geothermal energy is compared to the application of energy efficiency measures in homes in the city of Groningen, where one of the largest projects for the development of geothermal heat distribution network is taking place.

A thermal simulation of two typical residential buildings in the city before and after being refurbished was performed, so that their current gas consumptions and their simulation values could be match, and in order to find out what energy savings would result from the refurbishment measures applied. This approach is then compared to the use of geothermal energy not only in terms of the amount of energy saved but also in terms of the costs spent.

Keywords: Thermal simulation, energy efficiency, geothermal energy, building refurbishment.

Contents

List of Figures

List of Tables

1. Introduction

Over the last decade the Netherlands became the leading natural gas trading hub in Europe and the second highest natural gas producer, following Norway [1]. The largest natural gas field in Europe is located in the Netherlands, being the country's main energy source [2-3]. This gas reserve is being explored since 1963 in the city of Groningen and, by now, more than half of its capacity has been used. At current consumption rate this reserve will be depleted in the next 50 years [4] and there is need to develop alternative energy sources or reduce consumption by increasing energy efficiency.

The Dutch Administration has thereby set a maximum allowance for total production from the field as of 2015, which was also driven from seismic activity linked to gas extraction [5]. Hence, natural gas prices are expected to rise over the next decades and upcoming reductions in production will cause the Netherlands to change from a net exporter of gas to a net importing nation [6]. Furthermore, concerns over climate change and greenhouse gas emissions resulted in targets of 60% reduction in building energy consumption by 2050 [7]. Reducing natural gas consumption by expanding the energy sources, increasing renewable energy use and applying energy refurbishment measures are crucial to materialize the current Dutch energy transition.

In the Netherlands, the residential sector accounts for the second largest share of natural gas use (22%), only surpassed by the transformation sector [4]. Moreover, 96% of all households are connected to gas supplies, over 60% of electricity is from gas-fired generation and almost all space heating comes from natural gas sources [8]. The potential to reduce natural gas demand from the building sector is immense. According to a recent study [9], the built environment has the highest potential for increased energy efficiency: nearly 42TWh per year could be saved worldwide up to 2020. The same study shows that average residential gas consumption in the Netherlands represents 79%, 19% and 2% for space heating, domestic hot water and cooking respectively, clearly, reducing the energy needs for space heating is a priority. In total, a Dutch dwelling uses on average 3.5MWh electricity and 1500m^3 gas every year [9]. Thus, interest in finding solutions to reduce heating demand in residential buildings has been increasing not only in the Netherlands but also worldwide [10], mostly by improving the buildings skin in its insulation and infiltration values, by replacing the boiler to a more efficient one, by installing heat recovery systems or by using renewable technologies such as solar or geothermal energy.

In this study, two energy reduction approaches in terms of energy savings and costs for a time period of 40 years in the city of Groningen were compared. The first approach is to implement refurbishment measures focused on lowering heating demand in typical Dutch homes, while the second is to connect those homes to a geothermal grid, where the heat is transferred from an underground aquifer to the individual heaters inside the dwellings. This comparison centers on what is more beneficial to homeowners from individual and communal perspectives, both in terms of energy savings and costs.

Groningen is the largest province and eponymous city in the north of the Netherlands, having currently nearly 200.000 inhabitants and a total area of 83.75km^2. In the last few years, the municipality of Groningen has been strongly supporting and encouranging the application and expansion of new renewable heat applications, with the main ambition of making Groningen an energy neutral city by 2035. However, due to the high number of buildings in the city that could be renovated and significantly decrease their gas demand for heating, a different path could be taken into achieving the zero energy goal. Therefore, Groningen is ideal for our case study.

1.1. Residential energy use and efficiency in the Netherlands

In the Netherlands, the residential sector accounts for the second largest share of natural gas use (22%), only surpassed by the transformation sector [1]. However, there has been a decline on average residential gas consumption over the years, having the average annual gas demand per dwelling in the past decades fallen sharply from about 2200m^3 in 1995 to about 1500m^3 in 2012. It is also expected to be further reduced to approximately 1350m^3 by 2020 [5]. These reductions are due to the increasing use of energy efficient appliances and improved building insulation, along with a higher share of renewable energy which as incremented from 1.4% to 4.5% over the past decade. Nonetheless, this value is still way below the 14% renewable energy goal agreed with the European Union (EU) by 2020. In addition, there is still a long way to go if all households are to be converted into energy neutral ones by 2035.

Since the beginning of 2015, the Energy Performance Coefficient (EPC) – which is an instrument used by the government to lower CO_2 emissions consisting of minimum norms for new to-be-built buildings – was reduced to 0.4, which is a value that substantially requires a high energy performance of new homes [5]. Related to the EPC is the Energy Label (EL) each building must have, which shows the energy efficiency of a building by rating it from A to G (to keep up with advances in energy efficiency, A+, A++, A+++ and A++++ were later introduced) - Figure 1 shows a relation between the EPC and the EL [11]. For instance, dwellings built before the 21st century that have not been renovated are typically rated between the B and G marks, which are clearly far from the 0.4 EPC level. Homes with a higher EL are evidently preferable, since more energy efficient homes means lower energy bills, more comfort and less CO_2 emissions, becoming also more attractive to potential buyers or tenants than less energy efficient homes. Hence, investing in energy-saving measures is an incentive [12].

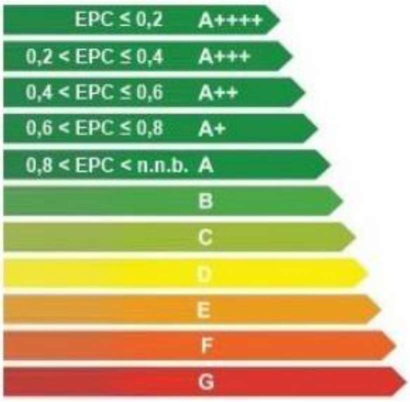

Figure 1- Energy labels for households in the Netherlands.

In order to improve the energy efficiency of a building, several measures are usually implemented in the Netherlands, by using mature technologies in terms of insulation, lighting, and heating. Usually, improvements in insulation account for not only the walls and the floor but also the roof. However, it is crucial to have in mind that dwellings in the Netherlands are not regularly equipped with air conditioning or any other active cooling system. Considering the effects of climate change over the next decades [6], it is imperative that these improvements are adaptive to such reality so overheating inside the buildings can be prevented. In terms of lighting, using CFL's or LED's is also a better choice, since they use little energy compared to other types (such as incandescent lamps). There are also several ways to improve the heating efficiency either by using solar energy or by having highly efficient boilers [9]. Lately, the number of buildings using solar-powered heat sources has also increased and has been growing anually, being one of the few European countries who have a positive annual growth in the last few years [13].

1.2. Geothermal district heating in Dutch homes

As previously mentioned, demand for heat in the Netherlands is a major factor in the Dutch energy sector, representing the most dominant energy function in Dutch dwellings nowadays and accounting for 40% of national energy output (over 300GWh per year) [14-15]. Therefore, implementing a system for distributing heat for residential and commercial requirements in a stable, sustainable, renewable and carbon neutral manner appears as the ideal option for the upcoming goals set by the Dutch government. Moreover, this technology would diminish the high number of earthquakes caused by extracting gas, which has been a problem for the last decades in the Netherlands [16].

Interest in deep geothermal energy arose since it started being used to heat greenhouses in a few places, but the risk of unsuccessful drilling limited its possibilities since a large part of the costs come from deep underground drilling [17]. Nonetheless, deep geothermal energy is already economically feasible and used where aquifers can be found near the surface in a district heating network for different types of heat. On the other hand, shallow geothermal energy is currently less costly and already established for offices, horticultural greenhouses and new buildings [17].

According to [5], the number of Stimulation of Sustainable Energy Production[a] applications for geothermal projects increased significantly and the consumption of renewable heat has also been rising in the Netherlands. There are already 13 large district heating networks with over 227 thousand homes connected [18]. For instance, a 44MW biomass-to-heat facility was installed in Purmerend to replace a combined cycle natural gas plant and to provide district heating to 25.000 homes, reducing natural gas demand in 30 million cubic meters per year [19]. Direct use of geothermal heat is also being developed in The Hague (4000 homes) and three doublets have already been planned to be built in Delft and Pijnacker [20].

1.3. The Groningen geothermal grid project

According to the municipality of Groningen, the city’s annual use of natural gas equivalents[b] accounts for 305 million m^3. Assuming that, following the national trend, half of this energy is used for heat generation, about 100 million euros are being spent every year on this sector only [21]. Hence, considerable savings regarding heat can truly be made and have an impact in the overall gas consumption in the Netherlands.

In the city of Groningen, a wide variety of locations are appropriate for the use of geothermal heat. One of those locations is in the northwest of the city, which has led to the start of a project between the municipality of Groningen (WarmteStad BV) and Groningen’s water company to deploy a geothermal district heating grid. At this point, the business case has already been carried out and demonstrates that district heating in the northwest can be a success. It is estimated that the energy will be extracted from a water bearing sandstone at a depth between 2750-3200m with temperatures ranging 120-125ºC [22]. The geothermal grid is expected to provide heat to 10.000

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[a] The Stimulation of Sustainable Energy Production (SDE+) is an operating grant where producers receive financial compensation for the renewable energy they generate. Since renewable energy production is usually not profitable, differences in cost compared to fossil fuels are compensated by the SDE+ for a fixed number of years.

[b] All energy sources (i.e. coal, oil) are added and converted to their equivalent natural gas use.

homes and buildings to the nearby neighborhoods and is planned to be completed in 2017 - *Appendix I* displays a map of the project. The effect of no longer having gas demand for space heating and hot water in these households would reduce greenhouse gas emissions in about 15.000 tons of CO_2.

The estimated costs for the capital and operational expenditures account for 51 million euros and 2.55 million euros respectively. The capital expenditure (CAPEX) represents the double and grid construction costs plus the surface installation costs, while the operational expenditure (OPEX) refers to the yearly maintenance and electricity consumption costs. There are also projected costs for homeowners who do not want to participate in the investment, represented in Table 1. These include the cost to connect to the grid, the yearly fee and tariff for metering, and the heat price per kWh consumed.

Table 1 - Predicted costs for the deployment of a geothermal district heating grid in Groningen. *: Yearly costs.

CAPEX	51 M€
OPEX*	2.55 M€
Cost for new connections	963€
Connection fee*	276€
Tariff for metering*	150€
Heat price*	0.9x(Gas cost)

1.4. Research Aim

Having in mind that current natural gas stocks in the Netherlands have already led to an energy production equivalent to more than half their capacity and that the need to reduce CO_2 emissions accentuates over the years, more renewable and carbon neutral energy carriers are needed so that a sustainable energy transition can be made.

Geothermal district heating appears as a possibility to not only help reduce natural gas dependence and greenhouse gas emissions but also to lower the energy cost that is currently being afforded for space heating and hot water in households. At the same time, it is now required that new homes follow high energy efficiency standards so that their footprint and energy consumption are minimized. It is also advantageous for old dwellings to be upgraded, since investing in energy-saving measures makes them more attractive to potential buyers or tenants, and more and more owners are starting to follow this trend. For those reasons, households are expected to change over time towards higher energy efficiency, which can have an impact on the heat grid.

Hence, the research aim of this study is: "To compare whether it is more feasible for homeowners to go for better energy labels by refurbishing their homes or to connect their dwellings to a geothermal district heating grid".

1.5. Research questions

The research aim of this study leads to the core research question: “Is it more feasible for homeowners to go for better energy labels by refurbishing their homes or to connect their dwellings to a geothermal district heating grid?”.

Following the main research question, other sub questions have been identified:

1) What type of residential buildings are the most suitable to be refurbished in Groningen?

There are approximately 77 thousand apartments in Groningen, distributed through different building typologies such as detached, semi-detached, high-rise and townhouse buildings, all built between the 19th and the 21st century. It is then crucial to find what the most representative dwellings with the need for refurbishment measures are in the city.

2) What are the most appropriate refurbishment measures to be done in typical Dutch homes?

Having in mind not only the refurbishments that are usually implemented in the Netherlands but also others that are commonly used in Nordic countries and are suitable for Dutch homes, thoroughly choosing the ideal measures to implement is an important step to optimize the apartment’s energy need.

3) How much energy can be saved by implementing the refurbishment measures or by connecting the homes to the geothermal grid?

Reducing natural gas consumption is the main goal of this study. Therefore, assessing how much energy can be saved by each approach and which saves the most energy can influence the homeowners and investors decision, particularly on which is the most beneficial to achieve the goals set by the municipality of Groningen and the Dutch government.

4) What are the costs for either following a refurbishment or geothermal approach to homeowners?

The energy saved is one of the most relevant factors in decision-making yet not sufficient. The feasibility of each approach is also highly dependent on their cost, which is crucial for a project to move forward. In this case, a much higher cost for one of the approaches can lead homeowners to admit the other.

1.6. Relevance

This research was initially proposed by WarmteStad, which is the company responsible for providing renewable heat in Groningen and in charge of the project taking place in the northwest of the city. Groningen’s Water Company and the municipality of Groningen are both fifty percent shareholders of WarmteStad.

This work serves as a complement for the energy transition that is currently being planned by the municipality, which is only focused on the implementation of the geothermal district heating grid. Therefore, this master thesis discusses a different way of achieving that energy transition, based on refurbishing the households into more energy efficient ones.

1.7. Structure of the Thesis

This Master Thesis is divided in six more chapters, as shown in Figure 2. Chapter 2 describes some of the fundamental concepts in heat transfer, serving as a basis to understanding the types of heat losses that occur in residential buildings. This chapter also defines insulation, infiltration, mechanical ventilation with heat recovery and boilers, since comprehending these concepts is crucial to understand the refurbishment measures that are further presented in this work. Also, a short explanation about EnergyPlus (the thermal simulation software used) is provided. Chapter 3 reflects the case study, emphasing on the residential buildings chosen and their energy consumption. Two typical Dutch buildings are considered based on current literature and statistical analysis, with the building materials, infiltration levels, heating equipment and occupant behavior all set for what represents the majority of buildings with the same typology in the Netherlands. Chapter 4 presents the refurbishment measures implemented in the two buildings. In Chapter 5, all information regarding the buildings thermal simulation is presented, from the weather file, geometry and simulation input parameters to the residential buildings simulation model applied. The results from the first simulation are presented in this chapter, in order to calibrate the dwellings natural gas consumptions and to assess their current energy performance. Chapter 6 discusses the simulation results obtained with the refurbishment measures implemented and whether or not these cause overheating indoors. The comparison between implementing these measures and connecting to the geothermal source is then debated from both energy saving and cost perspectives. In the last chapter, answers to the research questions are given.

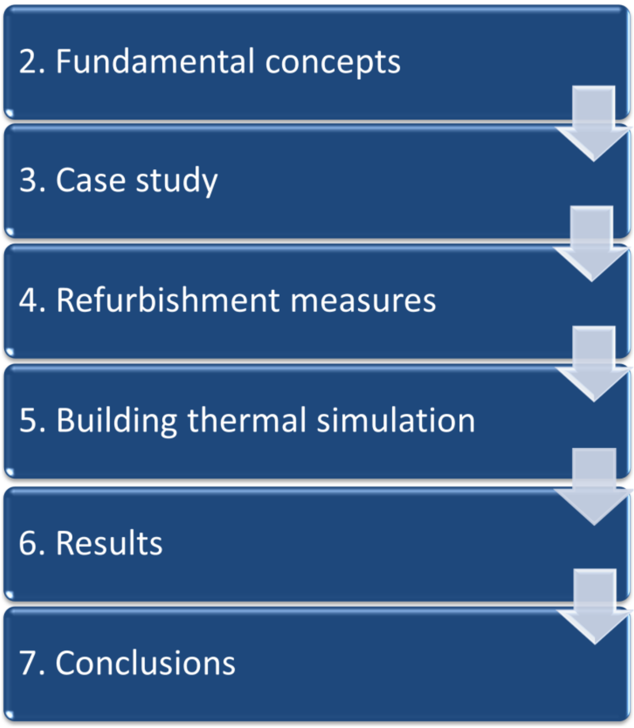


Figure 2 - Structure of this work.

2. Fundamental concepts

The fundamental concepts described in this chapter form the basis for the case study further presented in the document. These include the three heat transfer mechanisms; insulation and infiltration; mechanical ventilation with heat recovery, boilers and geothermal energy systems; and EnergyPlus.

2.1. Heat transfer

Heat transfer occurs when there is a temperature difference between two points until these reach thermal equilibrium. The direction of heat transfer is from the highest temperature point to the lowest, without any changes in the energy transferred (conservation of energy). There are three fundamental modes of heat transfer: conduction, convection and radiation. These heat transfer mechanisms are crucial to evaluate the performance of a building in its thermal behavior, so that the building itself and all energy systems installed can be optimized.

