

# Green Light District: Energy renovation of monumental buildings



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July 2021

MSc. Architecture, Urbanism & Building Sciences

Building Technology Track

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## Executive Summary

By 2050 the municipality of Amsterdam plans to become climate neutral. The historic city center of Amsterdam poses a challenge in this ambition, as it is home to numerous monumental buildings. Conservation is the starting point for the renovation of monumental buildings and consequently additional regulations are in place. Furthermore, each building is unique, thus renovation of monuments requires customization, making it more expensive and unattractive. Research has shown that due to restricted renovation possibilities, the indoor comfort and energy performance of monumental buildings are often below standard.

This research aims to create an energy-neutral renovation for a monumental building in the oldest neighborhood of Amsterdam: the Burgwallen-Oude Zijde. Resulting in the following research question: *"How can monumental buildings be renovated to become energy neutral and comfortable for the users, whilst preserving the monumental status?"* A renovation design is made for a mixed-use monumental building and elaborated into a generic approach.

Through careful analysis of the Oudezijds Voorburgwal 30, the chosen case study building, it was determined that a significant part of the building is not monumental. Furthermore, it was confirmed that the energy usage of the building is relatively high, and that the indoor comfort is currently not up to standard. To improve the energy performance and indoor comfort, a design is proposed in which different design measures are suggested. The design makes use of the potential of the neighborhood as it uses aquathermal heat (LT) from the canal in combination with heat pumps as basis for the heating of the building. The building is insulated using a combination of exterior and interior insulation, crack & seam filling, and double-glazed windows. For the monumental parts of the building a wall heating system is proposed, in which the walls are slightly heated to minimize energy losses to the exterior ('WarmBouwen' concept'). Energy is produced on site using PV roof tiles on the South facing roofs and several other small design interventions are proposed. Evaluation of the proposed design reveals that none of the identified monumental elements are altered, the energy demand of the building is lowered by 73% and that the indoor comfort increases significantly.

By following the proposed generic approach of (1) identifying the heritage values, (2) assessing the current performance of the building, (3) creating concept designs, (4) finalizing the design, and (5) evaluating the design, the remaining energy demand of the proposed design for the Oudezijds Voorburgwal 30 has not been reduced to zero and is thus not energy neutral. This is mostly due to restricted renovation possibilities and limited roof area for on-site energy production. The proposed design does make the Oudezijds Voorburgwal 30 BENG compliant: a step in the right direction, but for monumental buildings to become energy neutral a fairer middle ground between conservation and sustainability should be found. We should ask ourselves: how far should one go to preserve the past if it limits or damages our future?

## Acknowledgments

This thesis is the result of eight months of hard work and dedication. This thesis would not have been the same without the help and support of many people. First, I would like to thank my graduation mentor Andy van den Dobbelsteen. Andy guided me through the whole graduation process and gave me the confidence that I was able to write this whole thesis individually. Andy's feedback was always to the point and constructive so I could continue after each meeting. Second, I would like to thank my second graduation mentor Regina Bokel. The COVID-19 pandemic made graduation slightly more intense, besides her fast feedback and calmness, Regina was able to listen and reassure me. Furthermore, I would like to thank my consultant from the Heritage & Design department, Wouter Willers. Wouter guided me through a process I had never done but was extremely patient and always willing to help. For Wouter, a Building Technology student trying to analyze a monumental building was new too. Yet he put effort in to finding a method which provided me with the necessary information but did not make me lose focus of the original goal of my thesis. I would also like to thank Maéva Dang who was willing to share her research experience and results with me and gave me the opportunity to take infra-red images on site. Moreover, I would like to thank Jantien Stoter, my delegate of the board of examiners for the organization during presentations and her kind words.

I would also like to thank everyone who provided me with the necessary information on the case study building. Stadsherstel Amsterdam for providing me with all the drawings quicker than I could have ever imagined. The Stadsarchief Amsterdam for providing me with all the necessary historical information. The municipality of Amsterdam for providing me with the reasoned statement of the monument. Fer Kok of the Prael for providing me with the energy bills of the store and his always honest replies. But mostly I would like to thank the residents of 30B, Sander Daniëls and his girlfriend, for being of extreme help. They provided me with all materials I needed, allowed me to visit their home and even leave measurement equipment for over a week in their house. Their kindness and willingness to help has made me extremely grateful and has helped me during this thesis more than they can imagine.

Lastly, I would like to thank my family and friends. My parents for always providing me with a solid foundation to fall back on during both my bachelor's and master's degree and for joining me on several site visits. My sister for understanding my struggles as she was also writing her master thesis simultaneously. My friends for providing me the much-needed motivation during more difficult periods but most of all for providing the necessary social distraction so I could start fresh again the next day or week.

Thank you all.

**Sophie van Hattum**

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## Abbreviations

AHU	Air Handling Unit
ATES	Aquifer Thermal Energy Storage
BENG	'Bijna EnergieNeutraal Gebouw' (NZEB)
COP	Coefficient of Performance
DHW	Domestic Hot Water
EPC	Energy Performance Coefficient
HT	High Temperature (heating)
HVAC	Heating, Ventilation and Air-Conditioning
IAQ	Indoor Air Quality
LT	Low Temperature (heating)
MT	Medium Temperature (heating)
NZEB	Nearly Zero-Energy Building (BENG)
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
ppm	Parts per million
RH	Relative Humidity
TABS	Thermally Active Building System
TEA	Thermische Energie uit Afvalwater (thermal energy from waste water)
TED	Thermische Energie uit Drinkwater (thermal energy from drinking water)
TEO	Thermische Energie uit Oppervlaktewater (thermal energy from surface water)
ZEB	Zero-Energy Building

# 1. Introduction

## 1.1 Background

Amsterdam: the city known for its canals and the iconic canal houses. Yet, Amsterdam is also the city known for the Red Light District, in Dutch called 'de Wallen'. Located in the heart of the city center (see figure 1), it is a popular tourist attraction as it is one of the few places in the world where prostitution is legalized and visible. The official name of the Red Light neighborhood is the Burgwallen-Oude Zijde and it is one of the oldest neighborhoods of Amsterdam, dating back to the 13th century.



Figure 1: Location of the Burgwallen-Oude Zijde. Source: Maps Amsterdam: gebiedsindelingen, n.d.

The Burgwallen-Oude Zijde has been the subject of many debates and discussions in the past years. Due to mass tourism, the neighborhood has become less attractive to the residents of Amsterdam. Many residents have complained about the negative effects of mass tourism (Ulrich, 2020; Claus, 2020). The COVID-19 pandemic has made the residents and municipality realize that change in the neighborhood is necessary (Couzy, 2020b). It has become clear that the current way of exploitation in the area is not sustainable, nor future proof and that the area is too dependent on tourism (Couzy, 2020a).

Since the historic inner city is in need of a thorough development and a more sustainable approach, De Groene Grachten, NV Zeedijk, the municipality of Amsterdam, De Gezonde Stad, Rooftop Revolution, TU Delft and EIT-Climate-KIC have teamed up under an initiative named the 'Green Light District'. They attempt to make the historic inner city, in specific the Red Light District (the Burgwallen-Oude Zijde neighborhood), more green, sustainable and carbon neutral (Green Light District, n.d.).

## 1.2 Problem statement

Besides the social need for improvement in the neighborhood, the world is facing the energy transition. The overall goal is to minimize climate change and maintain quality of life for future generations. The world will transit from fossil fuels to renewable energy sources such as solar and wind power (Gemeente Amsterdam, 2020a). Consequently, the municipality of Amsterdam plans to be climate neutral in 2050: by then 95% less CO<sub>2</sub> has to be emitted in comparison to 1999. In 2040 all buildings have to be off natural gas and in 2030, 80% of the energy demand has to be derived from renewable sources (Gemeente Amsterdam, 2020a).

The built environment is a large contributor in the usage of fossil fuels and the total greenhouse gas emissions. In Amsterdam 25% of the CO<sub>2</sub> emitted on a yearly basis derives from the building sector and the built environment (Gemeente Amsterdam, 2020a). On a global level it is even estimated that 33% of the greenhouse gas emissions originate from the built environment, and in more developed countries this percentage is even higher (La Roche, 2012). Since the built environment has such a large share in the greenhouse gas emissions it is necessary to make the sector more sustainable to achieve the goals of the municipality and consequently, the national agreements and the Paris Agreement. In order to reduce the emissions of the built environment, an important step is to lower the energy usage of buildings drastically (Gemeente Amsterdam, 2020a).

### 1.2.1 Monuments and energy performance

The goals for the energy transition set by the municipality will not be easy to achieve, especially in the historic city center of Amsterdam. The city center of Amsterdam (Burgwallen-Oude Zijde included) has numerous monumental buildings (see figure 2). These monuments use a significant amount of energy due to their age but also due to the fact that buildings with a monumental status are protected and therefore have an extensive list of rules and regulations to adhere to when renovating: leaving little room for adjustments to the building to reduce its energy usage. Often, the most ideal solutions to reduce the energy usage cannot be implemented. Furthermore, there are several different types and classes of monuments, all with their own rules and regulations and historical past, and thus requiring custom solutions. Each monument is unique. This, in its turn, makes renovating a monument relatively expensive and sometimes unfeasible.

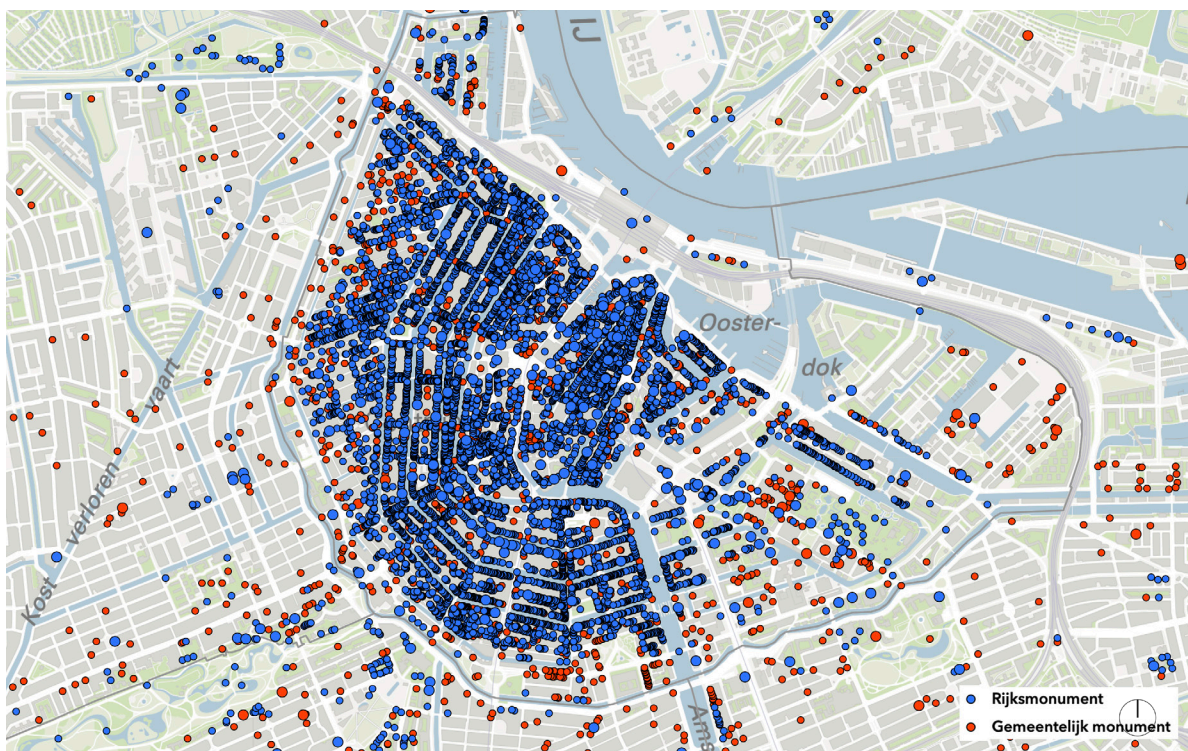


Figure 2: Monuments in the city center of Amsterdam. Source: Maps Amsterdam: monumenten, n.d.

### 1.2.2 Monuments and indoor comfort

Another challenge that often occurs in monumental buildings is to create a comfortable indoor climate. Due to the building's age and the difficulties of renovating a monument, the indoor climate in a monumental building is often far from ideal for the residents, leading to discomfort and sometimes even health problems for the residents (Blyussen, 2009, p. 4).

In conclusion, due to the historical value of monumental buildings and the accompanying regulations, the indoor comfort and energy performance of the buildings are often below standard. Renovation of a monumental building needs to be custom designed because each monumental building is unique, making renovations expensive and unattractive. Yet, renovating monumental buildings is necessary to tackle climate change.

### **1.3 Objectives**

The objective of this thesis is to create a design for the energy-neutral renovation of a monumental building in the inner city of Amsterdam (preferably the Burgwallen-Oude Zijde). The renovation need to improve the indoor comfort of the resident and the monumental status of the building has to be maintained. The objective will be elaborated in a generic approach and tested specifically on a mixed-use monumental building in the inner-city of Amsterdam, the Netherlands.

### **1.4 Research questions**

The main research question that will be addressed in this thesis is:

*“How can monumental buildings be renovated to become energy neutral and comfortable for the users, whilst preserving the monumental status?”*

To answer this question several subquestions are formulated:

1. What is the history of the case study building and which building elements cannot be altered due to their monumental value?
2. What is the current energy performance and indoor comfort of the case study building?
3. Which of the inventoried design measures can be implemented in the case study building for the renovation design?
4. What is the effect of the renovation design on the monumental status, the energy performance and indoor comfort of the case study building?
5. What is a generic approach to energy-neutral, comfortable monuments?

Several background questions are formulated as well:

1. What are the different types of monuments in Amsterdam and what are the associated regulations for renovation?
2. Which sustainable design measures can be implemented to improve the energy performance and indoor comfort of monumental buildings in general?
3. What are the requirements for indoor comfort in monumental buildings?

### **1.5 Research scope**

As there are many types of monuments in the Netherlands and the rest of the world, this research and consequently the design has its limitations. First of all, in this thesis solely monumental buildings are considered and not any other types of monuments. As assigned by the municipality of Amsterdam, these monumental buildings are ‘order 1’ buildings, meaning they are either national or municipal monuments. It has been decided that the research focuses on monumental buildings built before 1900 as most monumental buildings in Amsterdam were constructed before 1900. Furthermore, as aquathermal energy might be used in the design this thesis focuses on monumental buildings close to a water body (around twenty meters). Regarding the building typology, this research focuses on mixed-use buildings as they are very common at the Burgwallen-Oude Zijde. The chosen typology are buildings with a store on the ground floor and dwellings above as little research has been done on the typology yet. Lastly, this thesis solely focuses on improving the thermal comfort and indoor air quality in regard to indoor comfort.

The research and design are focused on monumental buildings in the historic inner city of Amsterdam. However, the generic approach could also potentially be applied to other buildings in a city similar to Amsterdam with a similar history.

## **1.6 Research approach & structure**

This research has been divided into five phases. A brief explanation on each phase is given below. In figure 3 an overview can be found.

### *Phase 1: Literature research (part A in this report)*

In phase 1, literature research is done on different topics. These topics can roughly be divided into three categories: monumentality, energy performance and indoor comfort.

### *Phase 2: Analysis of the case study building (part B in this report)*

In phase 2, a case study building is chosen. The necessary information and drawings are collected. In order to get a proper understanding of the case study building's performance, the building is then analyzed on the three topics which were researched: monumentality, energy performance and indoor comfort. The monumental elements of the building are identified by researching the history and creating a timeline of the alterations which were made throughout the centuries. The energy performance is analyzed using the energy bills. For indoor comfort the residents are interrogated and several measurements are conducted. For both the energy performance and indoor comfort the existing building is also modeled in the energy simulation software called Design Builder.

### *Phase 3: Design proposal (part C in this report)*

In phase 3, the outcomes of the literature research and the analysis of the case study building are combined. Possible design measures are inventoried and several design concepts are proposed. By using several criteria (such as the effect on the energy performance, indoor comfort and monumental status but also functionality, aesthetics etc.), one concept is chosen and at last an integral design is proposed.

### *Phase 4: Evaluation of the design (part C in this report)*

In phase 4, the proposed design is evaluated on all three criteria again. The energy performance and indoor comfort are assessed by implementing the proposed design measures in Design Builder, using the model of the current building as a base model for comparison. Furthermore, it is assessed whether the design does not make any alterations to the monumental elements which were identified in phase 2. Small alterations are made accordingly to the design.

### *Phase 5: Generic approach (part C in this report)*

In phase 5 the final integral design is translated into a generic design approach which can then theoretically be used for the energy renovation of other monumental building, similar to the case study building.

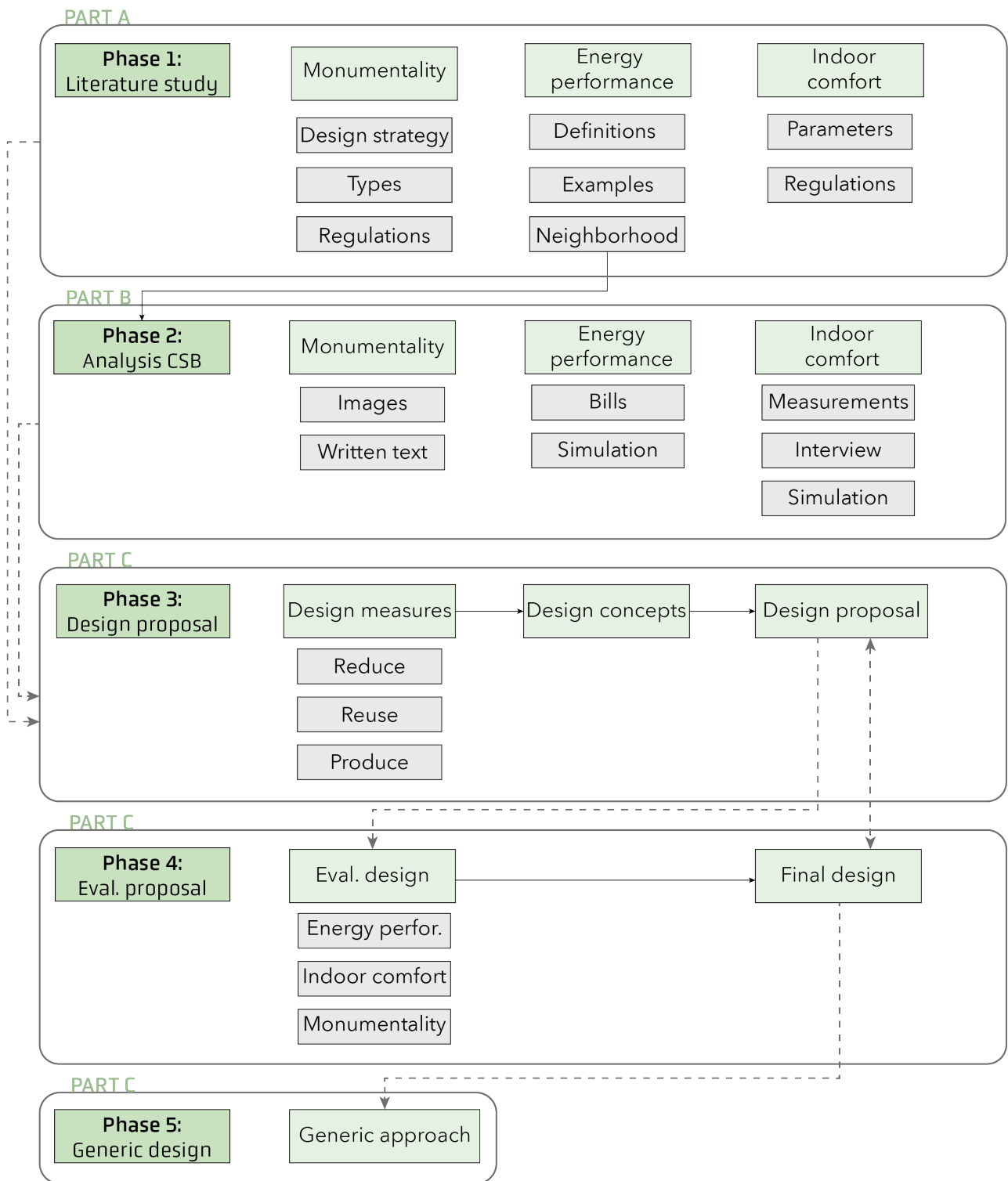


Figure 3: Methodology scheme. Own work.



PART A: THEORY

## 2. Monumentality

When designing a retrofit or renovation, the designer is left with an existing building and framework to work within. This requires more careful planning and designing. In the case of monumental buildings, this framework is also present. However, monumental buildings have an additional set of regulations which need to be adhered. This makes the renovation design more difficult and requires more planning from the designer. This chapter addresses the following background question: *“What are the different types of monuments in Amsterdam and what are the associated regulations for renovation?”* To answer this question firstly the definition of a monument and how to design for a monument are addressed.

### 2.1 What, why & how of monumentality

The word monument is derived from the Latin verb ‘monere’, which translates to commemorate or remind (Kuipers & de Jonge, 2016). Van Dale (2020) defines a monument as a building, terrain, etc. which is of common interest because of its beauty, cultural or scientific value. Kuipers and de Jonge (2016), state that by naming a heritage site a monument, the building becomes a carrier of the commemorative values. They make a distinction between a deliberate commemorative value and unintended monuments. The latter meaning that the monument was not erected to embody the memory of a certain event or person. Most heritage with a monumental status as of today are unintended monuments (in Amsterdam as well). They were not built to commemorate but rather had an actual function. However, that does not mean that these monuments do not have any historical, cultural or aesthetic value. As can be derived from the definition a monument can be a building but also numerous other things such as bridges, an area or even objects. As mentioned in the introduction this thesis focuses on monumental buildings.

A question that often arises when talking about monumental buildings is: why do we need to renovate the monumental building? Why not demolish the building and start with a clean slate? Orbasili (2008) mentions that monuments are often an intrinsic part of the built environment in a specific location. Besides being an intrinsic part of the built environment, the buildings are often a carrier of the cultural identity of a country or city. They can promote the cultural identity and thus stimulate tourism. Moreover, monumental buildings can evoke some sense of nostalgia for a certain time period. It gives us the opportunity to place ourselves in the past and get a better understanding of the past (Orbasili, 2008).

Conservation of monuments is the process of managing change. However, this needs to be done in a sustainable manner. In general, renovation of heritage can be quite sustainable as it is not necessary to demolish a building and build a whole new building. Also, monumental buildings were often constructed using solely local materials (Orbasili, 2008). In today’s society our focus has shifted to sustainability and minimizing our impact on climate change. Renovating, refurbishing and retrofitting of existing buildings fits perfectly within this focus.

Architectural conservation of monumental buildings is just like any other form of architecture a creative process where design skills need to be applied (Orbasili, 2008). There are several different strategies of dealing with heritage:

1. Adaptive reuse/adaptation: Making changes to accommodate a new use. The appropriateness of the new use for the monument should be considered beforehand.
2. Conservation: The process of understanding, safeguarding, maintaining, repairing, restoring and adapting historic property to preserve its cultural significance.
3. Consolidation: Undertaking of physical interventions to stop further decay or structural instability.
4. Preservation: To maintain the building in its existing form and condition and undertaking maintenance as necessary.
5. Prevention: To alter conditions to reduce or slow the process of decay. No intervention to conserve or restore is done.

6. Protection: Putting in place legal, physical or other tangible measures to safeguard cultural property from damage.
7. Restoration: Returning a building or parts to a form in which it appeared at some point in the past.

Before starting the design of the renovation for a monumental building it should be made clear which strategy is adhered to. For each part of the building the strategy can be different (Orbasili, 2008). The key question for every design decision is whether preserving the original idea or conserving the original substance is more important (Kuipers & de Jonge, 2017). In this thesis the strategies which will be adhered to are mainly adaptive reuse and conservation.

Another step which has to be taken before commencing with the design, is careful examination and analysis of the building. Understanding the past use of the building, the materials and the construction helps with the design of the renovation (Orbasili, 2008). For monumental buildings in the Netherlands, it is required to perform a building historical examination ('*bouwhistorisch onderzoek*') before making any alterations. During the examination research is done on the history of the building, previous renovations and the user history of the building. It is done based on the shape, construction, materials and finishing (Hendriks & van der Hoeve, 2009). Besides the building historical examination done by a professional historian, it is advisable for the designer to analyze the building themselves as this will provide a more thorough understanding of the building, the construction and use. A site visit is necessary to get a proper feel of the building and its present state. It is important to make notes, draw sketches and take photos (Kuipers & de Jonge, 2017).

The building historical examination and the analysis of the designer will reveal the historical value and characteristics of the building. These need to be the point of departure for the design (Kuipers & de Jonge, 2017). When designing with a monument it is necessary to seek reversibility and reduce any damage that might be irreversible. This way the monumental building can always be returned to its original state (Orbasili, 2008). The primary goal of designing a renovation for a monument is to make use of what is already present and to get inspired by the original building (Kuipers & de Jonge, 2017). In general, the design process of the renovation of a monumental building requires more preparatory work (Kuipers & de Jonge, 2017). It is thus advisable to take sufficient time for the designing and planning of the renovation.

## **2.2 Monuments & regulations in Amsterdam**

There are many different types of monuments in the city center of Amsterdam and the Netherlands in its whole. The regulations which have to be adhered to are dependent on the type of monument. It is thus important to be aware of the type of monument one is designing for.

### *2.2.1 Types and orders of monuments*

The lowest level of monumentality in the Netherlands are municipal monuments. These monuments have heritage value which is solely of local interest (Gemeente Amsterdam, 2016). Several provinces (including North-Holland) have assigned provincial monuments. Provincial monuments have more interest than municipal monuments but are not of national importance. The city center of Amsterdam does not have any provincial monuments but does have several municipal monuments (Provincie Noord-Holland, 2020). The highest level of monumentality in the Netherlands are national monuments. These buildings are deemed to have high value and are of national interest to preserve. The city center of Amsterdam counts numerous national monuments (Ministerie van Onderwijs, Cultuur en Wetenschap, 2015).

A building within a city or village can be a part of a protected city view. It means that the whole area is deemed important because of its beauty, coherence or societal or cultural significance. In the case of a protected city view not only the buildings in itself are protected but also the underlying fabric. A protected city view can be assigned on national or municipal level. The historic city center of Amsterdam (including the Burgwallen-Oude Zijde) is an assigned national protected city view

(Gemeente Amsterdam, 2016). Furthermore, a large part of the canals and the adjoining canal houses have been assigned UNESCO heritage, meaning that there is global interest in preserving the area (UNESCO World Heritage Centre, 2020).

Since the city center of Amsterdam has many monumental buildings and is protected in its whole by the protected city view area, the municipality of Amsterdam has introduced a class system. The class system is established to classify each monument and provide a basis for the rules and regulations and as a starting point for the renovation of monuments (Gemeente Amsterdam, 2016). Figure 4 shows the different orders of monuments in the city center.



Figure 4: Orders of monuments in Amsterdam. Source: Maps Amsterdam: Waarderingskaart architectonische en stedenbouwkundige kwaliteit, n.d.

Order 3 buildings are built before 1940. They fit into the facade they are a part of; however, they do not have any architectural or urban value. When making plans for the renovation of an order 3 building the starting point should be conservation of the facade elements. It is allowed to alter the material, size and detailing, as long as it does not disturb the original character of the building. In case the renovation is relatively drastic, it is necessary to carry out a heritage value evaluation. Based on the evaluation it will be determined whether the building has any specific historic value. In case there is value, conservation and restoration of the facade and roof is the starting point. The level of value determines whether demolition and new construction is possible (Gemeente Amsterdam, 2016).

Order 2 and 3 buildings also include buildings built between 1940 and 1970 which contribute in a positive manner to the image of the city or are of specific significance for the city (Gemeente Amsterdam, 2016). Buildings constructed after 1970 are not classified in the orders, as they have little historical and cultural value, they can however not affect the city view in a negative manner.

An order 2 monument significantly contributes to the city view. The starting point of an order 2 building is always to conserve and to restore. The original facade elements have to be maintained and restored. However, it is possible to restore elements with the use of non-authentic materials, as long as they are visually the same color, shape and detailing. The ground floor is an exception to this rule in case it is a store (as long as the original storefronts are maintained). If the facade and roof are in such a deplorable state that restoration and conservation is no longer possible, they can be rebuilt in the same manner, as long as the city view is not compromised (Gemeente Amsterdam, 2016).

Order 1 monuments are all national monuments as well as municipal monuments, or buildings with a similar importance. The starting point of an order 1 building is always conservation and

restoration. Order 1 buildings need to adhere to the rules and regulations stated for the type of monument that it is: a national or municipal monument (Gemeente Amsterdam, 2016).

### 2.2.2 Regulations for monuments (order 1 buildings)

All monuments in the Netherlands are protected by law via the 'Erfgoedwet' (formerly called the 'Monumentenwet') and the local 'Erfgoedverordening'. The 'Welstandsnota' protects all buildings in the Netherlands, including monumental buildings ('Erfgoed'). When a building is assigned as a monument, the owner has to inform the municipality (in rare cases even the province or national government) when making almost any alteration to any type of monument. For most alterations a permit is required. The municipality can oblige the owner to carry out a building historical examination before applying for the permit (Gemeente Amsterdam, 2015).

The following actions cannot be done without reporting to an inspector of the local or national authorities (Ministerie van Onderwijs, Cultuur en Wetenschap, 2015):

- Moving of the object
- Auctioning of the object
- Selling of the object
- Renting out of the object
- Loaning of the object
- Giving out of the object
- Demolishing of the object
- Disrupting of the object
- Altering of the object

However, the owner is required to perform all necessary maintenance in order to conserve the monument. Actions which can be performed without a permit are regular maintenance on the exterior without altering the detailing, shape, material, color and profiling and any activity on the interior of the monument which does not alter the monumental parts (Gemeente Amsterdam, 2015). In case the building is part of a protected city view (national and municipal) very little alterations can be done on the exterior.

If the building is only located in a protected city view area and is not classified as another type of monument, alterations to the interior can be done without permit. However, when a building is a national, provincial or municipal monument the owner is not allowed to alter the monumental parts of the interior without a permit either (Gemeente Amsterdam, 2016; Ministerie van Onderwijs, Cultuur en Wetenschap, 2015).

## 2.3 Conclusion

Renovation of a monumental building can be quite challenging as the building is protected. Prior to starting the renovation design it is necessary to choose a renovation strategy. In the case of this thesis the building will be renovated to be adaptively reused, but the building will also be conserved. Furthermore, prior to designing, a thorough analysis of the building has to be undertaken. Before suggesting any alterations the building has to be analyzed properly and the monumental elements which require to be conserved need to be identified. Legally, a building historical examination is required.

The city center of Amsterdam is home to many municipal and national monuments, but the city center is also part of the protected city view area. All national and municipal monuments are classified as order 1 buildings in the class system of the municipality of Amsterdam. For almost any alteration regarding an order 1 building a permit is required. Actions which can be performed without a permit are regular maintenance on the exterior without altering the detailing, shape, material, color and profiling and any activity on the interior of the monument which does not alter the monumental parts. None of the monumental elements can be altered both on the interior and exterior. Furthermore, due to the protected city view any alterations visible from the street cannot disturb the city view.

## 3. Energy & Renovation

National and international climate agreements have been signed by the Netherlands to counter climate change. Minimizing the energy usage of the built environment is an important step to achieve the goals set by these agreements. To lower the energy usage many different concepts and terms were introduced. This chapter introduces the climate goals that need to be achieved, the definition of several important terms for energy performance in the built environment, a design strategy for the energy renovation of buildings and the current energy performance of Amsterdam, the Burgwallen-Oude Zijde and its buildings. Furthermore, this chapter addresses the following background question: *“Which sustainable design measures can be implemented to improve the energy performance and indoor comfort of monumental buildings in general?”* and analyzes monumental buildings which have been already been renovated sustainably.

### 3.1 Energy performance in the built environment

In 2016 the Paris Agreement went into effect. The main goal of the Paris Agreement is to limit global warming to a maximum of 2.0 degrees Celsius (preferably 1.5 degrees Celsius), when compared to pre-industrial levels. In order to achieve that and to become climate neutral in 2050, greenhouse gas emissions have to be reduced drastically (United Nations, 2015). A second goal is to become better adapted to climate change. Besides the internationally signed Paris Agreement, the Netherlands also has national laws and agreements. The most important one being the climate law ('Klimaatwet'). The two main goals are to lower carbon emissions in 2050 by 95% compared to pre-industrial levels and in 2050 all electricity production has to be carbon neutral. As a step in the right direction the carbon emissions have to be lowered by 49% in 2030 already (Klimaatwet, 2019).

The Dutch climate agreement has specified measures to achieve the goals of the 'Klimaatwet' per sector. For the built environment the national agreements state that in 2050 seven million dwellings and one million other buildings have to be off natural gas. By 2030, 1.5 million existing homes have to be made sustainable. These buildings will transition from natural gas to renewable sources of energy. The focus lies on the neighborhood level, as each neighborhood is different, has its own potentials and problems and thus requires an individual approach (Ministerie van Economische Zaken en Klimaat, 2020). Each municipality had to present a plan before the end of 2021 on how to transition the neighborhoods in their municipality from natural gas to renewable sources (Ministerie van Economische Zaken en Klimaat, 2019). Natural gas connections will not be supplied anymore, unless no other solution can be found. Furthermore, standards for sustainable renovation will be given, making the transition easier. Financially, the economical help will be bound to the building, and not the owner. Moreover, the taxes on natural gas will be raised and on electricity will be lowered (Ministerie van Economische Zaken en Klimaat, 2019).

#### 3.1.1 Definitions energy performance

When it comes to energy performance in the built environment, many terms for different concepts are used. The different terms are often interchanged and have different definitions depending on the context. Before being able to make a monumental building energy neutral it is first necessary to define the different energy performance terms.

The terms 'project border' and 'system border' are frequently mentioned in the definitions of energy performance in the built environment. The project border includes all buildings and energy systems which are in the direct sphere of influence of the project owner. This can often be seen as a physical border or barrier (W/E Adviseurs, 2009). The system border includes the project itself and energy systems which are located outside of the direct sphere of influence of the project owner. The energy or carbon neutrality of a building is calculated on the base of the energy exchange or the emission of CO<sub>2</sub> (W/E Adviseurs, 2009).

An often-heard term in the built environment is energy neutrality. Especially in the past years the term has gained more interest and more significance in the industry. An energy-neutral building can also be called a Zero-Energy Building (ZEB). A project can only be called energy neutral if there is no need to import fossil or nuclear fuels from outside the system border, to build, use and demolish the building, on a yearly basis. The yearly energy usage must be equal to what is produced within the project border. The energy needed for demolition and construction of the building is divided by the life expectancy of the building (W/E Adviseurs, 2009).

The total energy usage of a building or project includes the following energy usages: energy for cooling, energy for heating (including DHW), energy for electricity (building and user related), and material related energy. The sum of all these types of energy usages over a year has to be produced within the project border to become energy neutral (W/E Adviseurs, 2009). In this thesis the focus lies on the renovation of monumental buildings. It is not likely that the building will be demolished since it is protected, thus the energy required for demolition and the material related energy for all existing parts is not calculated in. However, the material related energy for any newly added material will be taken into account.