2.1.1. Conduction

Heat conduction happens when adjacent atoms and molecules collide against each other, or when electrons exchange from one atom to another. It is the most significant heat transfer mechanism within solids or between solids in thermal contact, since these have their atoms tightly bond to each other. Conduction also occurs in liquids and gases due to the vibrations caused by their random motion, leading to the collisions and diffusion of molecules [23].

Fourier's law, also known as the law of heat conduction, states that a material's heat flux density is proportional to the negative gradient in the temperature and to the area, where the heat flux density corresponds to the amount of energy flowing through a unit area per unit time:

$$q''_x = -k\frac{dT}{dx} \tag{1}$$

where:

q''_x is heat flux density [W/m^2];

k is the material's thermal conductivity [W/m.K];

$\frac{dT}{dx}$ is the temperature gradient [K/m].

2.1.2. Convection

Convective heat transfer occurs when the movement of fluids causes the transfer of heat from one point to another. It implies that both conduction and advection (heat transfer by bulk fluid flow) happen simultaneously, leading to the transfer of heat mostly between a solid surface and a fluid. Typically, the energy is transferred as sensible heat, where macroscopic variables such as volume and pressure remain unchanged, but it can also be transferred as latent heat where a phase change occurs [24].

In buildings, convection takes place between the building envelope and the air surrounding it, where a phase change might happen, causing air condensation. Water particles are then formed, and are usually visible in the windows. The convective heat flux is given by Newton's Law of cooling:

$$q''_{conv} = h_c(T_s - T_\infty) \tag{2}$$

where:
q''_{conv} is the convective heat flux [W/m^2];
h_c is the heat transfer coefficient;
T_s is the object's surface temperature;
$T\infty$ is the fluid temperature.

2.1.3. Radiation

All matter with a temperature above the absolute zero (0K) emits thermal radiation, with the transmission being performed by electromagnetic waves generated by the thermal motion of charged particles in the substance. Radiation does not need the presence of matter to propagate, infinitely traveling in vacuum if unobstructed [23-24].

A surface with perfect absorptivity and emissivity at all wavelengths is characterized as a black body. The Stefan-Boltzmann law relates the power radiated from a black body to its absolute temperature. In the real world, the radiative transfer between two surfaces is influenced by their emissivity, following the equation:

$$q_{rad} = \varepsilon\sigma(T_a^4 - T_b^4) \tag{3}$$

where:
q_{rad} is the radiative heat flux [W/m^2];
ε is the emissivity;
σ is the Stephan-Boltzmann constant;
T_a is the surface a temperature [K];
T_b is the surface b temperature [K].

2.2. Insulation

Thermal insulation reduces heat transfer between two objects due to their temperature difference. Good thermal insulation always has poor thermal conductivity, thus having a high heat capacity. Therefore, the amount of energy needed to move from a low temperature to a high temperature increases. For that reason, the temperature gradient between both objects is smaller, and the heat transfer reduced.

Resistance to the transfer of heat is often expressed by a material's R-value. The R-value is calculated by dividing the material's thickness by its thermal conductivity, being expressed in m^{2}K/W. The higher the value the better it works as an insulator. The R-value is also used when it is necessary to calculate the heat flux through materials in parallel, by adding the inverse of all the adjacent layers R-values. U-values, which are the reciprocal R-values, are often used for systems that are made up of different materials, such as windows.These are calculated as the inverse of R, therefore the lower the U-value the more slowly heat is transmitted through the material. Hence, the R-value describes resistivity to heat, while the U-value defines thermal conductivity.

In cold climates, thermal insulation in buildings is an effective way to achieve thermal comfort for its occupants. There are two types of building insulation: bulk insulation and reflective insulation. The first blocks conductive heat transfer and convective flows, while the second serves as a radiant barrier that reflects infra-red energy from within the building. Several types of materials are used as bulk insulation, with the most common being spray foams, rigid panels, glass wools and natural fibers. These are typically added to the wall and roof cavities, or added as another layer to the wall and roof surfaces. As for the reflective insulation, materials such as foil, reflective painting and low emissivity coatings are usually used, which are often installed in the walls, roof and windows.

2.3. Infiltration

Infiltration can be defined as an uncontrolled air leakage across a building envelope, having a significant impact in the energy performance of a building. Its level is mainly influenced by the climate (mainly wind conditions) and the building structure such as the size of cracks [25-26]. The units of measurement usually used for infiltration are cubic meters per second (m^3/s) and air changes per hour (ach). The first defines the volumetric flow rate of outside air into a building, while the second describes the air volume added or removed from a space divided by its volume.

According to [27], measurement standards for building envelopes such as in the infiltration level are defined by the power law, which relates pressure differences and the corresponding leakage air flows:

$$Q = C\Delta P^n \tag{4}$$

where:

Q is the leakage air mass flow rate [m^3/s];

C is the flow coefficient related to the size of the opening [m^3/sPa];

ΔP is the pressure difference across the crack [Pa];

n is the flow exponent characterizing the flow regime.

In order to find out the leakage rate of a building, a blower door is installed to pressurize the building at a constant pressure (usually at 50Pa) or to depressurize the building to be 50Pa less than the exterior. Both tests are different and deliver different results, since the cracks are most of the times not pure and in places that are partially blocked. This means that, for instance, housewrap would be tight under negative pressure, but leak the other way around. These values are often described as ach_{50}.

It should be noted that the calculated value does not correspond to an average infiltration rate during the year, since the obtained value widely depends on the weather conditions from when the tests were performed. Moreover, the infiltration rate also varies from location to location, both with site exposure and building height. For those reasons, an average infiltration rate is calculated by dividing the pressurization test result by a factor usually between 20 and 25 [28]. This factor varies depending on the location, with the highest corresponding to colder and windier climates. Thus, ach_{50} is converted to what is usually seen in literature as ach_{nat}.

A building with less than $0.6ach_{50}$ is considered extremely airtight, with airtightness within the Passive House requirements [29]. Buildings with airtightness between $3\text{-}5ach_{50}$ are considered typical and buildings with over $5ach_{50}$ are considered leaky.

2.4. Energy systems

2.4.1. Mechanical ventilation with heat recovery

Infiltration has a significant impact on heat energy consumption. For instance, ventilation and infiltration losses account for 48% of the energy consumption needed for space heating [30]. Moreover, air leakage can also increase moisture levels in the apartments, deteriorating building fabric or other materials inside the dwelling [31]. To avoid high levels of infiltration or/and moisturing issues, the buildings airtightness is increased. This is often achieved by installing mechanical ventilation with heat recovery (MVHR), which ensures that the necessary amount of fresh air to maintain indoor air quality is injected to the building at the lowest possible energy consumption [32].

MVHR works by continuously extracting the stale air from the home, where its heat is recovered via a heat exchanger located inside the heat recovery (HRV) unit. At the same time, fresh air from the outside draws into the property, passing through the heat exchanger where it is pre-heated before it is pumped to the inside. MVHR systems can be installed in three different ways: centralized, in a single room unit and in pair-wise units - Figure 3. The centralized system is mostly used for detached or townhouse dwellings, where the HRV unit is easily installed in the attic. In this case, a ductwork is needed to transport both supply and extract air. The single room unit is a decentralized system where each unit works as a small centralized system per room, providing and extracting air using two fans and a cross counterflow heat exchanger. The pair-wise units are also a decentralized system where each unit has a regenerative heat exchanger and an axial fan. It works in pairs, by having the first unit transporting the fresh air from the outside to the inside and the second unit extracting the air from the inside to the outside. Both decentralized systems are more suitable for high-rise apartments, since installing a centralized system in those building typologies is more complicated.

A centralized system has the drawbacks of higher pressure losses and harder installation procedures due to the ductworks, which also require some level of maintenance. However, it has the advantage of lower noise pollution and stack effects compared to decentralized systems, due to their location.

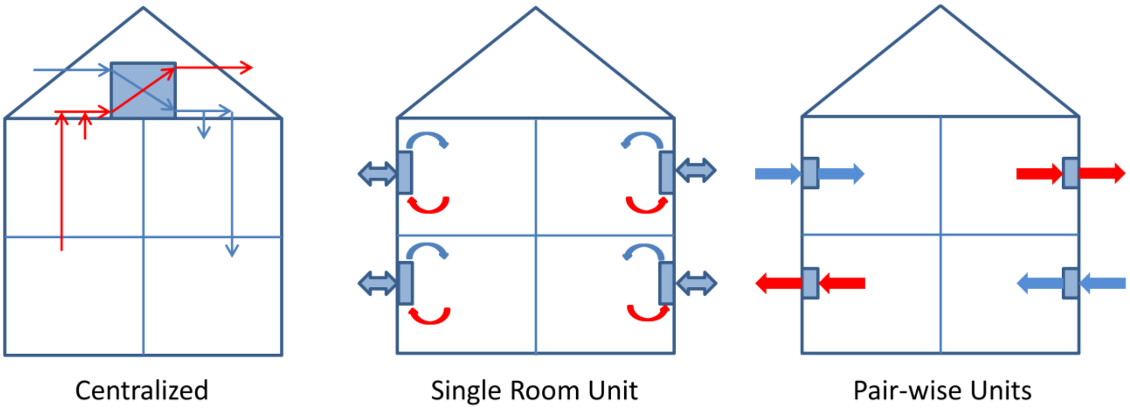


Figure 3 - Types of MVHR systems for residential buildings (figure modified from [31]).

2.4.2. Boilers

The most common heat generation method in households involves the combustion of natural gas in a boiler, which is then distributed in the dwelling by circulating the warmed up water through pipes in a loop. There are several types of boilers, with the most recurrent being conventional boilers (also known as regular boilers or open vent boilers) in older homes and condensing boilers in newer buildings [33].

In conventional boilers, natural gas is burned to heat the water, producing water vapour, carbon dioxide and other residues as by-products of the combustion reaction. Then, these gases escape through a flue to the outside atmosphere, as well as some of the heat generated in the boiler. In condensing boilers, these gases travel through a heat exchanger, where they are cooled down and condensed. The condensed fluid is then used to recover most of the heat that otherwise would have been lost – Figure 4. With this technology, up to 1200kg of carbon emissions a year can be avoided. State of art condensing boilers can reach theoretical efficiencies of 107%, being at least 25% more efficient than conventional boilers. However, since boilers are mostly used in conditions where optimum efficiency is not guaranteed, particularly during cold days where losses increase, the actual efficiency is a bit lower than the theoretical efficiency set by the manufacturers.

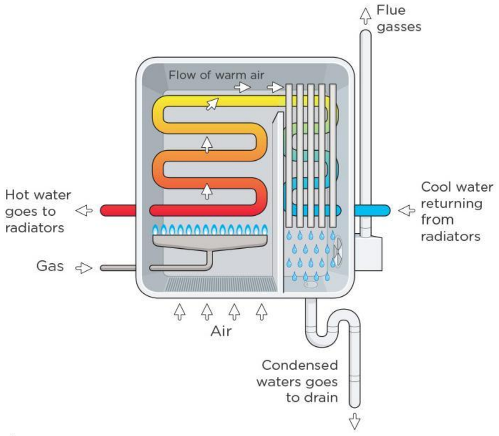


Figure 4 – Simplified diagram of a condensing boiler [33].

2.4.3 Geothermal

Geothermal energy is thermal energy derived from the Earth's internal heat, generated from the radioative decay of isotopes in the earth's core and from the planet's formation [34]. The heat stored in the subsurface can reach temperatures up to 200ºC, being useful not only for the direct supply of heat but also for electricity generation. For that reason, different types of geothermal energy systems can be developed depending on the reservoir's temperature – Figure 5 [35]. This study focus on low-enthalpy geothermal systems, where the temperature range is located between 40ºC and 150ºC. Nevertheless, Figure 5 shows other ways of using the geothermal heat. For instance, closed and open loop ground source heat pumps, with temperatures between 5ºC and 15ºC, are typically dedicated to single households, while deep ground source heat pumps, where temperatures range between 40ºC and 150ºC, are used for the connection to multi-storey buildings. On the other hand, the highest temperatures are used for electricity generation with Enhanced Geothermal Systems (EGS), where temperatures are located between 150ºC and 200ºC [34].

Low-enthalpy geothermal systems are better for the direct supply of heat, due to these being mostly low temperature. Thus, only heat generation and no electricity production are considered in the study. These systems are used to provide energy to neighborhoods for both space heating and hot water. Depending on the reservoir's size they could last more than half a century [34]. The Groningen geothermal grid is an example of a low-enthalpy geothermal system.

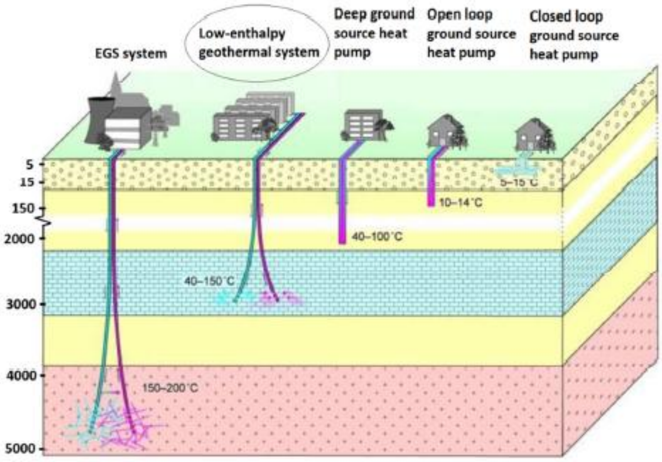


Figure 5 - Types of geothermal energy systems.

A geothermal district heating system is characterized by three main components: the geothermal doublet, the heat distribution system and the customer [36]. The geothermal doublet comprises two wells drilled into the ground until they reach the reservoir's depth, where the hot water is located. One of the wells is the production well, which is used to pump the hot water up from the aquifer with an electric submersible pump located inside the wellbore. [37]. The other well is used to pump the cold water back into the aquifer so that a closed loop between production and injection is created. Both wells are drilled in the same location but deviated along their depth 1.5-2km apart [36-38].

Figure 6 shows the geothermal district heating process of a low-enthalpy geothermal system [39]. After the hot water is pumped up from the aquifer, it goes through a heat exchanger where the heat is transferred to the fresh water used in the heat distribution network. The water extracted from the aquifer is not supplied to the customers due to its corrosive nature, where dissolved salts, heavy metals and possibly radioactive materials can be found in it. The fresh hot water is then piped to the consumers, which in this study are only residential buildings. Then, the cold water goes through a district heating return pipe where it is injected back into the ground [38]. The geothermal system is also composed by a back-up/peak-load system, which is used when an alternative energy source is needed due to either maintenance or technical issues, or when there is higher heat demand than the base load set (particularly during winter's coldest days) [40]. Moreover, the heat distribution system is equipped with pumping stations to maintain water pressure, and with a secondary heat exchanger at the consumer, in case the network does not have a direct connection to the customers. The district heating network is insulated to diminish heat losses during transport, that fall between 15-40% depending on the network's age, flow rate, distance, and pipe diameter. In state of the art district heating networks, heat losses reach values as low as 5% [35].

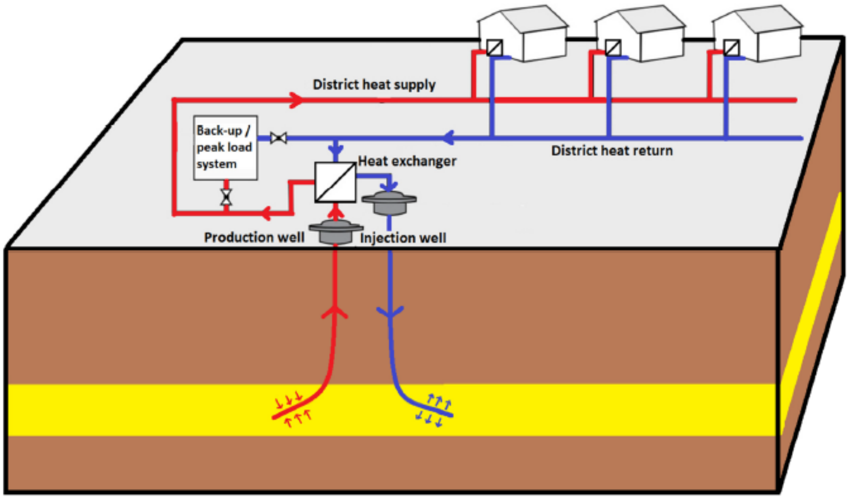


Figure 6 - Geothermal district heating process and its components.

2.5. EnergyPlus

Thermal simulation tools allow us to analyze buildings thermal behavior and test energy efficiency measures before they are even built or implemented, by using models that have been developed in the last decades.

EnergyPlus is one of the few simulation tools that can be used to perform such calculations. It is a validated software developed by the United States Department of Energy that calculates heating and cooling loads according to highly detailed building parameters. It resulted from the combination of two other softwares: DOE-2 and Building Loads Analysis and System Thermodynamics (BLAST). Figure 7 depicts, in a simplified manner, the three main phases a user goes through to achieve the desired results.

In the first phase, the user has to input the building geometry, the simulation parameters and a weather file. Since EnergyPlus does not have a graphical interface, the building geometry has to be defined in a software that allows doing so. Thus, Google Sketchup was used along with the plugin Legacy OpenStudio that exports the geometry to EnergyPlus in a compatible format. Here, various zones in the apartment are divided in thermal zones, defining areas with similar thermodynamic properties. A weather file that adequately represents the climate surrounding the buildings is also required to perform the simulation. These files contain information about weather data in general that are crucial for the thermal calculations performed by the software. Several other parameters are needed for the simulation, such as the building orientation, the building materials, infiltration, occupancy, lightings, electric equipment, etc.

In the second phase, EnergyPlus calculates inside and surface heat balances assuming perfectly mixed air and uniform temperature conditions in each thermal zone. The software has three main components: the heat balance simulation module, the building systems simulation module and the simulation manager. The heat balance simulation module calculates thermal and mass loads, where factors such as heat transfer by conduction, heat transfer by convection, infiltration, etc. are taken into account. The building system simulation module handles HVAC water and air loops, as well as their attached components, such as coils, boilers, pumps, chillers, etc. Finally, the simulation manager controls the whole simulation process and links the two modules.

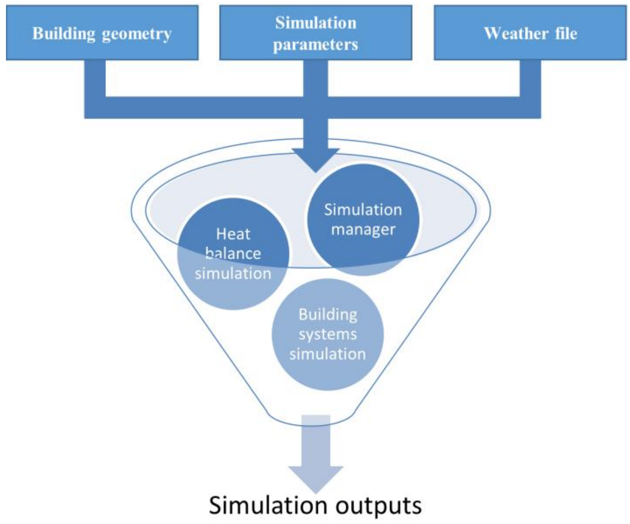


Figure 7 - Work phases on EnergyPlus.

The heat balance on the thermal zone air is calculated as follows:

$$C_z\frac{dT_z}{dt} = \sum_{i=1}^{Nsl}\dot{Q}_i + \sum_{i=1}^{Nsurfaces} h_i\,A_i(T_{si}-T_z) + \sum_{i=1}^{Nzones}\dot{m}_i\,C_p(T_{zi}-T_z) + m_{inf}C_p(\dot{T}_\infty - T_z) + \dot{Q}_{sys} \qquad (5)$$

where:

$C_z\frac{dT_z}{dt}$ is the energy stored in zone air;

$\sum_{i=1}^{Nsl}\dot{Q}_i$ is the sum of the convective internal loads;

$\sum_{i=1}^{Nsurfaces} h_i A_i(T_{si} - T_z)$ is the convective heat transfer from the zone surfaces;

$\sum_{i=1}^{Nzones} \dot{m}_i C_p(T_{zi} - T_z)$ is the heat transfer due to interzone air mixing;

$\dot{m}_{inf} C_p(T_\infty - T_z)$ is the heat transfer due to infiltration of outside air;

Q_{sys} is the air systems output;

$C_z = \rho_{air} C_p C_T$

ρ_{air} is the zone air density;

C_p is the zone air specific heat;

C_T is the sensible heat capacity multiplier (equal to one by default).

The heat balance on the outside faces is calculated as:

$$q''_{\alpha sol} + q''_{LWR} + q''_{conv} - q''_{ko} = 0 \tag{6}$$

where:

$q''_{\alpha sol}$ is the absorbed direct and diffuse solar (short wavelength) radiation heat flux;

q''_{LWR} is the net long wavelength (thermal) radiation flux exchange with the air and surroundings;

q''_{conv} is the convective flux exchange with the outside air;

q''_{ko} is the conduction heat flux into the wall.

The heat balance on the inside faces is written as:

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0 \tag{7}$$

where:

q''_{LWX} is the net longwave radiant exchange flux between zone surfaces;

q''_{SW} is the net short wave radiation flux to surface from lights;

q''_{LWS} is the longwave radiation flux from equipment in zone;

q''_{ki} is the conduction flux through the wall;

q''_{sol} is the transmitted solar radiation flux absorbed at surface;

q''_{conv} is the convective heat flux to zone air.

The third phase consists in choosing the simulation outputs desired. These are only available after successfully running the simulation once, being then possible to export a wide variety of data from the simulation. This data can be exported in summary reports, tables and schemes. It addresses outdoor site weather components and characteristics; internal zone temperatures, energy gains and losses; surfaces heat gains and losses; infiltration and natural ventilation heat losses; heating systems energy, and a lot more.

3. Case study

Since this study is aimed at reducing the energy consumption of typical Dutch residential buildings and because the geothermal source is located in Groningen, the most common archetypes in the city were first explored. Consequently, research on actual building energy consumption and the main factors influencing energy needs such as building materials, infiltration and occupant behavior was also carried out, being presented in the following subchapters.

3.1. Buildings representativity and description

According to a construction and housing study carried by Statistics Netherlands (CBS), terraced houses (29%) and flat buildings (56%) such as medium and high-rise account for the highest share of residential constructions in the city – Table 2 [41]. Nevertheless, it is important to note that besides detached and flat buildings, all other archetypes have a very similar typology. In addition, the same study shows that most residential buildings were built between 1960 and 1990 – Table 3. Thus, two different residential buildings are considered for the study: a terraced house and a high-rise building.

Considering the facts that residential buildings in the Netherlands were not typically built with wall insulation and were poorly insulated in the roofs until the late 1970s, targeting these would be ideal so that a wider energy consumption reduction could be achieved. Hence, both buildings considered for this study are from the early 1970s.

Table 2 – Number of buildings (x1000) per archetype in Groningen. 2 under 1 roof are terraced houses with one apartment above the other; corner houses are apartments located at the corner of a street; flat apartments are located in medium and high-rise buildings [41].

Detached	*2 under 1 roof*	*Corner house*	*Terraced house*	*Flat*
2.5	4.2	5.0	22.4	43.0

Table 3 - Number of buildings (x1000) per construction year in Groningen [41].

Before 1906	*1906 to 1945*	*1945 to 1960*	*1960 to 1975*	*1975 to 1990*	*1990 to 2000*	*2000 to 2012*
2.9	19.3	7.4	17.0	16.9	8.1	5.6

The buildings chosen are ideal since their apartments have two to four rooms, which are what typical Dutch apartments have – Table 4. The high-rise apartment considered has two bedrooms while the townhouse has three to four, since using the attic as a bedroom is quite common in the Netherlands. In this study, the attic is divided in two: half is a bedroom and the other half is a storage room.

Table 4 – Number of apartments (x1000) per their amount of bedrooms in Groningen [41].

0 to 2	***3***	***4***	***5***	***6***	***7 or more***
11.8	24.6	21.6	11.4	4.1	3.5

3.1.1. High-rise building

The high-rise building chosen for this study is located northwest from the city center, south from the geothermal source. It was built in 1974 and it has 63 apartments, each with a floor area of 90m^2. The average energy label among all apartments in the building is E [42]. Figure 8 shows a photo of the high-rise building and a floorplan of the apartments inside. These have two bedrooms, one living room, one kitchen and one bathroom. An apartment like this usually has two to four occupants. This study considers three occupants per high-rise apartment.

Figure 8 – a. High-rise building; b. Floor plan of the apartments in the high-rise building.

3.1.2. Townhouse building

The townhouse building used is also located northwest from the city center, but southeast from the geothermal source. Since townhouses are located between buildings of the same type, the one in the center was chosen. This row of townhouses comprises eight similar looking buildings, each with one apartment, and was built in 1970. Each apartment has three floors with a total floor area of 141m^2. The row of townhouse apartments has an average energy label of D [42]. An apartment like this usually has three to seven occupants. This study considers five occupants per townhouse home. Figure 9 displays a photo of the townhouse building and the floorplans for the three floors in the apartment.

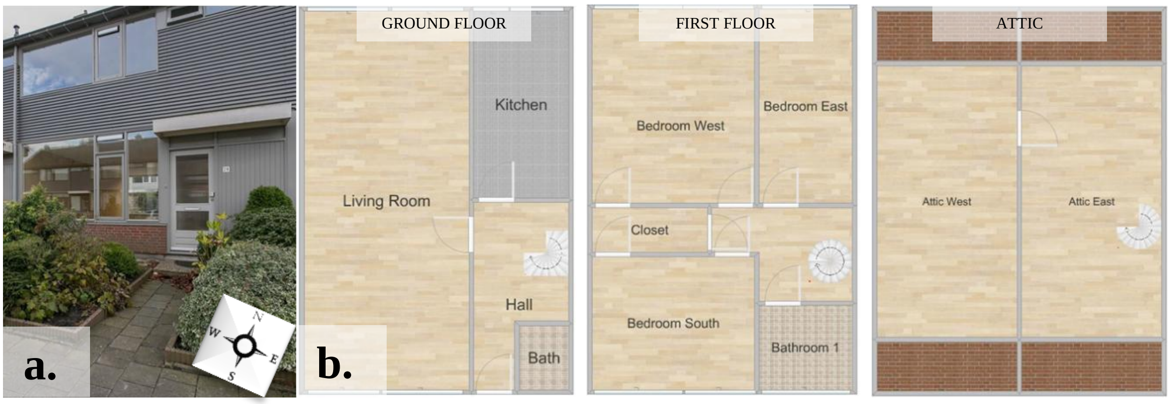
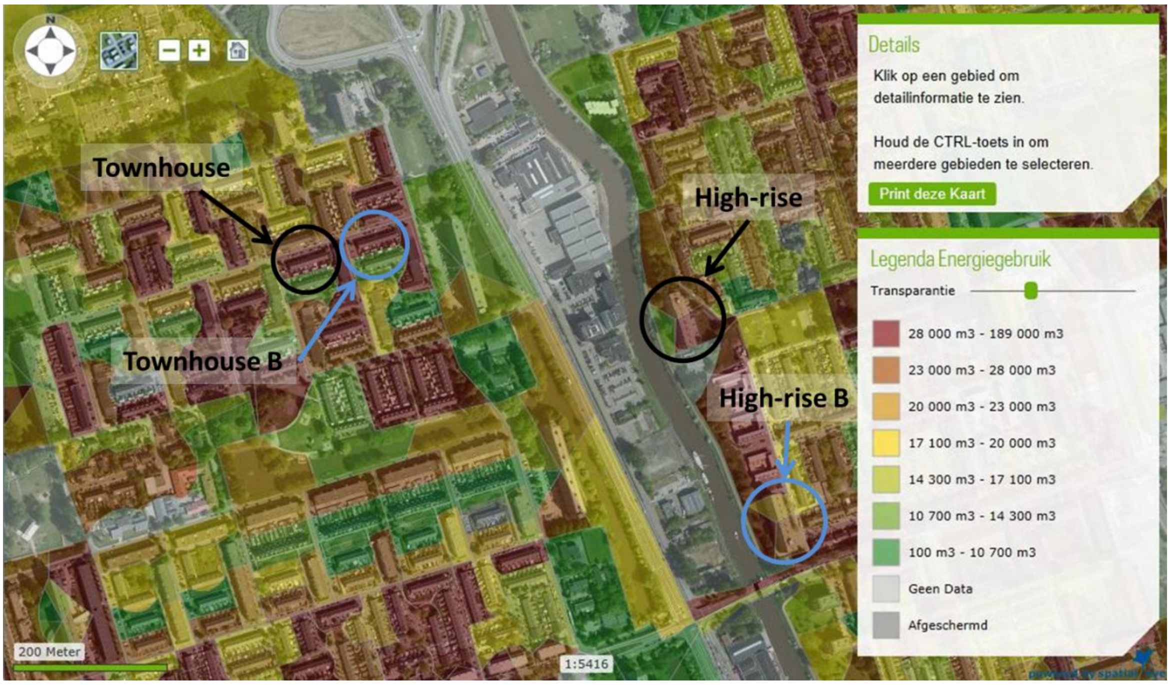


Figure 9 - a. Townhouse building; b. Floor plan of the apartment in the townhouse building showing the ground floor, first floor, and attic.

3.1.3. Measured buildings energy consumption

In order to find out the average energy consumption for these building types, a monitoring energy consumption software run by the main energy operators in Groningen named Energie in beeld was used [43]. Figure 10 shows how the software is displayed. This software shows the yearly gas consumption data throughout the city at a neighborhood level, with the summed energy consumption for groups of dwellings of the same type. A color code from red to green throughout the buildings in the city represents the amount of gas consumption in 2014 according to the description in the bottom right. The image can be either zoomed in or zoomed out to show the energy consumption for large or small groups of buildings, e.g. the whole gas consumption in Groningen or the gas consumption in a neighborhood. Figure 10 shows it at maximum zoom in, meaning that it is possible to know the gas consumption for a group of apartments, but not for a single apartment (due to privacy legislations). Thus, the average gas consumption for an apartment in a high-rise and in a townhouse building was calculated using more than one group of apartments displayed.

For the high-rise apartments, two buildings were used: the one mentioned in 3.1.1. and an identical one, named high-rise B in Figure 10. Each building has consumption data for 45 to 47 apartments from 2009 to 2014. For the townhouse apartments, a group of 16 buildings including the one in 3.1.2. and a group of 14 buildings identical to the previous named townhouse B were used. The first group also had consumption data for the whole fraction from 2009 to 2014, while the second had consumption data for 12 to 14 apartments over these years.


Details

Klik op een gebied om detailinformatie te zien.

Houd de CTRL-toets in om meerdere gebieden te selecteren.

Figure 10 – Energie in beeld software display showing the gas consumption for several buildings in Groningen. The buildings circled were the ones used to calculate average natural gas consumptions for typical high-rise and townhouse apartments.

Table 5 shows the high-rise and townhouse buildings yearly gas consumption divided by the number of apartments in each one of them, obtained from Energie in beeld. In Table 6, the correlation between both high-rise and townhouse gas consumption values is presented, showing how similar the variation of the yearly energy consumption between buildings is. The obtained correlation values prove that some of these vary in a very similar way due to climate changes and other possible factors, such as occupant behavior. Hence, by averaging the yearly gas demand for each building type, gas consumption values for the high-rise of 1 296m^3 and for the townhouse of of 1 899m^3 were used.

Table 5 – Yearly gas consumption in the high-rise and townhouse buildings divided by their number of apartments.

Year	***High-rise gas consumption (m^3)***	***High-rise B gas consumption (m^3)***	***Townhouse gas consumption (m^3)***	***Townhouse B gas consumption (m^3)***
2014	1 319	1 008	1 758	1 739
2013	1 340	1 147	1 907	1 753
2012	1 398	1 260	2 028	1 877
2011	1 409	1 287	2 018	1 877
2010	1 468	1 287	2 021	1 912
2009	1 366	1 261	2 076	1 953
High-rise average	1 296m^3	***Townhouse average***	1 899m^3	

Table 6 – Correlation between the different building group consumptions.

Correlation	***R^2***
High-rises	0.65
Townhouses	0.84
High-rise and Townhouse	0.45
High-rise B and Townhouse	0.93
High-rise and Townhouse B	0.47
High-rise B and Townhouse B	0.76

Assuming that the high-rise apartment has three occupants and the townhouse apartment has five, a comparison between both high-rise and townhouse archetypes in terms of their their gas consumption per number of occupants, gas consumption per floor area and floor area per number of occupants was made. The results, presented in Table 7, show that the two apartment types are relatively similar in all of the three normalized indicators. Both gas consumption per floor area and floor area per number of occupants values differ only in 6%, while the gas consumption per number of occupants values differ in 12% between the two archetypes.

Thus, it is assumed that typical Dutch high-rise and townhouse apartments do not diverge much from these profiles, with these being suitable representations for the whole residential building portfolio in the city.

Table 7 - Normalized indicators for the high-rise and townhouse buildings.

Archetype	***m^3 gas per occupants***	***m^3 gas per m^2 floor area***	***m^2 floor area per occupants***
High-rise	432	14.4	30
Townhouse	380	13.5	28.2
% difference	12%	6%	6%

3.3. Building Materials

A base case for typical residential building materials from the 1970s in the Netherlands was used for both high-rise and townhouse constructions [44], with the corresponding thermal properties from [45]. Moreover, a common exterior floor layout including riprap, ground slab and screed was considered in the second [46]. Since a few other materials such as brick, metal siding and wood floor are part of the two buildings considered, these were also included – Table 5 and Table 6. Windows were selected according to the fact that 75% of all Dutch dwellings have double glazing in every room [41]. The settings used for these were based on a study about courtyard and atrium dwellings in the Netherlands, with generic double glazed 3 mm clear windows and an air cavity of 13 mm between the layers [47]. Internal shading was also added to the living room, kitchen and bedrooms for both base case scenarios.