A ZEB requires very thoughtful designing and compromises to the design. For renovation projects it is quite a task to design it in such a way that the energy production and the energy usage is equal. In those cases, it is often opted to design a Nearly Zero-Energy Building (NZEB). The Dutch term for NZEB is 'Bijna energieneutraal gebouw' (BENG). Like ZEB's, NZEB's have a very high energy performance. However, they still require a little bit of energy to be imported from outside of the system border. Preferably, this energy must come from a renewable source (D'Agostino & Mazzarella, 2019). The exact definition and requirements for NZEB's differs per country, even within the European Union (D'Agostino & Mazzarella, 2019). As the primary location of this thesis is Amsterdam the Dutch definition and requirements are adhered to in this thesis.

In the Netherlands the definition and standards of NZEB's are based on the NTA 8800 standard: Energy Performance of Buildings - Determination Methods (2020). In the Netherlands a ZEB needs to have an Energy Performance coefficient (EPC) of 0. The EPC of a NZEB is not determined, however, it has to be nearly 0 (European Commission, 2012).

From January 1, 2021, all newly constructed buildings have to adhere to the rules and regulation of BENG (NTA 8800, 2020), thus all newly constructed buildings will be NZEB's. BENG has requirements in three categories (Rijksdienst voor Ondernemend Nederland, 2020b):

- BENG 1: Energy demand for heating & cooling (considers the insulation, shape and location of the building)
- BENG 2: Primary fossil fuel demand for heating, cooling, DHW & systems (minus production on site)
- BENG 3: Percentage of primary energy demand from renewable sources

The requirements for all three categories of BENG, for dwellings (soil bound and non-soil bound) and stores are presented in table 1.  $A_{ls}/A_g$  is the ratio between loss area ( $A_{ls}$ ) and usable surface ( $A_g$ ). A term often used for the ratio is the compactness of a building.

	<b>BENG 1 (kWh/m<sup>2</sup> per year)</b>	<b>BENG 2 (kWh/m<sup>2</sup> per year)</b>	<b>BENG 3 (%)</b>
<b>Dwelling (non-soil bound)</b>	If $A_{is}/A_g \leq 1.83$ BENG 1 $\leq 65$	$\leq 50$	$\geq 40$
	If $1.83 \leq A_{is}/A_g \leq 3.0$ BENG 1 $\leq 55 + 30*(A_{is}/A_g - 1.5)$	$\leq 50$	$\geq 40$
	If $A_{is}/A_g > 3.0$ BENG 1 $\leq 100 + 50*(A_{is}/A_g - 3.0)$	$\leq 50$	$\geq 40$
<b>Dwelling (soil bound)</b>	If $A_{is}/A_g \leq 1.5$ BENG 1 $\leq 55$	$\leq 30$	$\geq 50$
	If $1.5 \leq A_{is}/A_g \leq 3.0$ BENG 1 $\leq 55 + 30*(A_{is}/A_g - 1.5)$	$\leq 30$	$\geq 50$
	If $A_{is}/A_g > 3.0$ BENG 1 $\leq 100 + 50*(A_{is}/A_g - 3.0)$	$\leq 30$	$\geq 50$
<b>Store</b>	$A_{is}/A_g \leq 1.8$ BENG 1 $\leq 70$	$\leq 60$	$\geq 30$
	$A_{is}/A_g > 1.8$ BENG 1 $\leq 70 + 30*(A_{is}/A_g - 1.8)$	$\leq 60$	$\geq 30$

Table 1: BENG requirements for dwellings and stores. Source: Rijksdienst voor Ondernemend Nederland, 2020b

Besides a building being (nearly) energy neutral, a building can also be built carbon neutral. A project is carbon neutral if on a yearly basis there is no net emission of greenhouse gases to build, use and demolish the project. Meaning that the yearly greenhouse gas emission within the project border is to be equal to the amount of greenhouse gas emissions captured, stored and compensated within the system border (W/E Adviseurs, 2009). La Roche (2011) states that the total greenhouse gas emission of a building is equal to the sum of the operation emissions (use of building), construction emissions (building of project), water emissions and the waste emissions. All energy used in the different categories has to be converted a common measuring unit ( $\text{CO}_2/\text{m}^2$  per year) to calculate whether a project is carbon neutral (La Roche, 2011).

Carbon neutrality is sometimes easier to achieve, as the  $\text{CO}_2$  captured, stored and compensated can be located outside of the project border (but within the system border). This makes it easier to achieve carbon neutrality than energy neutrality, where all energy has to be produced within the project border (W/E Adviseurs, 2009). Capturing, storing and compensating of  $\text{CO}_2$  is done is so called carbon sinks (La Roche, 2011).

The last neutrality term which is often mentioned is climate neutrality. The definition of this term is often interchanged with the other neutrality definitions, leading to confusion (W/E Adviseurs, 2009). In theory, a climate neutral building has no positive or negative effect on the climate and climate change (Rijksdienst voor Ondernemend Nederland, 2020a). It is not advised to use the term climate neutral because the climate entails much more than energy and carbon usage. The municipality of Amsterdam plans to be climate neutral in 2050 (Gemeente Amsterdam, 2020b). Meaning that the municipality intends to have shifted to renewable energy completely in 2050 (Gemeente Amsterdam, 2020b).

Besides the neutrality terms, energy performance in the built environment can also be measured using other terms. However, for this thesis ZEB (energy neutrality), NZEB (BENG) and carbon neutrality are the most important terms.

### 3.1.2 The New Stepped Strategy

A common strategy used to design a ZEB is the New Stepped Strategy (van den Dobbelsteen, 2008). It follows the steps: research, reduce, reuse and use of renewable energy sources.

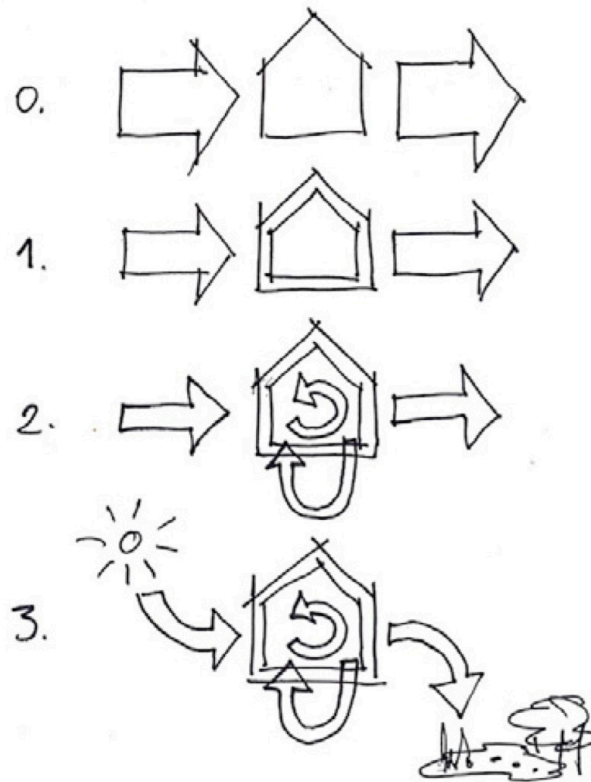


Figure 5: The New Stepped Strategy. Source: van den Dobbelsteen, 2008.

Step 0 in the design of a ZEB is research and study of the local circumstances to analyze what is available that might have potential in making the building energy neutral. The first step is called reduce. In this step the energy demand of the building is reduced by the use of energy efficient appliances but also by using passive and smart bio climatic design. The next step is reuse. In this step waste flows of energy, water and materials are reused. Water is for example collected or a heat recovery is applied to the ventilation system or the showers. The last and third step is to produce the remaining energy demand from renewable sources. This can be done on site or by the import of renewable energy (van den Dobbelsteen, 2008). The New Stepped Strategy can also be used for designing a NZEB or a carbon neutral building.

## 3.2 Energy performance of the Burgwallen-Oude Zijde

To gain proper understanding of the energy usage in Amsterdam and the Burgwallen-Oude Zijde the energy usage of the city and the neighborhood were analyzed and compared with Almere, a relatively new city (built in the 1970's). Furthermore, the functions in the neighborhood were analyzed for a better understanding of the area.

### 3.2.1 Energy demand of Amsterdam & Burgwallen-Oude Zijde

One way of analyzing the energy usage of the city of Amsterdam is by looking at the energy labels of the buildings. Energy labels range from G, very poorly performing on energy usage, to A++++, very well performing on energy usage. In the historical city center of Amsterdam, the energy label map (figure 6) is predominantly red and orange, meaning that there are quite some buildings with a low energy label. As a general rule it can be said that buildings built before 1976, if not yet renovated, have an energy label G. Buildings in Amsterdam have an average energy label D, which makes Amsterdam the fifth worst performing municipality in the Netherlands when it comes to energy labels (Isover, 2015).



Figure 6: Energy labels in the city center of Amsterdam. Source: Nationale EnergieAtlas, 2020.

The Centraal Bureau voor Statistiek (CBS, 2019), has calculated that an average dwelling in 2019 in Amsterdam uses 800 m<sup>3</sup> of natural gas and 2,050 kWh electricity. A percentage of 5.8 of the dwellings is connected to a heat grid. The average energy use of a row house (a common housing typology in the city center of Amsterdam) is 970 m<sup>3</sup> natural gas and 2,890 kWh electricity (CBS, 2019). Figure 7 and 8 show the natural gas and electricity usage per connection. It can be seen that in the historical city center the gas and electricity usage in general is higher than in the neighborhoods surrounding the city center.

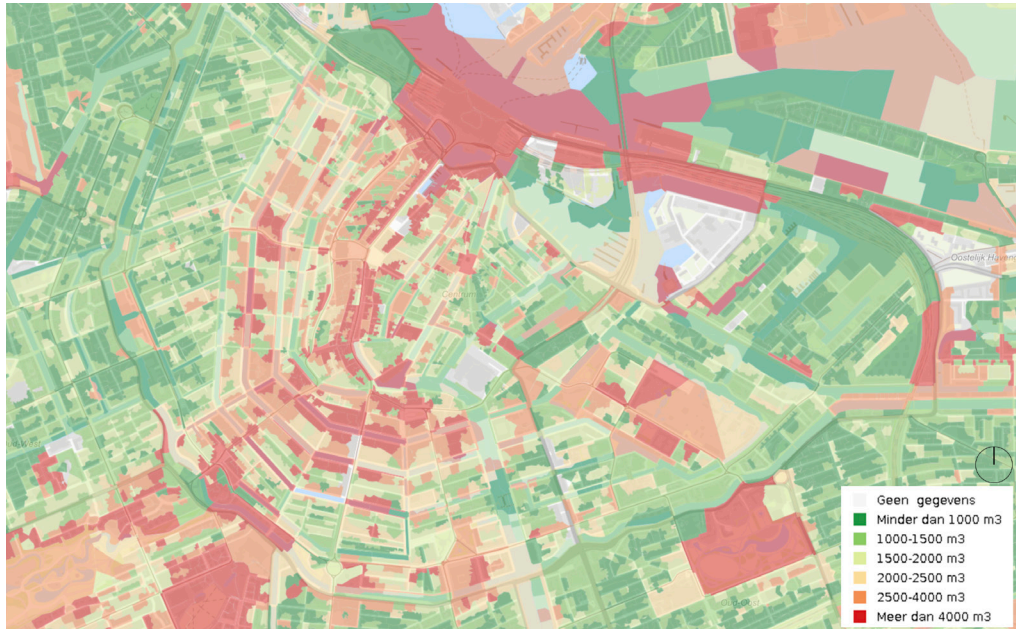


Figure 7: Natural gas usage per connection in Amsterdam. Source: Geodan, n.d.



Figure 8: Electricity usage per connection in Amsterdam. Source: Geodan, n.d.

For better understanding of the energy performance, the energy usage of Amsterdam is compared to Almere and the Netherlands. The total energy usage of an average dwelling in Amsterdam, Almere and the Netherlands is converted into one common denominator: kWh. One m<sup>3</sup> of natural gas equals 10.2 kWh (van den Dobbelsteen, van der Ham, Blom & Leemeijer, 2019). The results of the conversion can be found in table 2.

	Gas (m <sup>3</sup> )	Gas (kWh)	Electricity (kWh)	Total (kWh)	Total (kWh/m <sup>2</sup> )
<b>Amsterdam</b>	800	8,160	2,050	10,210	208
<b>Almere</b>	420	4,284	2,930	7,214	127
<b>The Netherlands</b>	1,180	12,036	2,730	14,766	227

Table 2: Energy usage of an average dwelling in Amsterdam, Almere & the Netherlands. Source: CBS, 2020b & CBS, 2019

To compare the energy usage fairly the total energy is divided by the average surface area one person lives on. A resident of Almere has an average living area of 57 m<sup>2</sup>, whereas a resident of Amsterdam only has 49 m<sup>2</sup>. On average in the Netherlands one person has 65 m<sup>2</sup> to live on (CBS, 2018). Table 2 shows that on average dwellings in Amsterdam uses less energy than Dutch dwellings (per m<sup>2</sup>). However, not the whole of Netherlands is urbanized, making it difficult to compare the two. When comparing Almere and Amsterdam, two urban areas, it is quite apparent that dwellings in Almere use less energy. The average energy usage of a dwelling in Almere is around 39% lower than a dwelling in Amsterdam. One very apparent reason for the large difference in energy usage between Almere and Amsterdam is that most buildings in Amsterdam were built before 1860, whereas all buildings in Almere were built after 1975.

The average energy usage at the Burgwallen-Oude Zijde (a neighborhood with mostly monumental buildings, constructed before 1860) is 980 m<sup>3</sup> of natural gas and 1,990 kWh electricity per dwelling (CBS, 2019). The yearly energy usage of an average monumental dwelling (a four-person household with a volume of around 600 m<sup>3</sup>) is around 3,600 m<sup>3</sup> natural gas and 5,000 kWh electricity (Stichting Erkende Restauratiekwaliteit Monumentenzorg, 2019). The van Hasseltsteeg 49, a national monument, has a yearly usage of 4,280 m<sup>3</sup> of natural gas and 5,364 kWh of electricity. The building was built in 1645 and has 4 floors, a floor area of 118 m<sup>2</sup> and an energy label G. Like most houses in the city center of Amsterdam, it is a row house. Table 3 shows the average usage of a row house (a common typology) at the Burgwallen-Oude Zijde, Amsterdam, Almere and the Netherlands.

	Gas usage (m <sup>3</sup> )	Electricity usage (kWh)	Total (kWh)	Total (kWh/m <sup>2</sup> )
<b>The Netherlands</b>	1,100	2,830	14,050	216
<b>Almere</b>	410	3,110	7,292	128
<b>Amsterdam</b>	970	2,890	12,784	261
<b>Burgwallen O-Z</b>	1,680	3,150	20,286	414
<b>Van Hasselsteeg 49</b>	4,280	5,364	49,020	1000
<b>Average monument</b>	5,000	3,600	54,600	840

Table 3: Average energy usage of row houses. Source: CBS, 2019.

On average a row house at the Burgwallen-Oude Zijde uses roughly 37% more energy compared to an average row house in Amsterdam and 31% more than an average Dutch row house. When comparing to Almere, a row house at the Burgwallen-Oude Zijde even uses 64% more energy. Yet, the energy usage of an average monumental building and the Van Hasselsteeg 49 is even higher than the average energy usage of a row house at the Burgwallen-Oude Zijde.

	Gas usage (m <sup>3</sup> )	Electricity usage (kWh)	Total (kWh)	Total (kWh/m <sup>2</sup> )
<b>The Netherlands</b>	770	1,970	9,824	151
<b>Almere</b>	250	2,020	4,570	80
<b>Amsterdam</b>	760	1,920	9,672	197
<b>Burgwallen O-Z</b>	980	1,930	11,926	243

Table 4: Average energy usage of apartments. Source: CBS, 2019.

The same can be observed when comparing the average energy usage of apartments in the Netherlands, Amsterdam, Almere and the Burgwallen-Oude Zijde. The average energy usage of an apartment at the Burgwallen-Oude Zijde is roughly 19% higher than an apartment in Amsterdam and an apartment in the Netherlands. Compared to Almere an average apartment at the Burgwallen-Oude Zijde uses 62% more energy.

The energy usages discussed previously are mostly focused on dwellings. In this thesis the focus lies on mixed-use buildings with a residential and retail function. For retail stores it is more difficult to find figures on the energy usage, especially for monumental buildings. The energy usage also heavily relies on the type of retail store. A clothing store requires less energy than for example a store with any types of coolers (food). In general, a retail store for clothing uses 12 m<sup>3</sup> natural gas per m<sup>2</sup> floor surface and 65 kWh electricity per m<sup>2</sup>, when built before 1946 (as is the case with most of the buildings in the Green Light District, the Burgwallen-Oude Zijde) (CBS, 2020a).

### 3.2.2 Functions of the Burgwallen-Oude Zijde

As mentioned in the introduction the Burgwallen-Oude Zijde is one of the oldest neighborhoods of Amsterdam. The neighborhood was developed around the river 'de Amstel' and was one of the two city centers of the city. Throughout the centuries neighborhoods were erected around the Burgwallen-Oude Zijde (see figure 9 for the boundaries of the neighborhood).



Figure 9: Boundaries of the Burgwallen-Oude Zijde. Own work.

At the Burgwallen-Oude Zijde there is a large variety of functions. Figure 10 shows all the different identified functions in the area. In the neighborhood however there is also a large number of dwellings. Often buildings have a mixed use function (de Haan, n.d.).

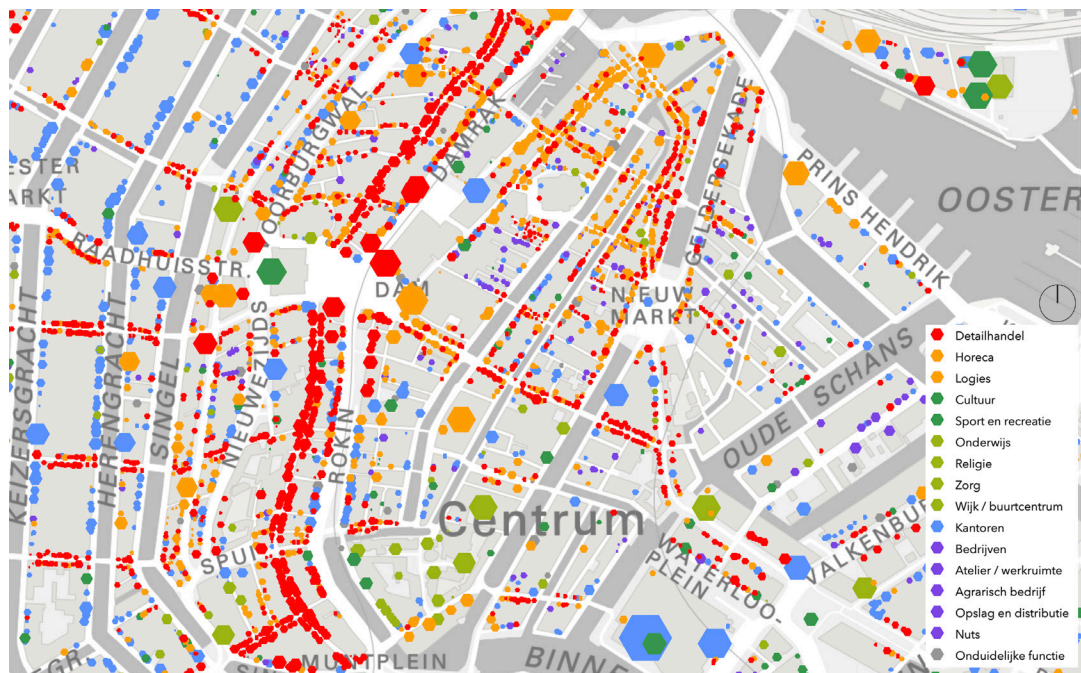


Figure 10: Functions at the Burgwallen-Oude Zijde. Source: Maps Amsterdam: Functiekaart, n.d.

### 3.3 Possible design measures for energy renovations

The previous sub chapters have shown that the Burgwallen-Oude Zijde and its buildings use a significant amount of energy. There are many measures which can be implemented to better the energy performance of the buildings and thus the neighborhood. In the table 5,6 and 7 several options for energy sources, general design measures and HVAC installations can be found. These lists are not exhaustive as there are many possible adjustments which can be done to reduce, reuse and produce energy. The measures range from small alterations to larger renovations and for an energy-neutral renovation it is necessary to combine the different measures. In the tables the suitability of the different measures for the implementation in monumental buildings in general can be found as well. A range from ++ to -- is used.

Category	Technology	Advantage	Disadvantage	Suitability
<b>Solar</b>	PV	Solely requires a battery		++
	PVT	Hot water & electricity production	Requires buffer tank (space)	0
	Solar panels		Requires buffer tank	0
<b>Wind</b>	Turbine	Wind is a year-round energy source in NL	Not allowed in city center	--
<b>Water</b>	TEO	Widely available in city center	Building needs to be close to water body	++
	TEA		Can only be produced at water treatment plant	--
	TED	Available in city center	Relative low potential	0
<b>Gas</b>	Natural gas	Easily available	Not renewable	--
	Biogas	'Climate neutral'	Questionable sustainability & limited availability	-
	Hydrogen	Potentially CO <sub>2</sub> neutral	Expensive & not yet CO <sub>2</sub> neutral	0
<b>Biomass</b>		'Climate neutral'	During combustion release of particulate matter	-
<b>Geothermal</b>	Soil	Widely available & can be combined with heat & cold storage	Requires space around building	0
	Deep		Impossible in urban areas	--
	Ultradeep		Impossible in urban areas	--
<b>Air</b>		Widely available	In winter possibly insufficient by itself	+
<b>Rest heat</b>	Heat network	Reuse of energy	Underground crowding issue & questionable sustainability	0

Table 5: Possible energy sources. Own work.

Energy for the usage of the building can be derived from various sources. Some of the listed energy sources in table 5 are non-renewable or not sustainable and are thus not suitable for energy renovation of buildings (such as natural gas and biomass). Other energy sources are not suitable for the use within the city center of Amsterdam such as deep geothermal energy and wind energy due to restrictions and limited available space. Analysis of the suitability of the different energy sources has shown that solar energy (within the regulations for monumental buildings), aquathermal energy (energy from water), soil geothermal energy (only if there is space available near the building), rest heat (only if underground crowding is limited), air and new types of gas (biogas and hydrogen) have the most potential as energy sources for monumental buildings in Amsterdam.

Category	Technology	Advantage	Disadvantage	Suitability
<b>Insulation</b>	Interior insulation	Allowed for monumental buildings	Risk of internal condensation & loss of internal space	0
	Exterior insulation	Higher performance & no loss of interior space	Not allowed for monumental buildings	0
<b>Windows</b>	Thick curtains	Very little alterations required & cheap	Low insulative capacity	0
	Window foils	Very little alterations required	Low insulative capacity	0
	Single glazing	Little alterations required	Low insulative capacity	--
	'Achterzet-raam'	Can be used for monumental windows	Two separate windows & limited insulative capacity	0
	Double glazing	High insulative capacity	Increased weight	+
	Triple glazing	'Optimal' insulative capacity	High weight	0
	Wooden frames	Allowed for monumental buildings	Lower insulative capacity	+
	Aluminum frames	High insulative capacity	High embodied energy & not historic	-
	uPVC frames	High insulative capacity	Shorter life span & not a historic	0
<b>Crack sealing</b>	Removable	Allowed for monumental building	Requires regular replacement	++
	Non removable	Better performance	Not allowed in monumental buildings	-
<b>Shower heat recovery</b>	Vertical	Higher performance	Pipe needs to be installed in room underneath shower	-
	Horizontal	Floors do not require alterations	Floor height needs to be sufficient	+

Table 6: Possible general design measures. Own work.

<b>Other</b>	LED lighting	Significant energy reduction & requires little alterations		++
	Energy efficient appliances	Energy reduction & requires little alterations	Can be more expensive & only worth when appliance requires replacement	+
	Hot fill appliances	Energy saving	Expensive & requires DHW connection	0
	Water reducing faucets	Reduces use of DHW	User must get used to lower amount of water	+
	Insulate pipes	Reduces energy losses for DHW & heating	For visible pipes less aesthetic	++
	Radiator foil	Quick and easy improvement	Relative limited effect	+
	Green roof	Insulative function & increase biodiversity & water retention	Roof needs to be able to carry increased weight	0

Table 6: Continuation possible general design measures. Own work.

Besides shifting to renewable energy sources it is also important to lower the energy usage of the building. There are several different methods of reducing the energy usage of a building. One of the most effective measures to reduce the energy demand (and improve the comfort of the occupants) of the building is to improve the building envelope and minimize heat losses to the exterior. Improving the building envelope includes the opaques parts of the facades, the windows, the roofs, the floors but also lowering the infiltration rate (filling of cracks and seams). There are many ways of improving the building envelope as can be seen in table 6. However, not all measures are suitable for monumental buildings. For example, exterior insulation is not allowed in most cases. The measures which are most suitable depends on the specific building and should be assessed prior to designing. Apart from improving the building envelope there are also other small measures which can be implemented to lower the energy usage and reuse energy, such as shower heat recovery, LED lighting and energy efficient appliances. There are also numerous interventions which are dependent on the occupant and not influencable by the designer such as turning down the heating and turning the lights and heating off when not present.

Lastly, the HVAC installations of the building also heavily influence the energy usage of the building but also the comfort of the occupants. Table 7 shows the different HVAC installations which can be implemented. The type of HVAC installation also greatly depends on the energy source as not each energy source is compatible with each installation type. It is thus necessary to simultaneously choose the energy source and HVAC installations, based on the building and the surrounding potentials. Currently most monumental buildings rely on high temperature (HT) heating with natural gas driven boilers and radiators. To improve the energy performance of the building it can be opted to use low temperature (LT) heating. LT heating is often combined with a heat pump (collective or individual), the type depending on the source of energy. For LT heating with a renewable source such as geothermal heat or aquathermal heat it is often opted to store heat and cold underground with an ATEs system but that requires sufficient space in for example the garden. Also for LT heating insulation of the building envelope is necessary and thus it is not always suitable for monumental buildings. LT heating furthermore requires a larger surface area for the heat distribution as the temperature difference between the heat distributor and the air is lower than with HT heating. It can thus be opted to use floor heating or wall heating.

Category	Technology	Advantage	Disadvantage	Suitability
<b>Heating type</b>	HT	Quick heating of building	High energy usage & losses	--
	MT	No large alterations required	Less energy efficient	0
	LT	Energy efficient	Requires insulated building	0
	Collective	Low cost & no space loss in apartments	Requires communal space	+
	Individual	Each apartment has own system and can adjust accordingly	More expensive & requires space in each apartment	+
<b>Heating system</b>	Heat pump (air-water)	Financially beneficial & quick installing	Noise & insufficient in winter	+
	Heat pump (air-air)	Can also be used as air-conditioning	Insufficient in winter & incompatible with current heating systems	--
	Hybrid heat pump	Can boost T in winter	Requires natural gas, biogas or H	0
	Electric boiler	Quick heating & renewable source	High energy usage	+
	Regular boiler	Quick heating & HT	Requires natural gas	--
	Pellet stove/boiler	Radiant heating & 'CO <sub>2</sub> neutral'	Local heating, safety issues & particulate matters	--
<b>Heating storage</b>	ATES	Can be used for cooling & heating	Requires space in e.g. garden	0
<b>Heating distribution</b>	Radiators	Quick heating	Visible	+
	Convectors	Heat is distributed around room	Visible	+
	Floor heating	Large distribution area & perceived as comfortable	Slow responsive & works best with thermal mass	-
	Wall heating	Large heat distribution area	Thermal mass of wall is not used	-
	Thermally active building system	Thermal mass creates buffer between in & out	Requires exterior insulation of facades	--
	'WarmBouwen' concept	Makes building think it is always ± 20 °C outside, insulation not required & no risk of condensation	Walls are not insulated	++

Table 7: Possible HVAC installations. Own work.

	Ventilation air	Can heat and cool	Increased size ventilation ducts & lower comfort level	--
	Infra-red heating	Radiant heat is perceived as comfortable	Only local heating & requires elec. grid to be improved	+
	Radiator fans	Distributes heat from radiators		++
<b>Ventilation</b>	System A	Requires little alterations	Ventilation flow can't be controlled	-
	System B	Incoming air can be treated	No guaranteed air flow & unwanted infiltration	--
	System C	Requires less space than D & guaranteed air flow	Unwanted infiltration	+
	System D	Air can be treated & no unwanted infiltration	Requires space for ducts	+
	Heat recovery	Reuse of energy & warmer inlet of air	Larger air handling unit	+
<b>DHW</b>	Buffer tank (+HP)	Energy efficient & DHW quick to user	Requires space	+
	HP booster	Sufficient DHW & quick to user	High electricity usage	0
	Heat network	Sustainable reuse of rest heat	Heat network required	0
	Electrical boiler	Less space required & quick heating	Relative high energy usage	+
	Regular boiler	Less space required & quick water heating	Use of natural gas	--
	HP boiler	Energy efficient	Separate system from heating	+
	'Doorstromer'	Immediate hot water	High energy usage when used for the bathroom	-
	Circulation pipe	Continuous flow of DHW & collective	Heat losses due to long pipes	0

Table 7: Continuation possible HVAC installations. Own work.

For floor heating to work most effectively a floor finishing which conducts heat well, such as tiles, is necessary. This is not always what the occupant prefers and impossible if the floor finishing is historical. It is thus sometimes opted to use wall heating. Roughly there are three wall heating systems. The first one being regular wall heating which requires insulation between the wall heating system and existing wall and thus a significant amount of interior space. In the case of wall heating the walls are an important part of the heating of the room. Another option is to use a thermally active building system (TABS). In the case of TABS the thermal mass of the wall is activated to create a buffer between the interior and exterior. TABS requires the wall to be insulated from the exterior, which is often not allowed in monumental buildings. The last type

of wall heating is the concept of 'WarmBouwen' or 'Temperierung'. In this case the wall (thus the thermal mass) is heated with a renewable LT source to make the room think it is around 20 degrees outside and transmission of more expensive heat, which has been upgraded to a higher temperature, from the radiators (or other heat distributors) to the exterior is minimized. The wall heating system basically creates an insulation layer without the risk of condensation and with minimal loss of interior space. Furthermore it minimizes the cold radiation from the walls and in general dry constructions insulate better than humid constructions (WarmBouwen, 2018). The 'WarmBouwen' concept seems promising for monumental buildings.

For the ventilation of the building there are four systems ranging from complete natural ventilation to complete mechanical ventilation (balanced). The suitability of each system depends on the available space. It is advised to use fully mechanical ventilation (system D) if there is sufficient space for the ducts and air handling unit (AHU) as the air flow can be controlled. Regarding DHW, there are also many options. The DHW system which is chosen should depend on the chosen heating system as it is most effective to combine the two.

### 3.4 Examples of sustainably renovated monuments

Throughout the years the monumental buildings in the city center of Amsterdam have been renovated and altered numerous times. As sustainability has become more important over the last years some monumental buildings have already been renovated in a sustainable manner.





	Zonnewijzer <sup>1</sup>	Doelenzaal <sup>2</sup>	L.A.N.X <sup>3</sup>	Mient <sup>4</sup>	Singel <sup>5</sup>	Grote Kerkstraat <sup>6</sup>
<b>Address</b>	Herengracht 182	Kloveniersburgwal 87-89	Nieuwezijds voorburgwal 167	Mient 27	Singel 28	Grote kerkstraat 47-59
<b>City</b>	Amsterdam	Amsterdam	Amsterdam	Alkmaar	Amsterdam	Leeuwarden
<b>Picture</b>						
<b>Year of construction</b>	1772-1781	1881	1775	1530	1880-1825	1625
<b>Year of renovation</b>	2018	2016	2018	2018	2020	2013
<b>Type of monument</b>	National	National	National	National	National	National
<b>Function</b>	Office	Dwelling & office	Cultural association	Retail & dwelling	Dwelling	Dwellings
<b>Insulation</b>	Roof & facades	??	Glass & roof	Roof, facades, floor & glass	Roof, facades & floor & glass	Roof, facades & floor & glass
<b>Heating &amp; cooling system</b>	2 heat pumps (air-water)	6 heat pumps (air-air)	4 heat pumps, rest heat from beer cooling & infrared panels	Heat pump (water-air)	Green foundation (soil heating & cooling)	HR combination boiler (natural gas)
<b>Heating distribution</b>	LT floor & convectors	Ventilation air (VFR system)	Ventilation air	LT floor heating	TBD	Floor heating & radiators
<b>Cooling distribution</b>	LT floor cooling	Ventilation air (VFR system)	Ventilation air	LT floor cooling & AC on ground floor	TBD	NA
<b>Ventilation system</b>	D, with CO <sub>2</sub> sensors	D, with heat exchange	D, with heat exchange	D, decentralized	TBD	D, with heat exchange
<b>Energy production</b>	---	---	20 solar panels	24 solar panels	PVT panels	---
<b>Extra</b>	Plumbing in fire shaft, biobased insulation	---	Water saving toilets	Circular, natural & recycled materials	---	Elevator in monumental closet, six houses into one large complex

Table 8: Examples of sustainably renovated monumental buildings. For sources see list of tables.

Table 8 shows a summary of six sustainably renovated monumental buildings which were analyzed. Most of the examples are located in Amsterdam, however as the objective of this thesis is to create a generic approach, a few buildings outside of Amsterdam were also analyzed. It can be seen that many of these examples have switched to heat pumps as well as to fully mechanical ventilation. For heat distribution within the building low temperature (LT) floor heating is used in two of the cases.

During the initial research it was noticed that in general the literature is quite pessimistic about the sustainable renovation of monumental buildings. Often the challenges are highlighted rather than the opportunities. During the research of examples of sustainably renovated monumental buildings the outcomes were more optimistic. It showed that more can be done than originally thought. One example is that quite often in literature it can be found that LT heating is unsuitable for monumental buildings, even when insulated. The examples however show the potential of LT heating, as it has been implemented in two of the six examples. Regarding heat distribution in the buildings in most examples a combination of heating systems is used. Often LT floor or wall heating is combined with another type of heat distribution, such as radiators or convectors, to increase the comfort in the building as well as to provide a solution for the extreme cold days. In most buildings cooling was introduced as well.

Concerning ventilation, the literature research could not fully give a definitive answer on the best ventilation system. Natural ventilation would alter the monumental facades whereas mechanical ventilation requires a significant amount of space. Most of the examples use mechanical ventilation (centralized or decentralized), showing that fully mechanical ventilation has potential in monumental buildings. Regarding insulation, in most case study buildings insulation was applied on the interior of the buildings (so-called 'voorzetwanden'). In all cases it was noted to be extremely careful near thermal bridges as condensation can occur when insulated. Furthermore, in some cases solar collectors, PV panels or even PVT panels were used to produce energy. All of these were placed out of sight from the street to not disturb the protected city view.

### **3.5 Conclusion**

The world is shifting from fossil fuels to renewable energy sources to counter climate change and achieve the goals set by national and international agreements. There are many terms used in the built environment for sustainable building concepts. In this thesis energy neutrality is the most important term and will be aimed for in the design. All energy used for the renovation (embodied energy of new materials) and energy usage of the building on a yearly basis needs to be compensated within the project border. In this thesis energy usage for demolition is not taken into account as the building will most likely not be demolished due to its monumental status. Furthermore, solely the energy for new materials will be taken into account as most materials are already present and have been for centuries. For the renovation the New Stepped Strategy is used as a guideline.

Analysis of the neighborhood has shown that the energy usage in the neighborhood Burgwallen-Oude Zijde is significantly higher than in the rest of Amsterdam and the Netherlands. The energy usage of monumental buildings is even higher than the average energy usage at the Burgwallen Oude-Zijde. It confirms that monumental buildings have a low energy performance and require energy renovation to achieve the climate goals. The analysis has also shown that the Burgwallen-Oude Zijde has many different types of functions. Buildings with a mixed-use function are common, especially dwellings with a retail function on the ground floor. It was thus chosen to choose a case study building with a mixed-use function of retail and dwellings.

To improve the energy performance and indoor comfort of monumental buildings many design measures can be implemented. It is however necessary to critically assess whether the measures can be implemented in each individual building. As renewable energy sources aquathermal energy, air, solar energy, soil energy, rest heat and new gases seem promising. To reduce energy a combination between large renovations (improving the building envelope) and smaller alterations (e.g. changing the lighting to LED) is necessary. The type of HVAC installations highly depend on the energy source and general design measures which can be implemented. Even though there is quite some skepticism about making monumental buildings energy neutral, carbon neutral or to take them off natural gas the researched examples have shown that it is possible to renovate monumental buildings in a sustainable manner. More is possible for the energy renovation of monumental buildings than initially thought by the author of this thesis and suggested by literature.

## 4. Indoor Comfort

One of the sub-objectives of this thesis is to increase the indoor comfort in the building. It is thus necessary to define indoor comfort and set criteria for the desired comfort for the renovation design. This sub chapter will try to answer the background question: *“What are the requirements for indoor comfort in monumental buildings?”* Furthermore, a brief overview of common indoor comfort related problems in monumental buildings is given, according to literature.

### 4.1 Definition & requirements of comfort

As we spend a lot of our time inside, it is important that our indoor living and working environment is healthy and comfortable (Bluyssen, 2014). Especially in times of the COVID-19 pandemic, when people spend even more time at home, indoor comfort has become ever more important. The level of comfort and health are often related to each other. An unsuitable indoor environment can lead to extreme discomfort but also numerous different health complaints (Bluyssen, 2009). A general feeling of being unwell can often be related to an unhealthy indoor environment (Harris & Moore, 2019). Many diseases and disorders we know about these days can be related to an uncomfortable indoor environment in some sort of way.

But what is comfort? The Cambridge Dictionary (2021) states that comfort is a pleasant feeling of being relaxed and free from pain. A comfortable indoor environment is an environment which is pleasant to be in and does not cause any pain or any type of physical or mental discomfort. As the definition shows, the concept of indoor comfort is quite vague and elusive. Many different aspects can be categorized under indoor comfort. Furthermore, many factors can seem to influence the indoor comfort. In general, indoor comfort can be divided into four categories: thermal comfort, indoor air quality (IAQ), acoustical comfort and visual comfort (Bluyssen, 2009).

Thermal comfort is sometimes called the indoor climate. Thermal comfort is: *“the condition of the mind which expresses satisfaction with the thermal environment”* (ANSI/ASHRAE Standard 55, 2013). There are several parameters that influence thermal comfort:

- Air temperature
- Radiant temperature
- Relative humidity
- Air velocity

The most important aspect of the IAQ of a building is the exposure to pollutants in the building. There are many different types of pollutants and pollution sources. They can come from occupant related indoor activities such as smoking as well as from building materials, the exterior and even the ventilation system components (Bluyssen, 2009). There are several parameters for IAQ:

- Ventilation rate of the space
- Production of pollutants in a space
- Concentration of pollutants in the ventilation air

The indoor comfort parameters are related to one another and not independent. For example, the ventilation rate has an effect on the amount of pollutants in the space. But, the indoor temperature also has an effect on the IAQ.

There are also many parameters for acoustical and visual comfort. These will not be elaborated on as these do not lie within the scope of this thesis. However, the proposed design of this thesis will adhere to the rules and regulations mentioned in BouwBesluit 2012 for acoustical and visual comfort (see following paragraph).

#### 4.1.1 Requirements for indoor comfort in (monumental) buildings

Since indoor comfort is such a large factor in the health and the wellbeing of the users of the indoor space, requirements for the indoor environment are set. In the Netherlands the building

decree is in effect (BouwBesluit 2012, 2021). There are also the so called NEN standards. Officially NEN standards do not have a legal status, but are merely guidelines, unless other appointed in Bouwbesluit 2012 or elsewhere (GGD & Peters, 2007).

Before looking into the different requirements, it is important to mention that in Bouwbesluit 2012 a distinction between a residential area and a residential space is made for dwellings. A residential area is an area enclosed with constructive walls on one floor (spaces such as the toilet and bathroom are not counted in). A residential space is an enclosed space (room) with a residential function where the users tend to stay for longer periods of time, such as a bedroom or living room. A residential area can contain multiple residential spaces (GGD & Peters, 2007). Moreover, Bouwbesluit 2012 occasionally has different requirements for new construction than for renovation. However, there are no specific requirements for monumental buildings.

Bouwbesluit 2012 does not specify many regulations which can be related to thermal comfort. The main thing which is specified is the insulation value (R-value) of the different kinds of exterior partition constructions (see table 9). To counter condensation the temperature coefficient on the interior surface should not be larger than 0.65 for dwellings and 0.5 for retail locations. To minimize draft and thermal discomfort due to ventilation, the maximum air velocity in a residential area and residential space is 0.2 m/s (in winter), however air velocity at ventilation inlets may be higher.

	$R_{\text{façade}}$ ( $\text{m}^2 \cdot \text{K}/\text{W}$ )	$R_{\text{floor}}$ ( $\text{m}^2 \cdot \text{K}/\text{W}$ )	$R_{\text{roof}}$ ( $\text{m}^2 \cdot \text{K}/\text{W}$ )	$U_{\text{frame, window, door}}$ ( $\text{W}/\text{m}^2 \cdot \text{K}$ )
<b>Dwelling (new)</b>	4.7	3.7	6.3	1.65
<b>Retail (new)</b>	4.7	3.7	6.3	1.65
<b>Dwelling (renovation)</b>	1.4	2.6	2.1	2.20
<b>Retail (renovation)</b>	1.4	2.6	2.1	2.20

Table 9: Minimum R-values and maximum U-values of the different exterior partition constructions per function. Source: Bouwbesluit 2012, 2021.

Bouwbesluit 2012 does not specify minimum and maximum temperatures. NEN-EN 15251 (2007) specifies minimum and maximum operative temperatures as can be seen in table 10. These are based on the assumptions on the regular activity level per function (sedentary in dwellings and walking in retail stores) and a clothing factor (Clo) of 0.5 in summer and 1.0 in winter.

	<b>Min. T in winter (°C)</b>	<b>Max. T in summer (°C)</b>
<b>Dwelling</b>	20	26
<b>Retail</b>	16	25

Table 10: Minimum and maximum temperature per function. Source: NEN-EN 15251, 2007.

The temperatures above are category II comfort criteria. Thermal comfort is often measured in the predicted mean vote (PMV). It indicates the mean value of votes of a large group on a scale of 7. Ranging from -3 (very cold) to +3 (hot). In general a PMV between -0.5 and +0.5 is considered comfortable for most people, which is classified as category II comfort criteria. In this case the predicted percentage of dissatisfied (PPD) is lower or equal to 10 (NEN-EN-ISO 7730, 2005).

For IAQ the main parameters are the relative humidity and the minimum ventilation rate. The ventilation rates for dwellings are based on the surface area of the residential areas (see table 11). For a retail store the amount of ventilation is specified per person present and should be 4  $\text{dm}^3/\text{s}$  per person. The air for a residential area and space should come directly from the exterior. Furthermore, each building should have a provision to quickly get rid of strongly polluted air, called airing. For renovation this airing should have a minimum air rate of 6  $\text{dm}^3/\text{s}$ .

	Min. vent. rate (dm <sup>3</sup> /s/m <sup>2</sup> )	Min. total vent. (dm <sup>3</sup> /s)
<b>Residential area</b>	0.9	7.0
<b>Residential space</b>	0.7	7.0
<b>Bathroom &amp; toilet</b>	--	14.0 & 7.0
<b>Kitchen</b>	--	21.0

Table 11: Minimum ventilation rate for dwellings. Source: Bouwbesluit, 2012, 2021.

NEN-EN 15251 (2007) specifies that a minimum requirement for a good indoor air quality is 7 l/s per person, which is the same as Bouwbesluit 2012. As guideline a ppm of 500 above the outdoor concentration of CO<sub>2</sub> is good. The relative humidity should have a maximum of 70%, otherwise mold may grow, and a minimum of 40% (GGD & Peters, 2007). NEN-EN 15251 (2007) advises general ventilation in all rooms and exhaust of pollutions in kitchens, bathrooms and toilets.

Bouwbesluit 2012 has slightly different acoustical criteria for renovation and new construction. It is however advisable to aim for the criteria set for new construction, even for a renovation. All exterior partition constructions of a residential area should have a minimum sound proofing of 20 dB (in case of renovation 10 dB). In the case of traffic noise (present in the city center of Amsterdam) the sound absorption of an exterior partition construction of a residential area should be the maximum allowed sound level of the road (65 dB, 50 dB is preferred) minus 33 dB for new construction. In case of renovation the minimum sound absorption of traffic noise is equal to the sound absorption of the exterior partition prior to the renovation. Regarding any criteria related to interior noise: any installation mechanism or device bordering a residential area cannot emit more sound than 30 dB (40 dB for renovation). Furthermore, table 12 shows the required sound differences between two interior spaces for new construction. In the case of renovation, the sound difference level between the two spaces prior to the renovation is the minimum required sound difference level. In summary, the floor or wall between two apartments (new construction) needs to reduce air noise by 52 dB and the contact noise through the partition cannot exceed 54 dB.

	From	Min. air noise insulation to residential area (D <sub>nT,A,k</sub> )	Min. air noise insulation to other areas (D <sub>nT,A,k</sub> )	Max. contact noise to residential area (L <sub>nT,A</sub> )	Max. contact noise to other areas (L <sub>nT,A</sub> )
<b>Residential</b>	Other parcel	52 dB	47 dB	54 dB	59 dB
	Same parcel, different functions	52 dB	47 dB	54 dB	59 dB
	Same parcel, same functions	32 dB	-	79 dB	-
<b>Retail</b>	Other parcel	52 dB	47 dB	59 dB	64 dB
	Same parcel, different functions	52 dB	47 dB	59 dB	64 dB

Table 12: Minimum sound pressure difference between interior spaces (new construction). Source: Bouwbesluit, 2012, 2021.

NEN-EN 15251 (2007) specifies that the typical sound pressure in a living room is between 25 to 40 dB and should not exceed this for a longer period of time. In bedrooms the typical sound pressure is between 20 to 35 dB and in retail stores 35 to 50 dB. No other requirements for retail stores on acoustical comfort were found.

For visual comfort Bouwbesluit 2012 does not have many requirements. The minimum size of a daylight opening in a residential area should be 10% of the floor area. The total minimum size of the daylight opening should be 0.5 m<sup>2</sup> for a residential space. For a retail store there are no

minimum requirements, meaning that daylight is not mandatory in retail stores. Bouwbesluit does not specify a daylight factor. BREEAM (2016) advises a daylight factor of 2% which should cover 80% of the floor area of the residential area.

NEN-EN 12464-1 (2011) and NEN 3087 (2011) state that the following things should be avoided to create visual comfort:

- Too high luminance; may cause glare
- Too high differences in luminance; may fatigue the eye due to constant adaptation
- Too low luminance and luminance difference; creates a dull visual environment

Furthermore NEN-EN 12464-1 (2011) specifies a lux level of 300 lx for a retail store. The lux level for dwellings is not stated but generally kept at around 200 lx. However, for most tasks a lux level between 300 lx and 500 lx is necessary. To create more ambiance lower lux levels are recommended.

The quality of visual comfort is not only dependent on the amount of light but also of view. The following factors should be taken in consideration when designing daylight openings (NEN 3087, 2011):

- Wideness of the view
- Being able to see the weather
- Being able to see movement
- Presence of natural elements such as trees and plants

#### **4.2 Comfort in monumental buildings**

Often in monumental buildings the indoor environment is not ideal. Building techniques have developed throughout the centuries and so have people their wishes and needs. Users and residents of buildings tend to expect more from their indoor environment than they used to do in the past. However, in general, residents of historical buildings, tend to have lower expectations and wishes when it comes to the indoor environment and thus comfort. Residents are more adaptive to the indoor environment in a historical building (Kramer, et al., 2015). However, this does not mean that there are no problems perceived in the indoor environment of monumental buildings.

Firstly, it is hard to maintain a strict indoor environment in historical buildings (Kramer et al., 2015) Regarding thermal comfort, insulating from the exterior is often not allowed due to the monumental status of the building. On the other hand, insulating from the interior often leads to problems with the relative humidity and can lead to condensation in the walls (Kramer et al., 2015). As a result, most monumental buildings have a low thermal resistance of the building envelope, which leads to thermal discomfort or high energy usage. Other aspects which often cause thermal discomfort in monumental buildings are air leakages (infiltration) in the building envelope, as well as thermal bridges. Moreover, a centralized heating system is not always present, or performs poorly (Bakhtiari et al., 2019). Very noticeable discomforts which are often perceived by the user are draft and downdraft near the windows (Rijksdienst voor het Cultureel Erfgoed, 2018).

In the summer, the thermal comfort in a monumental building is not ideal either. Most monumental buildings in Amsterdam do not have any type of sun shading and owners are not allowed to add external sun shading. This can lead to unnecessary heating up of the building (Rijksdienst voor het Cultureel Erfgoed, 2018). Furthermore, most buildings in the Netherlands, monumental buildings as well, are not equipped with a cooling system. Yet, at the same time, the temperatures are rising, and urban heat island is becoming an ever-growing problem. Amsterdam also faces issues with the urban heat island effect, the temperature in the inner city is two degrees Celsius higher than in surrounding nature areas (Atlas Natuurlijk Kapitaal, n.d.). Consequently, the temperature inside of buildings also increase, increasing the thermal discomfort in (monumental) buildings.

When analyzing the indoor air quality of monumental buildings, it can be concluded that most buildings are naturally ventilated, sometimes leading to a lack of ventilation (Bakhtiari, et al., 2019). When insulating the building envelope, the natural ventilation is often compromised, leading to an unhealthy IAQ. Nowadays, the exterior air quality in the city center of Amsterdam is not ideal (de Haan, n.d.). With the use of natural ventilation, the air is not filtered before entering the building, leading to pollutants entering the indoor environment and polluting the indoor air quality. Another problem with natural ventilation is that the air change rate cannot be controlled. Often in the winter it is too high and, in the summer, too low, leading to thermal discomfort and a decreased IAQ (Abdul Hamid et al., 2020). Insufficient ventilation can also cause problems to the indoor relative humidity (Abdul Hamid et al., 2020).

Frequently, there are also problems of insufficient light and acoustical disturbances (Bakhtiari, et al., 2019). Most historic buildings were designed when lighting was different than today. This sometimes leads to insufficient lighting in monumental buildings, as the building is not equipped for it (Orbasili, 2008). Many monumental buildings have changed function, the original warehouses on the canals are now dwellings or offices, but the openings in the facades are not always ideal for these functions, leading to a lack of daylight.

Acoustical problems are often related to noise from the exterior and from neighboring buildings. In monuments, the windows are often a weak point in the sound insulation as well (Mersch, 2020). Many historic buildings are not acoustically insulated and share walls and floors with their neighbors leading to vertical and horizontal acoustical bridges (Verrips, 2018). Especially in urban settings such as the historical city center of Amsterdam this can create nuisances, leading to discomfort for the user. The biggest hinder in general is contact noise. However, noise disturbance is also sometimes caused by noise transfer through old openings, for example the chimney (Mersch, 2020).

In general, inadequate servicing is an indoor environmental challenge in monumental buildings. Servicing includes everything from lighting, power, heating, cooling, ventilation and plumbing (Orbasili, 2008). Due to inadequate servicing, it is sometimes nearly impossible to maintain the original function of the building, because the requirements for the function are too high. Monumental buildings can make use of adaptive reuse with a function that has less requirements on services and indoor comfort (Orbasili, 2008). Besides the indoor environment being very important to the users' comfort and health, an incompetent indoor environment could irreversibly damage the interior of a monumental building as well (Rijksdienst voor het Cultureel Erfgoed, 2018).

### **4.3 Conclusion**

As the indoor environment is key in a healthy and comfortable life, a sub-objective of this thesis is to renovate monumental buildings in such a way that the indoor comfort of the residents will be improved. According to literature there is sufficient to be improved in monumental buildings regarding the indoor environment. The requirements and thus design criteria which will be adhered to for the renovation design can be found in table 13. As the focus of this thesis is on thermal comfort and indoor air quality the criteria set for these are taken into account for the design. The criteria which are set for visual and acoustical comfort are not designed for.

	<b>Parameter</b>	<b>Dwellings</b>	<b>Retail store</b>
<b>Insulation</b> (indirectly related to comfort)	Min. R-value façade (m <sup>2</sup> *K/W)	4.7 (1.4 for renovation)	4.7 (1.4 for renovation)
	Min. R-value floors (m <sup>2</sup> *K/W)	3.7 (2.6 for renovation)	3.7 (2.6 for renovation)
	Min. R-value roof (m <sup>2</sup> *K/W)	6.1 (2.1 for renovation)	6.1 (2.1 for renovation)
	Max. U-value window (W/m <sup>2</sup> *K)	2.2	2.2
<b>Thermal</b>	Min. T winter (°C)	20	16
	Max. T summer (°C)	26	25
<b>IAQ</b>	Min. ventilation rate (l/s per person)	7	4
	Min. RH (%)	40	40
	Max. RH (%)	70	70
<b>Acoustical</b>	Typical sound pressure (dB)	25 to 40	35 to 50
	Min. sound proofing exterior partition (dB)	20 (10 for renovation)	20 (10 for renovation)
	Min. sound proofing exterior partition in case of traffic (dB)	50 or 65 - 33 (current sound proofing for renovation)	50 or 65 - 33 (current sound proofing for renovation)
	Max. sound pressure installations (dB)	30 (40 for renovation)	N.A.
	Min. air noise difference to other dwelling (dB)	52 (current level for renovation)	52 (current level for renovation)
	Max. contact noise to other dwelling (dB)	54 (current level for renovation)	59 (current level for renovation)
<b>Visual</b>	Min. lux level (lx)	200	300
	Min. size daylight opening	10% of floor area (min. 0.5 m <sup>2</sup> )	No daylight required

Table 13: Comfort requirements for the design. Own work.

## 5. Methodology

As mentioned in the introduction, based on the neighborhood analysis (chapter 3) a case study building will be selected and analyzed on the three criteria of monumentality, energy performance and indoor comfort. After the finalization of the design, the proposed design is also evaluated on these three criteria. This chapter describes how all three aspects are analyzed and evaluated for both the current building and the proposed design.

### 5.1 Analysis of monumentality

To understand the case study building and its individual elements better, a historical analysis of the building is carried out. The overall goal of the analysis is to assess which elements of the building can be altered and which elements have monumental value and thus cannot be altered. First, information about the building is collected. The internet is searched as well as the Archive of the city of Amsterdam. Furthermore, for the analysis of the monumental elements of the building the so-called reasoned statement ('redengevende verklaring') is retrieved from the municipality of Amsterdam. By combining the information from the archive, the reasoned statement and personal observations (site visits) an analysis of the building is made. Drawings and pictures from different time periods are compared, permit requests are assessed and other written information about the building is analyzed.

By using the different sources a chronological timeline of the most important alterations and renovations is made. These alterations are divided into the building scale level and the urban scale level as the building is also a part of the urban fabric and part of the protected city view area. By defining the timeline of the building it is then possible to assess which elements can and cannot be altered. A classification of very valuable, valuable, neutral and negative is used. Very valuable meaning the element cannot be altered, valuable meaning it is not advisable to alter, neutral meaning it does not have any specific monumental value but does not disturb the monumental expression of the building and negative meaning that the element damages the monumental expression of the building. On the building level they are subdivided into exterior, interior and structural monumental values. A summary and the conclusions of the analysis can be found in this the following chapter. The extensive analysis can be found in a separate booklet, upon request.

The proposed design cannot alter any of the identified monumental values. During the design phase these values will be kept in mind. Finally, the proposed design is analyzed by laying the values next to the design. It is examined whether the design alters any of the identified monumental values of the building. If this is the case, the proposed design is to be altered.

### 5.2 Analysis of the energy performance

The current energy performance of the case study building is analyzed using two different methods. Firstly the energy performance is assessed by analyzing the energy bills. All residents are contacted to provide their energy bills. For the residents which do not reply the average energy usage of the specific building typology at the Burgwallen-Oude Zijde is used, according to the CBS (2019). The actual energy usage is converted into a common denominator (kWh, one m<sup>3</sup> natural gas equals 10.2 kWh) and then compared with the average usage of the Netherlands, Amsterdam and the Burgwallen-Oude Zijde. Secondly, the energy usage of the building is analyzed by modeling the building in Design Builder: an environmental performance simulation software. The input for the model can be found in appendix C. The energy usage of the simulated model has to be similar to the actual energy usage. The model has to be adjusted until the difference between the actual and simulated energy usage is no larger than 5%.

To analyze the energy performance of the proposed design the bills cannot be used. The Design Builder base model (current situation) is adjusted to simulate the proposed design. The different proposed design measures are input in the model and the energy usage is simulated. The energy usage of the current situation and the new situation are then compared to assess the effects of the design on the energy performance of the building.

### 5.3 Analysis of the indoor comfort

To analyze the current indoor comfort of the building the residents are contacted. An informal interview with (some of) the residents is held. Furthermore, different measurements are taken. Firstly through the use of HOBO data loggers which measure the temperature and relative humidity. The light intensity (lux levels) is measured as well to rule out daylight as an explanation for extreme measurements. The data loggers are first tested, of which the results can be found in appendix B. The data loggers are then placed at two different locations within one apartment for ten days. Infrared measurements of the interior and exterior of the building are taken as well to assess whether there are any thermal leakages in the building envelope. The infrared camera used is the FLIR-T62101 camera. The pictures are modified in the FLIR Tools software so the scales of the pictures match for easy comparison.

Lastly, the current indoor comfort of the building is also analyzed by making use of the Design Builder model (also used for energy performance). The simulation outcomes can also be used to assess indoor comfort. To assess the indoor comfort of the proposed design the Design Builder model is used as well (same model as used for the energy performance of the new situation). The simulation outcomes of the current building and proposed design are then compared and assessed.

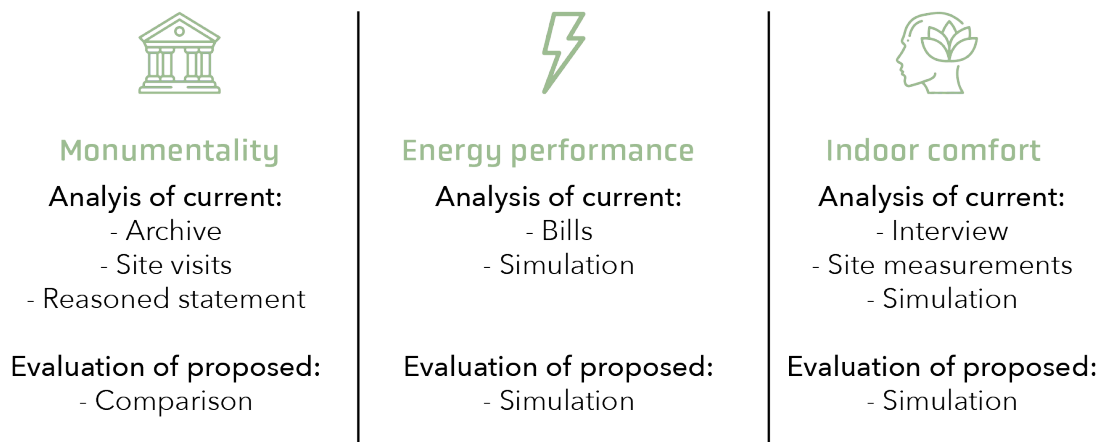


Figure 11: Analysis methods for current situation & proposed design. Own work.



PART B: CASE STUDY

## 6. Case Study Building: OZVB30

For the energy-neutral renovation design a case study building is chosen. This chapter introduces the selected building and provides background information about the history of the building. The subquestion that will be answered is: *“What is the history of the case study building and which building elements cannot be altered due to their monumental value?”* By careful analysis of the building and its history, the monumental elements are identified. The identified elements which can and cannot be altered are then used as input and boundary condition for the design.

### 6.1 Selection of the case study building

During the neighborhood analysis (chapter 3) several buildings with a monumental status and mixed-use function were identified which could be used as a case study for the design proposal. As mentioned in the introduction there are several limitations for the choice of a case study. The building needs to be assigned as a national monument (order 1 building), have been constructed before 1900, have a mixed-use function and has to be located near a water body. Table 14 shows the different options which can be used as a case study.

	Address	Year of construction	Type of monument	Function (besides dwelling)	Advantages	Disadvantages	Conclusion
<b>Hempstory</b>	Oudezijds Achterburgwal 142	1725-1750	National	Clothing store	Part of GLD		✓
<b>Patta</b>	Zeedijk 67	1800-1825	National	Clothing store			-
<b>Stüssy</b>	Zeedijk 22	17 <sup>th</sup> -18 <sup>th</sup> century	National	Clothing store			-
<b>Jacob Hooy</b>	Kloveniersburgwal 12-14	1882	National	Pharmacy			-
<b>Perdu</b>	Kloveniersburgwal 86	1908	National	Book store		Post 1900	✗
<b>Condomerie</b>	Warmoesstraat 141	1875-1900	National	Condom store	Part of GLD	Not in proximity of canal	✗
<b>Winkel de Prael</b>	Oudezijds voorburgwal 30	19 <sup>th</sup> century	National	Beer store	Part of GLD		✓
<b>Bulldog souvenirs</b>	Oudezijds voorburgwal 206	18 <sup>th</sup> century	National	Souvenir store		Commercial	✗

Table 14: Possible case study buildings. Own work.

The two most suitable options are Hempstory and the store of De Prael, as these are already a part of the Green Light District and fit within the other criteria. Hempstory was first chosen, however the municipality of Amsterdam was not able to provide a reasoned statement. It was thus decided to continue the case study with the store of De Prael, as it has an extensive reasoned statement. This makes it easier to identify the monumental elements without having to enter the building during COVID-19 restrictions.

### 6.2 Introduction to the Oudezijds Voorburgwal 30

The building on the Oudezijds Voorburgwal 30 has a mixed-use function. On the ground floor (30A) the store of the beer brewery 'de Prael' is located. On the four floors above three apartments (30B, 30C and 30D) are located. The building was constructed in the 16<sup>th</sup> century but the East facade facing the Oudezijds Voorburgwal dates from the 19<sup>th</sup> century. The building has quite an extensive history and has had many owners and residents throughout its existence. The latest renovation was performed in 2005 during which a large part of the building was completely renewed. The building is owned by Stadsherstel Amsterdam and is classified as an order 1 building. The building thus has the status of a national monument and is also located within the protected city view area.



Figure 12: Location Oudezijds Voorburgwal 30. Own work



Figure 13: Oudezijds Voorburgwal 30. Own picture. For more pictures see appendix A.

### 6.3 Monumental analysis of the Oudezijds Voorburgwal 30

As mentioned in sub chapter 6.2, the Oudezijds Voorburgwal 30 is a monumental building and thus has several additional regulations to adhere to. Since it is a national monument, few alterations can be done to the monumental elements of the building (both on the interior and exterior). Moreover, because it is located in the protected city view area, little major exterior alterations can be done which are visible from the street. The monumental elements which cannot be altered are not specified. Consequently, it is necessary to analyze which elements are of value and which elements can be adjusted. A thorough historical analysis is done on both the urban scale as well as the building scale. Figure 14 and 15 show the timeline of the owners and the most important alterations from the construction of the building to the present.

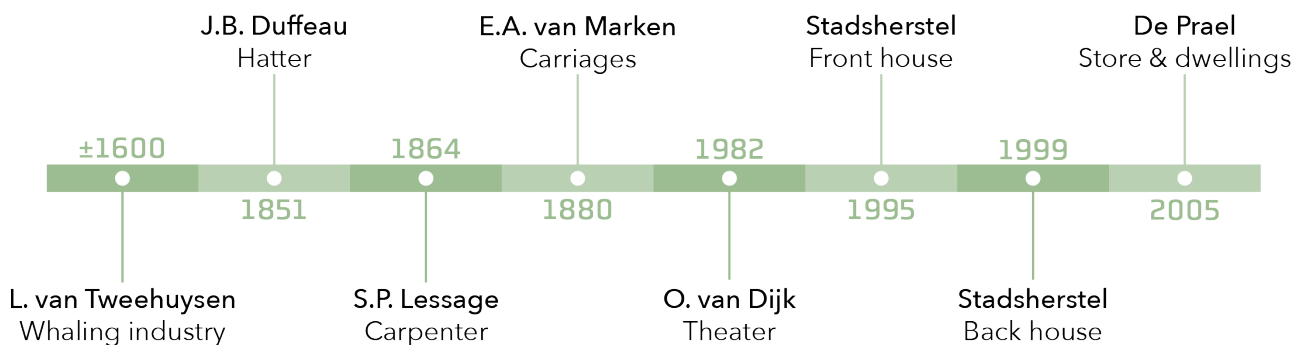


Figure 14: Timeline of the owners of the Oudezijds Voorburgwal 30. Own work.

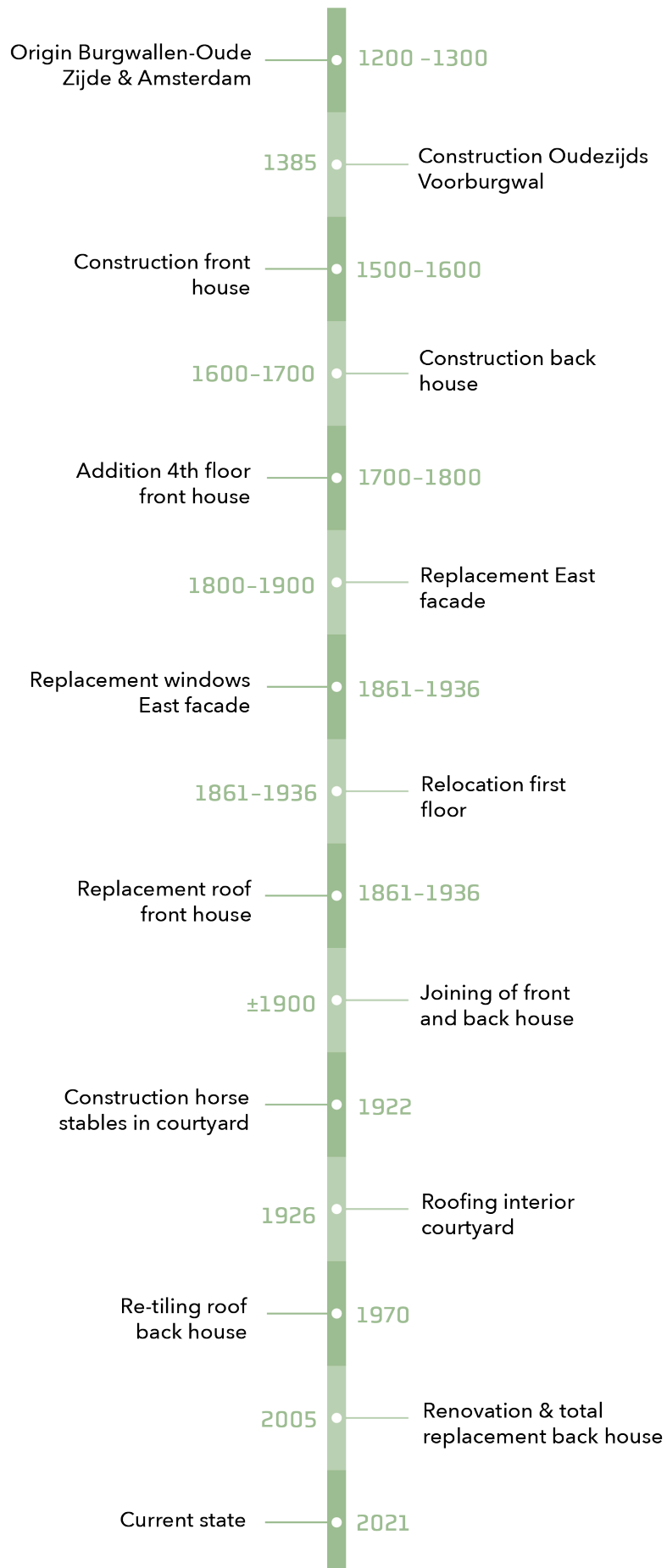


Figure 15: Timeline of the alterations of the Oudezijds Voorburgwal 30. Own work.

### 6.3.1 Monumental elements on the urban scale

On the urban scale it is important to mention that the front house was built in the 16th century as an independent house. In the 17th century an additional independent house (nowadays the back house) was built behind the front house, in the courtyard of the building block. Around 1900 the two independent buildings were connected by the construction of an intermediate member. The back house has been completely reconstructed in 2005 as it partially collapsed and could not be renovated anymore.



Figure 16: Value mapping on the urban scale. Own work.

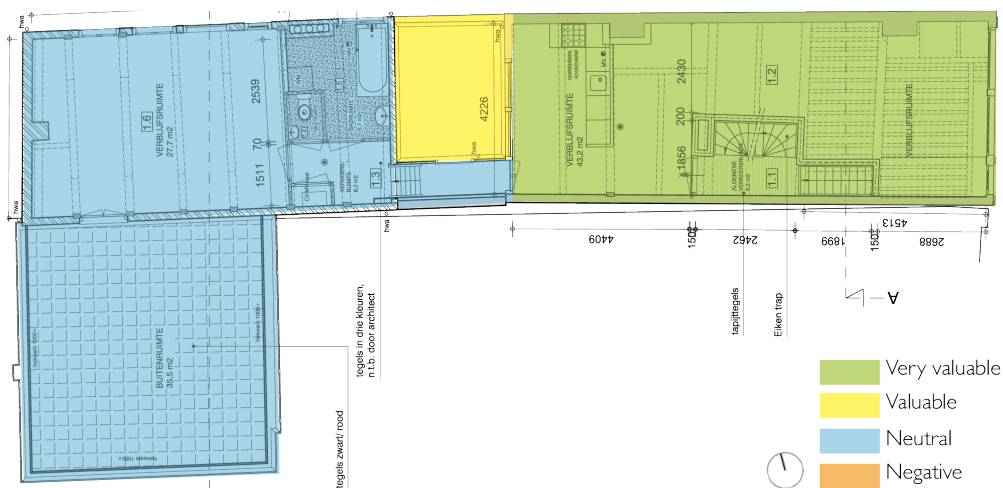


Figure 17: Value mapping on the building scale. Adapted from Stadsherstel, 2005.

At the urban scale the organization of the front house, intermediate member and back house is quite valuable as it explains the history of the building and how the building was organized before and after the joining of the two independent buildings around 1900. Furthermore, the position of the building within its block has not been altered since the construction of the houses and is valuable. Another valuable element on the urban scale is the courtyard in which part of the building is located. The courtyard has been present since the construction of the building or even earlier and even though buildings were constructed in the courtyard throughout the centuries, parts of the courtyard are still present and should be preserved. Furthermore, an alley is located right next to building. This alley has been present since the construction of the building and refers to the industry present at the time and should be maintained.