Table 8 – High-rise building materials.

		Material	***Thickness (m)***	***Conductivity (W/m.K)***	***Density (Kg/m^3)***	***Specific Heat (J/Kg.K)***	***Thermal resistance (m^2.K/W)***
Exterior Wall	**Outside**	*Metal Siding*	0.0015	44.96	7689	410	-
		Plaster board	0.012	0.22	800	840	-
		Air space	-	-	-	-	0.15
	Inside	*Plaster board*	0.012	0.22	800	840	-
Interior Wall	**Outside**	*Plaster board*	0.012	0.22	800	840	-
		Air space	-	-	-	-	0.15
	Inside	*Plaster board*	0.012	0.22	800	840	-
Interior Ceiling	**Outside**	*Concrete*	0.1	0.53	1280	840	-
		Air Space	-	-	-	-	0.18
	Inside	*Acoustic tile*	0.02	0.06	368	590	-
Floor	**Outside**	*Concrete*	0.1	0.53	1280	840	-
	Inside	*Wood Floor*	0.01	0.107	681	1210	-

Table 9 – Townhouse building materials.

		Material	***Thickness (m)***	***Conductivity (W/m.K)***	***Density (Kg/m^3)***	***Specific Heat (J/Kg.K)***	***Thermal resistance (m^2.K/W)***
Exterior Wall	**Outside**	*Brick*	0.1016	0.89	1920	790	-
		Air space	-	-	-	-	0.15
	Inside	*Plaster board*	0.012	0.22	800	840	-
Interior Wall	**Outside**	*Plaster board*	0.012	0.22	800	840	-
		Air space	-	-	-	-	0.15
	Inside	*Plaster board*	0.012	0.22	800	840	-
Exterior Roof	**Outside**	*Slate/tile*	0.0127	1.59	1920	1260	-
		Fiberboard sheating	0.0127	0.07	400	1300	-
		Batt Insulation	0.089	0.05	19	960	-
	Inside	*Plaster board*	0.012	0.22	800	840	-
Interior Ceiling	**Outside**	*Concrete*	0.1	0.53	1280	840	-
		Air space	-	-	-	-	0.15
	Inside	*Acoustic tile*	0.02	0.06	368	590	-
Floor	**Outside**	*Soil*	1.64	1.14	1000	1280	-
		Riprap	0.25	1.20	1000	800	-
		Ground Slab	0.1	2	2100	880	-
		Screed	0.1	1.35	1800	1000	-
	Inside	*Wood Floor*	0.01	0.107	681	1210	-

3.4. Infiltration

In a wide variety of articles, infiltration and ventilation values are presented as one. In this study, infiltration values are considered as the leakage rate of a building from cracks and ventilation values as natural ventilation.

Few publications address infiltration measurements in the Netherlands. *Hasselaar E.* [48] showed that the infiltration level ranged between 0.5-0.7ach$_{nat}$ for 38 dwellings, while *De Gids* [49] showed that over 50% of the ventilation rate reaches levels over 0.5ach$_{nat}$. Moreover, *Entrop et Al.* [50] measured a maximum of 0.53ach$_{nat}$ for buildings built since 1988, while *van der Wal et Al.* [51] showed that Dutch apartments averaged an air change rate of 0.6ach$_{nat}$. Therefore, standard infiltration flow rate the levels of 0.55ach$_{nat}$ and 0.65ach$_{nat}$ for the high-rise and for the townhouse respectively are considered.

3.5. Heating equipment

Latest data on housing settings in the Netherlands was made available by the Ministry of the Interior and Kingdom Relations in a report completed in 2013 [52]. It shows that 77% of the buildings are equipped with hot water boilers that have efficiencies between 85% and 93%, while 23% have efficiencies lower than 85%. This goes along with the information given to us by the Municipality of Groningen, showing the characteristics for a standard boiler currently used in most residential buildings – Table 10. Since this study focuses on older buildings that likely have lower boiler efficiency values, it is assumed an 85% yield for both case studies. Moreover, it is considered that these buildings are centrally heated with a hot water loop that has 20% distribution and emission losses [53-54].

Table 10 – Typical boiler used in most of the dwellings from the 1970s in Groningen.

Boiler	***Power***	***Pressure class***	***Supply temperature***	***Return temperature***
AWB Thermomaster SV	24kW$_{th}$	PN16	90ºC	70ºC

The radiators inside the apartments were sized considering the fact that in rooms with a height over 2.50m, which is the case for all rooms in the high-rise and townhouse dwellings, the power should be equal to 30W per room volume [55]. Furthermore, [55] also states that in poorly insulated buildings the power should be increased in 20%, which is also the case for the two households. Table 11 shows the sized radiator power per zone according to the floor plans presented in the subchapters 3.1.1. and 3.1.2.

Table 11 – Radiator power per zone in the high-rise and townhouse apartments.

	Zone	*Area (m^2)*	*Radiator power (W)*
High-rise	*Living Room*	26	2635
	Bedroom A	20.4	2068
	Kitchen	16	1621.3
	Hall	15.1	1519
	Bedroom B	11.2	1134
	Bathroom	4.8	486
Townhouse	*Living Room*	32	3000
	Attic West	19.5	1828
	Bedroom West	16.3	1526
	Bedroom South	13.1	1230
	Bedroom East	9.3	871
	Kitchen	9.3	871
	Hall	7.6	712
	Bath	4.4	409
	Bathroom 1	1.8	169

3.6. Occupant behavior model

User behavior and lifestyle, also known as occupant behavior, is characterized by the actions or reactions of an occupant to adapt to ambient environmental conditions, and it can affect energy consumption by up to a factor of two in dwellings with a similar theoretical energy performance [56].

Occupant behavior has been widely studied in several fields such as natural sciences, social sciences and economics, most of the times focusing on the relation between physical parameters (e.g. outdoor and indoor temperatures, solar radiation) and energy-related behavior [57]. For instance, when a person opens a window, several parameters might influence that choice. In literature, these are categorized as internal and external driving forces. Internal driving forces are a person's biological, psychological, and social influencing parameters, while external driving forces are the physical environment, the building properties and properties, and time [57].

Starting by the internal driving forces, the biological parameter is characterized by age, gender, clothing, health state and activity level of the occupant. The psychological parameter is associated to the people's expectations of indoor environmental quality and to financial and environmental concerns. Lastly, the social parameter is characterized by the interaction between all occupants in the same space.

In the external driving forces, the physical environment relates to temperature, humidity, air velocity, noise, illumination and indoor air quality. The building properties are associated with the insulation level, the materials, orientation, heating system and thermostat type. Finally, time is related to the season of the year, week or weekend day, and time of the day [57].

All these factors greatly influence heating energy use, so it becomes extremely complex to predict energy use through a vast amount of buildings, where each occupant has their internal driving forces. Thus, the most decisive factors that include as many internal driving forces as possible and influence how occupants heat their homes in the Netherlands have been identified and presented below.

3.6.1. Heating use

Heating use is one of the factors that already take into account most of the internal driving forces previously mentioned. For this study, typical heating use was taken from a national report which states that the highest and lowest thermostat chosen temperatures follow a standard pattern of 20ºC and 16ºC respectively, with the highest being set mostly during the day/evening and the lowest being set overnight - Table 12 [58]. These values resulted from residential surveys, building inspections and dwellings energy use data across the Netherlands – the WoON database - containing a considerable amount of samples enough to represent how Dutch people behave [59].

Table 12 – Used temperature patterns in the thermostat settings.

Type	***Pattern***	***Use percentage***
Standard	At night: 16ºC; During the day: 19ºC; In the evening: 20ºC.	48%
Low	At night: 15ºC; During the day: 15ºC; In the evening: 18-19ºC.	19%
High temperature	At night: 19ºC; During the day: 21ºC; In the evening: 21ºC.	8%
Others	-	25%

3.6.2. Natural ventilation

Natural ventilation affects the indoor climate of a building and is subsequently another factor that greatly influences energy consumption. Wind driven ventilation is one of the two types of natural ventilation occurring in buildings (with the other being buoyancy-driven ventilation) and is the one considered in this section, happening when windows are open. Window-opening behavior is also driven by most of the internal and external forces previously described [57], where regularly opening the windows during the night in the winter or during the day throughout the year is shown to have a substantial effect on energy consumption [60-61].

In the Low Countries (Belgium and the Netherlands), windows are more often opened in the morning and at night than any other period of the day [62], with a higher proportion of open windows in the weekend than during the week [63]. The WoON database also contains information on how often occupants open their windows in each part of the house – Table 13. Therefore, this data was used for all days except those in the summer, where windows are open when indoor temperatures reach 23ºC. Further, data on how often people turn off their heating while opening the windows is equally available and was equally used.

Table 13 - Typical occupant behavior on window-opening behavior in the Netherlands [59].

	Time windows are open (minutes/day)	*Time windows are open when heating is off (minutes/day)*
Living Room	64	38
Kichen	57	43
Bedrooms	431	366
Bathrooms	114	31

3.6.3. Internal gains

Internal gains are also a factor affecting energy consumption, since its use can reduce the heating load [64]. People, lights and electric equipment are the principal internal gains considered. Dutch people's typical presence at home was deduced from a time use survey done by the Netherlands Institute for Social Research (TBO) every five years, which studies what people are doing every five minutes during seven consecutive days throughout the year [65]. Figure 11 shows a typical week day and weekend day for a Dutch person according to the TBO data.

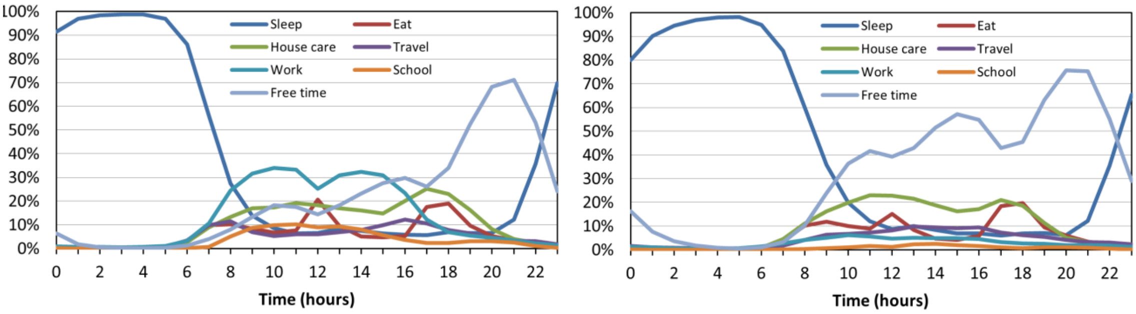


Figure 11 - Average time use in the Netherlands during weekdays (in the left) and weekend days (in the right).

In order to convert this data into how often Dutch people are home and outside, the time distribution presented in Table 14 is considered. According to a study done by CBS, people work on average six hours a week from home, which corresponds to approximately 5% of their weekly work load [66]. Moreover, as stated in a time use study done by The Netherlands Institute for Social Research, Dutch people spend on average 133 minutes of their day doing activities such as socializing, going to the cinema, theatre, concerts, exhibitions or museums, sports, etc. In contrast, they spend 191 minutes of their day resting, watching television, reading and using their computer for leisure [67]. Thus, the former outside presence and the latter home presence are used. Since, there are no available references to all the other activities, the values displayed on Table 14 are assumed.

Table 14 – Home and outside time distribution in the Netherlands.

Activity	*Home (%)*	*Outside (%)*	*Reference*
Sleep	100	0	-
Eat	50	50	-
House care	100	0	-
Travel	0	100	-
Work/School	5	95	[62]
Free time	59	41	[63]

Thus, Figure 12 shows the obtained approximation on how often people are home and outside. Overall, Dutch people spend 68% and 76% of their time at home during week and weekend days respectively. The corresponding internal gains per person considered were 80W during sleep and 120W during the rest of the time [68].

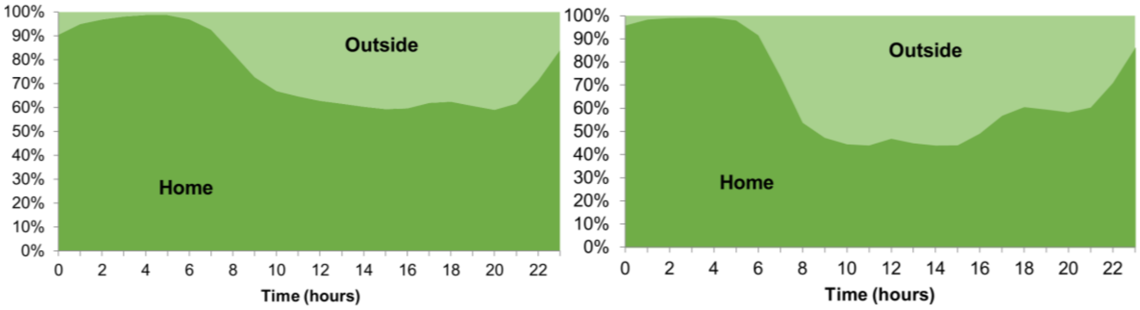


Figure 12 - Time spent at home and outside by the Dutch population. The figure in the left depicts weekdays and the right weekends.

Occupancy schedules in the kitchen, living room and bedrooms were based on [69], where the occupants are in the bedrooms from 10 pm to 8 am and in the other parts of the house from 8 am to 10 pm. Typical lighting and electric equipment use in the Netherlands were taken from [70] and are presented in Table 15.

Table 15 – Typical lighting and electric equipment use by the Dutch population [70].

	18:00 – 19:00 h	*19:00 – 23:00 h*	*23:00 – 18:00 h*
Electric equipment	100W	100W	25W
Kitchen Electric Equipment	600W	250W	250W
Lighting	15W/m^2 from 19:00 – 23:00 h in the Summer and from 17:00 – 23:00h in the Winter		

4. Refurbishment measures

This section presents the refurbishment measures used to reduce energy consumption for space heating in residential buildings. Several studies point towards the need to reduce energy demand with the right set of measures according to their study location and building typologies. These studies are presented in Table 16, serving as a review for similar work done in the field. For instance, the first three case studies listed are based on colder climates, particularly in northern Europe, in Denmark and Sweden [71-73]. All three studies follow the same refurbishment measures pattern: improving insulation of the buildings and reducing infiltration values. These measures led to an average energy reduction of 24%. Different modelling approaches were followed to achieve the results. *Thomsen et Al.* [71] used measured data before and after the refurbishments, while *Petrovic et Al.* [72] developed a heating model to calculate potentials and costs of the heat saving measures. *Wang et Al.* [73] used a simulation software called Indoor Climate and Energy performance simulation program (IDA ICE) for the simulation of thermal performance and energy modelling of the buildings.

The following three studies consider slightly less cold climates, in countries such as Germany, Ireland and the Netherlands [74-76]. In these, the retrofitting measures implemented were not only the ones previously mentioned but also adding solar shading, having a vegetated roof and solar thermal hot water, reaching an energy reduction as high as 90% for heating. *Van Hoof et Al.* [74] used EnergyPlus as their modelling approach, while *Konstantinou et Al.* [75] used Capsol, which is a software developed by Physibel. *Dineen et Al.* [76] used the Dwelling Energy Assessment Procedure (DEAP) associated software, which follows a calculation framework based on ISO 13790:2008, which takes into account space heating, water heating, ventilation and lighting calculated on the basis of standard occupancy, heating patterns and internal temperature.

The last two studies are done for southern Europe, in Italy and Spain [77-78]. These also consider most of the measures previously mentioned, with the difference of also improving the boiler. The results in both papers also show that considerable reductions could be achieved. *Cellura et Al.* [77] developed a heating model by combining an Input-Output Analysis and a Life-Cycle Assessment proposed in an earlier paper from the same authors to make both energy and environmental analysis. *Ortiz et Al.* [78] used EnergyPlus to assess how thermal discomfort could be lowered in the cold season.

In our approach four main measures were considered:

- Improving thermal insulation of both external buildings surfaces and windows;
- Improving airtightness of the buildings;
- Upgrading the boiler
- Shifting to a more efficient occupant behavior.

These were chosen based on the studies presented in Table 16 and on the high-rise and townhouse building envelopes where refurbishment is the logic step when turning older buildings into more energy efficient ones, being described in the following subchapters.

Table 16 - Overview of studies focused on heating energy consumption reduction in residential buildings. DEAP: Dwelling Energy Assessment Procedure – model developed by the Sustainable Energy Authority of Ireland to produce Energy Performance Certificates. IOA: Input-output analysis; I: Walls, roof and/or windows insulation; B: Boiler; V: Vegetated roof; I*: Infiltration; SS: Solar Shading; ST: Solar thermal hot water.