Other valuable elements on the urban scale are the buildings orientation towards the canal, the interior courtyard which arose after the joining of the two buildings and which was roofed in 1926 and the fact that the building is detached from its neighbors on both sides. In general, the back house and intermediate member have no monumental value as they were completely reconstructed in 2005.

### 6.3.2 Monumental elements on the building scale

Throughout the centuries of its existence the building has undergone many alterations and renovations. Some more rigorous than others. Important large alterations are the complete renewal of the representative East facade in the 19th century. Furthermore, between 1861 and 1936 several alterations were done. The roof was completely renewed as well as the windows of the East facade. The first floor was raised and as a consequence the vertical and the horizontal composition of the lower East facade were altered.



Figure 18: Value mapping of the facades. Adapted from Stadsarchief Amsterdam, 2005.

As mentioned previously, the back house was reconstructed from scratch in 2005 and does not have any specific monumental values on the exterior (or interior). The front house however was constructed in the 16th century and it is likely that the North and South facades are still the original materials and composition largely. These are of high value. The East facade of the front house was added in the 19th century but is quite valuable as little alterations have been done afterwards.

The composition of the lower East facade has been altered after the original construction in the 19th century. However, it is still of heritage value as a characteristic of the facade is its flexibility and possibility to alter according to the function behind the facade. The upper East facade has hardly been altered after its construction in the 19th century and is very valuable.

The roof tiling of the front house is most likely not original and not necessarily valuable. The chimneys and dormer on the roofs are deemed valuable because they were most likely changed after the roof alteration between 1861 and 1936. For the windows on the West facade of the front house the reasoned statement deems it unlikely that they are older than a century and are not of value. Most of the windows on the East facade were replaced between 1861 and 1936 and are not of monumental value (except the frames of the windows of the fourth floor). Probably none of the windows have monumental value.

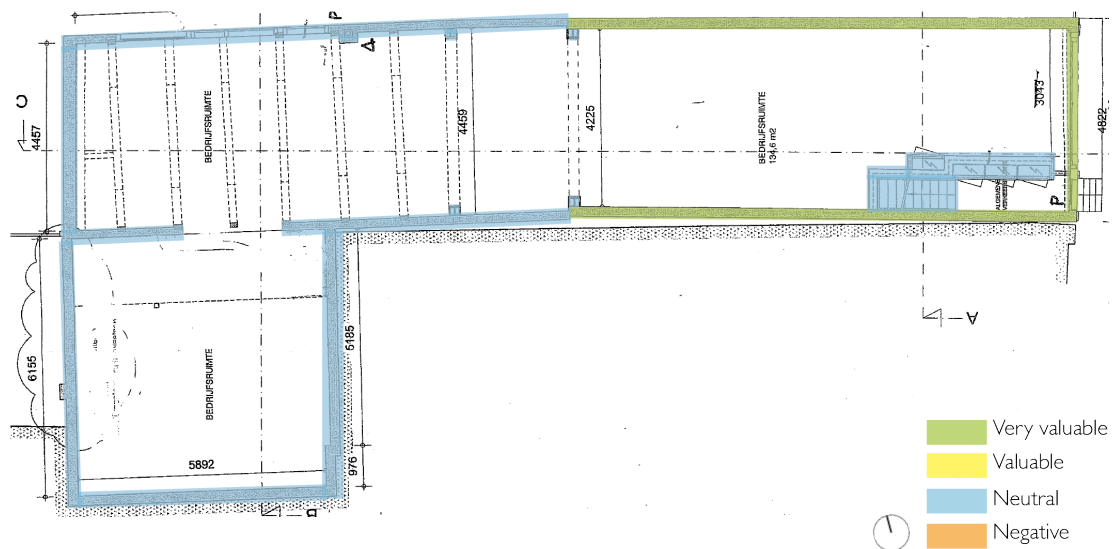


Figure 19: Value mapping of the ground floor. Adapted from Stadsherstel, 2005.

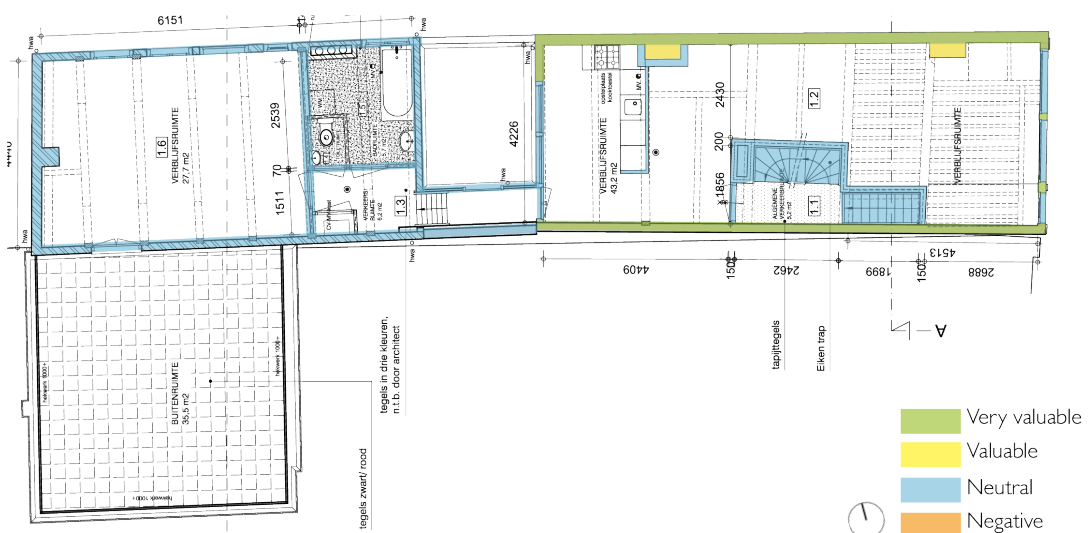


Figure 20: Value mapping of the first floor. Adapted from Stadsherstel, 2005.

The back house does not have any specific monumental value on the interior either. The only element which was incorporated from the original building was a 'korbeelstel' (a part of the original wooden structure) from the 17th century. This is very valuable, but unclear where it is exactly located in the building. In the front house the South and North exterior partition walls are most likely to be original and of high value. The West and East exterior partition walls were altered throughout the centuries but are also of high value as they are important for the expression of the

building. None of the interior walls are of value as they have been added during the renovation in 2005. On the interior several traces can be found from the old wooden frame structure, these are very valuable as they date back to the original 16th century construction. The chimneys have been present for multiple centuries too, and even though they are not in use anymore are valuable. The fireplaces however were added in the 20th century and not of specific value. The finishings on the interior for both the floors and walls were redone during the renovation in 2005 and are not valuable. The stairs were constructed during the renovation as well. Furthermore, there is no historical furniture. Concerning the function of the building it has always had a mix-used function of dwellings and industry. This is quite valuable to the building.

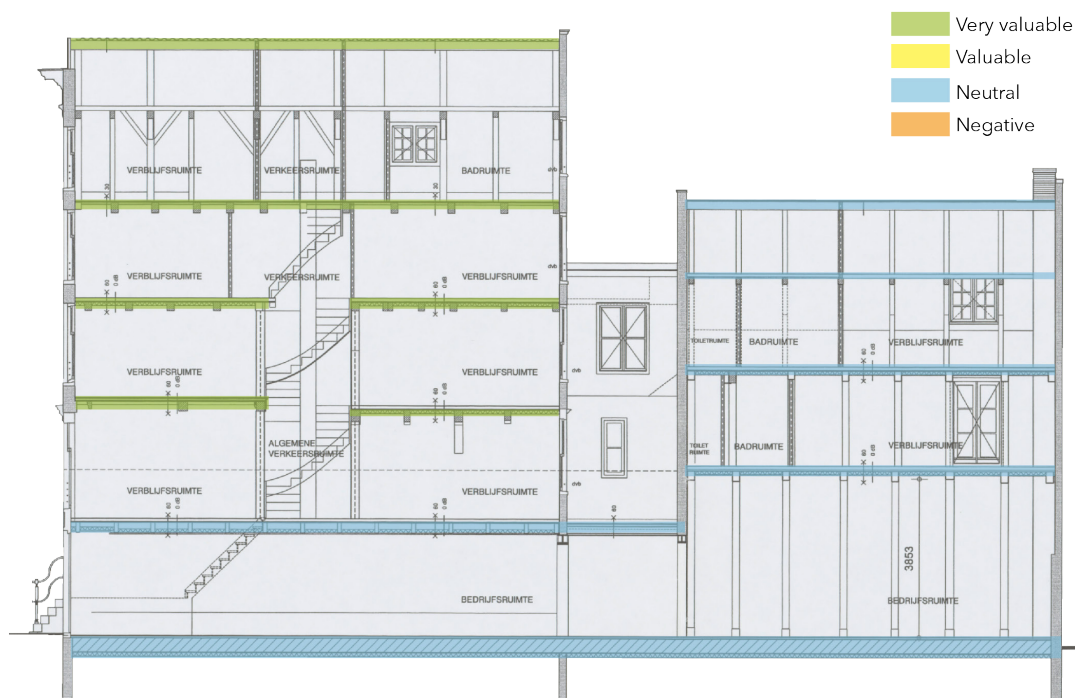


Figure 21: Value mapping of the structure. Adapted from Stadsarchief Amsterdam, 2005.

Since the back house was reconstructed in 2005, the structure of the building is not of monumental value. However, in the front house the floor structure of the second and third floor can be traced back to the 17th century and is of high value. The fourth floor dates back to the 18th or 19th century when the building height was increased and the roof was reconstructed. The roof and fourth floor are also of high monumental value. The ground floor and first floor of the front house were reconstructed in 2005 and not valuable.

#### 6.4 Conclusion

As a case study, the building at the Oudezijds Voorburgwal 30 was selected. It houses three apartments and the store of a beer brewery. It was built in the 16th century but has undergone many major and minor alterations throughout the years. The last alterations date back to 2005, when the whole back house and intermediate member were reconstructed. The historical analysis has identified that quite a lot of alterations can be performed without damaging the monumental elements and whilst adhering to the regulations of national monuments and the protected city view. Table 15 gives an overview of the mapped values of the building. The elements which fall under the category very valuable cannot be altered and for the elements which fall under the category valuable it is advised not to alter.

	Very valuable	Valuable	Neutral	Negative
<b>Urban scale</b>	Organization of front house, intermediate member and back house	Orientation towards canal	Back house in general	
	Presence of courtyard	Interior courtyard	Intermediate member in general	
	Contours back house	Detached from neighbors		
	Suikerbakkersteeg			
	Embedding in building block			
	Front house in general			
<b>Building scale exterior</b>	Composition East façade (lower & upper)	Dormers	Roof tiles front house	
	Flexibility lower East facade	Chimneys	Exterior back house	
	Facades front house (materials & composition)	Upper windows East façade front house	Most glazing & window frames front house	
	Raised entrance			
	Arches above windows East Facade			
<b>Building scale interior</b>	Exterior partition walls	Chimneys	Fireplaces	Interior finishes floors
	Any remains of wooden structure front house	Mixed-use function	Height of first floor	
	Remaining peerkraal stuk in back house		Interior walls and finishes	
			Stairs	
<b>Building scale structure</b>	Roof structure front house		Ground floor front house	
	2 <sup>nd</sup> , 3 <sup>rd</sup> & 4 <sup>th</sup> floor front house		First floor front house	
			Structure back house	

Table 15: Mapped monumental values of the Oudezijds Voorburgwal 30. Own work.

## 7. Energy Performance & Indoor Comfort OZVB 30

Prior to suggesting any design renovations it is necessary to analyze the current performance of the building, to assess what needs to be improved. Both the energy performance and the indoor comfort are analyzed, using various methods (see chapter 5). The subquestion related to this chapter is: “What is the current energy performance and indoor comfort of the case study building?”

### 7.1 Actual energy usage

In order to analyze the current energy performance of the building, the energy bills were collected. De Prael was emailed and letters were left for the residents. The residents of 30B (first floor apartment) and de Prael (30A) provided their energy bills. For the two other apartments (30C & 30D) the average energy usage for an apartment in the Burgwallen-Oude Zijde was taken (CBS, 2019). In table 16 the energy usage can be found. It must be noted that the Prael has one small beer cooler and that the residents of apartment 30B try to minimize their energy usage. The total energy usage of the Oudezijds Voorburgwal 30 is 68.8 MWh (181 kWh/m<sup>2</sup>).

	Period	Electricity (kWh)	Natural gas (m <sup>3</sup> )	Natural gas (kWh)	Total (kWh)	Total (kWh/m <sup>2</sup> )
<b>30A</b>	17-04-2019 to 17-04-2020	9,104.0	2,563.0	26,142.6	35,246.6	245
<b>30B</b>	04-09-2019 to 04-09-2020	1,669.5	785.1	8,008.0	9,677.5	118
<b>30C</b>	Average 2019	1,930.0	980.0	9,996.0	11,926.0	157
<b>30D</b>	Average 2019	1,930.0	980.0	9,996.0	11,926.0	151
<b>Total</b>	<b>One year</b>	<b>14,633.5</b>	<b>5,308.1</b>	<b>54,142.6</b>	<b>68,776.1</b>	<b>181</b>

Table 16: Actual energy usage of the Oudezijds Voorburgwal 30. Own work.

### 7.2 Simulated energy usage

To further analyze the energy performance, a Design Builder model was made to analyze the current energy performance. This model can also be used as a basis for the design measures which will be implemented and will show the effect of the design measures. In appendix C an overview can be found of the input.

Monthly energy usage					
	Room Electricity	Lighting	System Pumps	Heating (Gas)	DHW (Gas)
	kWh	kWh	kWh	kWh	kWh
01-01-2019	560,4	722,5	5,3	11901,5	874,3
01-02-2019	509,9	624,2	3,0	6935,0	790,2
01-03-2019	563,3	647,8	3,3	7184,4	840,9
01-04-2019	565,4	545,5	1,1	2505,2	830,9
01-05-2019	546,4	495,1	0,8	1806,9	762,8
01-06-2019	545,5	455,8	0,1	91,4	698,9
01-07-2019	574,8	486,8	0,1	33,8	721,1
01-08-2019	554,8	516,4	0,1	5,9	673,8
01-09-2019	551,4	589,0	0,2	351,5	680,9
01-10-2019	560,4	674,1	1,1	2335,1	749,7
01-11-2019	545,5	717,3	3,0	6995,8	747,8
01-12-2019	583,2	760,7	3,9	8998,6	856,7
Total energy usage (kWh)					
2019	6661,0	7235,2	22,1	49145,1	9228,1
Total energy usage yearly (kWh)					
Total elec usage	<b>13918,4</b>				
Total gas usage	<b>58373,3</b>				
Total energy usage	<b>72291,6</b>				

Table 17: Simulated energy usage of the Oudezijds Voorburgwal 30 in Design Builder. Own work.

The total simulated energy usage of the Oudezijds Voorburgwal 30 in Design Builder is 72 MWh (190 kWh/m<sup>2</sup>), which is average for a mixed-use building at the Burgwallen-Oude Zijde. However, the store on 30A use more energy than an average retail store. The average energy usage of a retail store (144 m<sup>2</sup> and constructed before 1946) is 27 MWh, whereas the actual usage of the store is 35.2 MWh: 23% more. In contrary, the residents of 30B use less energy (9.7 MWh) than the average usage of an apartment at the Burgwallen-Oude Zijde (11.9 MWh).

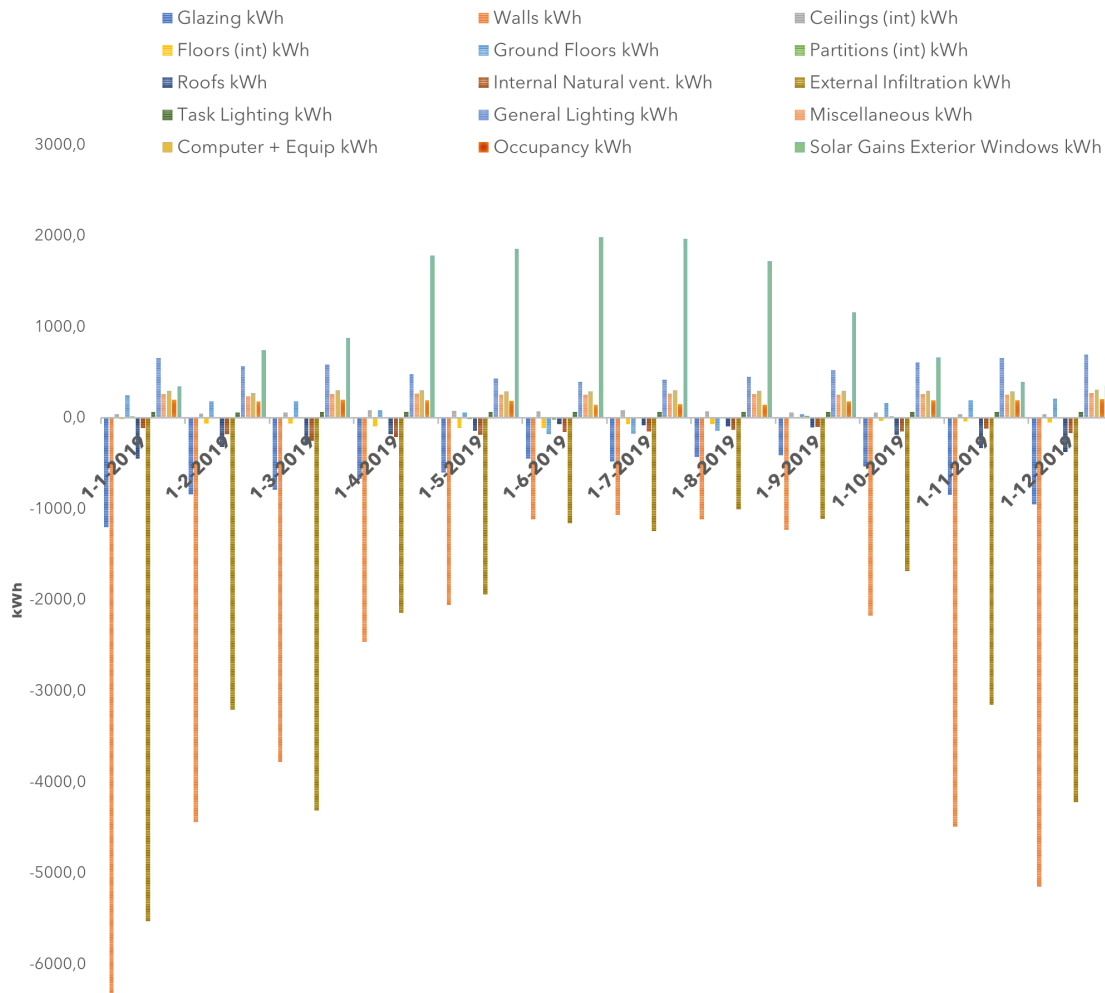


Figure 22: Heat balance according to simulation in Design Builder. Own work.

The heat balance in figure 22 shows that most of the heat is lost through the facades as well as through the cracks and seams of the building (infiltration). Heat loss through the glazing is also an important factor in the energy losses of the building.

### 7.3 Indoor comfort according to the residents

An interview with the residents of 30B made clear that they consider their energy usage too high for the level of comfort they experience. To limit the energy usage and expenses the residents do not turn on the heating completely in the front house and not at all in the back house. During the winter this often leads to low indoor temperatures. The residents have measured temperatures as low as 12 degrees Celsius and are forced to wear their coats inside. When talking about their home the first thing they tend to mention in a conversation is that in winter it is too cold which makes it highly uncomfortable. Furthermore, they mention that it takes a significant amount of time for the house to heat up and that they would prefer the house to heat up quicker. In winter the indoor air can be quite dry due to the fact that the heating has to be turned on quite high. Along the windows it can be quite drafty which is why they have used some sealant to close some cracks and seams. However, since the radiators are also located near the windows and the view to the exterior they do not avoid sitting near the windows.

In contrary to the winter, in the summer the residents of 30B think that their apartment is nearly perfect. The interior temperature does not get too high. They acknowledge that the house heats up but that it does not become uncomfortably hot. At night the house tends to cool down pretty quickly. One problem related to the IAQ in the building is the humidity in the bathroom, mold tends to grow pretty quickly and the residents thus always open the window during and after showering (both in summer and winter). The residents do think the air in their house is fresh enough. However, they would like the ventilation in the kitchen to perform better.

In regard to acoustical and visual comfort there are no serious problems. They have taken off the extractor hood in the kitchen so more daylight enters the kitchen. However, they still think the kitchen is slightly too dark. Regarding noise, they can hear the upstairs neighbors walking and the music from the store underneath. Yet, they acknowledge that this is part of the monumental building and does not cause any major disturbance. Surprisingly, they hardly hear any noise from the exterior, even prior to COVID-19 when there was a large number of tourists, day in and out.

The residents have asked the rental corporation (Stadsherstel) to make some alterations to make it more comfortable inside in winter. However, Stadsherstel has not taken any initiative yet. As a result the residents have started with putting foil on the windows themselves. Furthermore, they installed a sliding door between the kitchen and living room to make sure the heat from the living room does not go to the kitchen.

### 7.4 Measured indoor comfort

To take properly assess look at the current indoor comfort several measurements were performed. Two HOBO data loggers were placed in apartment 30B. One was placed in the living room and one in the bedroom (see appendix B for exact location), to compare the heated living room and the unheated bedroom. The measurements were taken during the period of 02-03-2021, 20:00 to 12-03-2021, 14:00 (every 10 minutes)

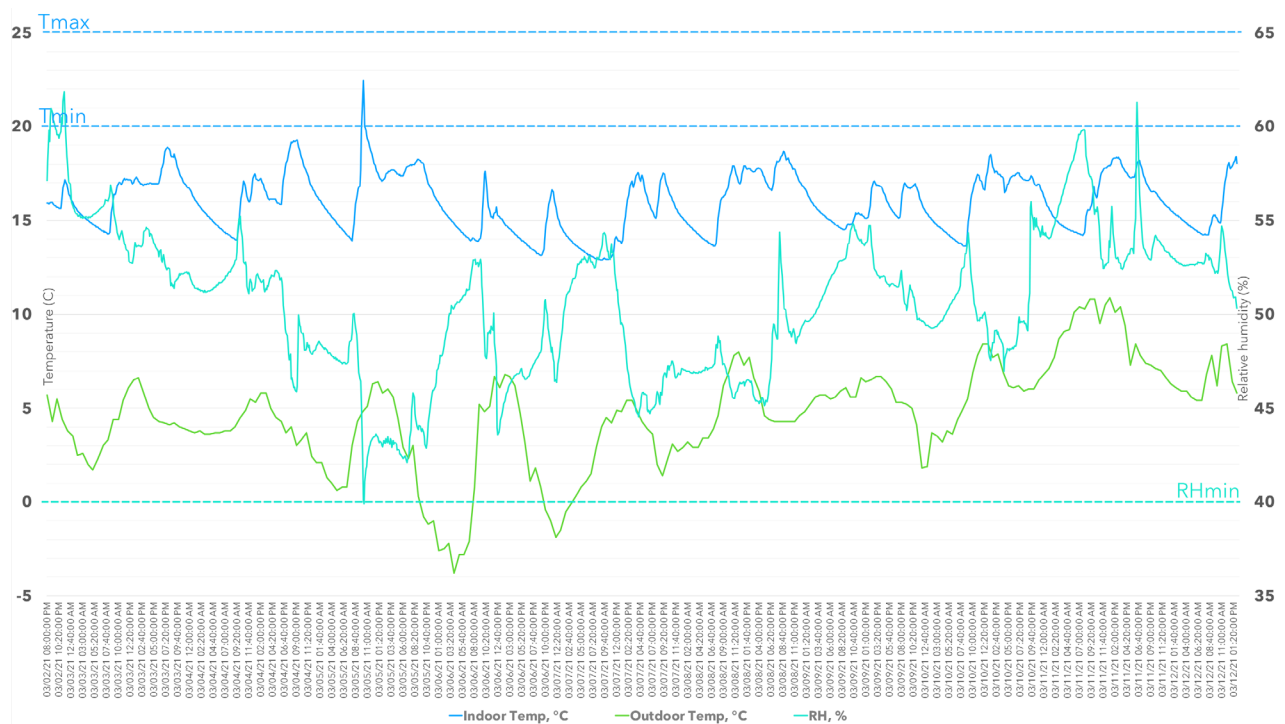


Figure 23: Measurement results of the front house. Own work.

Regarding the measurements in the front house it can be seen that at night the temperature tends to decrease and that the temperature only increases again between 8:00 and 10:00 in the morning. This is most likely to be caused by the heating being turned on during the day and off during the

night, as the residents explained. The maximum temperature measured is 22.5 degrees Celsius (05-03-2021, 10:10). However, this was the only time the measured temperature was above 20 degrees Celsius. When looking at the measured lux level it can be concluded that the increase in temperature was due to the sun shining on the HOBO data logger (this was confirmed using the shadow analysis in Design Builder). The minimum temperature measured is 12.9 degrees Celsius (07-03-2021, 8:50 to 9:10). The average temperature measured is 16.0 degrees. During the day the temperature mostly lies between 17 and 18 degrees Celsius. Towards the last days of the measurements the indoor temperature slowly increases, this was also when the exterior temperature increased (especially at night).

The lowest measured relative humidity is 39.9% and the highest measured RH is 61.6%. The average RH is 50.6%. In general, it can be seen that when the temperature increases the RH decreases and vice versa.

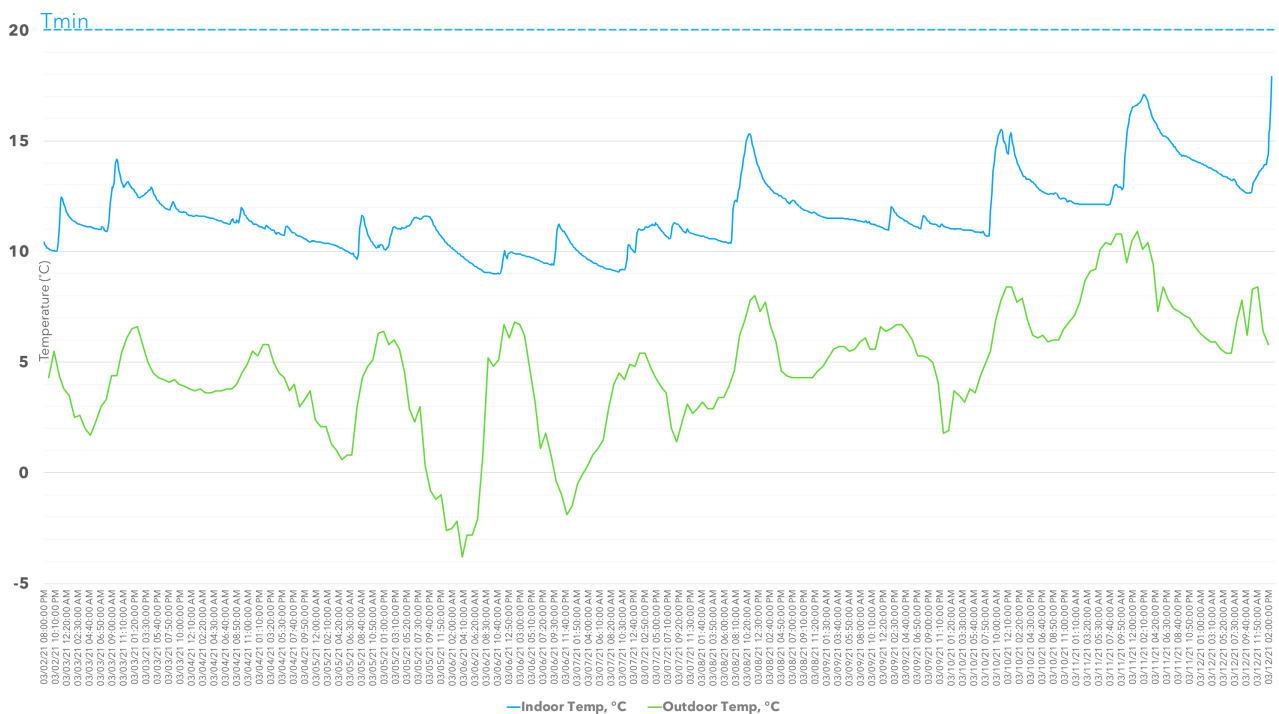


Figure 24: Measurement results of the back house. Own work.

Regarding the measurements of the back house it can be noted again that the temperatures increase during the day and decrease during the night. However, the peaks are less steep as the heating in the back house is not turned on during the day (or night). Consequently, the temperatures are lower than in the front house. The maximum temperature measured is 17.1 degrees Celsius (11-03-2021, 14:20) and the minimum temperature measured is 9.0 degrees Celsius (06-03-2021, 9:50 to 10:10). The average temperature measured is 11.6 degrees Celsius. The temperature during the day mostly lies between 10 and 12 degrees. Towards the end of the measurement period this increases to 15 to 17 degrees. The increase in temperature is likely to be caused by the increased outdoor temperature. The relative humidity was not measured due to a faulty HOBO data logger. It is however not likely that the RH stays within the comfort criteria with the measured temperatures. When comparing the front and back house the temperature difference between the two rooms is significantly present.

Besides the measurements taken with the HOBO data loggers, an infrared camera was used to assess whether and where large heat losses could be found in the building envelope. The measurements were taken between 19:30 and 20:00 on 02-03-2021, a non cloudy night. The outdoor temperature in Amsterdam at the time of measuring was roughly around 12 degrees Celsius with a relative humidity of around 80%. Pictures were taken on both the interior as well as the exterior.



Figure 25: Infrared image of the front house. Own picture.



Figure 26: Infrared image of the back house. Own picture.

Figure 25 shows that the upstairs floor is much warmer than the wall. The wall is an exterior partition wall whereas the floor above is an interior partition floor. It can be seen that temperature as low as twelve degrees can be measured along the wall in the front house. In figure 26 a picture can be seen of a corner in the back house. Behind the 'warm' wall, the bathroom is located with the boiler. However, the blue wall is the exterior partition wall. It can be noted that the front house seems warmer than the back house. An explanation for this is that the front house is heated and the back house is not.

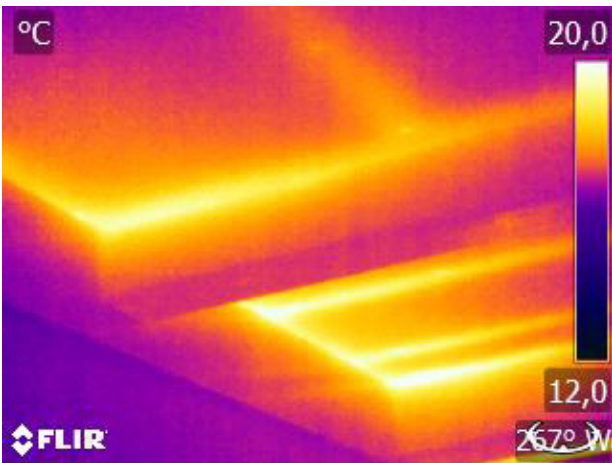


Figure 27: Infrared image of the front house. Own picture.



Figure 28: Infrared image of the back house. Own picture.

Figure 27 shows that around the beams of the second floor more heat is lost to downstairs. Figure 28 again shows that the interior partition floor is much warmer than the exterior partition wall.



Figure 29: Infrared image of the exterior. Own picture.



Figure 30: Infrared image of the exterior. Own picture.

The exterior infrared images could only be taken for the East facade as the alley which provides access to the other facades of the buildings was locked. When looking at the lower part of the facade it can be noted that the door on the ground floor was opened and leads to a significant heat loss. Furthermore, for the windows on the first floor (apartment 30B) a difference can be observed between the left window and the other two windows. The left window is located in the communal hallway which is not heated. No specific thermal bridges could be noted but the images do confirm that the facades are not insulated. More infrared images can be found in appendix B.

### 7.5 Simulated indoor comfort

The Design Builder model for the energy performance simulation can also be used to analyze the current indoor comfort of the building. Table 18 shows the comfort criteria and the current levels of the comfort parameters in the building.

	Parameter	Criteria dwellings	Criteria retail store	Current level
<b>Insulation</b> (indirectly related to comfort)	Min. R-value façade (m <sup>2</sup> *K/W)	4.7 (1.4 for renovation)	4.7 (1.4 for renovation)	0.6
	Min. R-value floors (m <sup>2</sup> *K/W)	3.7 (2.6 for renovation)	3.7 (2.6 for renovation)	2.8
	Min. R-value roof (m <sup>2</sup> *K/W)	6.1 (2.1 for renovation)	6.1 (2.1 for renovation)	3.9 (2.5 flat roof)
	Max. U-value window (W/m <sup>2</sup> *K)	2.2	2.2	4.48
<b>Thermal</b>	Min. T winter (°C)	20	16	± 16 (heated), ± 10 (unheated)
	Max. T summer (°C)	26	25	± 30
<b>IAQ</b>	Min. ventilation rate (l/s per person)	7 (0.25 ac/h for OZVB)	4 (0.10 ac/h for OZVB)	Average: 1.45 ac/h
	Min. RH (%)	40	40	± 25
	Max. RH (%)	70	70	± 75

Table 18: Comfort criteria & current level of comfort. Own work.

The insulation values of the building envelope are below the regulations and criteria for new construction. In the case of the facade, the current insulation value is even lower than the criterion set for renovations. Since the windows currently have single glazing the U-value of the windows is too high. Due to the poor performing building envelope the indoor temperature in winter is around 16 degrees Celsius (see figure 31). This is far below the set comfort criterion of 20 degrees Celsius for dwellings. In summer the indoor temperature can reach 30 degrees Celsius (see figure 32) which is above the set temperature criterion, yet this is only the case for a few days a year. In regard to the indoor air quality the RH meets the set criteria mostly throughout the year. However, the RH sometimes drops below or rises above the set criteria. Due to the poor performing building envelope which has many cracks and seams, the ventilation rate is more than sufficient: on average 1.45 ac/h. The air change rate within the building is too high, leading to discomfort due to draft and heat losses.

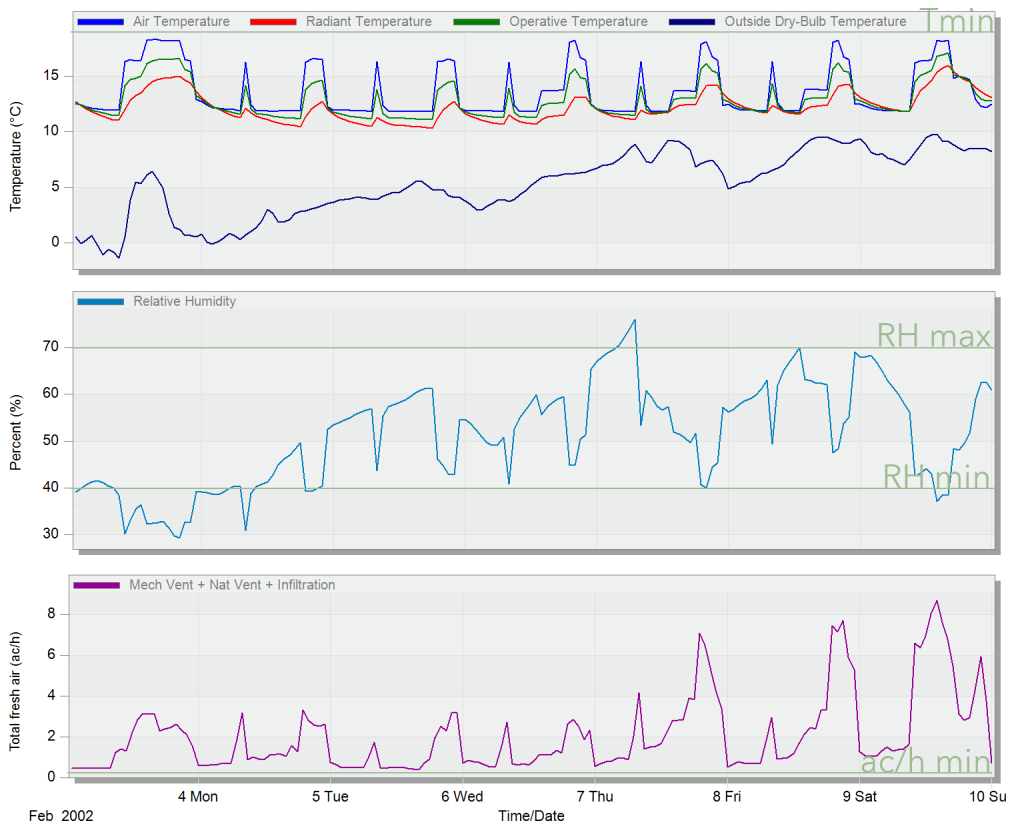


Figure 31: Simulated comfort in winter 2019. Image from Design Builder.

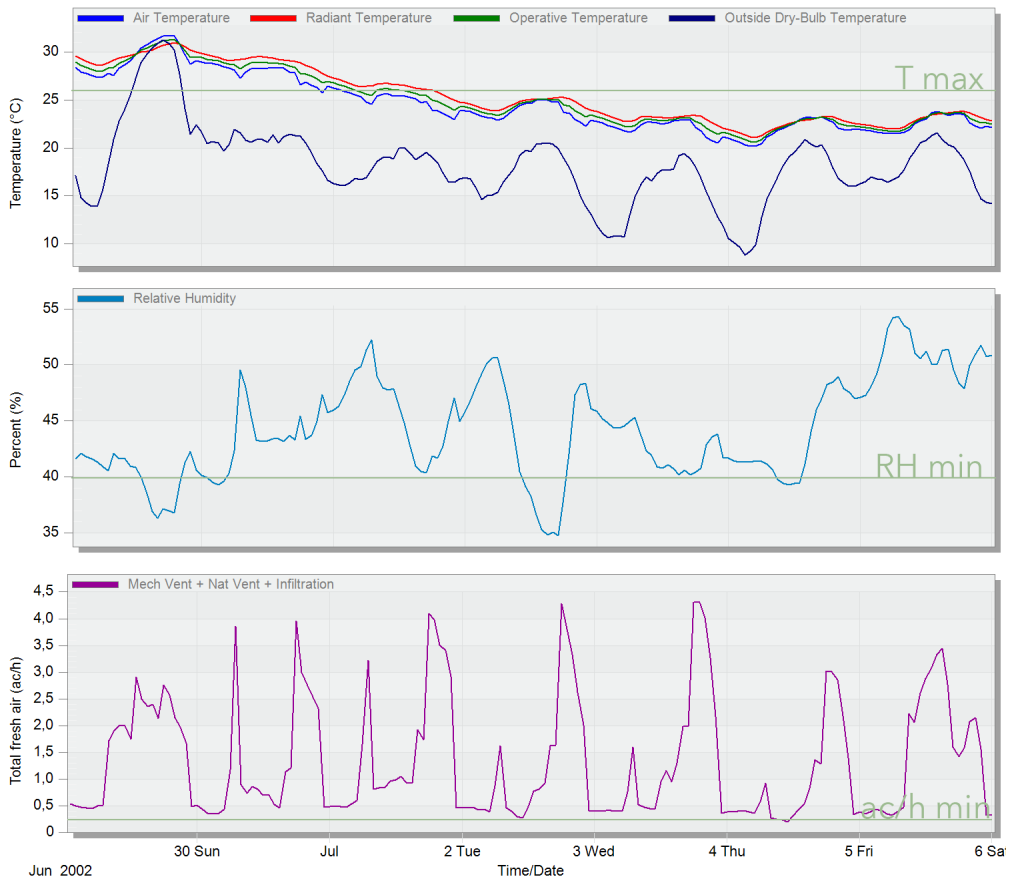


Figure 32: Simulated comfort in summer 2019. Image from Design Builder.

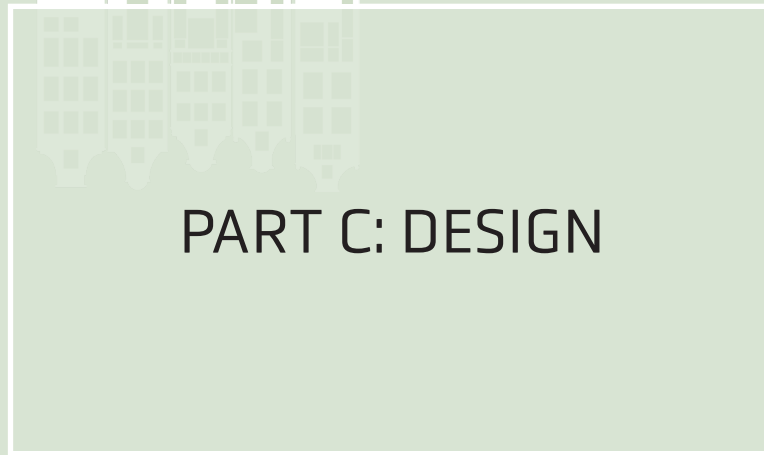
## 7.6 Conclusion

To assess the energy performance of the Oudezijds Voorburgwal 30 the bills were collected and the energy usage was simulated in Design Builder. The energy usage of the store on the ground floor (30A) is higher than the average energy usage of retail stores. Yet the energy usage of the apartment on 30B is lower than the average energy usage of an apartment at the Burgwallen-Oude Zijde. In total, the energy usage of Oudezijds Voorburgwal 30 is average for a building at the Burgwallen-Oude Zijde. However, as mentioned in chapter 3, the energy usage of Amsterdam and its buildings is too high. Consequently, the energy performance of the Oudezijds Voorburgwal 30 has to be bettered.

	Parameter	Measured	Simulated
<b>EP</b>	Energy usage (kWh)	68,776	72,292
<b>Thermal</b>	Min. T winter (°C)	± 17 (FH, heated) ± 9 (BH, unheated)	± 16 (heated) ± 10 (unheated)
	Max. T summer (°C)	N.A.	± 30
<b>IAQ</b>	Min. ventilation rate (l/s per person)	N.A.	Average: 1.45 ac/h
	Min. RH (%)	± 40	± 25
	Max. RH (%)	± 60	± 70

Table 19: Measured versus simulated indoor comfort levels. Own work.

With respect to the indoor comfort, the measurements have shown that the indoor temperatures are far below the comfort criteria, with the exception of the RH. The infrared images have revealed that quite some energy is lost through the exterior partitions, which was confirmed by the energy simulation. The residents of 30B do not think their house is comfortable in winter. It is often too cold and heating the apartment requires too much natural gas. The measurements and the simulation confirm that temperature in winter is too low. The interview, measurements and simulation have shown that the indoor comfort needs improvement, especially the indoor temperature. Of course, the apartments could hypothetically be made more comfortable by simply increasing the amount of heating. This would however lead to a significant increase of natural gas usage and consequently in carbon emission (and costs) which is undesirable to achieve the climate goals. It is thus necessary to find a sustainable solution to lower the energy usage and to improve the indoor comfort of the Oudezijds Voorburgwal 30.



## PART C: DESIGN

## 8. Design Concept

Analysis of the Oudezijds Voorburgwal 30 has revealed that the energy performance and indoor comfort of the case study building need to be improved. In chapter 3 an overview was provided of the possible design measures to lower the energy usage and improve the indoor comfort of monumental buildings. However, not all measures can be applied in the case study building. In this chapter the following subquestion will be answered: *“Which of the inventoried design measures can be implemented in the case study building for the renovation design?”*

### 8.1 Implemented general design measures

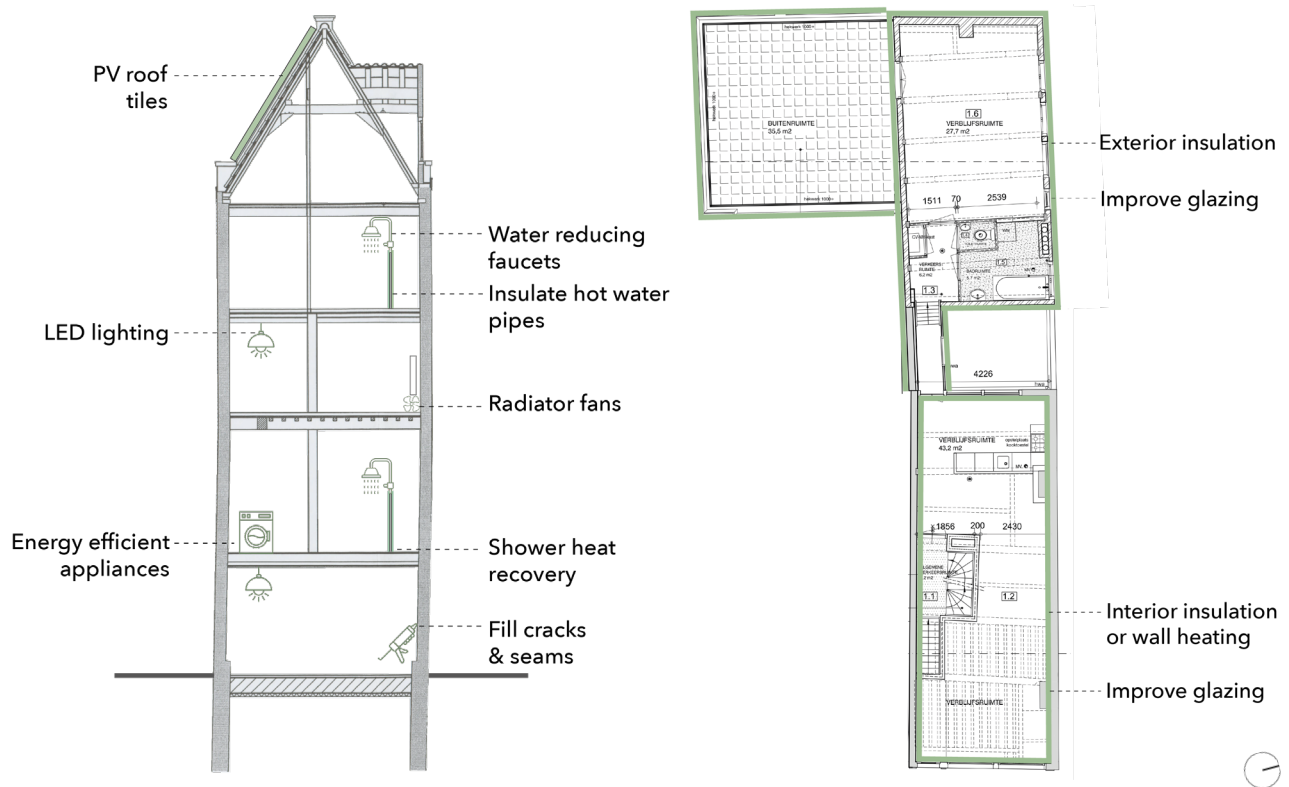


Figure 33: General proposed design measures. Adapted from Stadsherstel & Amsterdams Archief, 2005.

An important general design measure for the energy renovation of the Oudezijds Voorburgwal 30 is to improve the building envelope, as it currently is a major source for energy and heat losses (as mentioned in chapter 7). Since the back house is not monumental (see chapter 6), it is suggested to insulate the envelope (facades & roof) from the exterior as it minimizes the risk of internal condensation, does not compromise the interior space and has a better insulative performance. On the contrary, the front house is monumental (excluding the interior wall finishes) and the building envelope can thus not be insulated from the exterior. Depending on the HVAC design concept the facades either can be insulated from the interior or a wall heating system can be used. To further improve the building envelope and minimize heat losses, the windows and window frames are replaced and cracks and seams are filled to lower infiltration (another major source for heat and energy losses). The ground floor and roofs are re-insulated as well, as they are currently not up to standard. To further reduce the energy usage, water reducing shower heads and faucets will be installed and all hot water pipes are insulated. To lower the electricity usage, LED lighting is installed as well as energy efficient appliances. It was chosen to use energy efficient appliances instead of hot fill appliances as it requires less alterations to the building. To reuse energy, horizontal shower heat recovery (to not disturb downstairs neighbors) will be installed as well as heat recovery from ventilation air, depending on the HVAC installations. To produce energy on site PV panels will be used. PV panels are chosen as it solely requires a solar battery and space is often limited in monumental building for a solar buffer tank.

## 8.2 HVAC design concepts

In chapter 3 different HVAC installations were identified. The identified separate systems need to be combined for a well functioning energy renovation which improves the energy performance and the indoor comfort of the occupants. This sub chapter presents five individual concepts for the HVAC installations.

### 8.2.1 Concept 1: Biogas

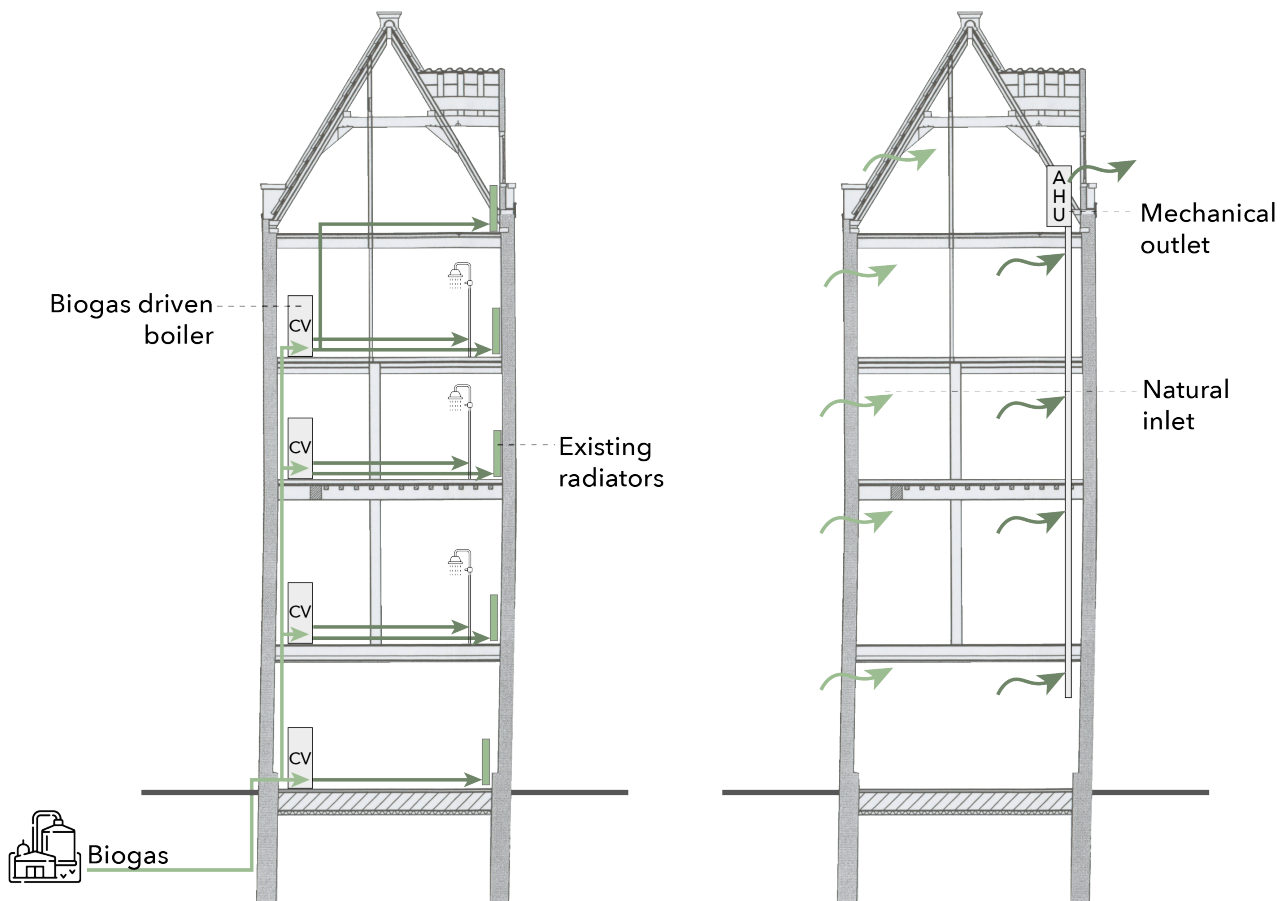


Figure 34: Heating & ventilation concept 1. Own work

Since the historic city center poses many challenges to become more sustainable, the municipality of Amsterdam plans to use biogas for the heating of monumental buildings in the historic center of Amsterdam (Gemeente Amsterdam, 2020c). Biogas is made from biological sources such as biomass. In this concept, the idea is to lower the energy usage of the building by insulating the building envelope as well as possible, without damaging the monument and its monumental elements. Biogas can then be used to provide HT heating ( $\pm 80$  degrees Celsius) through the use of a boiler and to make the building comfortable even though it is not insulated as well. In this concept biogas is also used for DHW. The existing pipes on both the exterior and interior of the building can be re-used. Furthermore, the boiler most likely does not have to be replaced, as well as any of the heat distribution systems (radiators). As biogas provides HT heating it is also possible to maintain the current ventilation system with natural inlet and mechanical outlet.

Biogas is officially 'climate neutral' and a more sustainable solution alternative for natural gas, it can provide HT heating and requires little alterations to the building. Hence the potential as energy source for monumental buildings. However, the use of biogas is a point of discussion as during the production particulate matters are released in the atmosphere and the biomass used for the production of biogas is not always sourced sustainably. Furthermore, the amount of biogas that can be produced is restricted and thus should only be used in limited cases.

## 8.2.2 Concept 2: All-electric



Figure 35: Heating & ventilation concept 2. Own work

Frequently proposed when renovating buildings sustainably (and encouraged by the authorities to achieve the climate goals), is to take the building off natural gas and make the building all-electric. In this concept gas is no longer used and the building solely runs on electricity. In this case air-water heat pumps are suggested as chapter 3 has shown the potential of air as an energy source. Air is widely available and an air-water heat pump does not require major alterations to the building or the urban fabric such as with geothermal energy. The air-water heat pump consists of both an interior and exterior unit, extracting heat from the air and upgrading it to around 55 degrees Celsius. This can subsequently be used for DHW (with the use of a storage tank) and heating. For heat distribution radiators are used as they and the accompanying systems are already present, with a few additional ones (necessary for LT heating). As heat pumps work most efficiently with LT heating it is necessary to insulate the building quite well and lower the infiltration through cracks and seams. As a consequence mechanical ventilation (with heat recovery) is incorporated in this concept, to guarantee an air flow. A disadvantage of an air-water heat pump is that in winter the temperature of the outdoor air might be too low for the heat pump to work sufficiently. To keep the indoor environment comfortable, additional heating is required for the extreme winter days when the heat pump alone is not sufficient. In this case infrared panels are used to provide some additional heating. It was chosen to use infrared panels as they are relatively easy to install, provide local heating (minimizes energy usage) and give of radiant heating (comfortable).

For an all-electric building, the electricity grid has to be improved. As underground crowding is an issue in Amsterdam this might pose problems. Underground crowding is also the reason why rest heat with a heat network was not considered for the heating of the building. Moreover, an air-water heat pump produces noise, so careful placement of the exterior unit is required. As in this concept relies on LT heating, the building envelope needs to be well insulated, this might pose a problem for monumental buildings and the Oudezijds Voorburgwal 30.

### 8.2.3 Concept 3: Hybrid not near water

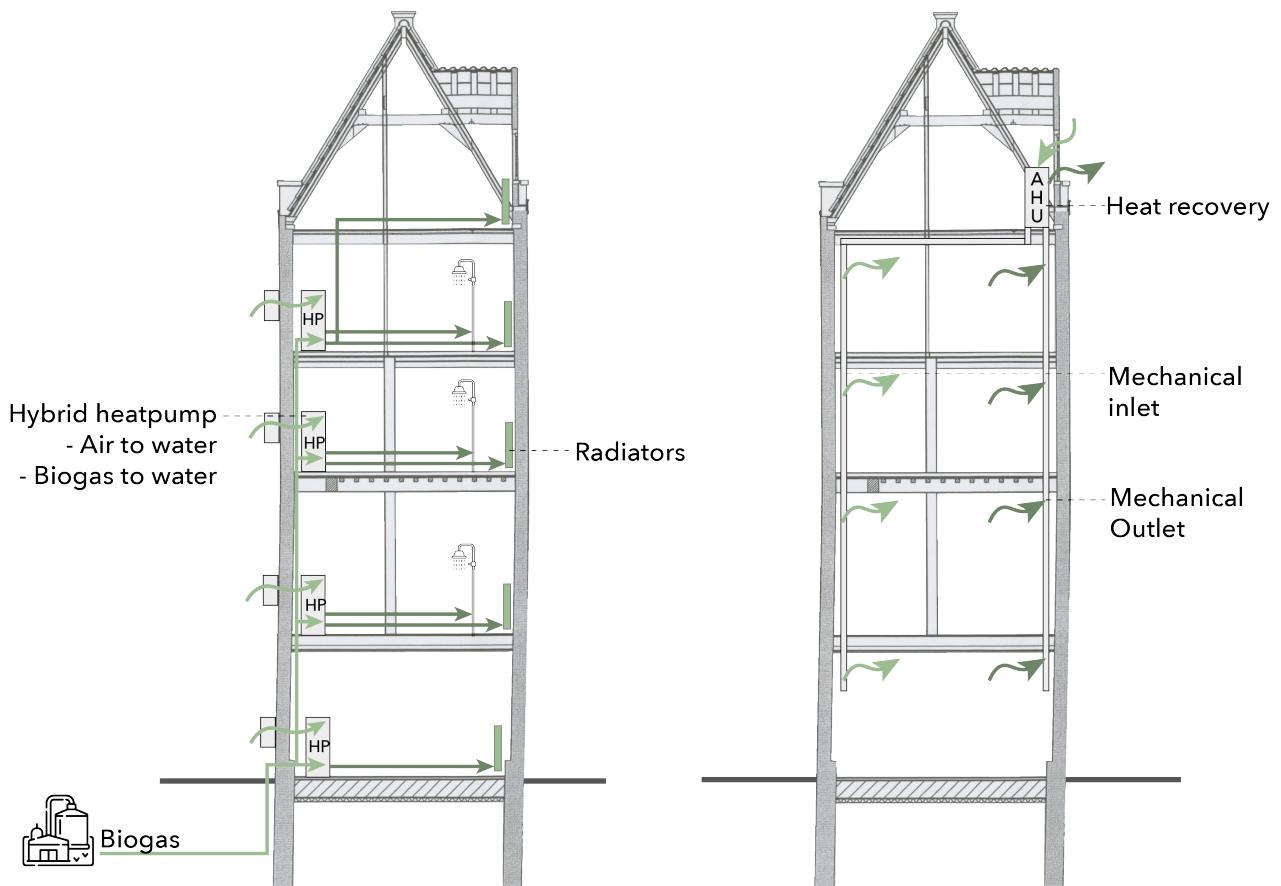


Figure 36: Heating & ventilation concept 3. Own work

Since monumental buildings are often not insulated and there are limited possibilities due to regulations to insulate the building envelope, and thus to make the building all-electric, it can be opted to use a hybrid heat pump. In this concept, an air-water heat pump is used for the larger part of the year for the heating of the building and the DHW demand (equal to concept 2). The temperature of the water is around 55 degrees Celsius and a storage tank is required for DHW. As mentioned in concept 2, the LT heating source of air might be insufficient during the more extreme winter days. Instead of using infrared panels as per concept 2, a hybrid heat pump is suggested. Besides the heat-pump part, a hybrid heat-pump also has a boiler part which can supply heat during the periods the heat-pump provides insufficient heat. The boiler part can run on natural gas, biogas, hydrogen or electricity. It was chosen to use biogas as it is more sustainable than natural gas, readily available (in contrary to hydrogen) and is more energy efficient than an electrical boiler. The existing radiators are re-used for the heat distribution. During the larger part of the year the system relies on LT heating, provided by the heat pump, thus a larger surface area for heat distribution is required. It is suggested to install additional radiators. For LT heating to be comfortable as often as possible throughout the year the building needs to be insulated as well as possible and infiltration should be limited by filling cracks and seams. Since infiltration is lowered, fully mechanical ventilation (with heat recovery) is suggested to provide a guaranteed air flow without uncontrollable infiltration through ventilation provisions.

Concept 3 still makes use of the controversial biogas and does not take into account the potential of the surroundings and the neighborhood. The concept can however be implemented in a large amount of monumental buildings as it does not rely on the potential of the surroundings.

### 8.2.4 Concept 4: Hybrid near water

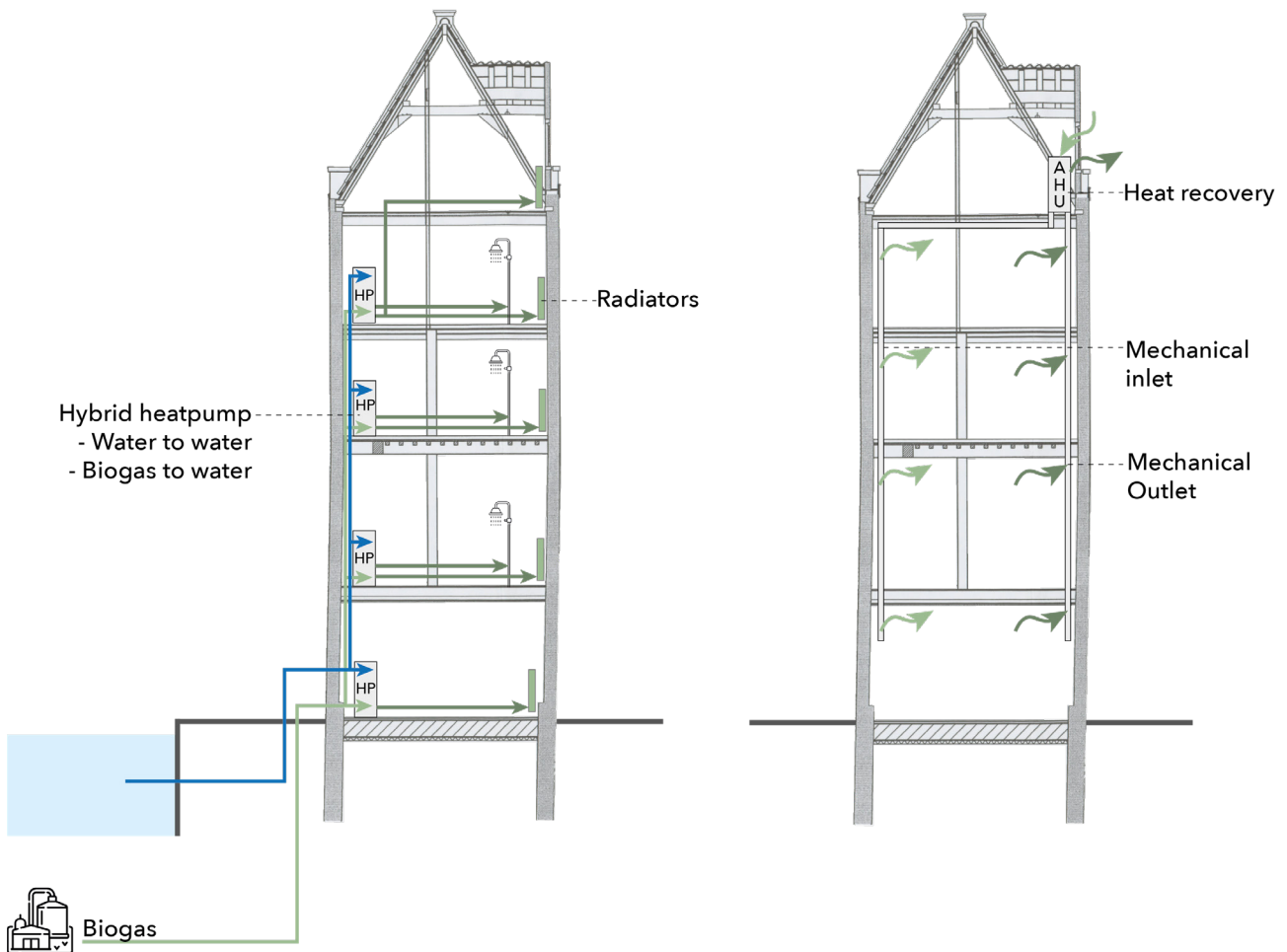


Figure 37: Heating & ventilation concept 4. Own work

Many of Amsterdam's monumental buildings are located near canals. Instead of using air as energy source, the canals can be used for the heating of the building, so-called surface water heat extraction (TEO). In this concept TEO is the source for a water-water heat pump. TEO is a LT heating source, meaning that in winter the heating source might be insufficient for a comfortable indoor environment in monumental buildings due to the limited insulation possibilities. Consequently, a hybrid heat pump is suggested where a biogas driven boiler provides additional heating during the colder periods. Heat is distributed through the use of the existing radiators and a few additional ones to increase the surface area of heat distribution (necessary for LT heating). To rely on the heat-pump with the aquathermal source as often as possible and to minimize biogas usage, it is necessary to insulate the building envelope as well as possible and decrease the amount of infiltration drastically. Fully mechanized ventilation (with heat recovery) is thus most suitable. For DHW, the hybrid heat pump is used as well, in combination with a storage tank.

An advantage of concept 4 is that it takes into account the surrounding potentials of the case study building and Amsterdam and minimizes the distance energy has to travel and thus energy losses. Yet, the aquathermal system requires a heat network from the canals to the building and back. As mentioned before, underground crowding poses an issue in Amsterdam. To minimize the disruption, it can be opted to combine this concept with the renewal of the quay walls and integrate heat exchanges in the quay walls. Instead of aquathermal energy, it is also possible to use soil energy as chapter 3 has shown the potential. However, it requires space around the building for the installations and drilling. The Oudezijds Voorburgwal 30 does not have a garden and drilling in public spaces is often not allowed.

### 8.2.5 Concept 5: Off gas, aquathermal

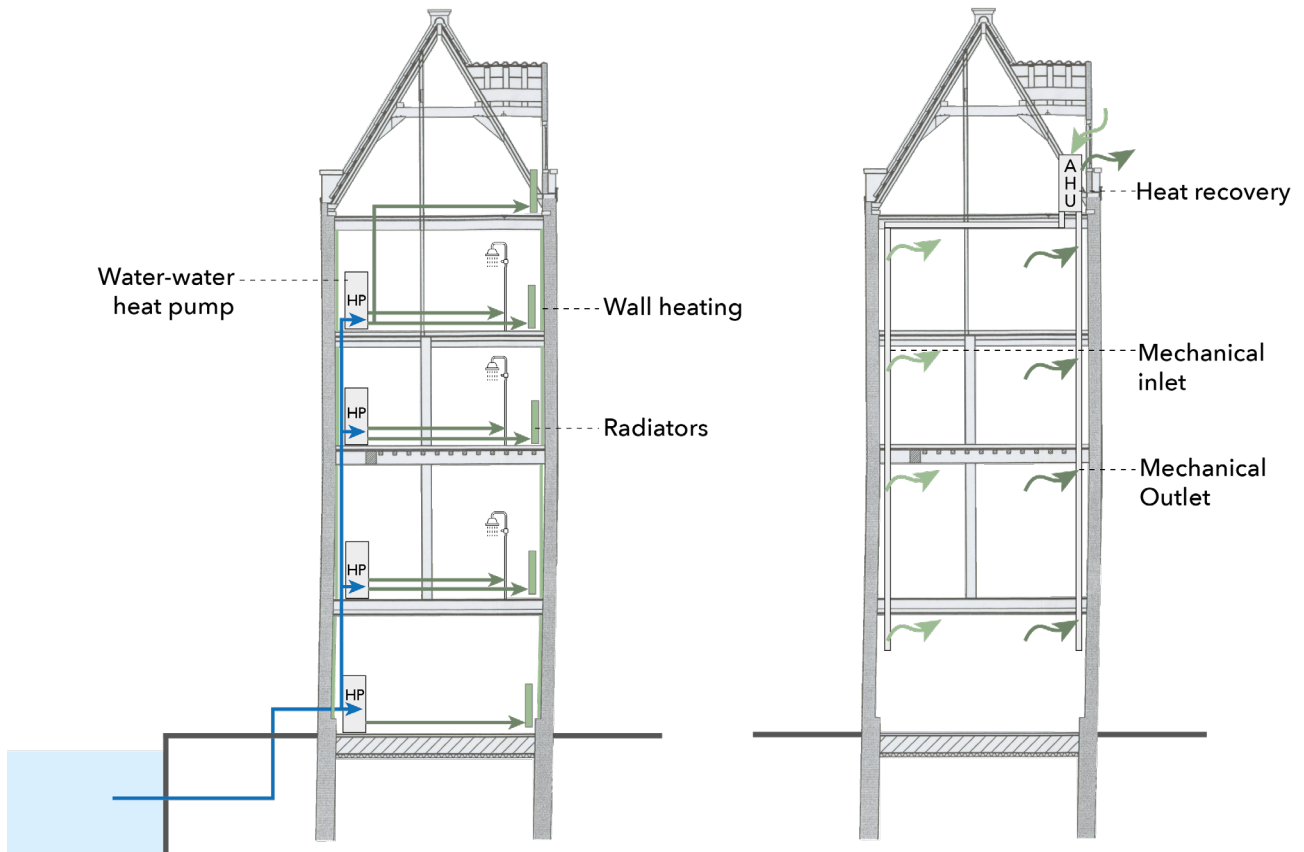


Figure 38: Heating & ventilation concept 5. Own work

As mentioned previously, the use of biogas is slightly controversial. Alternatively, it can be decided to take the building off gas completely and solely use the aquathermal heat as heating source combined with a water-water heat pump. Potentially during colder periods the temperature of the water could be boosted using a heat pump booster. For DHW a storage tank is required.

As this is a LT heating system, insulation of the building is necessary. However, insulating the building envelope from the interior (often the only possibility for monumental buildings) means a loss of interior space, which is often unwanted. Interior insulation could also lead to internal condensation in the construction which in its turn could have detrimental consequences to the building and the comfort of the occupants. Instead of interior insulation, the 'WarmBouwen' concept is suggested. Wall heating is installed on the interior walls and creates an insulative layer between the interior and exterior and prevents heat transmission from the interior to the exterior. It makes use of LT heating source ( $\pm 30$  degrees Celsius). The existing radiators and a few additional radiators are used to heat the room (55 degrees Celsius). As this option will make use of LT heating it is necessary to lower the infiltration through the building envelope. Mechanical ventilation (with heat recovery) is suggested. Moreover, the building parts which do not use the wall heating system do require to be insulated for sufficient comfort with LT heating.

Concept 5 makes use of the surrounding potentials of the neighborhood and presents a promising method of reducing energy losses while lowering the risk of internal condensation and minimizing interior space losses. A disadvantage however is that it solely relies on aquathermal heating, which might be insufficient in winter. Often aquathermal energy (or soil energy) is combined with an underground storage of heat and cold (ATES) as it makes the system work most efficiently. For the Oudezijds Voorburgwal 30 this is not possible as there is no garden to install the system.