Reference	*Location*	*Approach*	*Energy Efficiency Improvements*						*Cost Analysis*	*Energy Savings*
			I	*B*	*V*	*I**	*S*	*ST*		
Thomsen et Al. [71]	Denmark	Measured	●	○	○	●	○	○	x	31% heating
Petrovic et Al. [72]	Denmark	Heating model	●	○	○	●	○	○	x	20-25% heating
Wang et Al. [73]	Sweden	IDA ICE	●	○	○	●	○	○	-	16-22.2% heating
van Hoof et Al. [74]	Netherlands	EnergyPlus	●	○	●	○	●	○	-	57% for a 1970's townhouse
Konstantinou et Al. [75]	Germany and Netherlands	Capsol	●	○	●	●	○	●	-	90% heating
Dineen et Al. [76]	Ireland	DEAP	●	●	○	○	○	●	-	Up to 240kWh/m^2 per annum
Cellura et Al. [77]	Italy	Heating model	●	●	○	○	○	●	x	254TJ for the whole country
Ortiz et Al. [78]	Spain	EnergyPlus	●	○	○	○	●	○	x	-

4.1. Increased thermal insulation

In this study, bulk insulation was added to all external building surfaces by injecting 50mm of insulation with a thermal conductivity of 0.03W/m.K into the walls [45]. These were the settings chosen due to the fact that most Dutch buildings built between 1920 and 1974 have cavity walls between 50mm and 80mm [79].

Further, reflective insulation was also added by replacing all double glazed windows in the living room, kitchen and bedrooms by windows with low emissivity coatings located in the exterior face of the interior glass, with a light transmittance of 55% and an infrared emissivity of 0.05 [80-81]. These significantly reduce the amount of infrared light passing through the windows, maintaining the building warm for a longer period of time.

4.2. Increasing the airtightness

A centralized MVHR unit is installed in the townhouse building, while a decentralized one is used for the high-rise. Since these systems have manual settings that allow the user to reduce the infiltration levels to a chosen value, they were reduced to a value as close as the Passive House standard: roughly 0.06ach in the whole dwellings [29]. Although this is not a passive measure, [82] states that the tradeoff between the electricity needed and the heating load reduced is highly favorable, thus the energy required becomes negligible when compared to other residential energy uses.

4.3. Replacing the boiler

Since current boilers in both apartments have efficiency values of 85%, about 15% of the energy used to heat the water is wasted. Although this seems like a reasonable value for a boiler (old, low efficiency heating systems reach values between 56% and 70%), they still already have 20 years, which goes beyond their estimated lifespan: 12 to 15 years [83]. Thus, replacing the boilers is not only a refurbishment measure but also a mandatory one.

As prevlsously mentioned, state of art condensing boilers can reach theoretical efficiencies of 107%. Hence, conventional boilers in the high-rise and townhouse dwellings were switched to highly efficient condensing boilers with an actual performance of 98% based on [84].

4.4. Improving occupant behavior

Window opening behavior has a high impact on heating demand, particularly because most windows are left open for a very long period of time throughout the day. This leads to either having to make up for the heat that was lost while the windows were left open or to maintaining the heating on while natural ventilation occurs. Thus, a more efficient occupant behavior is proposed where windows are not opened as much as they currently are, with natural ventilation in the bedrooms being reduced to 60 minutes per day, while in the living room, kitchen and bathroom being reduced to 30 minutes per day. Nevertheless, since it is difficult to persuade people into following this behavior, two views further in the study are provided: one showing the total potential energy reduction where people improve their occupant behavior and one where they do not. Table 17 shows how long the windows are typically open every day in the Netherlands versus the time proposed as an efficiency measure. In the latter, heating is always off when the windows are open.

Table 17 – Current window opening behavior versus improved window opening behavior.

	Time windows are currently open (minutes/day)	***Time windows are open with the improvement (minutes/day)***
Living Room	64	30
Kichen	57	30
Bedrooms	431	60
Bathrooms	114	30

5. Building thermal simulation

5.1. Weather file

An International Weather for Energy Calculations (IWEC) file containing weather data for the city of Groningen was used [85]. This file is derived from 18 years of hourly weather data including information on the wind speed and direction, dry-bulb temperature, dew-point temperature, atmospheric pressure, liquid precipitation and others.

5.2. Buildings geometry

Figure 13 shows the geometry built for the high-rise and townhouse apartments using Google Sketchup. The high-rise model represents an apartment located in the center of the building, at a height of 11.5 meters. A few details from the floorplan presented in Figure 8b were simplified for the simulation, and external shading was added to both sides to simulate the shading caused by the upper floor balconies. The townhouse model also represents an apartment located in the center of the row, directly connected to the ground. The three floors look exactly like the floorplan presented in Figure 9b. In both models, the surfaces in the left and right side of the buildings are connected (*Outside Boundary Condition: Surface*), as well as the interior ceiling and interior floor in the high-rise. This gives an approximation of the heat losses through these surfaces. The buildings orientations are also the same as in reality, with the high-rise front facing east and the townhouse front facing south.

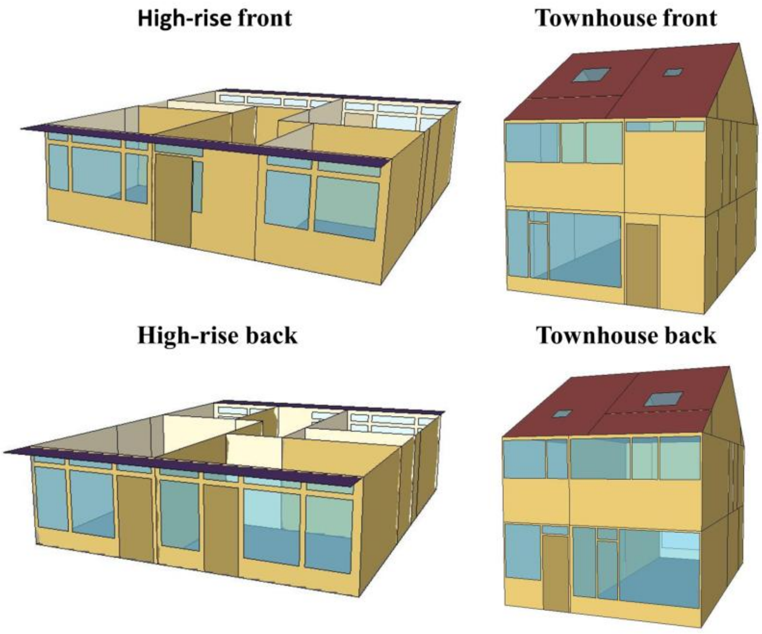


Figure 13 - Simulation architecture for the high-rise and townhouse apartments.

The window to floor area ratio in the high-rise and the townhouse apartments is 15% and 21% respectively. Table 18 shows the floor and glazing areas in each zone.

Table 18 – Floor area and glazing area per typology zone.

	Zone	*Area (m^2)*	*Glazing area (m^2)*
High-rise	*Living Room*	26	4.7
	Bedroom A	20.4	6.9
	Kitchen	16	4.2
	Hall	15.1	0.6
	Bedroom B	11.2	3.4
Townhouse	*Living Room*	32	13.8
	Attic	19.5	2.5
	Bedroom West	16.3	4
	Bedroom South	13.1	4
	Bedroom East	9.3	2.5
	Kitchen	9.3	2.1
	Bathroom 1	1.8	0.5

5.3. Simulation and building parameters

Once the building geometry is defined, a few simulation parameters need to be specified on EnergyPlus, such as the simulation type and calculations performed, the heat transfer algorithm, the number of timesteps for heat transfer and load calculations and the run period of the simulation. Further, all building parameters are also specified in the software, such as the building materials, the infiltration and natural ventilation settings, the heating system and the occupant behavior characteristics.

The simulation type and calculations performed are chosen in the *SimulationControl* class. The fields selected were to do zone sizing calculations and to run the simulation for weather file run periods. This means that a theoretical ideal zonal system is used, determining the zone design heating and cooling flow rates and loads, and that the simulation is run on all the *RunPeriods*, which is from the 1st of January to the 31st of December. The number of timesteps per hour used was 12.

The heat transfer algorithm selected for interior surface convenction was the detailed natural convection model, where the heat transfer coefficient is correlated to the temperature difference for several orientations. For the exterior side of the interior surfaces, the convection algorithm considers heat transfer coefficients that depend on rugosity, wind, terrain and location. The heat transfer by radiation coefficients are all calculated by the program automatically. The heat transfer algorithm for the building surroundings was the *ConductionTransferFunction*, which considers sensible heat and does not take into account neither moisture storage nor diffusion in the building materials.

As for the buildings, the terrains chosen for the high-rise and townhouse in the *Building* class were *Suburbs* and *City* respectively, due to their locations. Also, the solar distribution considered was

FullExterior, where all beam solar radiation entering the zone is assumed to fall on the floor, being absorbed according to the floor's solar absorptance. The reflected radiation is added to the transmitted diffuse radiation, which is then assumed to be uniformly distributed on all interior surfaces.

The building materials, occupant behavior and people schedules were all introduced as described in Chapter 3, in the *Material, WindowMaterial, Construction, Schedule, People, Lights and ElectricEquipment* classes. The thermostat, hot water loop and boiler were all sized using the *HVACTemplate*, which allows for the specification of simple zone thermostats and heating systems with hot water boilers. A baseboard heating system was chosen, with heating capacities per zone as stipulated in 3.5. This template also attaches a hot water loop from the boiler to the baseboard heating system throughout the various zones, which is assumed to have the default settings proposed by the program. The boiler was sized as shown in 3.5.

Natural ventilation and zone infiltration were simulated using the *AirflowNetwork* model. This model simulates multizone airflows driven by outdoor wind during all simulation timesteps, by performing pressure and multizone airflow calculations. Moreover, zone infiltration was input by matching an air mass flow when openings are closed to the infiltration flow rates considered for each apartment in 3.4. The program automatically generates four cracks on the windows, where the crack flow is equal to the air mass flow when openings are closed. The equation in the calculation is the same as the one presented in 3.4.

5.4. Energy consumption simulation

The high-rise building was simulated according to ASHRAE's simulation model [86] where the apartments are treated as separate thermal blocks – Figure 14 shows the model applied to our case study. The number of simulations performed accounts for the significance a thermal block has in the building as a multiplying factor. Since dwellings in the center and bottom of the high-rise have similar conditions, they were both combined. Thus, the apartment in the center was simulated fifteen times, while left and right apartments were simulated twice and the top apartment was simulated five times. A similar approach was used for the townhouse buildings, where the apartment in the center was simulated six times, while the apartments in the corner were simulated once.

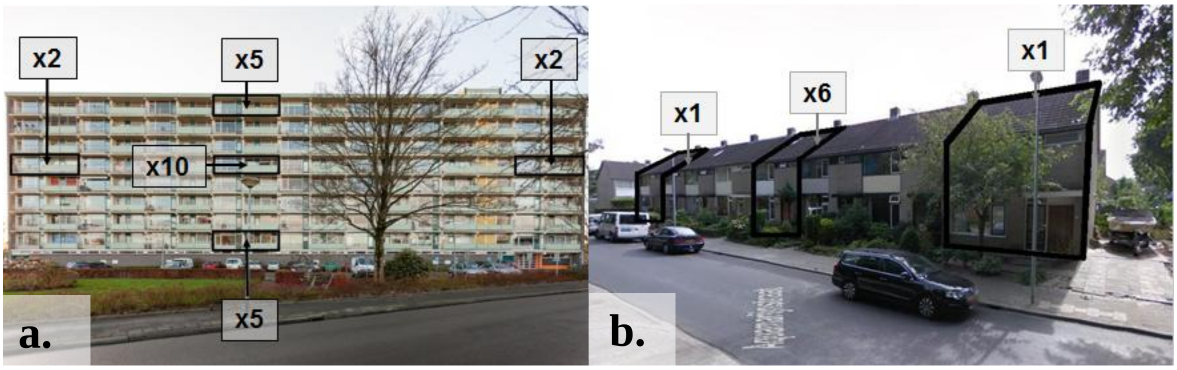


Figure 14 - Thermal blocks multiplying factor for the high-rise (a.) and townhouse (b.) buildings.

5.4.1. Calibration procedure

The gas consumption was obtained using the output *Boiler Gas Energy*, giving hourly energy consumption data per thermal zone in Joule (J). Since the gas consumption in the Energie in Beeld software is only displayed in m^3, the simulation value was converted using a gas heating value of $10.75 kWh/m^3$ [87].

Then, the simulated amount of gas needed for space heating was compared with the actual buildings energy consumption. Table 19 shows the simulated annual gas consumption for the high-rise and townhouse thermal blocks. It is noticeable that apartments with higher exposure to the exterior environment have a higher energy demand due to increased thermal losses through external walls. Hence, a weighted average based on the annual gas consumption following the approach in Figure 14 was calculated, where $1263m^3$ for the high-rise and $1928m^3$ for the townhouse were the obtained results.

Table 19 – Simulated annual gas consumption for the high-rise and townhouse thermal blocks.

Location	**Annual gas consumption (m^3)**	
	High-rise	*Townhouse*
Top	1424	-
Left	1472	2382
Center	1085	1866
Right	1540	2343
Weighted average	1263	1928

Table 20 compares the measured buildings annual gas consumption with the simulation values, showing that these barely differ - in both high-rise and townhouse cases this difference is equal to 2%. It is also depicted how much of the simulated annual gas consumption is typically used for heating, hot water and cooking in Dutch homes based on [9]. Since this study is only focused on reducing gas consumption for space heating, the other two will not be considered. However, it is relevant to mention that by improving the efficiency of the boilers, a considerable energy reduction for hot water needs is also achieved.

Table 20 - Actual and simulated annual gas consumption with the corresponding use distribution for space heating, hot water and cooking.

	Annual gas consumption (m^3)	
	High-rise	*Townhouse*
Real	1296	1899
Simulation	1263	1928
Heating	998	1523
Hot Water	240	366
Cooking	25	39

The following chapters focus on improving high-rise and townhouse apartments located in the center of the building/row, with annual heating demands of 857m^3 and 1474m^3 respectively – Table 21.

Table 21 - Centered high-rise and townhouse apartments total and heating annual gas consumption used for the case study.

Apartment location	**Annual gas consumption (m^3)**	
	High-rise	*Townhouse*
Center (all end uses)	1085	1866
Center (heating)	840	1447

5.4.2. Energy performance before refurbishments

An evaluation of the buildings energy performance before implementing efficiency measures was first conducted. Figure 15 displays the monthly heating demand for the high-rise and townhouse dwellings, showing that both are quite similar throughout the year. January and December are the two months with the highest heating demand, averaging 17kWh/m^2 for both building types. On the other hand, the heating demand from July to August is nearly zero, mostly due to much higher solar gains compared to the other months. Figure 15 also shows the relation between the heating demand and the average dry bulb temperature for each month, where it can be seen that the first is highly influenced by the second. In most months, the higher the temperature the lower the heating demand.

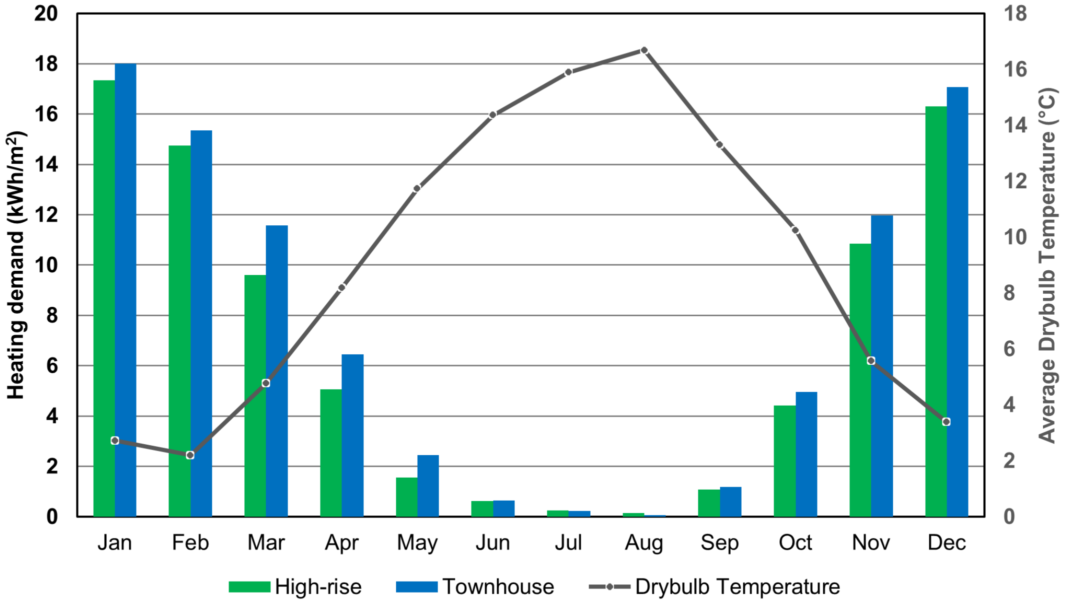


Figure 15 - Monthly heating demand for the high-rise and townhouse apartments with the corresponding average dry bulb temperatures.