### 8.3 Choice of HVAC design concept

All of the five presented HVAC design concepts have their advantages and disadvantages. To continue with the design, the different aspects of each individual concept need to be carefully considered (see table 20). Concept number 1, 3 and 4 make use of biogas as (partial) energy source. As mentioned, biogas is controversial since it is officially climate neutral but does release particulate matters into the atmosphere. Furthermore, sourcing of biogas is not always done in a sustainable manner. In general, the sustainability of biogas can be questioned. However, a major advantage of biogas is that it is more sustainable than natural gas and can provide HT heating. Since many monumental buildings have limited possibilities for insulation and need to adhere to many regulations, the use of HT heating can still provide a comfortable indoor climate and requires little alterations to the building and existing installations.

Concepts 2 and 5 propose solutions where the use of any type of gas is no longer necessary. However, in both cases it is unsure whether the proposed design concepts will provide enough comfort, especially during the colder periods, even though suggestions are made to counter potential discomfort. Yet both solutions theoretically are the most sustainable due to the complete dismissal of gas. Concepts 1, 2 and 3 do not necessarily consider the surrounding potentials of the building, the neighborhood or Amsterdam in general. Consequently, they could potentially be implemented in a larger number of buildings. Concepts 4 and 5 do consider the surrounding potentials by making use of the aquathermal heating concept. As the world is shifting from fossil fuels to renewable source it is important to investigate alternative energy sources. By producing energy close to where it is used, energy losses are minimized.

It was chosen to combine concepts 4 and 5 for the renovation design of the Oudezijds Voorburgwal 30. It was chosen to use a hybrid system to guarantee comfort for the occupants (concept 4) but with the use of the wall heating system (concept 5) as it seems a promising method to minimize energy losses in monumental buildings without all the negative side effects of interior insulation. It was chosen to use aquathermal energy (concepts 4 & 5) instead of air as the primary source for the heat pumps as it is widely available in Amsterdam and utilizes the surrounding potentials of the building and the neighborhood. Since biogas is controversial it is chosen to use electricity instead of biogas as secondary energy source. Electricity can be produced in a renewable manner. Cooling is not included as the Design Builder simulation of the current situation and the experience of the users does not show the need for cooling.

	<b>Concept 1: Biogas</b>	<b>Concept 2: All-electric</b>	<b>Concept 3: Hybrid not near water</b>	<b>Concept 4: Hybrid near water</b>	<b>Concept 5: Off gas, aquathermal</b>
<b>Surrounding potential</b>	--	-	-	+	++
<b>Sustainability</b>	--	++	0	0	++
<b>Energy performance</b>	-	++	+	+	++
<b>Indoor comfort</b>	+	?	+	+	?
<b>Monumentality</b>	++	-	-	+	+
<b>Technical</b>	++	0	0	-	0
<b>Aesthetical</b>	+	-	0	+	+
<b>New materials</b>	+	--	-	-	-
<b>Financial</b>	++	0	+	--	--

Table 20: Consideration aspects of the different concepts. Own work.

### 8.4 Design proposal

For the design proposal the general design measures and the chosen HVAC concept are combined. For the design it is necessary to keep in mind that the back house and front house of the Oudezijds Voorburgwal 30 are different and thus require different design strategies. The back house does not have any monumental significance whereas the front house does. All general design measures (sub chapter 8.1), such as LED lighting, energy efficient appliances, radiator fans, water reducing faucets, insulation of the hot water pipes and shower heat recovery, will be implemented.

### 8.4.1 Renovation design of the building envelope

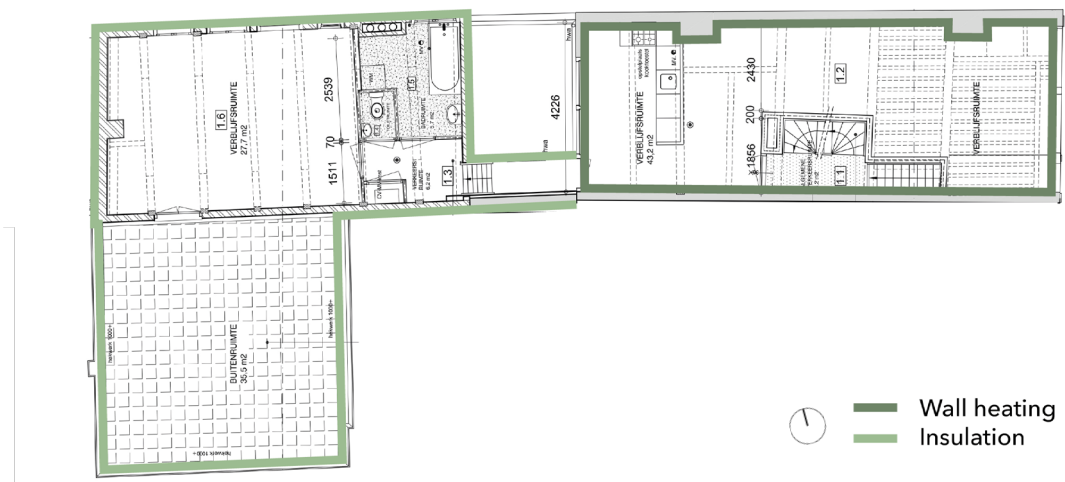


Figure 39: Proposed insulation design. Adapted from Stadsherstel, 2005.

As mentioned, the back house will be insulated from the exterior (EPS with a plaster finishing to not alter the appearance of the building) as this minimizes the risk of internal condensation and does not decrease the amount of interior space. The front house will not be insulated but wall heating is suggested. This decreases the risk of internal condensation in the monumental walls and the loss of interior space is minimized. Furthermore, the wall heating will reduce the heat losses to the exterior and discomfort due to cold radiation by basically creating an insulation layer without adding any insulation. It needs to be noted that the connections between the front and back house (where the wall heating and exterior insulation meet) need to be detailed properly as condensation could occur at those locations.

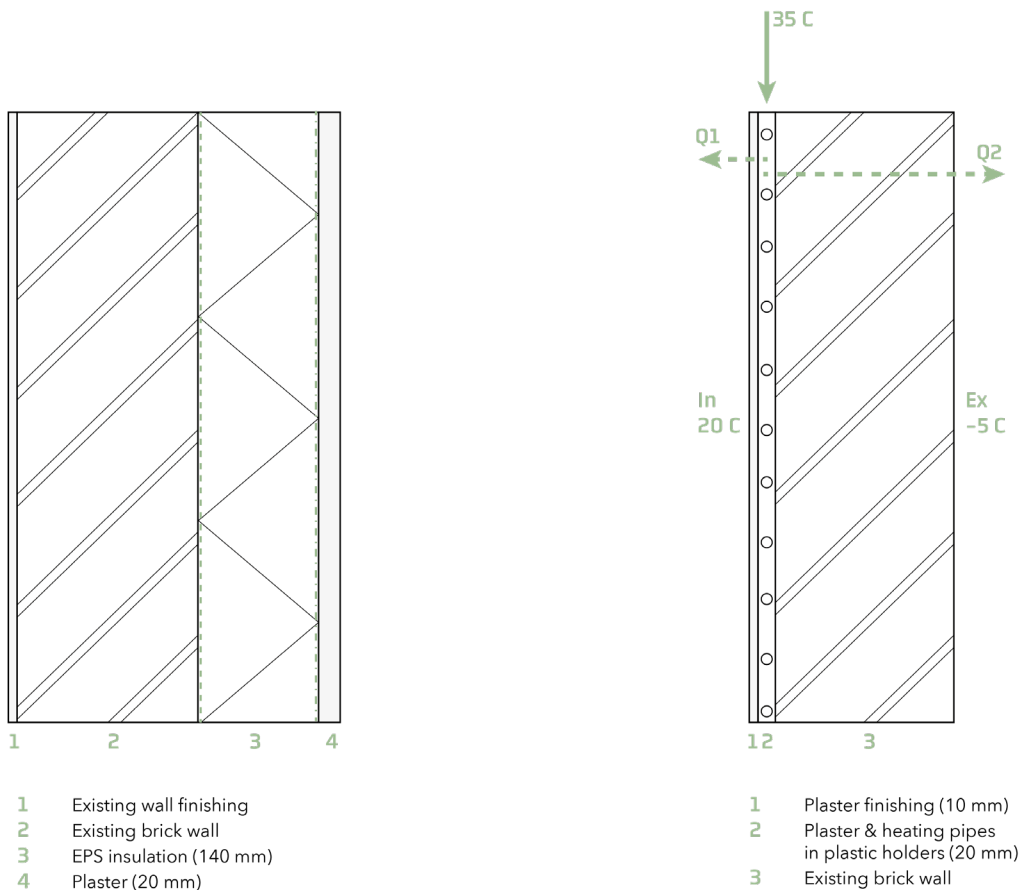


Figure 40: Renovation design of facades back house & front house. Own work.

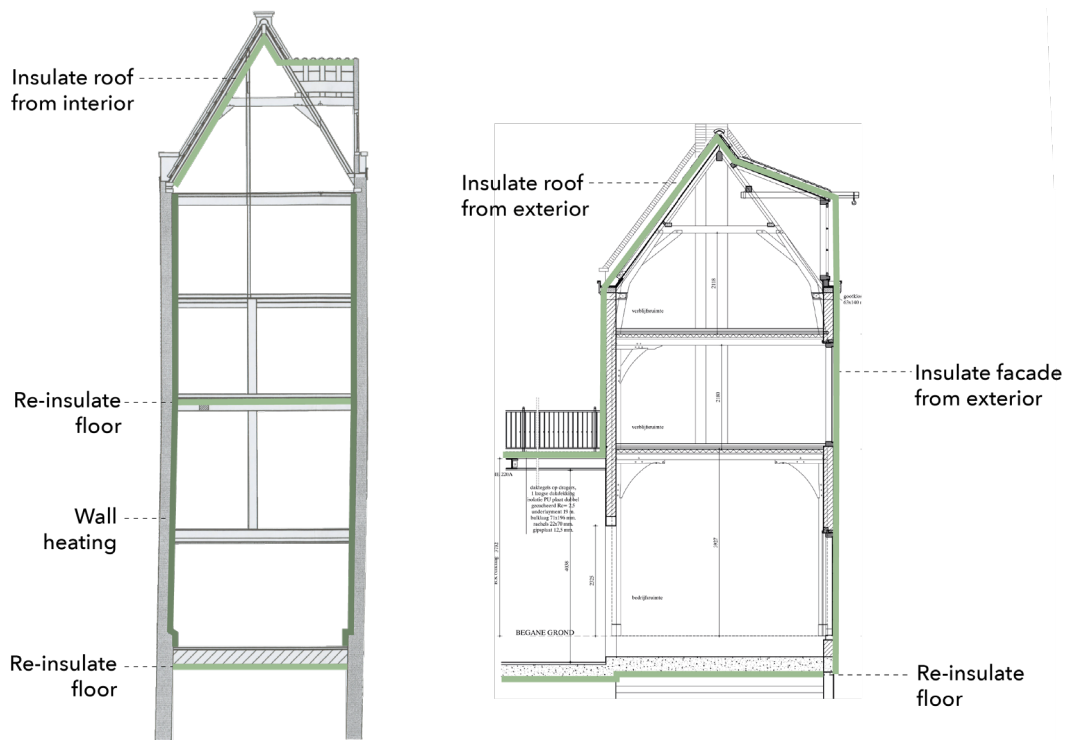


Figure 41: Proposed insulation design. Adapted from Stadsherstel, 2005.

To further lower the energy usage, the roofs and ground floor of both the back and front house will be re-insulated. The roof of the front house will be insulated (PIR insulation) from the interior. When insulated from the exterior the connection with the gutter needs to be altered, which is in conflict with the regulations for national monuments. The roof of the back house will be insulated (PIR insulation) from the exterior as the back house is not monumental, it is thermally the best solution and does not pose any problems for the detailing as the facades are insulated from the exterior as well. However, careful detailing of this connection between the facades and roof of the back house is necessary. The flat roofs (non-monumental) are insulated from the exterior as well for better thermal performance. The complete ground floor is insulated from underneath using thermo cushions, as they are easy to install and have a high insulative performance. To further improve the building envelope cracks and seams are filled to lower infiltration and thus energy losses. In the back house this can be done with any material as it is not monumental. For the front house it is necessary to use materials which do not damage monumental elements and can be removed such as draft profiles for the windows and doors and foam rubber with sealing tape.

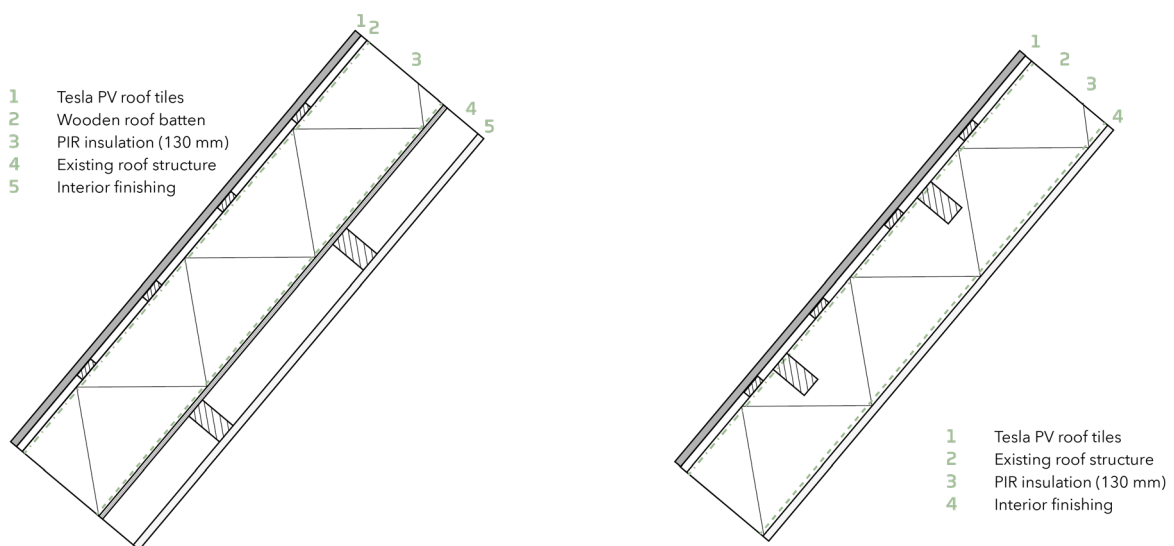


Figure 42: Renovation design of roofs back house & front house. Own work.

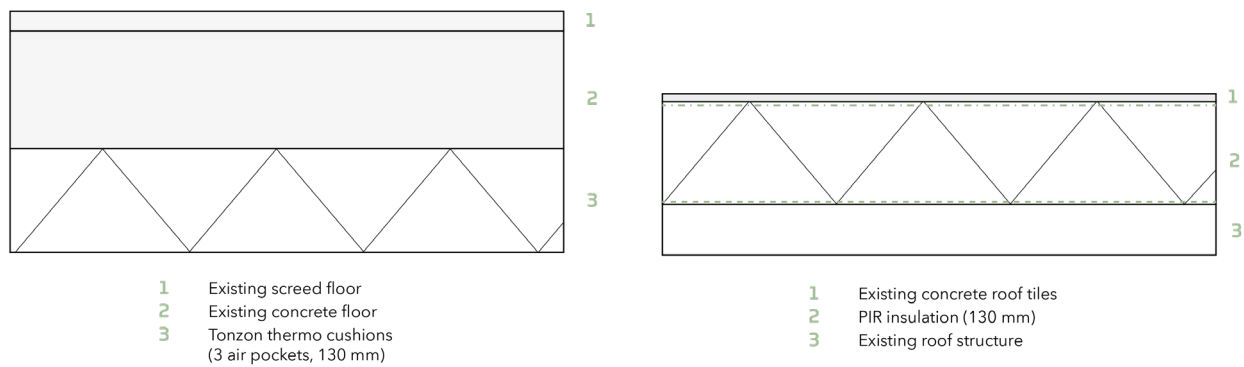


Figure 43: Renovation design of ground floor & flat roofs. Own work.

Lastly, the building envelope is improved by replacing the glazing and frames of all windows except the two upper windows of the East facade of the front house, as the frames are classified as monumental. For the front house it is required, according to the regulations, to use the same material for the window frames (painted wood) and the depth of the windows from the exterior in the facade has to remain the same. The glazing is replaced with double glazing for improved performance. As the frames of the upper two East facade windows need be conserved, either thin double glazing can be placed in the existing frames or an additional window pane ('achterzetraam') can be placed behind the existing window. The windows of the back house can be replaced completely as the building is not monumental. The glazing will be replaced with double glazing for better thermal performance and because of the lower weight and price than triple glazing. The frames will be replaced with uPVC frames as they have a better thermal performance than wooden frames but a lower embodied energy than aluminum frames.

#### 8.4.2 Renovation design of the HVAC installations



Figure 44: Proposed aquathermal heating concept. Own work.

For the installations and HVAC systems it was also chosen to make a distinction between the back and front house as they operate separately. In both cases aquathermal energy extracted from the nearby canal is used to heat the building (see figure 44 and 45). Two collective heat pumps are used as this is more efficient than individual heat pumps and require less space. For the front house the collective heat pump (heat pump number 1) uses heat from the canal water (through the use of a heat exchanger) and boosts this to around 30 degrees Celsius. This can be used directly for the wall heating. For the radiators in the front house and DHW in the kitchen the temperature of the water however needs to be increased. For this reason each apartment will have an individual boiler (with storage tank) in the front house which can consequently boost the temperature of the water provided by the heat pump to 55 degrees Celsius. If the current boiler in the apartments is still up to standard it can be re-used with biogas as energy source. When replacement is needed an electric boiler can be installed at the location of the gas boiler.

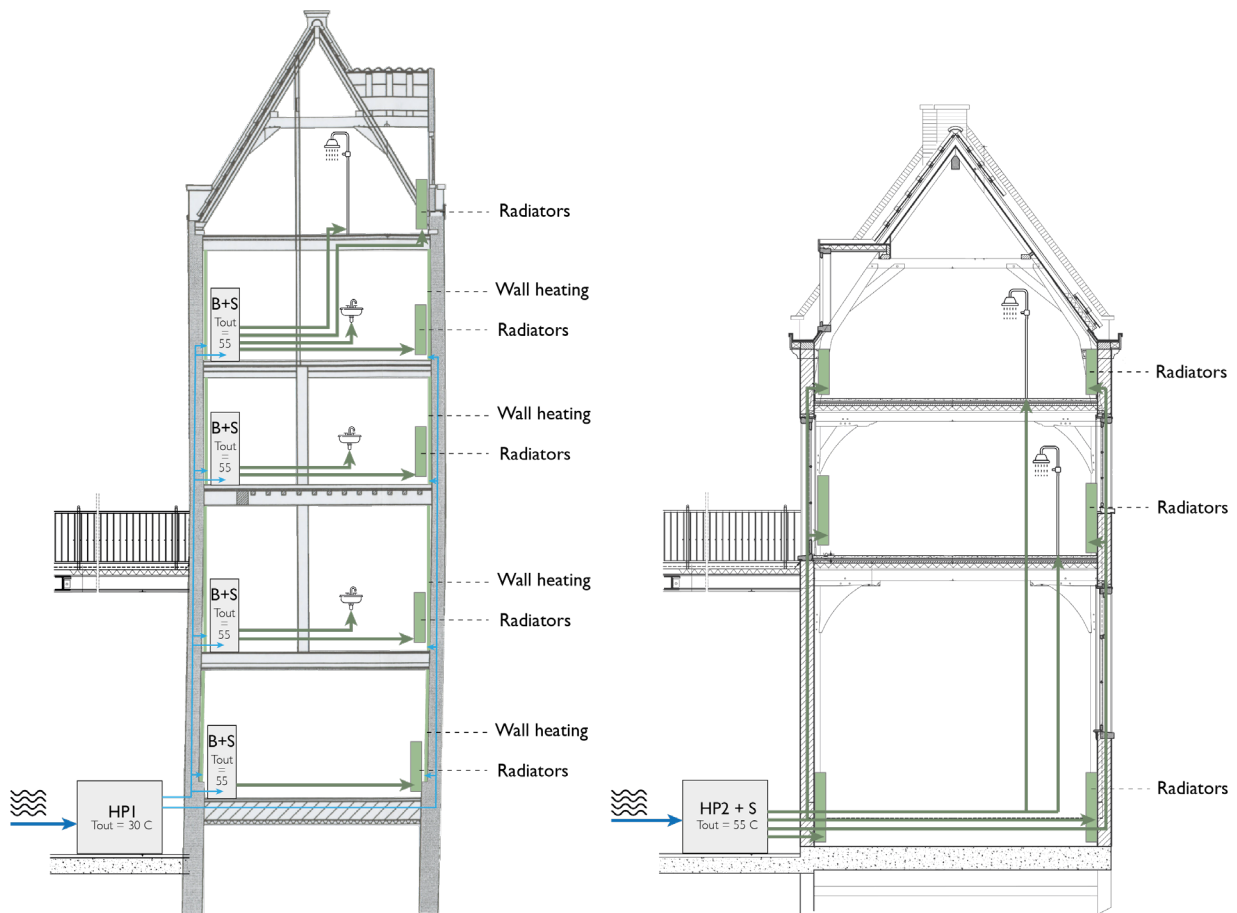


Figure 45: Proposed heating & DHW design of the front & back house. Adapted from Stadsherstel, 2005.

Since the back house is insulated from the exterior, wall heating is not necessary. The existing radiators with additional ones will be used for heating of the building. A collective heat pump with heat exchanger (heat pump 2) uses the aquathermal energy from the canal and boosts the temperature to 55 degrees Celsius. This can then be immediately used for the radiators and DHW (in combination with a storage tank) in the bathrooms.

Regarding ventilation, both the back and front house will make use of fully mechanical ventilation as cracks and seams are filled to lower infiltration and thus heat losses (see figure 47). Advantages of mechanical ventilation are that ventilation rate is guaranteed and that there is no unwanted infiltration. Both the back and front house will have individual air-handling units with heat recovery. In appendix D an overview of the systems per apartment, the location of all installations and several calculations can be found. To produce energy besides the aquathermal energy, PV roof tiles will be placed on the roof of the back house and the front house. It was chosen to use PV as the solar battery does not require as much space as a solar buffer tank. The production of the PV roof tiles in total is higher than regular PV panels as more roof area can be covered and is a more integrated solution. Tesla PV roof tiles were chosen as other PV roof tiles have a lower energy production and the Tesla PV roof tiles are more aesthetically pleasing. In appendix D a calculation of the energy production of the PV panels can be found.



Figure 46: Tesla solar roof tiles. Source: Tesla (n.d.).

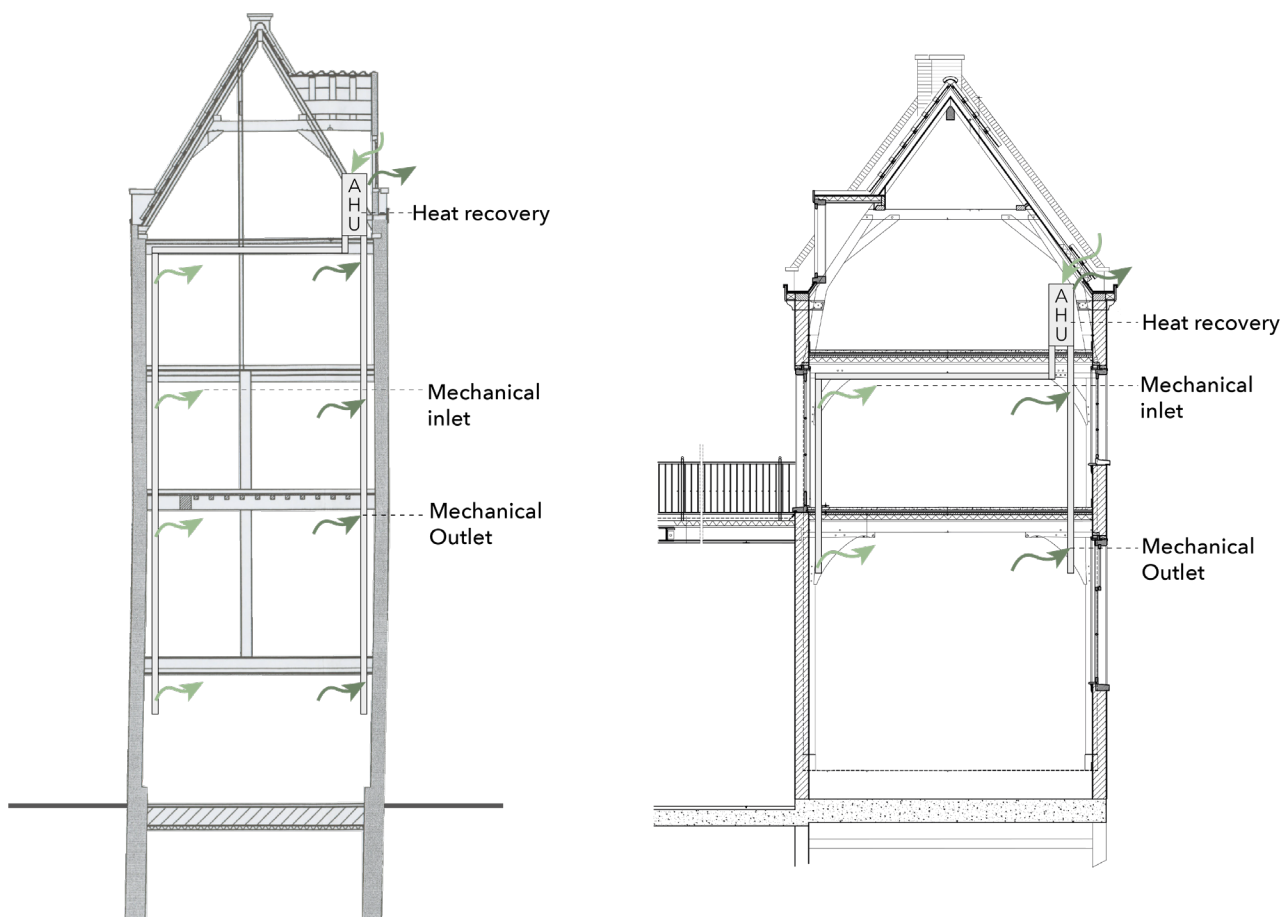


Figure 47: Proposed ventilation design front house & back house. Adapted from Stadsherstel, 2005.

As identified in table 20 (sub chapter 8.4) the chosen HVAC design concept is financially the least favorable as heat pumps and the aquathermal system are quite expensive. Calculation of the costs has shown that the investment of the implementation of all proposed design measures is around 168,000 euro (including government funding and subsidies). The yearly savings due to the lowered energy bills is around 5,500 euro. Resulting in a payback time of around 31 years. In appendix D the detailed calculation of the costs can be found.

Cost calculation (EUR)	
Investment costs	168179
Yearly savings	5486
<b>Payback time</b>	<b>30,7</b>

Table 21: Cost estimation of the proposed design. Own work.

## 8.5 Conclusion

After the suggestion of several different HVAC design concepts, it was chosen to continue with the concept that uses of aquathermal energy for heating and DHW, as it makes use of the potential of the surroundings and could potentially be implemented in other buildings as well. However, a hybrid variant was chosen to ensure the comfort of the occupants. The concept was combined with the concept which includes a wall heating system according to the concept of 'WarmBouwen' as it has a large potential for lowering energy losses, minimizing the loss of interior space and reducing the risk of internal condensation in monumental buildings. By combining the HVAC design concepts with the general design measures a design proposal was made.

The proposed design makes a distinction between the front and back house of the Oudezijds Voorburgwal 30. In table 22 the different design measures which are implemented in the proposed design can be found. Both the front and back house will use heat pumps for the room heating and DHW. However, the exit temperature of the heat pump differs. Furthermore, both parts of the building will make use a fully mechanical ventilation system (with heat recovery). These systems work separately but function in the same manner. The improvements of the building envelope are different for the front and back house as well. This mainly has to do with the fact that the front house is monumental and the back house is not. The material choices for the insulation are based on a trade off between thermal capacity, required thickness and sustainability (NIBE ranking). Energy is produced in the design with the use of PV roof tiles (and of course the aquathermal energy concept).

		Front house	Back house
<b>Building envelope</b>	<b>Roof insulation (sloped)</b>	Interior (PIR)	Exterior (PIR)
	<b>Roof insulation (flat)</b>	N.A.	Exterior (PIR)
	<b>Façade insulation</b>	Wall heating	Exterior (EPS)
	<b>Floor insulation</b>	Underneath (Tonzon)	Underneath (Tonzon)
	<b>Glazing</b>	Double glazing (one exception)	Double glazing
	<b>Window frames</b>	Wood	uPVC
	<b>Cracks &amp; seams</b>	Foam rubber & sealing tape	Kit
<b>Heating</b>	<b>Installations</b>	Collective heat pump ( $T_{out} = 30\text{ °C}$ )	Heat pump ( $T_{out} = 55\text{ °C}$ ) + storage tank
		Electric boilers ( $T_{out} = 55\text{ °C}$ ) + storage tank	
	<b>Heating source</b>	Canal water & electricity	Canal water & electricity
	<b>Distribution</b>	Radiators	Radiators
Wall heating			
<b>DHW</b>	<b>Installations</b>	Collective heat pump ( $T_{out} = 30\text{ °C}$ )	Collective heat pump ( $T_{out} = 55\text{ °C}$ ) + storage tank
		Electric boilers ( $T_{out} = 55\text{ °C}$ ) + storage tank	
<b>Ventilation</b>	<b>System type</b>	Fully mechanical with heat recovery	Fully mechanical with heat recovery
<b>Production</b>	<b>System</b>	PV roof tiles Tesla	PV roof tiles Tesla
<b>Other</b>	<b>Shower heat recovery</b>	In shower tray (horizontal)	In shower tray (vertical)
	<b>Faucets &amp; showerhead</b>	Water reducing	Water reducing
	<b>Lighting</b>	LED	LED
	<b>Appliances</b>	Energy efficient	Energy efficient
	<b>Heat distribution</b>	Radiator fans	Radiator fans

Table 22: Implemented design measures of the renovation design. Own work.

## 9. Design Evaluation

The goal of this thesis is to create an energy-neutral renovation design for a monumental building in Amsterdam, whilst improving the indoor comfort and maintaining the monumental status of the building. It is thus necessary to evaluate the effect of the proposed design on all three of these aspects. This chapter will give an answer to the following subquestion: *“What is the effect of the renovation design on the monumental status, energy performance and indoor comfort of the case study building?”*

### 9.1 Evaluation of monumentality

In sub chapter 6.3, the case study building's history was analyzed and the monumental elements and values were identified. These elements should not be altered by the design as these are of high value from a heritage viewpoint and could jeopardize the building's monumental status if altered. Furthermore, the proposed design needs to adhere to the rules and regulations for both national monuments as well as the protected city view. During the design phase the identified monumental elements were kept in mind to minimize the risk of altering any of the elements.

On an urban scale the aquathermal heating system will be installed. However, the systems do not alter the monumental elements of the urban scale. The organization of the front house, intermediate member and back house is maintained as well the presence of the courtyards, the alley, the buildings orientation and its embedding in the fabric of the city center and surrounding buildings.

With regard to the building scale, the back house (facades and roofs) will be insulated from the exterior. The back house is not of monumental value and can thus be altered. It is also not visible from the street so does not conflict with the rules and regulations of the protected city view. As analysis of the building has shown that infiltration is a large contributor to energy losses, cracks and seams are filled in the design. For the back house any material can be used but for the front house it was chosen to use materials which can be removed and are not visible from the outside to adhere to the regulations. For both the back and front house all glazing and window frames are replaced in the design. As the back house is not monumental this should not pose any problems. For the front house replacing the windows can be done within the regulations for national monuments as long as the detailing, shape, material, color and profiling is not altered. It was thus chosen to use wooden window frames with the same color and maintain the current depth of the windows in the facade. The single glazing is replaced with double glazing. This is possible since the building historical analysis has shown that the glazing is not monumental. The upper two windows of the East facade however are monumental, yet this only entails the window frame. By placing thin double glazing in the existing frame or a window pane behind the existing window the monumental window frames are preserved.

Another proposed design intervention on the exterior of the building is the use of PV roof tiles on the South facing roofs of both the back and front house. For the back house and a large area of the front house this does not pose any problems. However, for a part of the front house these roof tiles would be visible from the street (estimated to be around 12 m<sup>2</sup>). This is in conflict with the regulations of the protected city view. One possibility is to only lay the roof tiles on the non-visible areas of the roofs. However, on one hand the municipality of Amsterdam is allowing increasingly more in regard to monumental buildings and PV. On the other hand, innovation in the PV roof tile industry is fast paced, meaning that in the near future the PV roof tiles can possibly be placed within view because they look like the original roof tiling.

In regard to the alterations to the interior of the building, the front house and back house will be renovated using different design concepts. In the back house additional radiators will be installed. Since the back house is not of monumental value this will not cause any conflicts with the regulations. The front house is of monumental value. On the interior of the front house a wall

heating system will be installed. Considering that the front house does not have any wall paintings or monumental paneling this does not cause any problems. The only thing which has to be kept in mind during installation are the remnants of the wooden frame structure of the building. There are however, not many remnants left and should not cause any major issues with the wall heating system.

Another large intervention on the interior is the proposal of installing a fully mechanical ventilation system. This requires ducts to run through the building extracting 'dirty' air and blowing in fresh air. In the back house this will again not cause any problems. In the front house the vertical and horizontal air ducts cannot damage any of the monumental floor and wall structures. In appendix D it can be seen that it was chosen to fit the ducts into the old chimney shafts. These chimney shafts are of monumental value themselves too but do not need to be altered to place the ducts. The air handling unit will be placed on the attic and cannot be larger than whatever fits through the dormer windows as the roof structure cannot be altered due to its monumental value. Due to the monumental value of the roof structure of the front house, it is insulated from the interior. Therefore the roof structure does not need to be altered. Furthermore, insulating from the interior ensures that the gutter detailing on the exterior and the inclination of the roof do not alter and thus adheres to the national monument regulations. The ground floor of both the back and front house is re-insulated as well. However, this floor is not of monumental value and thus insulation will not damage any monumental value. To lower energy usage shower heat recovery is applied. Most bathrooms are located in the back house thus installation should not pose a problem. For apartment 30D the shower is located in the front house. It was thus chosen to use horizontal heat recovery to not damage the monumental floor. The heat pumps will be placed in the back house of the ground floor (see appendix D) and most likely can be installed through the front entrance of 30A.

## 9.2 Evaluation of the energy performance

To analyze the effect of the design proposal on the energy performance of the building the measures were modeled in Design Builder. The input can be found in appendix C. The results can be seen in table 23.

Monthly energy usage						
	Room Electricity	Lighting	System Fans	System Pumps	Heating	Production
	kWh	kWh	kWh	kWh	kWh	kWh
01-01-2019	352,4	359,1	67,7	4,0	4237,9	
01-02-2019	320,0	310,3	61,1	2,9	2947,9	
01-03-2019	352,8	322,6	67,7	2,9	2844,2	
01-04-2019	355,0	268,6	65,5	1,7	1343,9	
01-05-2019	343,2	244,1	67,7	1,5	1023,4	
01-06-2019	341,8	226,2	65,5	0,9	218,4	
01-07-2019	361,1	240,9	67,7	0,9	175,5	
01-08-2019	348,0	254,2	67,7	0,9	161,0	
01-09-2019	345,8	290,6	65,5	1,0	383,7	
01-10-2019	352,4	333,3	67,7	1,8	1537,2	
01-11-2019	341,8	358,9	65,5	3,0	3154,0	
01-12-2019	365,9	381,1	67,7	3,5	3645,2	
Total energy usage (kWh)						
2019 (COP = 3,5)	4180,3	3589,9	797,0	24,9	21672,1	-16112,2
Total energy usage yearly (kWh)						
Total usage	<b>30264,1</b>					
Total production	<b>-16112,2</b>					
Total demand	<b>14151,9</b>					

Table 23: Energy usage & remaining energy demand of the proposed design. Own work.