As previously mentioned, heating demand is mostly due to heat losses through walls, windows, infiltration and natural ventilation. Figure 16 depicts how these are distributed in the high-rise and townhouse dwellings, showing that globally, heat losses are higher in the townhouse building. Although the window to floor area ratio is higher in the townhouse, heat losses through the windows are relatively similar to the ones verified in the high-rise. However, heat losses through natural ventilation are considerably higher in the townhouse, which is due to the fact that there is a higher number of bedrooms, and thus more windows are open.

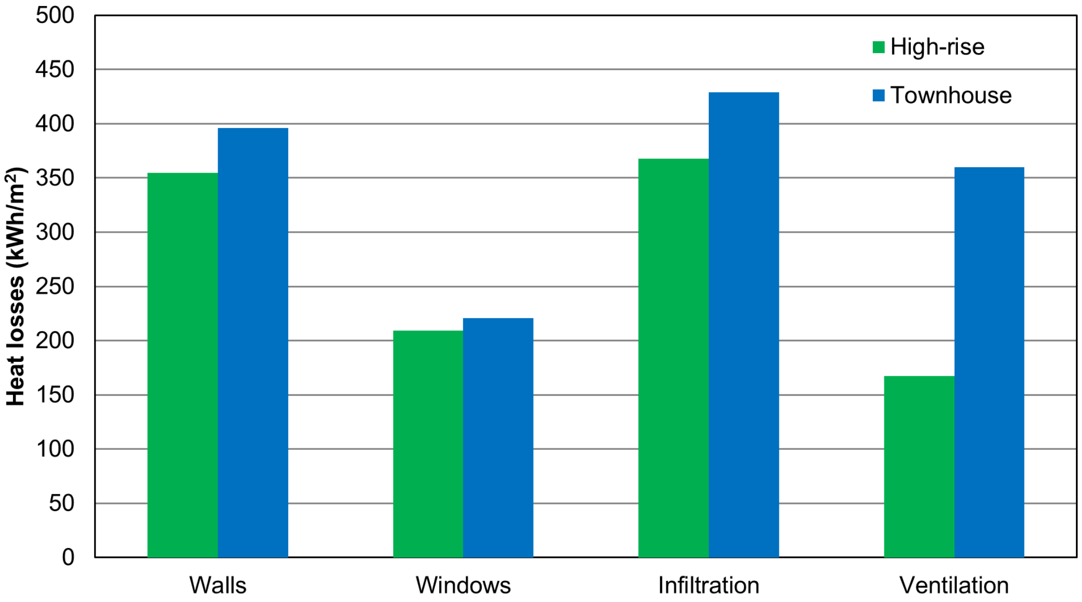


Figure 16 - Yearly heat losses in the high-rise and townhouse apartments.

Heat losses through exterior walls are also higher in the townhouse, which is an expected consequence of the difference in materials between the two dwellings. These are quite similar to the heat losses caused by infiltration, which is the main responsible for heat losses in the two dwellings, and consequently the main factor linked to gas demand. Infiltration losses are evidently higher in the townhouse, where the number of air changes per hour in each zone is higher than in the high-rise. Since these losses are the highest and most relevant for gas consumption, the monthly relation infiltration and natural ventilation have with wind speed was analyzed – Figure 17.

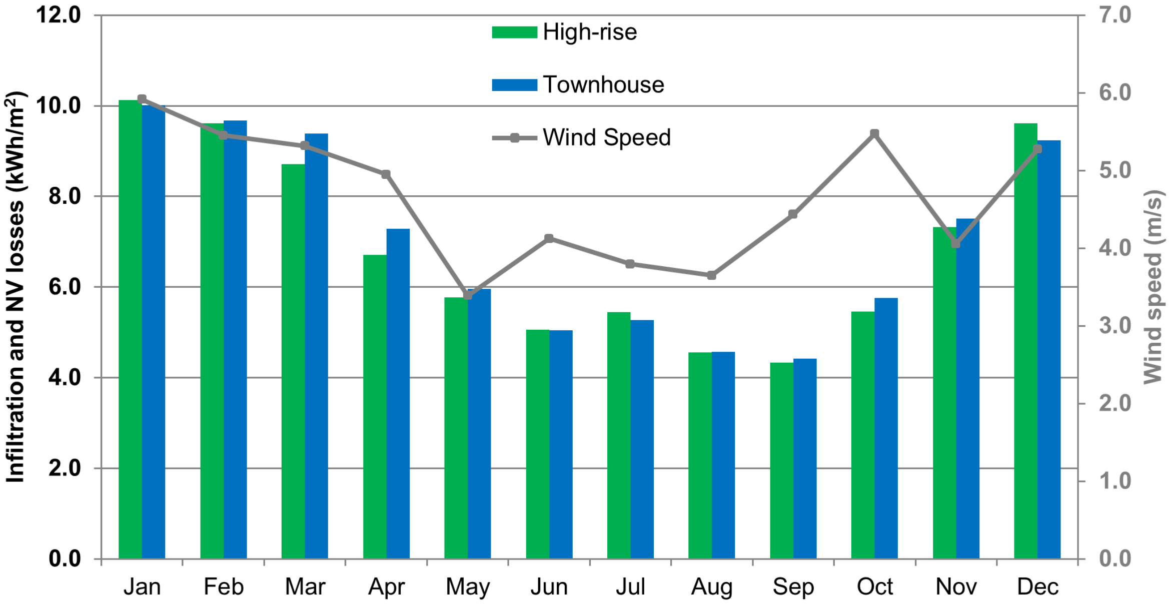


Figure 17 - Relation between infiltration and natural ventilation (NV) losses and wind speed.

It is clearly visible that with some exceptions (June, September and November), infiltration and natural ventilation losses follow a similar pattern to wind speed, showing a clear relation between the two. This means that in particularly windy areas, the impact in heat losses caused by these factors rises, and consequently increases the energy consumption.

6. Results

The simulation results obtained regarding buildings energy performance after refurbishment measures were implemented and the comparison between following the geothermal or the refurbishment scenarios are presented in the next subsections.

6.1. Energy performance after refurbishments

To evaluate the impact each refurbishment measure has on gas consumption, these were implemented in three different phases with the following order:

1. Building envelope (Thermal insulation + Airtightness);

2. Boiler replacement;

3. Improved occupant behavior.

Table 22 depicts how the annual gas consumption reduced through each implemented measure, having in mind that each phase includes the measures implemented in the phase before. Building envelope improvement measures accounted for 77% and 59% reductions in gas demand for the high-rise and townhouse respectively, while boiler replacements considerably increased these reductions to 86% and 65%. With an improved occupant behavior, the annual gas consumption was reduced to a total of 96% for the high-rise and 86% for the townhouse. However, since it is quite difficult to control whether or not people follow the same energy efficient behavior in the course of the analysis, this is considered to be the maximum potential for gas savings, while the actual energy reduction is assumed to be the one registered until the boiler replacements.

Table 22 - Annual gas consumption reduction through each refurbishment measure phase.

Refurbishment measures	**Annual gas consumption (m^3)**	
	High-rise	*Townhouse*
Current energy consumption	840	1447
1. Building envelope	186	590
1. + 2. Boiler replacement	133	482
1. + 2. + 3. Improved occupant behavior	39	207

It is noticeable that the first measure implemented had a greater impact in the high-rise rather than in the townhouse. This is mainly due to the effect caused by the thermal insulation added to the walls, which is bigger in the high-rise because it has a higher wall area per floor area. The second measure had a similar impact on both buildings, while the third measure caused a much greater reduction in gas demand for the townhouse. This happens because the townhouse has more bedrooms per total floor area than the high-rise, where natural ventilation habits lead to greater heat losses.

Table 23 shows the total reduction in heat losses for each feature of both dwellings influenced by the refurbishment measures considered. As expected, heat losses through walls decreased less in the townhouse, while the decrease in heat losses through natural ventilation was lower in the high-rise. Table 23 also indicates that there was a slight increase in heat losses through windows in the high-rise, which is linked to the fact that the apartment is effectively warmer for a longer period of time rather than it used to. However, results show that this increase did not significantly impact energy demand, since the reduction in gas consumption was still higher for the high-rise compared to the townhouse.

Table 23 - Change in the annual heat losses after all measures were implemented.

	Heat losses	
Through:	*High-rise*	*Townhouse*
Walls	-43%	-35%
Windows	+8%	-8%
Infiltration	-80%	-80%
Natural Ventilation	-63%	-69%

As shown in Figure 18, the most prominent heat loss reductions in the high-rise apartment happened in the *Bedroom B* and *Hall* zones, with reduction values of 54% and 56% respectively. *Bedroom A* and *Kitchen* reached reduction percentages of 46%, while heat losses in the *Living Room* were reduced in 40%. In all zones, reducing infiltration was the main cause for the heat losses overall reduction, followed by insulating the walls and improving the occupant behavior.

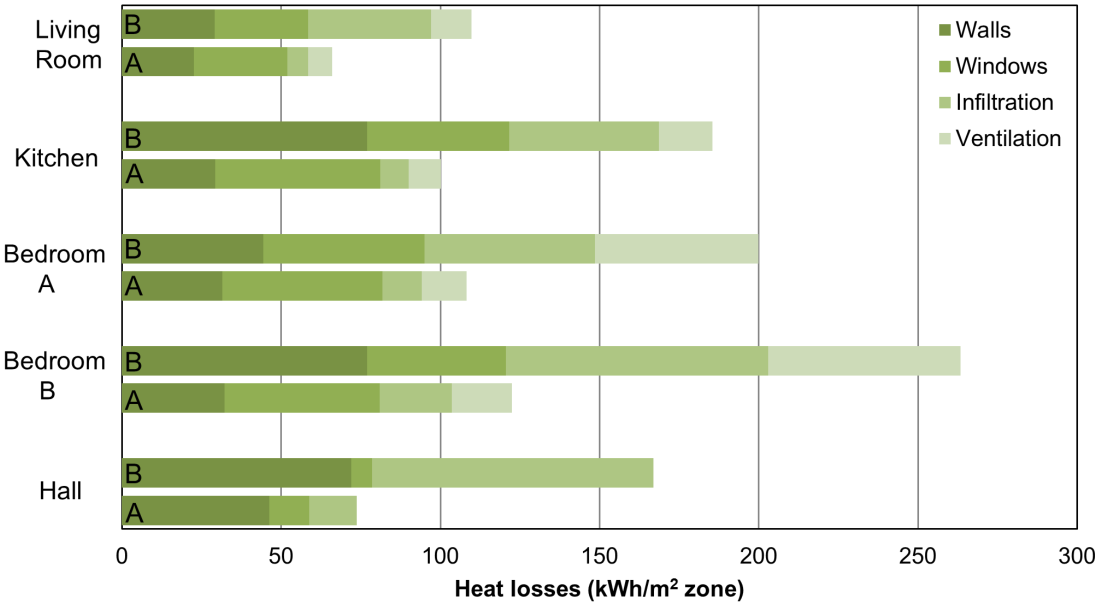


Figure 18 - Heat losses before and after refurbishments in the high-rise apartment. Columns with a B represent heat losses before the refurbishments and columns with an A denote heat losses after the refurbishments.

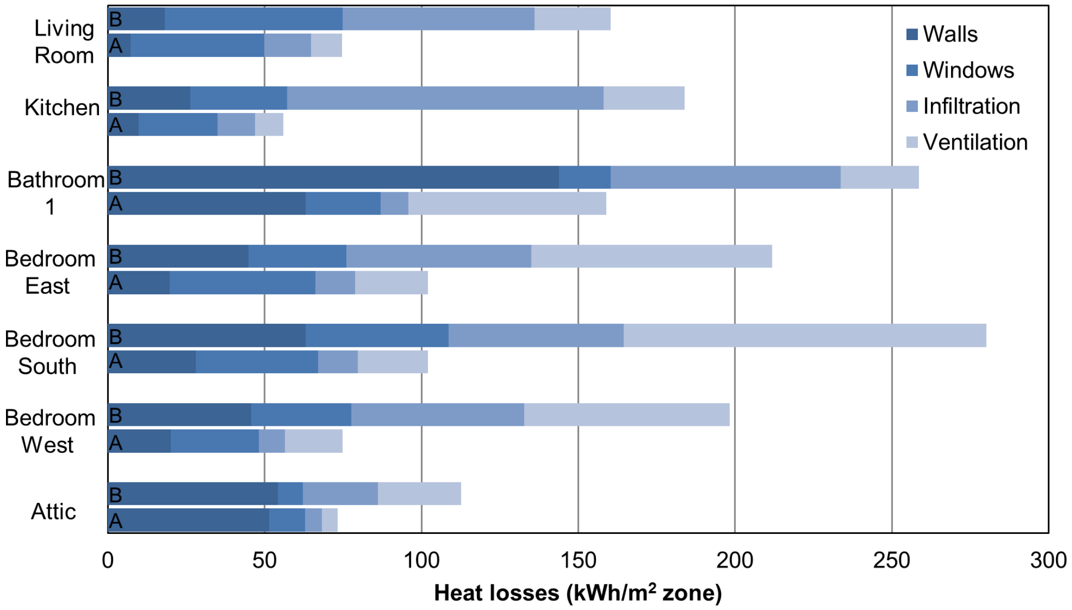


Figure 19 - Heat losses before and after refurbishments in the townhouse apartment. Columns with a B represent heat losses before the refurbishments and columns with an A denote heat losses after the refurbishments.

In the townhouse, the highest heat loss reduction took place in the *Kitchen*, reaching a reduction value of 70% – Figure 19. In the bedrooms, the reductions were equivalent to 64%, 62% and 62% in the *Bedroom South*, *Bedroom West* and *Bedroom East* respectively. In the *Living Room*, the reduction percentage was 53%, while the lowest reductions happened in the *Bathroom 1* and *Kitchen*, with values of 39% and 35% respectively. Once again, improving the airtightness proved to be the most effective refurbishment measure against heat losses. Also, by having more bedrooms, improving the occupant behavior also allowed significant heat loss reductions. Moreover, except for the *Attic*, wall insulation reduced the heat losses in every zone by approximately 50%. The other zones in the apartment (*Bath*, *Closet* and *Hall*) are not relevant for this analysis, since they do not have windows.

6.2. Overheating risk

After all refurbishment measures were implemented, it was analyzed whether or not maximum indoor temperatures reached unacceptable levels in both apartments. Since overheating risk is only an issue during the summer, this section focuses on all days from the beginning of June to the end of September.

Results shown in Figure 20 illustrate the difference in operative temperatures between the dwellings before and after refurbishments. It is quite clear that in both cases the apartments tend to stay warmer after the measures were implemented, with the highest number of hours between 23ºC and 25ºC in the high-rise and between 20ºC and 25ºC in the townhouse. It is also shown that temperatures above 25ºC occur during a very similar amount of hours between non refurbished and refurbished dwellings, proving that the measures implemented do not particularly cause indoor operative temperatures to reach levels that were not already being reached before. This happens because dry bulb temperatures are not significantly high in Groningen, with average summer temperatures below 20ºC, thus the impact caused by the refurbishment measures is easily overcome with natural ventilation.

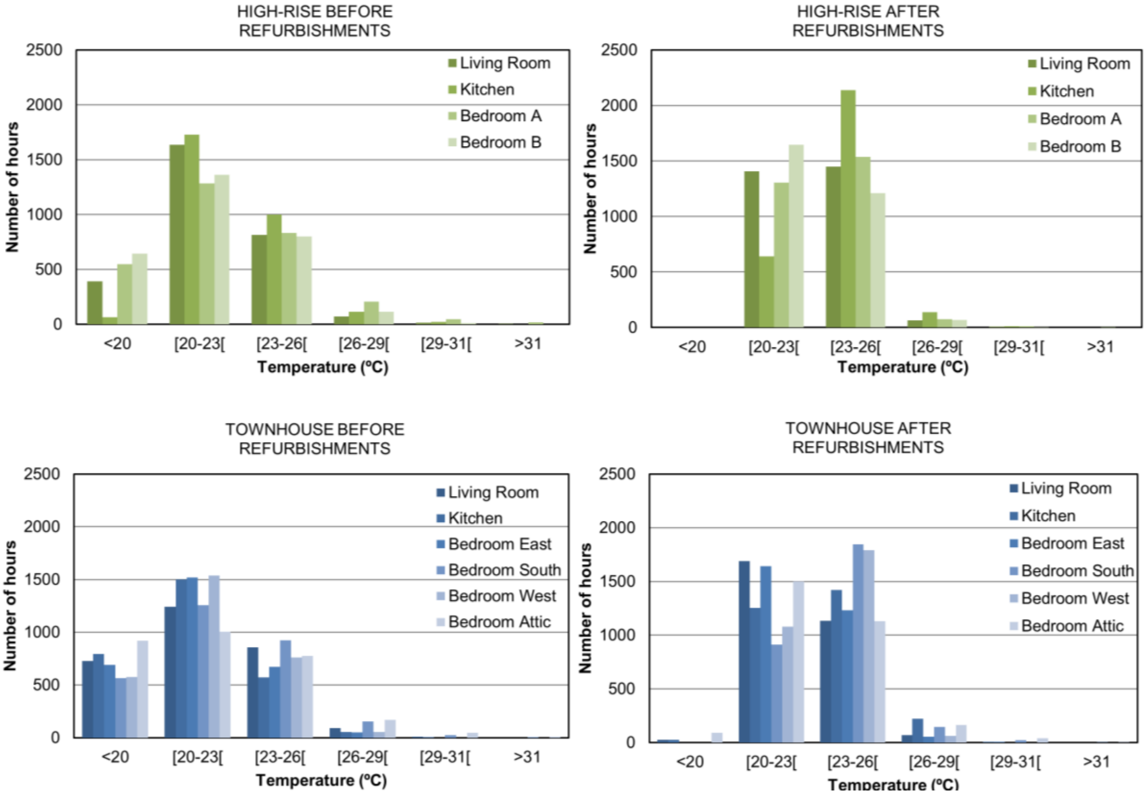


Figure 20 - Operative temperatures range before and after the refurbishments in the high-rise and townhouse dwellings.

Nevertheless, despite the fact that refurbished apartment temperatures reach higher levels more frequently in comparison to the current building scenarios, these do not surpass comfort levels more than 1% of the time – Figure 21. These comfort levels are set by ASHRAE's standard 55, where the allowable indoor operative temperatures are based on an adaptive model of thermal comfort derived from over 21 thousand measurements [92]. The model comprises an 80% acceptability range, defining upper and lower limits distanced by 14ºC.

Figure 21 only considers living room and bedroom zones with the highest temperatures. The results show that in the high-rise *Bedroom A* there are 11 overheating hours distributed through three different days, while in the *Living Room* there are 5 overheating hours distributed through two days. In *Bedroom A*, the warmest day has a maximum of four overheating hours, while in the *Living Room* the warmest day has a total of three overheating hours. In the townhouse, *Bedroom South* has a total of 15 overheating hours distributed through four days, whereas there is only one overheating hour in the *Living Room.* However, in *Bedroom South* there is a day with a total of 9 overheating hours.

It is then legitimate to conclude that the refurbishment measures considered do not negatively impact operative temperatures in both dwellings and that overheating is not a concern in our case study.

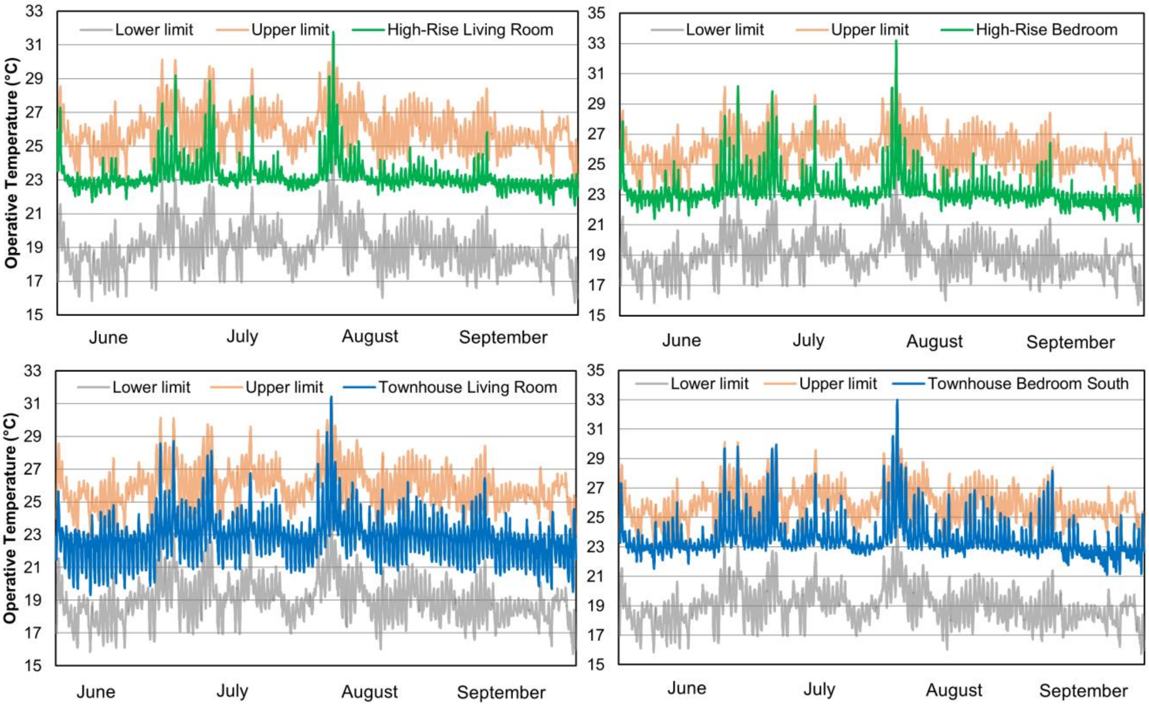


Figure 21 - Indoor operative temperatures and thermal comfort lower and upper limits according to ASHRAE Standard 55-2013 [88]. Only zones reaching the highest temperatures are considered, which are the Living Room and Bedroom A in the high-rise and the Living Room and Bedroom South in the townhouse.

6.3. Cost of energy refurbishment measures

As outlined above, dwellings can follow two different approaches: they are either refurbished in the first year and the gas consumption is substantially reduced (Table 24 summarizes the refurbishment measures used) or they are connected to a geothermal grid where the gas consumption for heating is cut down to zero. This comparison is assessed considering 10.000 homes, the expected number of connections to be part of the geothermal source, where 66% of the dwellings are high-rise apartments and 34% are townhouses (based on Table 2). Since the geothermal source is expected to provide heat for 40 years and most refurbishment measures last half that lifetime, a second investment is needed halfway through that 40-year period if the first approach is followed.

Hence, two different scenarios are considered in the cost analysis: in the first, it is assumed that all households join the geothermal investment in the beginning: full initial engagement. In the second, dwellings join the investment as they are connected to the grid: phased engagement. The former represents an ideal geothermal investment, while the latter characterizes the most common scenario when a geothermal grid is deployed. In both, investing in refurbishment measures is an individual option and does not require others involvement. Therefore, the financial impact between a full and a phased engagement is negligible.

Table 24 - Summary of the refurbishment measures considered in this study.

Increased thermal insulation	*Walls*	External building surfaces are upgraded by adding a 50 mm thick insulation layer with a thermal conductivity of 0.03W/m.K.
	Windows	Low emissivity coating is added to the living room, kitchen and bedrooms double glazed windows with a light transmittance of 55% and an infrared emissivity of 0.05.
Increasing the airtightness	Mechanical ventilation with heat recovery is used to reduce the air change rate to an average level of 0.06ach in the whole dwellings.	
Replacing the boiler	Highly efficient boilers are installed with a theoretical efficiency of 107% and an actual performance of 98%.	
Improving occupant behavior	Natural ventilation in the bedrooms is reduced to 60 minutes per day, while in the living room, kitchen and bathroom it is reduced to 30 minutes per day.	

All investments are performed considering a loan during the course of each approaches' lifetime, with an annual 3% interest rate and a monthly amortization. However, *Appendix II* shows the costs for a wider range of interest rates. The total amount of each payment is calculated as:

$$Rt = \frac{P * i}{1-(1+i)^{-n}} * n \tag{8}$$

where:

P is the present value of the loan amount;

i is the annual interest rate per period;

n is the duration of the loan in months.

A comparison between the two approaches is then assessed by calculating their gross cost plus what is still spent in gas during the 40 years, applying the following formulas:

$$Cmeasures = Rt_1 + Rt_2 + €_{gas} \tag{9}$$

$$Cgeo = Rt_3 \tag{10}$$

where:

Rt_1 and Rt_2 represent the true cost of the refurbishment measures in the first 20 years and in the next 20 years respectively;

$€_{gas}$ accounts for the money still spent on gas consumption during the whole period. The gas cost is calculated assuming a gas tariff based on an average between its current and future values between the 1st and 20th year, and between the 20th and the 40th year, with a 1.73% annual growth, which represents the average inflation rate between 2005 and 2014 in the Netherlands [89];

Rt_3 describes the true cost of connecting to the geothermal source and is the only factor considered in the geothermal approach, since gas for heating is no longer a necessity and the energy for heating becomes free.

Costs regarding the implemented refurbishments are highly variable and may depend on factors influencing material costs such as floor area, wall area, and total amount of windows, as well as other aspects that might affect installation costs. The material cost estimates used for this study were based on quotes from contractors which accurately reflect the current market situation, with a 30% increment related to installation costs. Consequently, changes in these costs due to technological improvements or price oscillations were not assessed. Since the high-rise and townhouse are significantly different in floor area, both boiler and MVHR costs were considered higher for the second, while wall and window insulation costs were fully contingent on their upgraded areas.

The cost analysis was performed assuming a 3% discount rate during a total lifetime of 20 years for all measures. The analysis accounts for the benefit each measure ensures in terms of the net present value of the investment, where savings were determined according to the simulated gas consumption reduction carried by each one of them. Thus, average gas tariffs charged in the Netherlands were used based on an international report which sets a unit price of 0.0642€/kWh, plus a network cost of 142.46€ per annum for the city of Groningen [90].

Table 25 shows how costs, energy savings and payback time vary for each refurbishment measure. In this case, the gas tariff remained constant through the whole analysis. Overall, refurbishment costs per floor area are slightly higher for the high-rise, with a value equal to 69€/m^2 compared to 57€/m^2 for the townhouse. However, energy savings per floor area are also higher for the first, with 85kWh/m^2 saved in comparison to 74kWh/m^2 saved in the townhouse. Results also show that in the high-rise, boiler energy savings are the lowest. This is due to the fact that this refurbishment measure was the last to be implemented. If this was the only measure in the dwelling, energy savings would be higher.

Table 25 - Costs used, energy saved and payback time in regards to each refurbishment measure. Cost and energy values rounded.

	High-rise			**Townhouse**		
	Cost (€)	*Energy savings (kWh)*	*Payback (years)*	*Cost (€)*	*Energy savings (kWh)*	*Payback (years)*
Wall Insulation	1 100	2 700	8	1 500	3 000	9
Window Insulation	1 600	950	-	2 000	550	-
MVHR	1 500	3 400	9	2 000	5 700	7
Boiler	2 000	600	-	2 500	1 200	-
Total	6 200	7 650	15	8 000	10 450	14

In both high-rise and townhouse cases, the payback time for the wall insulation and MVHR measures is lower than half their lifetime, making up for the fact that upgrading the windows and boiler does not save enough energy to amortize the cost over the 20-year period. Nevertheless, improving the windows is a crucial and needed measure to ensure no air leakage occurs and to guarantee the MVHR performs as expected. Moreover, since the boiler was the last measure to be implemented, it did not show any significant energy savings compared to the other measures, thus not having any payback time. This is also a mandatory upgrade, since boilers usually have a lifetime of 15 to 20 years and many of the current boilers installed throughout older Dutch buildings have already exceeded that mark, meaning that although they might still work, they are not performing as efficiently anymore.

Hence, all measures combined have a payback time of 15 and 14 years for the high-rise and townhouse respectively, which by the end of the 20-year period translate into 6 000€ and 9 000€ savings for both dwelling types. It is important to bear in mind that these values account for a constant gas tariff over the whole analysis. Since gas prices are expected to increase over the next 15 years [5], these values can reach even higher numbers.

6.4. Full Initial Engagement

In Figure 22, six lines describe the energy consumption for the cases where homes are and are not refurbished during the next forty years. In the cases where homes are fully refurbished, two distinct views are presented: one with improved occupant behavior and one without. These lines characterize the energy consumption for the whole sample considered in the case study, where the number of high-rise apartments is nearly twice the amount of townhouses. If no refurbishments were to be done, buildings would still need to upgrade their windows and boiler, which is assumed happening at a 5% per year rate. This would lead to having all buildings upgraded twenty years later, where the energy consumption would then stabilize for the upcoming years. In this case, energy savings for each home are only equivalent to 263m^3 and 353m^3 in high-rise and townhouse dwellings respectively.

In the case where refurbishments were to be done, buildings energy consumption would start at a much lower value. Since upgrading the boiler is a necessity but it does not provide any considerable energy reduction or advantage, this was also considered to happen at a 5% per year rate, where all boilers would be upgraded by the twentieth year. This scenario shows how refurbishments in standard high-rise apartments cause much higher energy reductions when compared to those in townhouses, where the gas demand in half the number of buildings is almost twice the gas consumption in high-rises.

Hence, the gas saved during the 40-year period by refurbishing all dwellings and without changing current occupant behavior is equivalent to the gas consumption of the business as usual minus the measures scenarios, reaching a total value of nearly 2.4TWh. On the other hand, connecting all homes to the geothermal source instead would provide gas savings equal to the business as usual scenarios, reaching a total amount of 3.5TWh. On a lower scale, one single home would save on average 237MWh or 353MWh following the measures or the geo approach respectively.

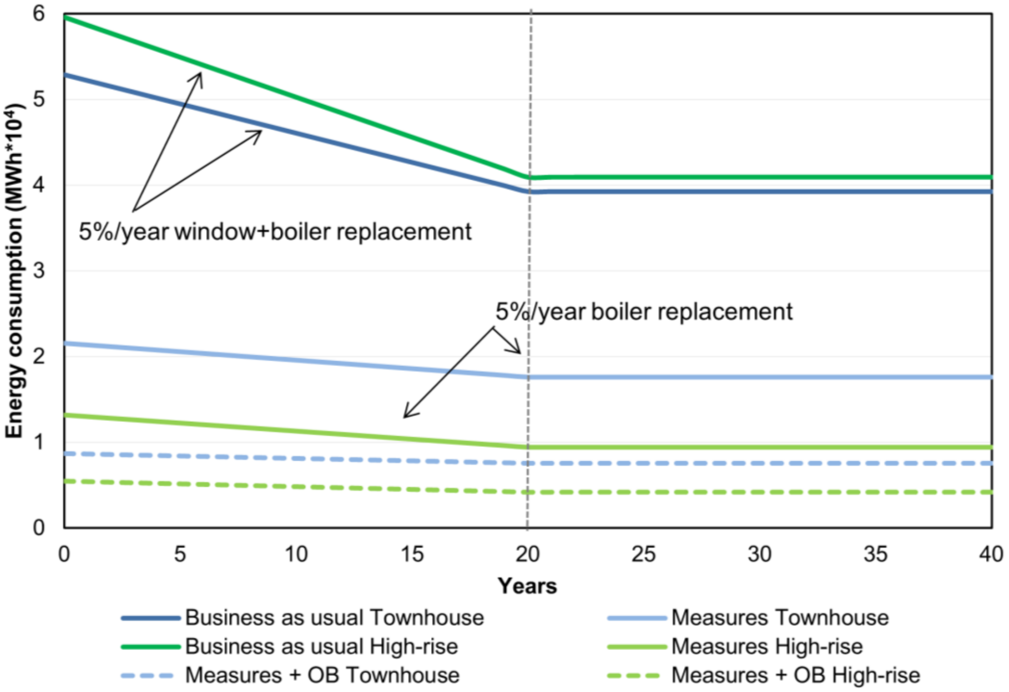


Figure 22 - Energy consumption for the three scenarios considered. The first scenario reflects the whole 10.000 homes following a business as usual model with the mandatory upgrades being implemented at a 5%/year rate. The second scenario considers that the whole household sample is refurbished in the first year with a 5%/year boiler replacement rate during the following years. The last scenario has the same characteristics as the latter, with an added energy efficient occupant behavior (OB).

From Figure 22, it is also quite clear how a significant overall energy consumption decrease occurs when people behave in a more efficient way, showing the potential savings from the whole refurbishment measures applied. In townhouses this reduction is to some extent more prominent than in high-rises, where an extra 430GWh could be saved in comparison to the 234GWh that would be saved in high-rises, even though there are more high-rise apartments in the study. This shows that having energy saving concerns has a much higher impact in townhouse occupants, which happens because there was still a substantial energy demand from these buildings. In this scenario, the gas saved would account for a total of 3.1TWh, which would still be slightly lower than the energy saved by connecting the homes to the geothermal source.

Table 26 shows the true costs for each approach, following the costs presented on Table 1 for the geothermal grid and the costs shown on Table 25 for the refurbishment measures. The initial costs represented in the geothermal side relate to the true costs of the investment plus the windows replacement, while on the measures side these account only for the true costs of the investment. In the latter, since the MVHR and the windows are only expected to last 20 years, a reinvestment on these upgrades has to be made halfway through the period of the analysis. Thus, the reinvestment costs are calculated based on their future value according to the standard inflation rate used. In both 20-year periods, running costs are slightly lower in comparison to the ones from the geothermal approach, where yearly costs due to the electricity consumption of the pump in the geothermal doublet are inevitable. Nevertheless, connecting to the geothermal source kills the need for gas, while applying the refurbishment measures still obliges to a few gas demand, with a consequent charge represented in the running costs. Therefore, the cost for connecting to the geothermal source with full initial engagement would be slightly lower than individually refurbishing a townhouse apartment, but higher than refurbishing a high-rise. However, the overall cost of connecting to the geothermal source would still be the lowest.