The total energy usage of the building is reduced to 30.3 MWh after implementation of the proposed design. This is a reduction of 58.1% compared to the current energy usage of the building (72.3 MWh). When the effect of the energy production on site is included (PV roof tiles) the energy demand is reduced to 14.2 MWh, which is a reduction of 80.4% in energy demand from the grid compared to the current situation. Most of the energy reduction is due to the lowered energy demand for heating. Furthermore, the use of energy efficient appliances (room electricity in table 23) and LED lighting reduces the user related energy from 13.9 MWh to 7.8 MWh: a reduction of 44.1%. The energy usage for system fans and pumps has increased due to the implementation of mechanical ventilation.

The heat balance (figure 48) shows that the heat losses through the exterior walls are reduced drastically compared to the existing situation. However, since the front house is not insulated some energy losses are still present through the walls. The energy losses through the walls in summer are higher because the wall heating system is turned off and no longer prevents heat from being transmitted to the exterior. In winter the wall heating system works as an insulation layer. Furthermore the energy losses through the windows and ground floor are reduced as well and the amount of infiltration is lowered quite significantly. Due to the lowered energy losses the amount of required heating is reduced as well. Furthermore, the energy for heating is reduced due to the use of LT heating and more efficient equipment. As expected heat gains due to solar radiation and occupancy have remained more or less equal.

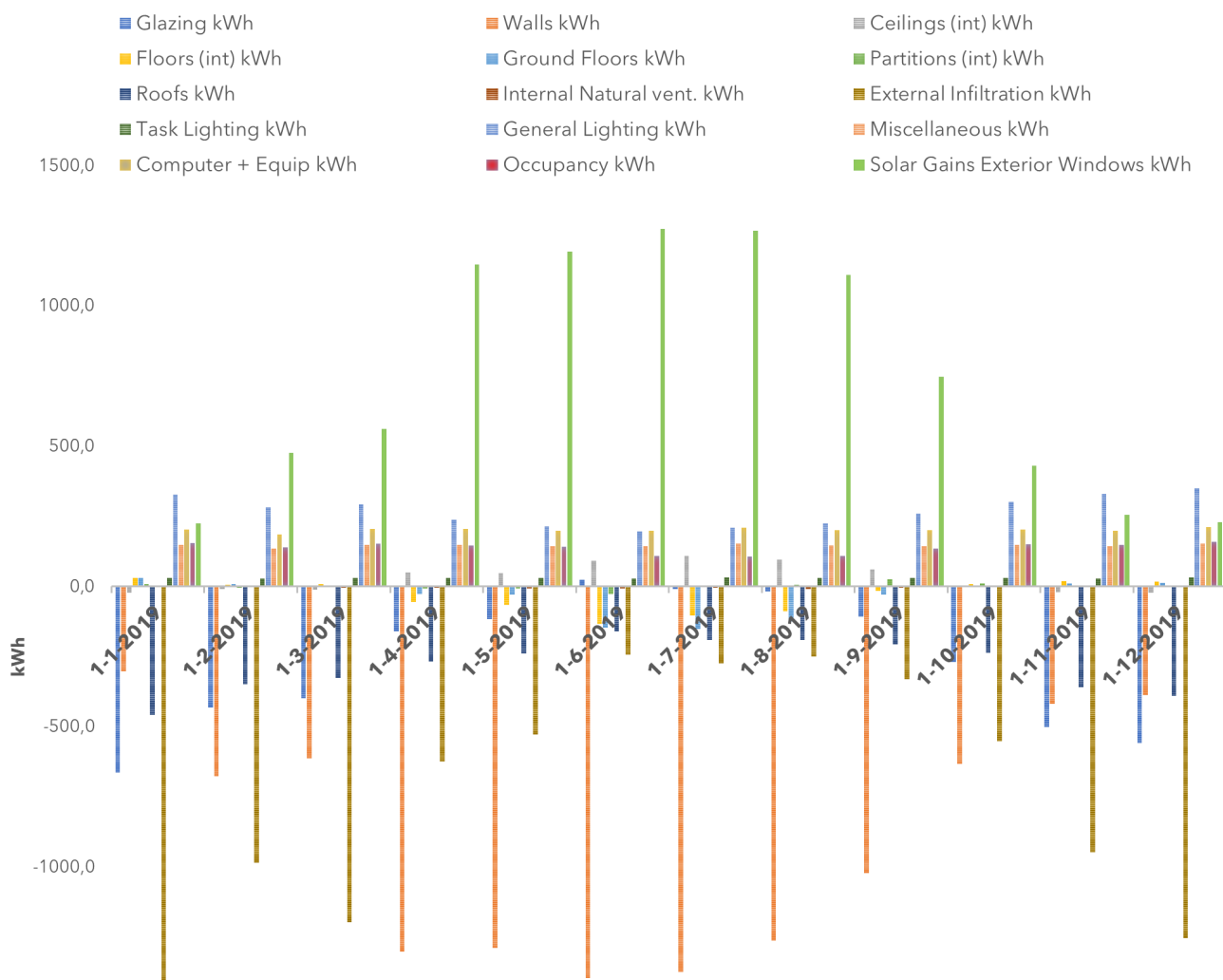


Figure 48: Heat balance according to simulation in Design Builder after renovation. Own work.

For an energy-neutral renovation, the embodied energy of the materials which are added in the renovation design need to be taken into account as well. The calculation can be found in appendix D. When taking into account the material related energy over a period of 50 years the energy usage of the building increases with 5.3 MWh on a yearly basis. This energy also needs to be compensated for an energy-neutral renovation. As can be seen in table 24, the energy demand has not been reduced to zero (but to 27.2 MWh) meaning that the building has not become energy neutral. Yet, the energy demand (including on-site energy production and embodied energy) is reduced by 73.1% compared to the current situation.

Yearly energy usage				
	Energy usage current	Energy usage renovation	Difference kWh	Decrease/increase
	kWh	kWh		%
User related energy	13896,2	7770,2	-6126	-44,1%
Systems	22,1	821,9	799,8	3792,8%
Heating	58373,2	21672,1	-36701,1	-62,9%
Production visible	0	-2257,2	-2257,2	N.A.
Production non visible	0	-13855	-13855	N.A.
Material related energy	0	5318,4	5318,4	N.A.
Building related energy	72291,6	30264,2	-42027,4	-58,1%
Energy demand	72291,6	14152	-58139,6	-80,4%
<b>Total (incl. PV &amp; MRE)</b>	<b>72291,6</b>	<b>19470,4</b>	<b>-52821,2</b>	<b>-73,1%</b>

Table 24: Comparison energy usage of the proposed & current situation. Own work.

The proposed design however, does make the Oudezijds Voorburgwal 30 adhere to the BENG criteria set by the government of the Netherlands (with  $A_{1s}/A_g = 969.1/364.0 = 2.66$ ). The energy demand is lower than the criterion set by BENG as well as the primary energy usage. The percentage of renewable energy is higher than the minimum required by BENG.

	Type	Criteria	Renovation
<b>BENG 1</b> - Energy demand	Dwelling soil (kWh/m <sup>2</sup> )	Max. 84,8	61,8
	<b>Dwelling non-soil (kWh/m<sup>2</sup>)</b>	<b>Max. 84,8</b>	<b>61,8</b>
	Store (kWh/m <sup>2</sup> )	Max. 95,8	61,8
<b>BENG 2</b> - Primary energy	Dwelling soil (kWh/m <sup>2</sup> )	Max. 30	38,6
	<b>Dwelling non-soil (kWh/m<sup>2</sup>)</b>	<b>Max. 50</b>	<b>38,6</b>
	Store (kWh/m <sup>2</sup> )	Max. 60	38,6
<b>BENG 3</b> - % renewables	Dwelling soil	Min. 50%	41,7%
	<b>Dwelling non-soil</b>	<b>Min. 40%</b>	<b>41,7%</b>
	Store	Min. 30%	41,7%

Table 25: Compliance of proposed design to BENG criteria. Own work.

### 9.3 Evaluation of the indoor comfort

The analysis of the current state of the building has shown that the indoor comfort is not up to standard. The indoor temperatures of the building are too low, leading to discomfort. The heat balance of the existing situation indicated that this mostly had to do with heat losses through the building envelope. In table 25 the criteria for the renovation design are presented as well as the achieved levels of comfort after renovation.

	Parameter	Criteria dwellings	Criteria retail store	Achieved level
<b>Insulation</b> (indirectly related to comfort)	Min. R-value façade (m <sup>2</sup> *K/W)	4.7 (1.4 for renovation)	4.7 (1.4 for renovation)	4.8
	Min. R-value floors (m <sup>2</sup> *K/W)	3.7 (2.6 for renovation)	3.7 (2.6 for renovation)	3.8
	Min. R-value roof (m <sup>2</sup> *K/W)	6.1 (2.1 for renovation)	6.1 (2.1 for renovation)	6.1
	Max. U-value window (W/m <sup>2</sup> *K)	2.2	2.2	2.06 (wood) & 1.99 (PVC)
<b>Thermal</b>	Min. T winter (°C)	20	16	± 20
	Max. T summer (°C)	26	25	± 30
<b>IAQ</b>	Min. ventilation rate (l/s per person)	7 (0.25 ac/h for OZVB)	4 (0.10 ac/h for OZVB)	Average: 0.52 ac/h
	Min. RH (%)	40	40	± 20
	Max. RH (%)	70	70	± 70

Table 26: Comfort criteria & achieved levels of comfort. Own work.

In the design proposal a large portion of the building is insulated from the exterior, leading to a R-value of 4.8 m<sup>2</sup>\*K/W for the facades (back house), 6.1 m<sup>2</sup>\*K/W for the roofs and 3.8 m<sup>2</sup>\*K/W for the ground floor. This means that the building envelope largely adheres to the criteria set for the renovation and even for new construction. However, the facades of the front house are not insulated but heated. These walls do thus technically not adhere to the R-value regulations set by Bouwbesluit 2012, but do improve the comfort of the occupants of the building. In the design all windows are replaced with double glazing. The U-value of the glazing in the design proposal is 2.06 W/m<sup>2</sup>\*K for the windows of the front house and 1.99 W/m<sup>2</sup>\*K for the back house. The windows thus adhere to the criteria set. In regard to the indoor temperature, the minimum temperature in winter meet the criteria set for both the retail store and the dwellings. The temperature during occupied hours in the dwellings lies around 20 degrees Celsius and in the store around 19 degrees Celsius (see figure 49). However, due to the LT heating the amount of radiators in the back house needs to be increased to meet the criteria. In the front house a combination of wall heating and radiators is used. The wall heating basically creates an insulation layer and minimizes cold radiation, which makes it more comfortable inside for the occupants. Due to the LT heating, the building requires more time to heat up. It is thus necessary to leave the setback temperature relatively high (18 degrees Celsius). In summer the temperatures sometimes exceeds the criterion of 25 or 26 degrees Celsius (see figure 50). However, this is for smaller periods of times and the building tends to cool down during the night. A functional disadvantage of wall heating, which could bother the occupants, is that drilling holes to hang frames onto the wall is not advisable. It can be opted to install rails from the ceiling so users can hang frames on the wall without having to drill.

In regard to the indoor air quality, the ventilation rate is larger than 0.25 air changes per hour (on average 0.52). The minimum ventilation criteria in the model were set to 7 l/s per person for the dwellings and 4 l/s per person for the store. The criteria for the ventilation rate are thus met. The RH needs to lie between 40 and 70%. The design largely meets the RH criteria. However, in winter the relative humidity sometimes drops to 20% (see figure 49), which could lead to discomfort. The low RH is most likely an effect of to the high heating demand in those periods. It was opted to install a humidifier in the air handling unit. This however increased the energy usage of the building drastically (5500 kWh/year) and would require a larger ventilation unit to be installed. If necessary the users can add a radiator humidifier for example. However, Design Builder does not take into account any humidity produced by the users by for example showering, cooking etc. This will also increase the RH within the building.

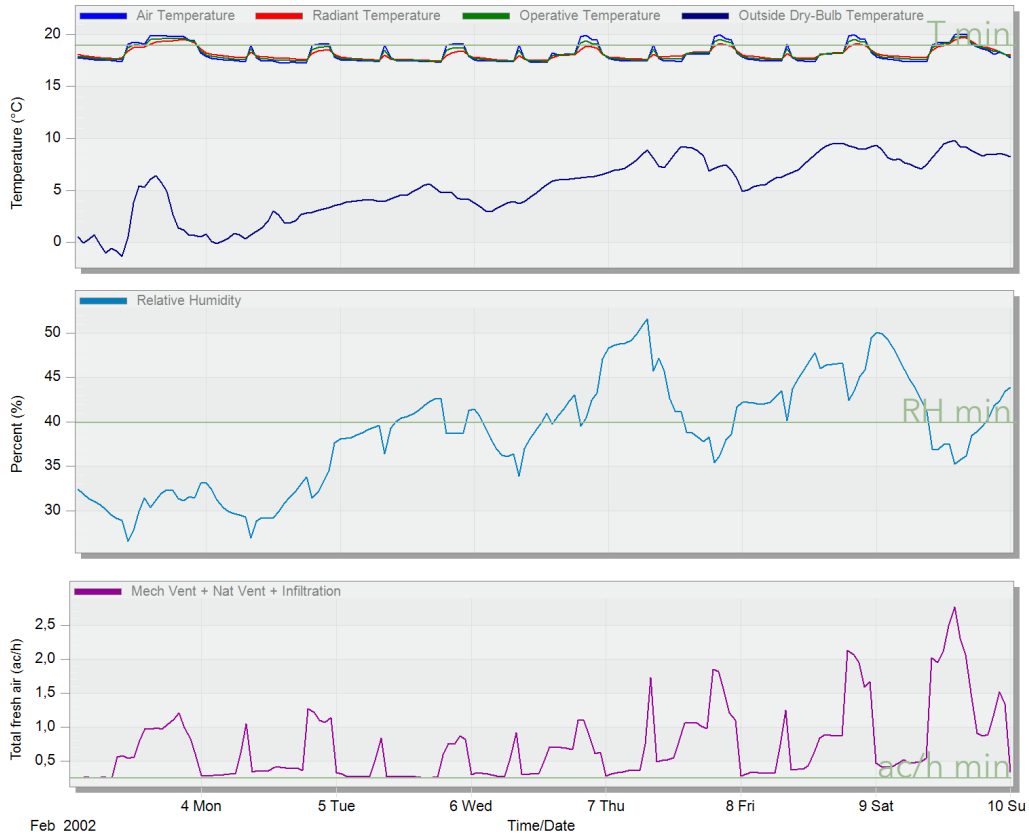


Figure 49: Simulated comfort in winter 2019, after renovation. Image from Design Builder.

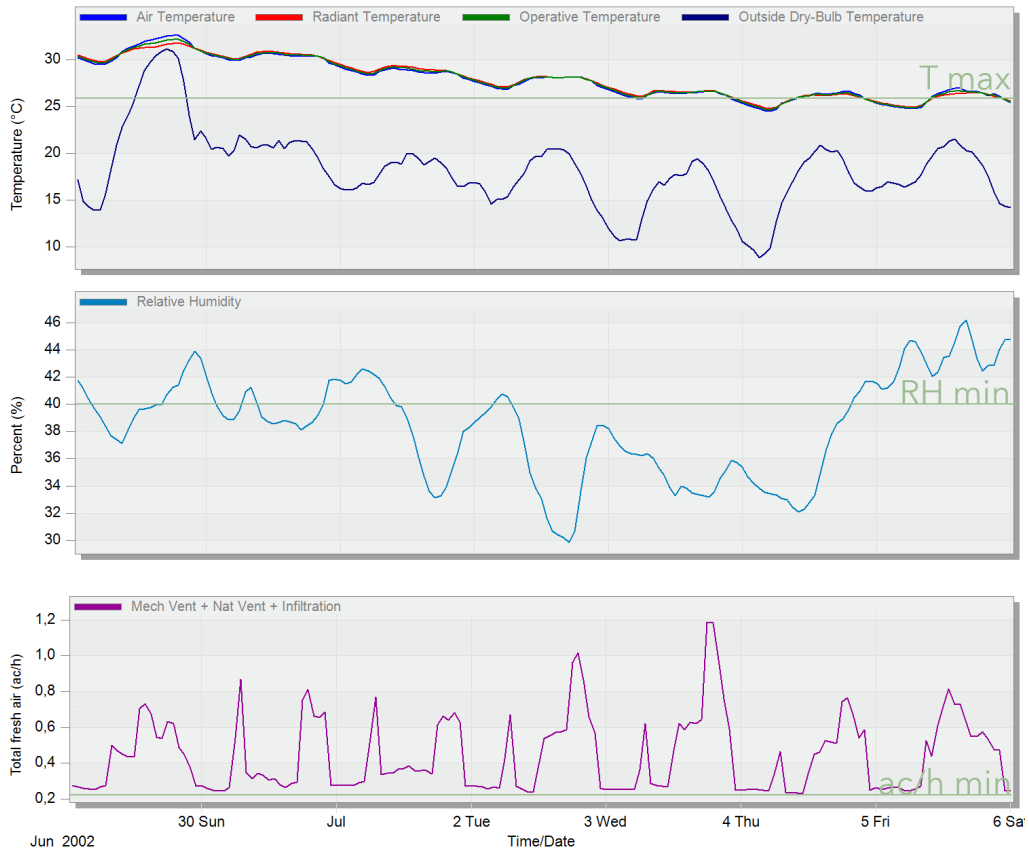


Figure 50: Simulated comfort in summer 2019, after renovation. Image from Design Builder.

## 9.4 Conclusion

The proposed design does not fully adhere to the regulations of the protected city view, due to the visible PV roof tiles from the street. Yet, it might be possible that in the near future this will no longer be seen as an issue. All other design measures do not alter or damage any of the identified monumental elements of the building and adhere to the regulations for national monuments and the protected city view and thus the design can be implemented from a heritage viewpoint.

Regarding energy performance, it is simulated that the total energy usage after implementation of the proposed design is reduced by 73% in comparison to the current situation. As there is still an energy demand from the grid the building is not energy neutral. Yet, the proposed design does make the Oudezijds Voorburgwal 30 BENG compliant and takes the building off natural gas.

The proposed design has increased the insulation value of the building envelope, and the energy and heat losses through the envelope have been reduced. Consequently, the indoor temperature is higher and more stable than in the existing situation. In winter the indoor temperature criteria are met. However, as the renovation design does not include cooling the temperatures in summer may reach 30 degrees Celsius which is above the criteria set for the indoor temperature in summer. Regarding the IAQ in the building the ventilation rate has been drastically reduced in comparison to the current situation due to the improved building envelope. Mechanical ventilation ensures that the minimum ventilation rate per person is still reached and meets the set criteria for ventilation. The RH criteria are largely met throughout the year. However, the minimum RH is sometimes lower than the set criterion. Yet, this is only for a small period of time.

In conclusion, the proposed design does not alter the monumental status of the building. Due to the visible PV roof tiles the regulations of the protected city view are not adhered to, the regulations could however change in the future. Moreover, the renovation design has reduced the energy demand of the building by 73%. In regard to the indoor comfort most design criteria are met. The comfort in winter increases compared to the current situation, due to higher indoor temperatures and lower infiltration rates.

## 10. Generic Approach

Each monument is unique and has its own history but on the other hand, the Burgwallen-Oude Zijde is home to many monumental buildings which are relatively similar. A conclusive method for the sustainable renovation of monumental buildings has not yet been presented. Consequently renovation of monumental buildings often needs to be customized which in its turn makes it expensive and unattractive. By proposing a generic solution the goals of the municipality of Amsterdam to become climate neutral by 2050 can be achieved more easily. In this chapter the following subquestion will thus be answered: *“What is a generic approach to energy-neutral, comfortable monuments?”*

### 10.1 Design strategy for the energy renovation of monumental buildings

To more efficiently renovate monumental buildings, the design process for the energy renovation of monumental buildings can follow the subsequent steps.

#### 10.1.1 Identifying the heritage values

Before starting any renovation it is indispensable to understand which elements of the building have historical or heritage value. These elements should not be altered as it would harm the monumental status of the building and history would be lost. It is thus first necessary to critically assess the history of the building and identify these valuable elements. Firstly, it is advised to collect all the available information on the building by contacting the archive of the municipality and using the internet. In Amsterdam each assigned national monument has a reasoned statement (*‘redengevende verklaring’*) which explains why the building was assigned as a monument. This can be requested at the municipality. Another important step in analyzing the historical elements of the building is to assess the building in its current state. A site visit (or even multiple) is thus recommended. When all information is collected the images, text and other materials of different time periods can be compared. This allows the designer to create a timeline of the most important alterations of the building. By identifying the most important alterations throughout the history of the building it will become clear which elements are of heritage value and which are not. Age is not the only indicator for this but can be quite important. It is important to not only identify tangible elements but also the intangible elements. For example, At the Oudezijds Voorburgwal 30 the building has always had a mixed-use function and is thus very valuable to maintain. Moreover, it is necessary to not solely look at the building itself but also its relationship with the surrounding buildings, its embedding in the building block and its relationship with the fabric of the city. The end product of the historical analysis should be the mapping of the identified heritage values in the drawings by using a color coding system ranging from very valuable, valuable, neutral and negative. The drawings will provide a quick overview to refer back to during the design stage. The identified values and elements significantly influence the possibilities for energy renovation and the success of the renovation and are thus important to assess before commencing the renovation design.

#### 10.1.2 Assessing the current performance of the building

The second step in the energy renovation of a monumental building is to assess its current performance. This includes both the energy performance as well as the indoor comfort, as they significantly influence each other. The energy performance of the building can be assessed by requesting the energy bills of the occupants and comparing these with the average energy usages of the same building typology in the neighborhood or city. Another option to assess the energy performance is to make use of energy simulation software. When using energy simulation software the effects of future proposed design measures can be evaluated as well. There are many methods of assessing the indoor comfort. The most simple one is to question the occupants of the building. To get a more objective view on the indoor comfort it is possible to perform on-site measurements or use the energy simulation software. By analyzing the current energy performance and indoor comfort the most important issues of the building will be revealed, which need to be addressed in the renovation design.

### 10.1.3 Designing the energy renovation

After the identification of the monumental elements and the current performance of the building is analyzed, the designer can start with the renovation design. It is first necessary to assess the different design measures which can be implemented and the different installations which can be placed. The installations depend on the design measures which can be implemented and vice versa. For example, in the proposed design of the Oudezijds Voorburgwal the back house is insulated from the exterior. Due to high level of insulation it was possible to use LT heating. In the design phase it is also important to assess the potentials of the surroundings of the building and make use of this in the design. It is advisable to create different concept ideas and evaluate the different options on suitability for the building. Aspects to take into account during the decision making are the effect on the energy performance indoor comfort and monumentality of the building but also aspect such as technical and functional feasibility. Furthermore, aesthetics are also important and the financial effect should not be ignored. For the Oudezijds Voorburgwal the specified concept was chosen because it makes use of the surrounding potential of the neighborhood. Simultaneously it lowers the energy demand drastically, increases the indoor comfort and does not harm the monumental status of the building.

### 10.1.4. Finalizing the design

After the evaluation of the different design options, a well-informed decision can be made on which concept(s) to continue with. The design then needs to be detailed and finalized. More detailed decisions need to be taken such as the thickness of insulation and placement of ventilation ducts. Occasionally to preserve monumental elements the design needs to be adjusted in such a manner that it is not ideal for the performance of the building. It is important to realize that this is always the case with monumental buildings, and a middle ground between preservation and performance has to be found.

### 10.1.5 Evaluation of the proposed design

Following the finalization of the design, it is essential to assess the effect of the design. Firstly, it is necessary to evaluate whether any of the identified monumental values have been altered by laying the design next to the identified value maps. If this is the case the design has to be adjusted. Furthermore, the indoor comfort and energy performance of the renovation design will have to be evaluated using simulations or calculations. Depending on the outcomes of the evaluation the design can be optimized. Figure 51 shows a summary of the different steps of an energy renovation for a monumental building.

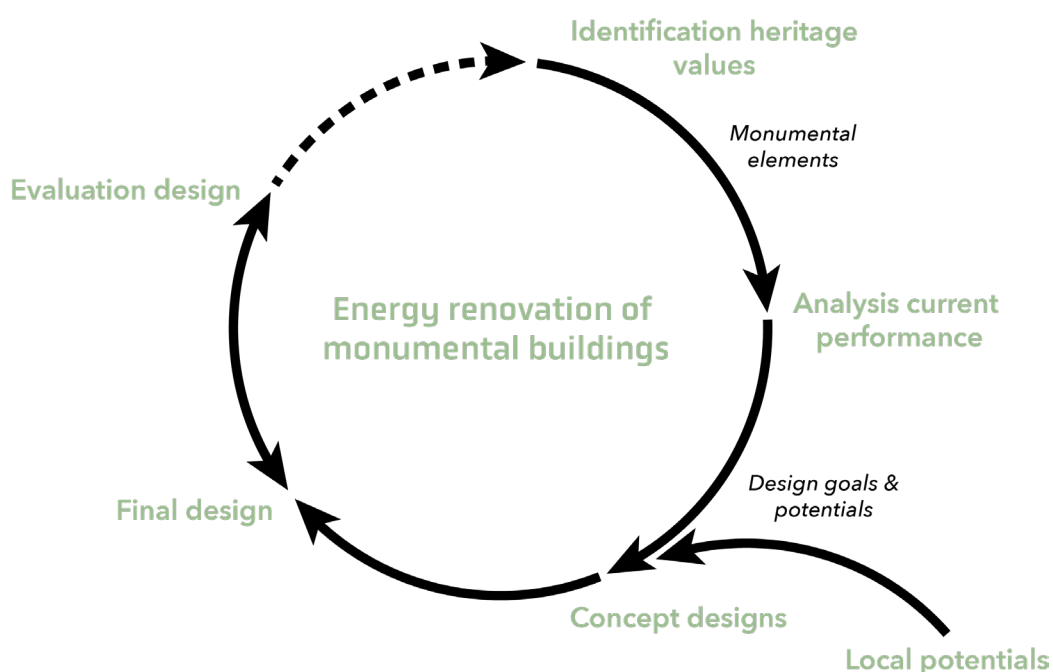


Figure 51: Design process for the energy renovation of a monumental building. Own work.

## 10.2 Limitations of the proposed design for generic application

The proposed renovation design for the Oudezijds Voorburgwal 30 has its limitations before it can be implemented in other buildings. Depending on the specific building some design measures which are proposed are more suitable than others.

The Oudezijds Voorburgwal 30 is located near a canal. In the renovation design the canal water is used for the heating of the building. Even though Amsterdam has many canals, not all monumental buildings are located within proximity of an open water body to extract heat. If the monumental building is not located near water ( $\pm 20$  meters) the aquathermal energy concept cannot be used. In that case a different heating concept has to be chosen. Sub chapter 8.1 has shown that an air-water heat pump might have potential in this case for the heating and DHW of the building.

To lower the energy usage and to increase the indoor comfort of monumental buildings, improvement of the building envelope is important. In the case of the Oudezijds Voorburgwal 30, the back house of the building is not monumental and the facades can be easily accessed through the alley and courtyard. The back house can thus be insulated from the exterior. However, often the entire building is monumental, which makes it against the regulations to insulate from the exterior. Moreover, in many cases in Amsterdam the facades are not accessible from the exterior, further limiting the possibilities to insulate from the exterior. An alternative could be the wall heating system as proposed for the Oudezijds Voorburgwal 30. For the application of wall heating the interior walls cannot have any monumental elements such as historical paint or paneling. In case of historical paint or paneling interior insulation cannot be placed either.

To further lower the energy losses the roofs and floors will be insulated at the Oudezijds Voorburgwal 30. The ground floor is insulated from underneath. A limitation is that the floor needs to be accessible from underneath, a crawl space needs to be present. Even if the floor is monumental, insulation from underneath should not cause any problems. Yet, the insulation material cannot damage the floor structure and should be removable. Roofs of monumental buildings can only be insulated from the exterior if the roof structure and tiles are not monumental and the inclination and gutter connection is not altered. Consequently, in most cases it is easier to insulate the roof from the interior. This is also proposed for the roof of the front house of the Oudezijds Voorburgwal 30. If the roof structure is monumental it is important to not damage the structure permanently when insulating.

Another weak point in the building envelope of monumental buildings are often the windows. The design for the Oudezijds Voorburgwal 30 proposes to replace most windows and window frames with wooden frames and double glazing and in the case of the back house with uPVC window frames. To replace the windows the framing and glazing cannot be of monumental value. If they are not of monumental value it is necessary to assess whether the window opening can hold the increased weight of double glazed windows. If the building is monumental, the detailing, shape, material, color and profiling of the frame cannot be altered. If the framing is of monumental value it can be opted to install thin double glazing in the existing window frames. If this is not possible the option of an 'achterzetraam' can be used. It is however then necessary to have sufficient space on the interior to place the window. If this is also not the case some insulating window foil can be placed. Besides the frame being monumental the glass itself can also be of monumental value. In that case the glazing cannot be altered and foils cannot be applied. The only option for monumental glazing is to add an 'achterzetraam'.

In further regard to the building envelope, unwanted infiltration is often a problem in monumental buildings (Kramer, et al., 2015). In the renovation design of the Oudezijds Voorburgwal 30 cracks and seams are filled. In the back house the material does not matter as it is not monumental. For the front house materials which can later be removed such as foam rubber and sealing tape are used and need to be placed from the interior. This can also be used for any other building with a monumental status.

Concerning the HVAC system at the Oudezijds Voorburgwal 30, a heating system with collective heat pumps is proposed. A limitation is that there should be sufficient space for larger collective heat pump within the building. If not, individual heat pumps can be used. The system at the Oudezijds Voorburgwal 30 relies on LT heating and wall heating. Due to the LT heating system a large surface area is required for the heat distribution and the building needs to be insulated to a certain level. The building thus needs to have a certain insulating potential and larger radiators need to be installed. For ventilation the Oudezijds Voorburgwal 30 will make use of fully mechanical ventilation. Limitations of the systems are that there should be sufficient space to place the air handling unit. Furthermore, there should be sufficient space for the ducts. In case of monumental floors and ceilings these cannot be altered. In the case of the Oudezijds Voorburgwal 30 the old chimney shafts will be used for the placement of ducts.

Other design measures which are implemented at the Oudezijds Voorburgwal 30 are the use of energy efficient appliances, LED lighting, radiator fans and water reducing shower heads. These can be implemented without any limitations and will most likely not alter monumental elements. Furthermore, shower heat recovery is proposed. At the Oudezijds Voorburgwal 30 this will be done using a horizontal heat exchanger so that the floors and walls do not require major intervention. Horizontal shower heat exchangers can also be applied in other monumental buildings if the floor height is sufficient.

Lastly, to lower the energy demand from the grid PV panels can be installed. To install PV panels the roof needs to be oriented towards the East, West or South. Furthermore, the roof structure needs to be able to hold the PV panels and the panels cannot be visible from the street. In the case of the Oudezijds Voorburgwal 30, PV roof tiles are used. This can only be installed if the roof tiles are not authentic and is from a sustainable viewpoint only advisable if the roof needs re-tiling.

In summary, the major limitation for the generic application of the proposed design for the Oudezijds Voorburgwal 30 is the use of LT heating. To create a comfortable indoor environment with LT heating the building envelope needs to be insulated quite extensively. In the case of the Oudezijds Voorburgwal 30 this is achievable since the back house is not of monumental value. Insulation of the monumental front house is proven to be slightly more complicated. However, wall heating could be an alternative. In table 27 an overview of the limitations of the proposed design for the Oudezijds Voorburgwal 30 can be found.

<b>Design measure</b>	<b>Limitations</b>
<b>Roof insulation</b>	<ul style="list-style-type: none"> <li>• Inclination of monumental roof cannot be altered</li> <li>• Gutter &amp; roof connection cannot be altered in case of monumental roof</li> <li>• From exterior not allowed if roof structure is monumental</li> <li>• Cannot damage any monumental roof tiling</li> </ul>
<b>Facade insulation</b>	<ul style="list-style-type: none"> <li>• From exterior: only if not monumental and visible from street</li> <li>• From exterior: requires outdoor space around building for placement</li> <li>• From interior: be aware of internal condensation</li> <li>• From interior: floor surface area decreases</li> </ul>
<b>Ground floor insulation</b>	<ul style="list-style-type: none"> <li>• Insulation cannot damage floor and needs to be removeable if floor is monumental</li> <li>• For insulation from underneath a crawl space is required</li> </ul>
<b>Double glazing</b>	<ul style="list-style-type: none"> <li>• Existing glazing cannot be monumental</li> <li>• Wall openings need to be able to carry the increased weight</li> </ul>
<b>Replacing window frames</b>	<ul style="list-style-type: none"> <li>• Window frames cannot be monumental</li> <li>• Wall openings need to be able to carry the weight of new windows</li> <li>• Color, detailing, shape &amp; material needs to be same as existing</li> <li>• Depth in façade should remain the same as in existing situation</li> </ul>
<b>Filling cracks and seams</b>	<ul style="list-style-type: none"> <li>• For monumental buildings filling needs to be removeable</li> <li>• Needs to be placed from the interior</li> </ul>
<b>Aquathermal concept</b>	<ul style="list-style-type: none"> <li>• Building requires to be located close to water body</li> <li>• Only provides LT heating so building needs to be suitable</li> </ul>
<b>Collective heat pumps</b>	<ul style="list-style-type: none"> <li>• Sufficient communal space is required</li> <li>• Building needs to be able to heat with MT or LT heating</li> </ul>
<b>LT heating</b>	<ul style="list-style-type: none"> <li>• Thorough insulation of building envelope is necessary</li> <li>• Works most efficiently with controlled, mechanical ventilation</li> <li>• Large surface area for heating distribution required</li> </ul>
<b>Wall heating</b>	<ul style="list-style-type: none"> <li>• Wall finishing cannot be monumental</li> <li>• Building needs to be suitable for LT heating</li> </ul>
<b>Mechanical ventilation</b>	<ul style="list-style-type: none"> <li>• Ducts cannot be placed in monumental walls or create holes in monumental floors &amp; ceilings</li> <li>• There needs to be sufficient space for the AHU (also when placing)</li> </ul>
<b>PV panels</b>	<ul style="list-style-type: none"> <li>• Roof tiling cannot be monumental</li> <li>• Monumental roof structure cannot be altered</li> <li>• Cannot be visible from street in protected city view</li> </ul>
<b>Shower heat recovery</b>	<ul style="list-style-type: none"> <li>• Vertical heat recovery: cannot damage monumental walls &amp; floor</li> <li>• Horizontal heat recovery: minimum free height of floors should be 2.1m</li> </ul>
<b>LED lighting</b>	<ul style="list-style-type: none"> <li>• No limitations</li> </ul>
<b>Energy efficient appliances</b>	<ul style="list-style-type: none"> <li>• No limitations</li> </ul>

Table 27: Limitations of integrated measures of proposed design for the Oudezijds Voorburgwal 30. Own work.