Table 26 - Measures and geothermal approaches' gross costs (in Euros) during the whole case study. The running costs considered on the measures side account for the gas demand with no changes in occupant behavior, while on the geothermal side account for the OPEX costs for the 40-year period. Total costs are related to a single dwelling, while overall costs reflect the communal investment.

	Refurbishment measures			***Geothermal***		
		High-rise	Townhouse			
1st 20 years	*Initial Costs (€)*	8 250	10 650	*Initial Costs (€)*	11 900	**40 years**
	Running Costs /€)	1 700	3 000	*Running Costs (€)*	7 700	
Last 20 years	*Reinvestment (€)*	6 000	7 500			
	Running Costs (€)	2 000	3 700			
	Total Costs (€)	**17 950**	**24 850**	***Total Costs (€)***	**19 600**	
Overall Cost (€)		**202 M**		***Overall Cost (€)***	**196 M**	

In the third scenario, gas demand would be lower and the running costs would not have the impact they have on the total and overall costs presented on Table 26. These are shown on Table 27, where significant savings are achieved – total costs to be 12% lower in high-rise apartments and 16% lower in townhouse dwellings. The overall cost considering a community investment would also reach an inferior value – around 13% lower. Thus, total costs would reach approximate to even lower values compared to the geothermal approach for the high-rise and townhouse respectively, assuming all households joined the investment in the beginning.

It is important to note that following the refurbishment measures or the geothermal approach is more beneficial than keeping a business as usual approach, where natural gas is still the main energy carrier in the homes. In this case, not only natural gas consumption would follow the business as usual scenario but also windows and boilers would have to be switched in the course of the geothermal project's lifetime, with total costs of 31 350€ for the high-rise and 53 650€ for the townhouse – Table 28.

Table 27 - Running costs with changes in occupant behavior in the refurbishment measures approach. Total costs comprise the sum of these costs with the initial and reinvestment costs.

	High-rise	***Townhouse***
Running Costs (€) in the first 20 years	700	1 200
Running Costs (€) in the last 20 years	900	1 600
Total Costs (€)	**15 850**	**20 950**

Table 28 – Business as usual natural gas consumption and total costs for single high-rise and townhouse dwellings during the 40-year period.

	High-rise	***Townhouse***
Natural gas consumption (MWh)	283	513
Natural gas expense (€)	25 200	46 000
Boiler replacement cost (€)	3 400	4 300
Windows replacement cost (€)	2 750	3 400
Total Costs (€)	**31 350**	**53 650**

6.5. Phased engagement

Figure 23 demonstrates the energy savings achieved by either following the refurbishment measures or the geothermal approach for both high-rise and townhouse homes. In this scenario, the energy efficiency measures are implemented at a linear rate over the first twenty years or the dwellings are simply connected to the geothermal grid at a logarithmic rate over that same time period. Since households only start saving energy when they are connected, the gas saved by implementing the refurbishment measures is considerably lower than the gas saved in the full initial engagement scenario. During the 40-year period, refurbishing all dwellings without changing occupant behavior is equivalent to 1.6TWh savings, which is 800GWh less than in the full initial engagement scenario. On the other hand, connecting all homes to the geothermal source delivers a combined value of 2.7TWh gas saved, also 800GWh less than the previous scenario. The energy saved by a single dwelling that either implements the refurbishment measures or connects to the geothermal source averages 160MWh and 270MWh respectively.

In the event of people behaving in a more efficient way, the energy savings in the refurbishment measures approach would reach a total value of 2TWh. This measure is also more prominent in townhouse homes, where an extra 280GWh gas are saved in comparison to the extra 150GWh gas saved in high-rises.

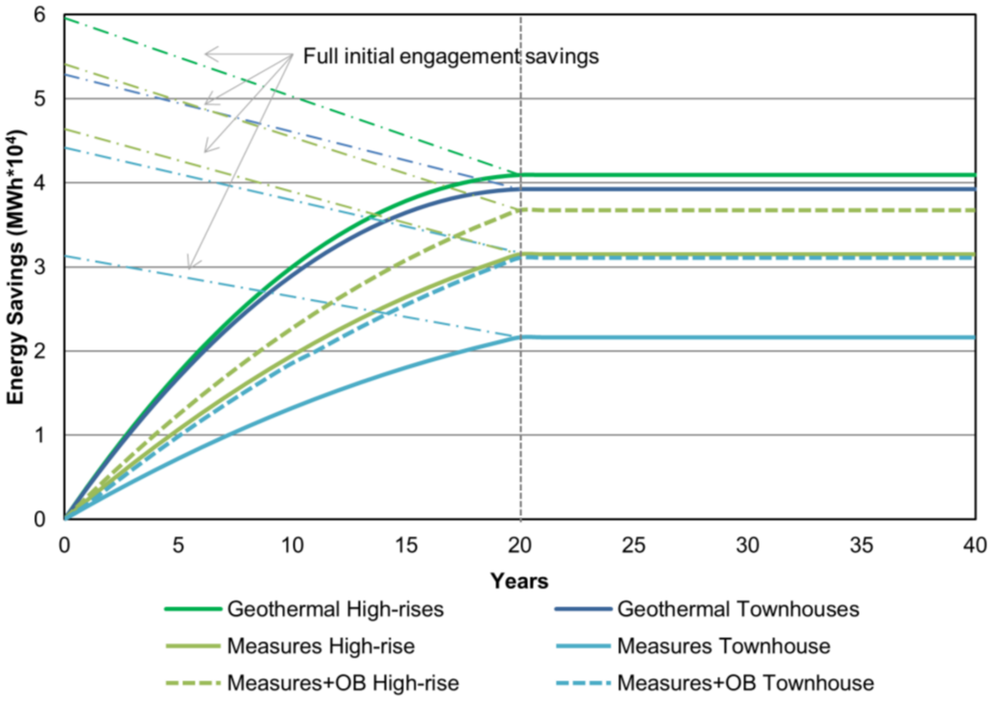


Figure 23 - Energy savings caused by the phased engagement to the geothermal source or to the refurbishment measures compared to those in the full initial engagement.

As energy savings increase during the first twenty years, participation in the investment also occurs accordingly, with the monthly amortization growing per number of dwellings involved. In this case, the monthly amortization in a phased engagement only matches the monthly amortization in a full initial engagement in the twentieth year, due to the gap caused by delaying most payments. This causes the true cost of the geothermal project to escalate in comparison to a full initial engagement in nearly 30 million euros, corresponding to a 22 600€ investment per household.

On the other hand, implementing refurbishment measures does not require a communal investment, and thus the true investment cost for that approach does not depend on others involvement in it. This means that by considering no changes in each refurbishment measure cost during the years, the true cost in refurbishing the dwellings in the phased initial engagement ends up being the same as the cost presented in the full initial engagement.

Table 29 shows a comparison between all scenarios corresponding costs, where the phased engagement is the most expensive approach taking into account a communal investment, while the refurbishment measures with a change towards a more energy efficient occupant behavior are the less costly investment.

Table 29 - Cost comparison between the scenarios studied.

	Refurbishment measures		*Geothermal*		*Business as usual*
	Without changing OB (€)	*Changing OB (€)*	*Full Initial Engagement (€)*	*Phased Engagement (€)*	*(€)*
High-rise	17 950	15 850	19 600	22 600	31 350
Townhouse	24 850	20 950	19 600	22 600	53 650
Overall	202 000 000	176 000 000	196 000 000	226 000 000	-

7. Conclusions

In this study, reducing natural gas consumption in typical Dutch residential buildings, particularly in Groningen, was analyzed from two different perspectives: by implementing refurbishment measures and by connecting the dwellings to a geothermal district heating grid. The most common residential building typologies identified were high-rise and townhouse apartments, which were both used for thermal simulations. This work resulted in the following conclusions:

- Using EnergyPlus, the measured natural gas consumption for heating was matched with a 2% difference only. This was possible due to the very detailed inputs regarding typical building typologies and characteristics such as infiltration values and occupant behavior used.

- The combination of all refurbishment measures resulted in a yearly gas consumption reduction of 86% or more. However, the payback time for these measures is at least fourteen years.

- For a typical meteorological year, the energy refurbishment measures may cause overheating (indoor operative temperature above thermal comfort's acceptability limits) in four days for around 4 hours per day.

- Having an energy efficient occupant behavior has the potential to reduce heating demand by up to 21%.

- In the geothermal approach, a full initial engagement is significantly less costly (15%) than a phased engagement.

- The cost of implementing refurbishment measures in a high-rise apartment is up to 43% lower than the geothermal system cost in every scenario.

- In the townhouse apartments, the refurbishment measures cost is only lower than connecting to the geothermal grid if an energy efficient occupant behavior is followed. If a communal investment was to take place, the cost for the measures without changing occupant behavior would be higher than a geothermal full initial engagement.

- Deploying a geothermal grid is a lot less flexible than refurbishing all homes, since the true investment cost depends on the amount of connections and time these take place.

- The geothermal approach has an exit strategy: when there is less energy demand, the grid can expand (at a cost). The system eliminates gas use for heating, while the refurbishment measures do not. Yet, similar results could be achieved by implementing other energy efficiency measures such as heat pumps and solar energy, which were not considered in this study.

- The refurbishments and geothermal approaches are more beneficial than keeping business as usual, both in terms of energy saved and costs.

With these outcomes, it is perceptible that following one approach is not clearly better than following the other: on the one hand, the refurbishment measures are less costly, but on the other hand, connecting to the geothermal grid saves more energy. This leads to the conclusion that either implementing refurbishments or connecting to the geothermal source is an important decision that has to be made by the interested parties (homeowners, investors and municipality), guided by the main goals outlined by the municipality of Groningen and supported by the Dutch government.

Future studies can be directed towards adding other refurbishment or renewable energy options that lower natural gas consumption and maintain costs at a lower level. Also, doing a life-cycle analysis to assess environmental impacts associated with each approach and comparing both can also influence which one to follow. Moreover, since this study only took into account energy savings for space heating, analyzing energy savings for domestic hot water and electricity can also be a complement to the results already achieved.

Finally, a more detailed economical study (that calculates future natural gas costs with higher precision and takes into account economies of scale in the refurbishment measures scenarios) should also be done in further works, which was not possible to develop due to time and data limitations.

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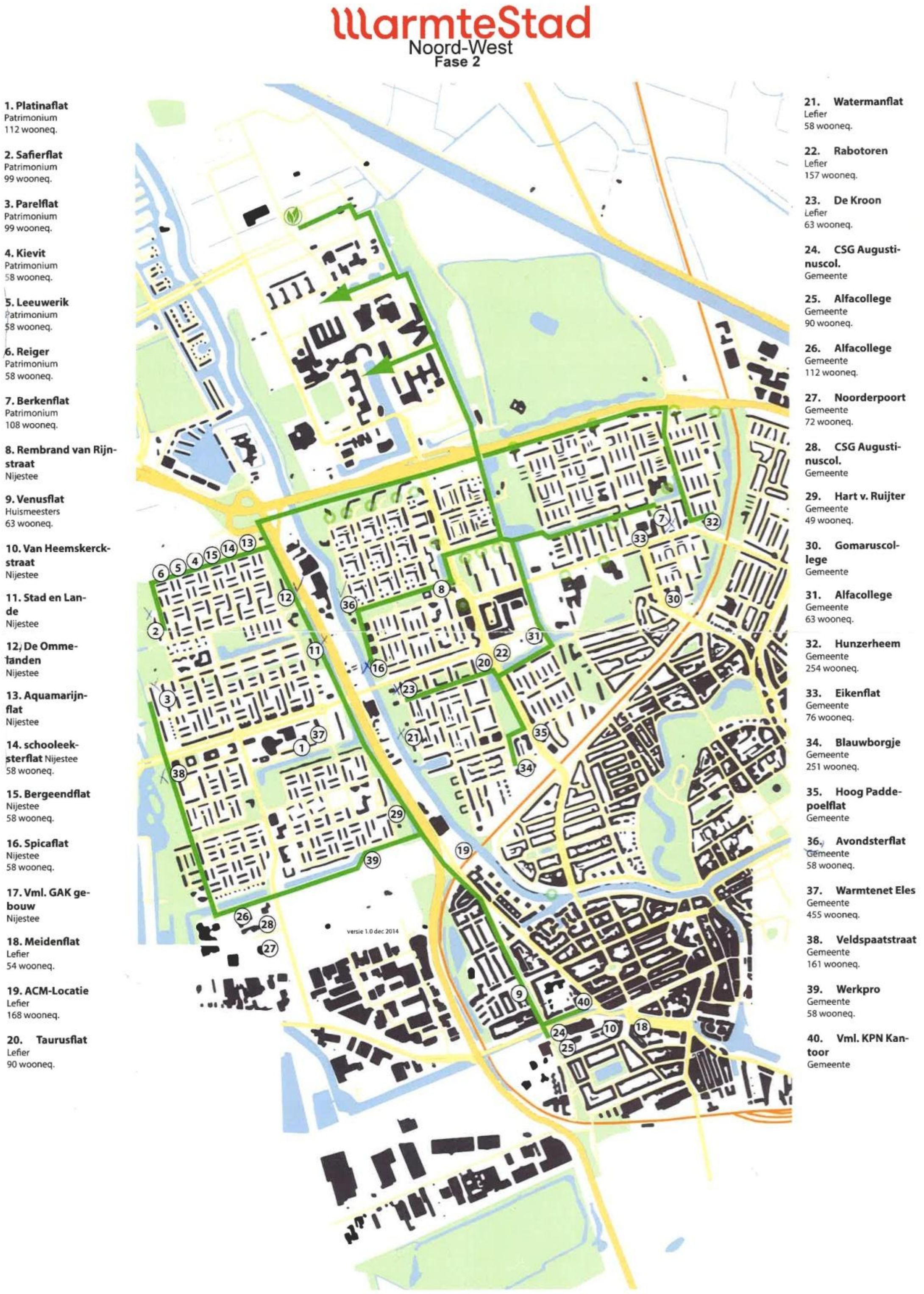
Appendices

Appendix I - The Groningen geothermal grid project



Appendix II - Variable interest rates

Although a 3% discount rate is presented all throughout the study, significant differences in costs might occur if the actual discount rates charged differ from this value. The following table presents the true costs with a 1-5% discount rate.

			Discount rates				
High-rise	Refurbishment measures		1%	2%	3%	4%	5%
	Wall insulation	Cost	1 214 €	1 336 €	1 464 €	1 600 €	1 742 €
		Payback time	8 years	8 years	8 years	8 years	8 years
	Window insulation	Cost	1 766 €	1 943 €	2 130 €	2 327 €	2 534 €
		Payback time	-	-	-	-	-
	MVHR	Cost	1 656 €	1 821 €	1 997 €	2 182 €	2 376 €
		Payback time	8 years	9 years	9 years	9 years	9 years
	Boiler	Cost	2 207 €	2 428 €	2 662 €	2 909 €	3 168 €
		Payback time	-	-	-	-	-
	Full initial engagement (no OB)		15 521 €	16 703 €	17 955 €	19 275 €	20 663 €
	Changing OB		13 421 €	14 603 €	15 855 €	17 175 €	18 563 €
Townhouse	Refurbishment measures		-	-	-	-	-
	Wall insulation	Cost	1 656 €	1 821 €	1 997 €	2 182 €	2 376 €
		Payback time	9 years	9 years	9 years	10 years	10 years
	Window insulation	Cost	2 207 €	2 428 €	2 662 €	2 909 €	3 168 €
		Payback time	-	-	-	-	-
	MVHR	Cost	2 207 €	2 428 €	2 662 €	2 909 €	3 168 €
		Payback time	7 years	7 years	7 years	7 years	7 years
	Boiler	Cost	2 759 €	3 035 €	3 328 €	3 636 €	3 960 €
		Payback time	-	-	-	-	-
	Full initial engagement (no OB)		21 752 €	23 257 €	24 851 €	26 533 €	28 300 €
	Changing OB		17 852 €	19 357 €	20 951 €	22 633 €	24 400 €
Overall	Full initial engagement (no OB)		176 M€	189 M€	202 M€	217 M€	232 M€
	Changing OB		149 M€	162 M€	176 M€	190 M€	205 M€
Geothermal	Full initial engagement	Single home	13 812 €	16 542 €	19 555 €	22 829 €	26 340 €
		Overall	138 M€	165 M€	195 M€	228 M€	263 M€
	Phased initial engagement	Single home	16 812 €	19 542 €	22 555 €	25 829 €	29 340 €
		Overall	168 M€	195 M€	225 M	258 M€	293 M€