## 11. Conclusion

The objective of this thesis was to create a design for the energy-neutral renovation of a monumental building in the historic inner city of Amsterdam. The accompanying main research question was: *“How can monumental buildings be renovated to become energy neutral and comfortable for the users, whilst preserving the monumental status?”* The objective was elaborated in a generic approach and tested on mixed-use building in Amsterdam. To answer the main research question several sub questions and background questions were formulated.

The city of Amsterdam has many historical buildings, most of which are located in the historic city center and have become part of the identity of Amsterdam and the Netherlands. As a result the municipality of Amsterdam has given many of these buildings a monumental status. Buildings with a monumental status are protected and alterations or renovations cannot be done without adhering to the regulations and applying for the correct permits. Besides the individual buildings being of importance, the fabric of the city and the relationships between the buildings are also of importance to conserve the history of the city. The city center of Amsterdam has thus been assigned a protected city view. The municipality of Amsterdam has introduced a class system to provide a basis for the regulations. The owners of order 1 buildings (national and municipal monuments) are required to perform all maintenance necessary to conserve the building. If the exterior requires any other, more drastic, alteration a permit is required and will not be issued if the detailing, shape, material, color or profiling of the building element is altered or if the element is of high monumental value. Furthermore, alterations on the exterior cannot disturb the protected city view. On the interior none of the monumental elements can be altered either.

Due to the strict regulations of monumental buildings, renovation of these buildings is slightly more complicated. Yet, to achieve the goals set by international, national and municipal agreements it is of essence that the historic city center of Amsterdam reduces its energy usage drastically, as its current demand is relatively high compared to the rest of the Netherlands. Furthermore the indoor comfort of these buildings is proven to be below standard. To lower the energy usage and improve the indoor comfort different design measures can be implemented. However, it is necessary to assess the suitability of these design measures for monumental buildings. One of the most important design measures to lower energy usage and improve the indoor comfort in monumental buildings is to improve the building envelope. Furthermore, it is also necessary to look at sustainable HVAC systems. In this thesis the main focus in regard to indoor comfort were on thermal comfort and indoor air quality as the literature research has shown that these often cause the most discomfort in monumental buildings. Several design criteria for indoor comfort were identified for the renovation design.

For the energy renovation design, a case study building was chosen: the Oudezijds Voorburgwal 30. The chosen case study building was constructed partially in the 16th century and partially in the 17th century. It was revealed that the back house and intermediate member were reconstructed in 2005 and do not have any monumental value. The front house however, still has monumental elements on both the exterior and interior. The exterior walls are of high value but the windows and window frames are not. On the interior not many monumental elements can be found besides the fire shafts and several floor and roof structures.

The current energy usage of the building according to the bills is 68,9 MWh and according to the energy simulation 72,3 MWh. The overall energy usage of the store and apartments is quite similar to the rest of the buildings at the Burgwallen-Oude Zijde. However, literature research has shown that the energy usage at the Burgwallen-Oude Zijde is relatively high compared to the rest of Amsterdam and the Netherlands. This confirms the need to reduce the energy usage of the building. In regard to indoor comfort several analysis methods have shown that the indoor temperature is much too low, causing discomfort. The simulation has shown that the building

envelope contributes largely to these heat and thus energy losses. Furthermore, simulation has also shown that the ventilation rate in the building is too high due to unwanted infiltration through the building envelope and thus results in discomfort.

Since the analysis of the building clearly showed the need for improvement for both the energy usage as well as the indoor comfort, several design concepts were made for the building. The concepts which made use of aquathermal energy and wall heating were chosen as they consider the potential of the surroundings and the wall heating system seems promising. In the design heat pumps are used to boost the temperature of the canal water before it is used in the wall heating system, radiators and for DHW. The renovation design further includes the improvement of the building envelope comprising the facades, roofs, floors, windows and infiltration rate. Several other smaller design measures were implemented to lower the energy usage further. To produce energy PV roof tiles are placed on the South facing roofs.

The proposed design does not harm any of the monumental elements of the building, but does not fully adhere to the protected city view regulations as the PV roof tiles, which are used for energy production on site, can be seen from the street. The simulation shows that the indoor temperatures have increased and adhere to the set criteria and standards. Furthermore, the ventilation rate has decreased due to lowered infiltration but still adheres to the set criteria. The energy demand of the building has been decreased with 73% in comparison to the original situation and now adheres to the BENG regulations.

Lastly, the design was translated in a generic approach. Starting with the identification of the monumental elements, continuing with the analysis of the current performance, the creation of design concepts, the finalization of the design and finishing with the evaluation of the design. The design proposed for the Oudezijds Voorburgwal 30 could be implemented in another monumental building located close to the water. The most important limitation of the design is that it depends on LT heating.

The main research question of this thesis was:

*"How can monumental buildings be renovated to become energy neutral and comfortable for the users, whilst preserving the monumental status?"*

A generic design for the energy renovation of monumental buildings is challenging as each building has its own history and different monumental elements to pay attention to during the design. A combination of different measures has to be found for each building. However, a generic approach for the energy renovation of monumental buildings was proposed in this thesis, as mentioned previously.

By following the generic approach, the proposed design for the Oudezijds Voorburgwal 30 does not make the building energy neutral. This largely has to do with the regulations of monumental buildings and the protected city view. The possibilities to improve the building envelope are limited as the alterations need to adhere to the monumental regulations. Furthermore, due to the protected city view the options for energy production on site are limited. Moreover, the roof surface is relatively small compared to the building size and occupation. The definition of energy-neutral buildings specifies that the energy production should be within the project border. If import of green energy was allowed the building could have become energy neutral. The proposed design does make the building BENG compliant. This is a right step in the direction but might be insufficient to reach the climate goals and agreements. For monumental buildings to become energy neutral a more fair middle ground between conservation and sustainability should be found. We should ask ourselves: how far should we go to preserve the past if it limits or even damages our future?

## 12. Discussion

In this thesis it was attempted to thoroughly answer the posed research questions and provide conclusions as complete as possible. Yet the research has its limitations and uncertainties, and future research could potentially improve the drawn conclusions.

### 12.1 Limitations of the research

Two significant uncertainties in this thesis are the use of the aquathermal energy concept and the wall heating concept of 'WarmBouwen'. Both concepts have not yet been applied on a larger scale, so the actual efficiency and performance of both systems is still slightly uncertain. In this thesis it was also assumed that a permit would be issued for the installation of the aquathermal infrastructure from and to the building. Furthermore, in this thesis the design considerations were not necessarily financially driven, which is however an important aspect for the feasibility and applicability of the design. Another limitation of the research is the focus on thermal comfort and indoor air quality regarding indoor comfort. Acoustical and visual comfort are also important parameters for the indoor comfort and research has shown that often they are far from ideal in monumental buildings as well. Moreover, the simulation of indoor comfort in Design Builder is slightly limited, especially in combination with low temperature heating concept. Furthermore, the modeling of the building in Design Builder was simplified. For example, most of the walls are deformed, yet this was not simulated in Design Builder and the functions in the model were only differentiated in residential and retail. Cold bridges were not considered in the simulation, yet these could have a large influence on the energy performance and indoor comfort in monumental buildings. Furthermore, the aquathermal system could not be simulated in Design Builder and thus a simplified system was used and corrected with the use of the COP. Lastly, some dimensions (e.g., the windows) were measured from scanned drawings and small errors might have occurred. Lastly, an important limitation of the Design Builder model is that the total energy usage could only be calculated on building level and not per building block (i.e., the individual apartments and store).

During the design process and simulation several assumptions had to be made as not all information was available. The residents of 30C and 30D could not be contacted and thus assumptions had to be made about their energy usage and behavior. Furthermore, as the documentation of the building was limited assumptions about the construction of the different partitions had to be made as well as about the monumental elements.

### 12.2 Recommendations for future research

As there are many possible design solutions future research could include the more thorough analysis of different design concepts through the simulation and comparison of the results of each concept. Furthermore, the proposed design of this thesis focuses on buildings located near water. Future research could be done on a design solution for monumental buildings which are not located near water. The proposed design does not consider the storage of energy because of the lack of space. However, the proposed aquathermal system works more efficiently when combined with heat and cold storage. Future research could thus entail the incorporation of an ATEC system but also cooling. The cooling demand is increasing due to climate change but was not considered in the proposed design of this thesis.

Lastly, as it was attempted to come up with a generic approach, research on the incorporation of the proposed design in another building in Amsterdam could be interesting to assess the suitability of the proposed design for other buildings.



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## APPENDICES

## Appendix A: Oudezijds Voorburgwal 30



Oudezijds Voorburgwal. Own picture.



North facade of the back house. Own picture.



East facade of the front house. Own picture.



West facade of the front house. Own picture.



North facade of intermediate member & East facade of the back house. Own picture.



Alley on the North side of building (Suikerbakkersteeg). Own picture.



Bedroom of apartment 30B. Own picture



Kitchen of apartment 30B. Own picture.



Bathroom of apartment 30B. Own picture.



Intermediate member 30B. Own picture.



Living room of apartment 30B. Own picture.



Living room of apartment 30B. Own picture.

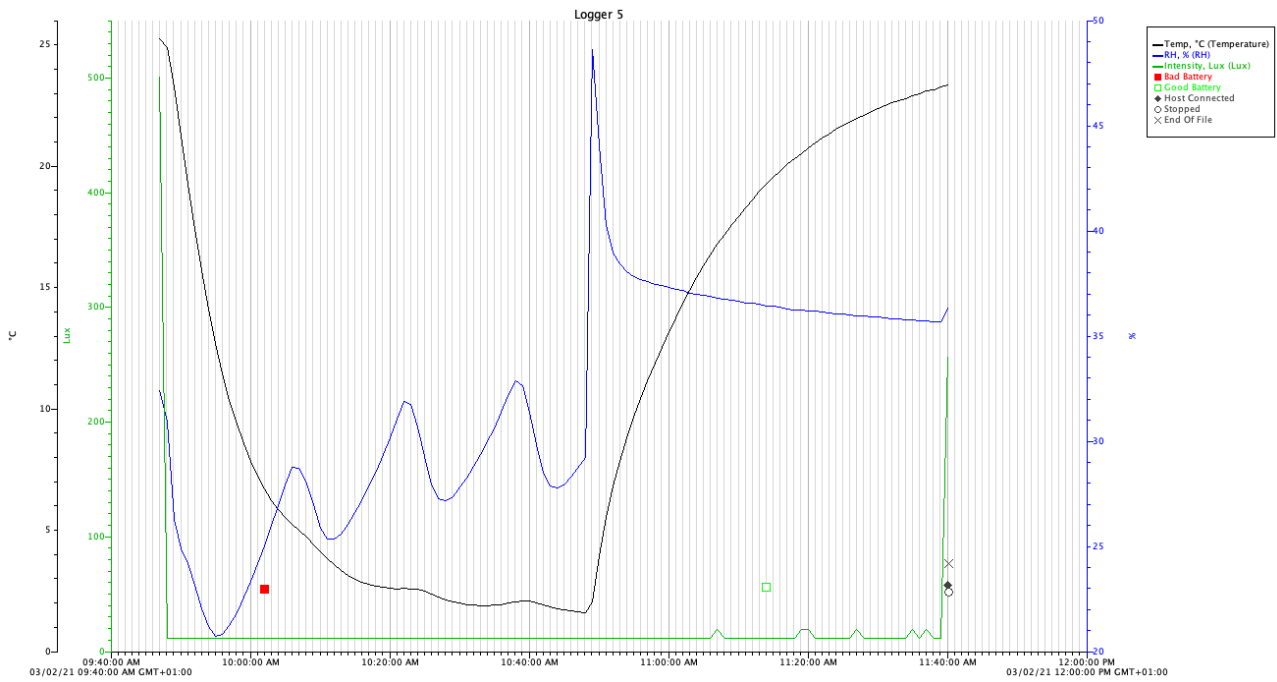
# Appendix B: Site Measurements

## B.1 Testing of the HOBO data loggers



Plot Title: Logger 4							
#	Date Time, GMT+01:00	Temp, °C	RH, %	Intensity, Lux	Host Connected	Stopped	End Of File
1	03/02/21 09:48:17 AM	24.557	1.000	547.9			
2	03/02/21 09:58:17 AM	23.208	1.000	1896.0			
3	03/02/21 10:08:17 AM	22.944	1.000	2077.4			
4	03/02/21 10:18:17 AM	22.992	1.000	2258.7			
5	03/02/21 10:28:17 AM	23.112	1.000	2384.8			
6	03/02/21 10:38:17 AM	23.256	1.000	2377.0			
7	03/02/21 10:48:17 AM	23.400	1.000	2991.9			
8	03/02/21 10:58:17 AM	23.954	1.000	563.7			
9	03/02/21 11:08:17 AM	24.171	1.000	579.5			
10	03/02/21 11:18:17 AM	24.291	1.000	571.6			
11	03/02/21 11:28:17 AM	24.339	1.000	579.5			
12	03/02/21 11:37:39 AM				Logged		
13	03/02/21 11:37:50 AM					Logged	Logged

Results of testing the HOBO data Logger above a radiator. Own work.



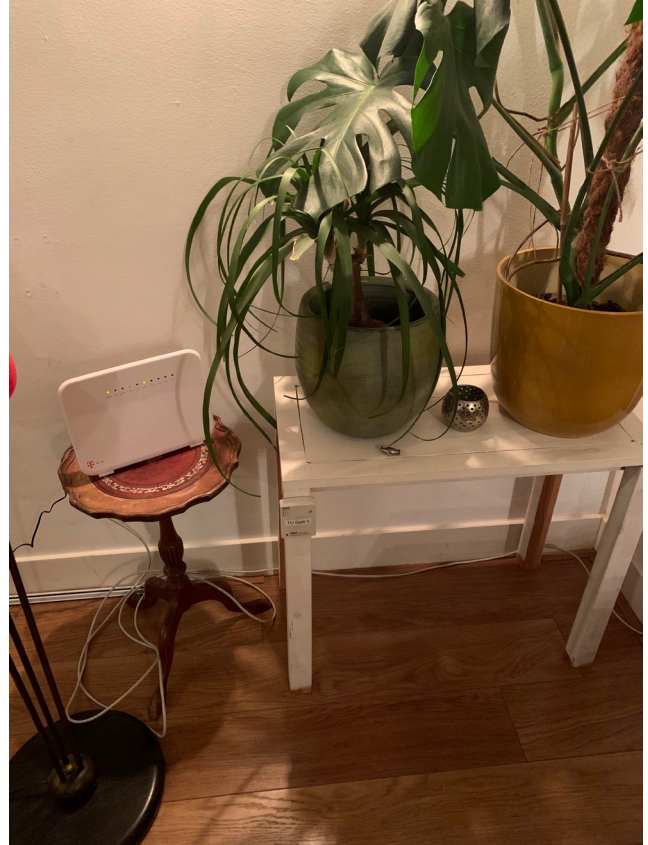
Plot Title: Logger 5							
#	Date Time, GMT+01:00	Temp, °C	RH, %	Intensity, Lux	Host Connected	Stopped	End Of File
1	03/02/21 09:47:02 AM	25.234	32.408	500.6			
2	03/02/21 09:57:02 AM	10.345	21.228	11.8			
3	03/02/21 10:07:02 AM	4.999	28.695	11.8			
4	03/02/21 10:17:02 AM	2.770	27.868	11.8			
5	03/02/21 10:27:02 AM	2.236	27.248	11.8			
6	03/02/21 10:37:02 AM	1.994	32.188	11.8			
7	03/02/21 10:47:02 AM	1.643	28.733	11.8			
8	03/02/21 10:57:02 AM	11.175	37.594	11.8			
9	03/02/21 11:07:02 AM	16.773	36.820	19.7			
10	03/02/21 11:17:02 AM	20.055	36.301	11.8			
11	03/02/21 11:27:02 AM	21.963	35.963	19.7			
12	03/02/21 11:37:02 AM	23.088	35.709	19.7			
13	03/02/21 11:40:02 AM	23.352	36.330	256.2	Logged		
14	03/02/21 11:40:09 AM					Logged	Logged

Results of testing the HOBO data Logger in a refrigerator. Own work.

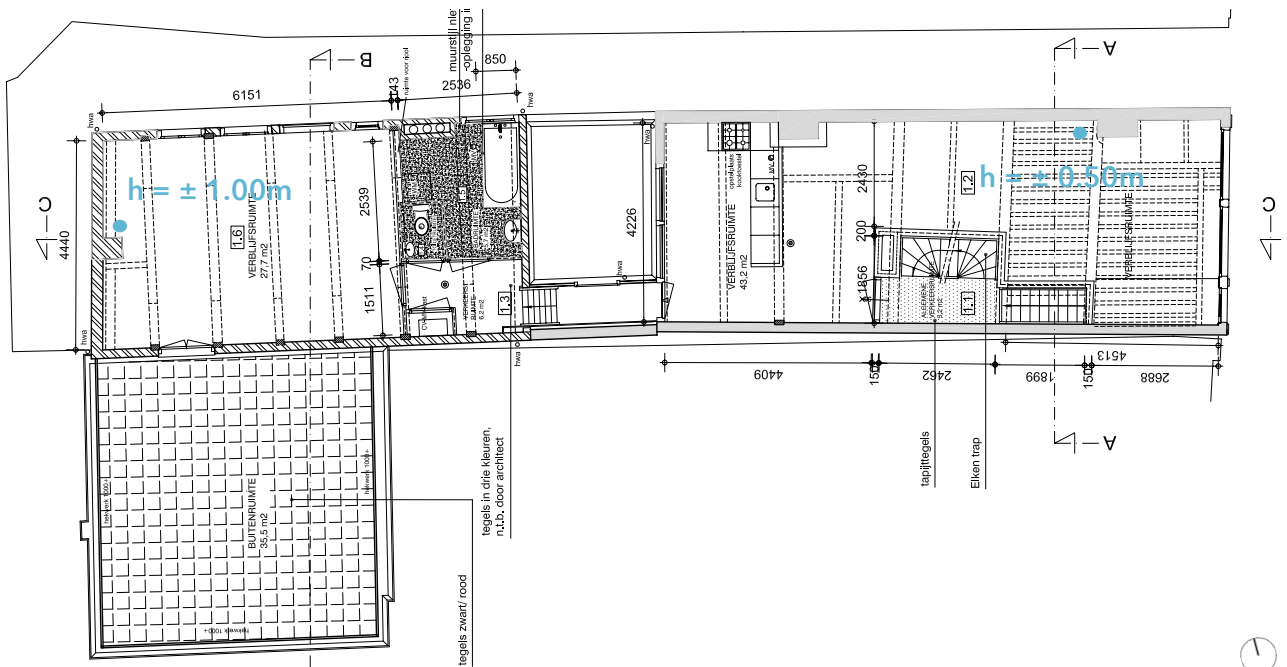
## B.2 Location of the HOBO data loggers



Location of the HOBO data logger in the back house of apartment 30B. Own picture.

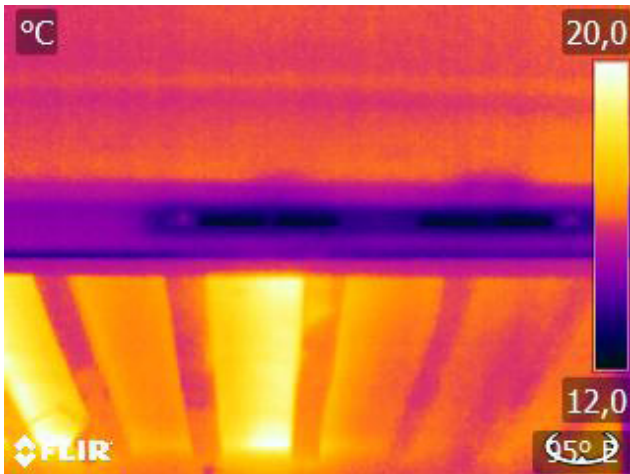


Location of the HOBO data logger in the front house of apartment 30B. Own picture.



Location of the HOBO data loggers in apartment 30B. Source: Adapted from Stadsherstel, 2005.

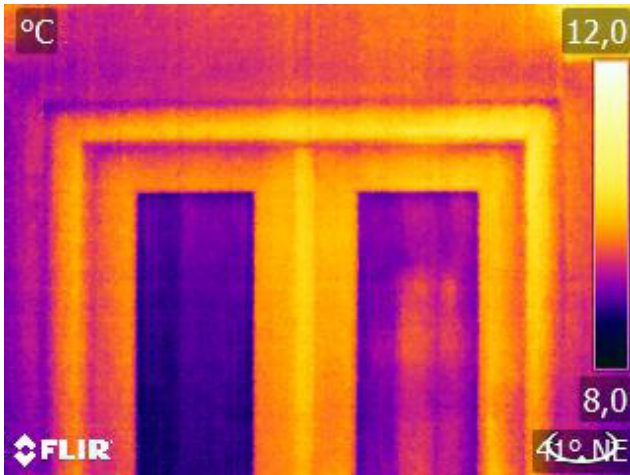
### B.3 Infrared images



Ventilation grill in the front house. Own picture.



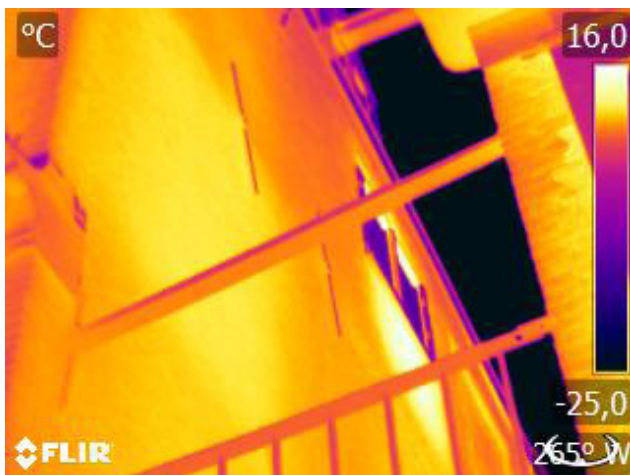
Intermediate member. Own picture.



Decorative door in the back house. Own picture.



Corner in the front house. Own picture.



North facade (alley). Own picture.



Back house. Own picture.

## B.4 Interview with the residents of 30B

### 1. Installations

#### *How is your house heated?*

The house is heated with gas using a DHW boiler and a 'CV ketel'. The 'CV ketel' has been replaced once since the current residents moved in at the Oudezijds Voorburgwal 30. The heat is distributed using radiators. There are not many radiators in the front house (near the windows at the East facade & one in kitchen) but the back house has many. As a result, the front house takes a long time to heat up.

#### *How is your house ventilated?*

There is air inlet through the ventilation grills at windows but mostly through cracks and seams. There are mechanical exhausts located in the kitchen & bathroom. In the kitchen the residents removed the extractor hood as it was blocking the light from the living room and the view to the living room. In the kitchen the residents are not happy with the effectiveness of the exhaust. In the bathroom they acknowledge that it works sufficient. In the bathroom the exhaust cannot be turned off completely, the residents can only increase the amount of suction. Both in kitchen and bathroom there is a knob which they can turn from 1 to 3.

#### *Do you cook on natural gas or on electricity?*

The residents of 30B cook on natural gas.

#### *Do you have any additional heating or cooling devices?*

The residents bought an electrical sweater, which is insufficient. The residents have not bought any other additional heating or cooling devices. They find cooling unnecessary as in summer it does not get very hot, especially in the front house & the kitchen the temperature in summer is comfortable.

### 2. Energy usage & behavior

#### *What do you think of your energy usage? Do you think it is low, high or are you neutral about your energy usage?*

The residents of 30B deem the energy usage much too high for the level of comfort within their home. During the colder period mid-February 2021, it was constantly 12 degrees in the home. They worked with coats on and still their energy bills were much higher compared to the period before. The residents acknowledge that they could make the home quite comfortable, but it would require a large amount of natural gas and thus money. Due to high costs and the desire to lower their energy usage to minimize their environmental impact, the residents do not turn up the heating completely. Furthermore, in the morning it takes several hours for the house to heat up. The residents are satisfied with their electricity usage.

#### *Are you conscientious about your energy usage? Do you turn off heating in rooms you are not present? Turn off lights when leaving the room?*

Yes, at night the residents turn off the heating and only heat the front house (as mentioned previously, not even completely). They always turn off lights when not in the room or when not home. Moreover, they installed a folding door between the kitchen and living room, so the heat of the living room is not lost to the kitchen. They mention that their house plants do not survive the winter.

#### *Do you heat in all rooms?*

No, the residents do not heat the back house at all.

***Do you have energy efficient appliances?***

No, the residents do not necessarily have energy efficient appliances. Mostly because none of the appliances were not purchased recently.

***Do you have any 'unusual' equipment or appliances that uses a lot of energy?***

No, the residents do not have any 'unusual' equipment or appliances. They do have a washing machine & dishwasher. Last summer, the residents rented their house to a friend and their electricity usage peaked. The residents themselves think their friend made use of air-conditioner.

### **3. Indoor comfort**

***In general, what do you think of the comfort in your house? Are you comfortable for the large amount of the day/year?***

In the summer the residents find the indoor environment comfortable but, in the winter they think it is horrible. When they talk to people about their home one of the first things they mention is that their home is too cold in the winter. The residents have asked Stadsherstel (the housing corporation) to make alterations to lower the energy usage and increase the indoor comfort, but until now Stadsherstel has not taken any action.

***What do you think of the indoor temperature in the winter? In the summer?***

The residents find the indoor temperature in summer comfortable, it does not necessarily heat up. They mention that it is hotter during the hot summer days but not highly uncomfortable. Due to the orientation, their home cools down well before going to sleep.

***To be comfortable in the winter is it necessary to put the heating up high? How high? What do you think of this?***

Yes, as mentioned before the residents acknowledge that in winter, they need to turn up the heating quite high if they would want it to be comfortable. To keep it comfortable the residents would have to leave the heating on continuously, which makes the air extremely dry.

***Did you personally take any measures to get comfortable? Such as shutting curtains, window foils, sun shading or a humidifier or dehumidifier.***

The residents have put window foil on some windows (Tesa moll thermo cover). They are not sure whether it is doing anything. They did not apply the foil on all the windows as the stores closed due to COVID-19 and visually it is not very pleasing.

The residents have not installed extra thick curtains. However, in the back house they keep the curtains closed. There are 'achterzet' windows in the bedroom. The residents mentioned that they do not work perfectly because they must open two windows and are old.

In the bathroom it is too humid which in the winter leads to mold, so they try to keep the bathroom window open. Furthermore, they keep the door closed during showering, so the humidity and mold stays contained in the bathroom.

***Are there places in your home where you would rather not sit or stay for an extended period because they are too hot or cold? What do you think of this?***

Both residents of 30B work from home due to COVID-19. As it would be too expensive to heat both the front and back house, they both work in the front house which is sometimes inconvenient.

***Do you experience discomfort near the windows? What do you think of this?***

The residents do sit near the windows because of the view and because the radiators are located there.

***Do you experience draft in your home?***

Yes, the residents do experience draft and even put polyurethane foam in the cracks and seams of

the windows of the East Facade. They mention that they do not feel the draft when walking around the house but only when sitting down near the windows. The residents think that compared to other houses their home is quite drafty.

***Do you think the ventilation in your home is adequate? Is the air quality sufficient?***

Yes, they think there is enough fresh air. It is one of the advantages of all the cracks and seams.

***Do you think the air in your home is too dry or too stuffy? Do you mind?***

Yes, the residents mention that it can be dry when the heating is turned on for longer periods of time. Also, they find it too humid in the bathroom. In summer they think it is not too humid in their home, but perfect.

***Do you think you have enough control over the ventilation and temperature in your home and adjust it according to your needs and wishes?***

The residents try to live with the seasons. They do not have a smart thermostat and therefore they put it down when going to sleep, consequently the heating of their home takes a significant amount of time in the morning. They would like the house to heat up faster. Furthermore, they kind of accept things the way they are because it is a monumental building. They would not allow it in a more modern home. They would not buy the house (the residents are currently renting) due to their discomfort in the winter and the high energy bills.

***Is there any noise disturbance from your neighbors?***

The residents can hear the radio from the Prael (the store underneath) and they hear a pipe leaking, a high frequency noise. Also, they hear their upstairs neighbors walking and when people walk in the communal staircase. The noise from outside does not necessarily cause disturbances. They do not hear the tourists (also pre-COVID-19). In general, they think the noise disturbance is relatively limited and is part of the canal houses.

***Do you think there is enough daylight in your home?***

In the living room the residents think there is enough light, but they do think the kitchen is quite dark, they almost always have to put on the light. It is one of the reasons why they removed the extractor hood.

***What would you like to change most about your home related to you comfort? More light? Better air? Cooling? Etc.***

The resident immediately acknowledges that they would try to insulate the building. There are no heat gains from sides as it is a detached house and none of the walls or windows are insulated. They also do not get a lot of heat from the store underneath as they do not heat that much.

#### **4. Future**

***Do you think it is necessary that your home is renovated?***

Yes, the residents think it is necessary that their home is renovated. They are surprised the building was not insulated or improved more thoroughly during the renovation of 2005.

***Are you planning on doing any renovation sometime soon? Small scale or large scale?***

Currently the residents are not planning on doing any renovation themselves as they are moving out and rent from Stadsherstel. They did ask Stadsherstel about their sustainability goals, but it is not Stadsherstel's priority according to the residents.

***What are the obstacles?***

The major obstacle for renovation is the fact that the current residents are renters. They see it as a problem that they pay the bills but are rent. It makes them hesitant to adjust or renovate anything as it is not an investment and is not allowed.

# Appendix C: Design Builder Models

## C.1 Input base model

Only adjusted parameters are specified. All others were left on default.

### Step 1: New file

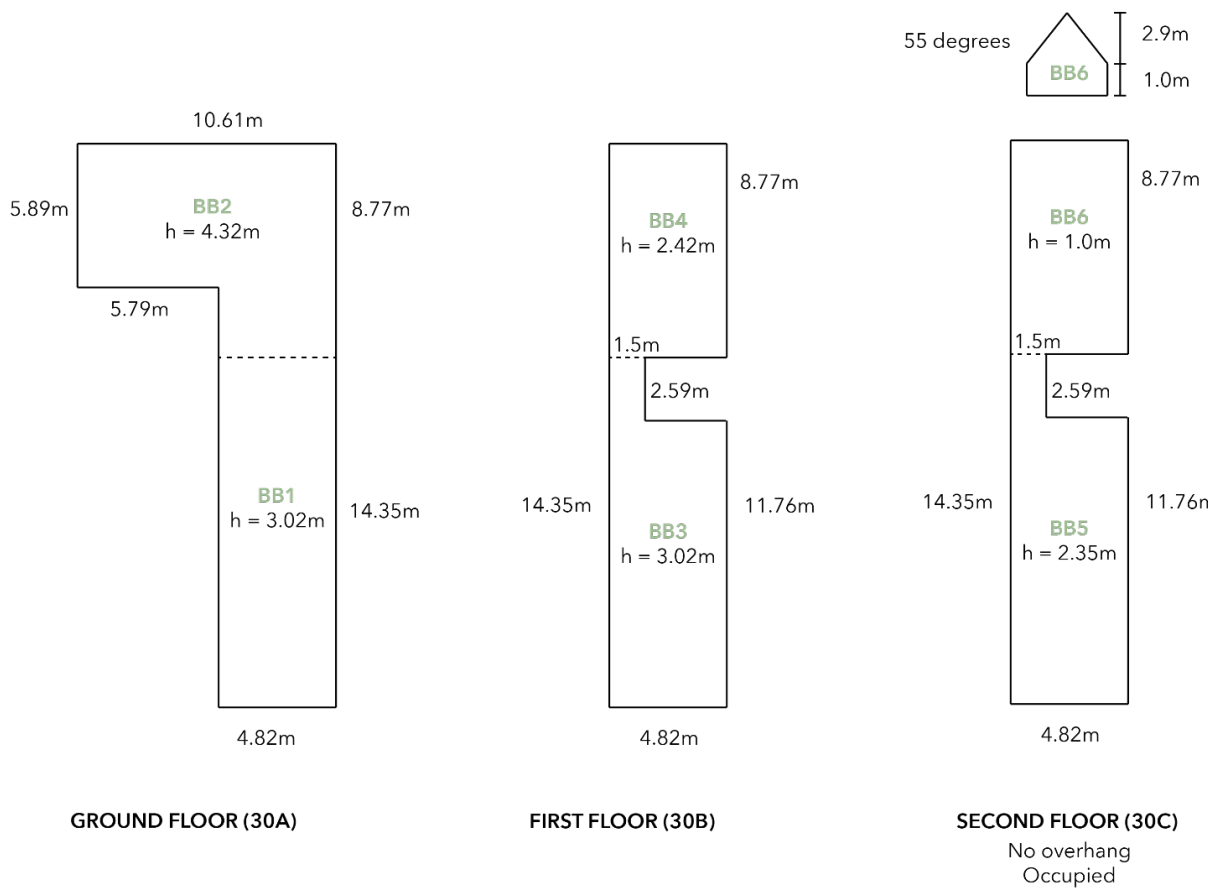
- **Location:** Amsterdam (Schiphol)
- **Hourly weather data:** Schiphol 2019 file (retrieved via fellow student)
- **Start day:** Sunday
- **Site orientation:** tilted 297 degrees

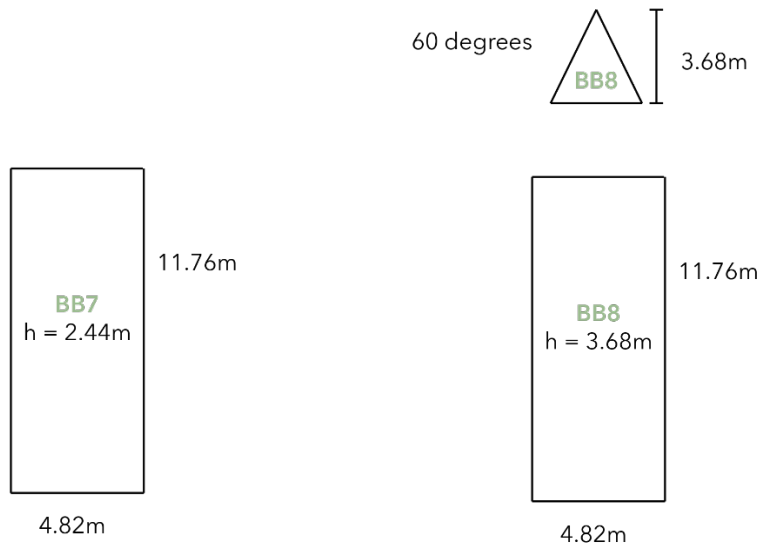
### Step 2: Model options

- **Timing:** Schedules
- **HVAC:** Detailed (simple HVAC data)

### Step 3: Create building

- **New building:** See drawings for dimensions of building blocks
  - Building block 1: 30A, front house & intermediate member, ground floor
  - Building block 2: 30A, back house, ground floor
  - Building block 3: 30B, front house & intermediate member, first floor
  - Building block 4: 30B, back house, first floor
  - Building block 5: 30C, front house & intermediate member, second floor
  - Building block 6: 30C, back house, second floor
  - Building block 7: 30D, front house, third floor
  - Building block 8: 30D, front house, fourth floor





THIRD FLOOR (30D)

FOURTH FLOOR (30D)

No overhang  
Occupied

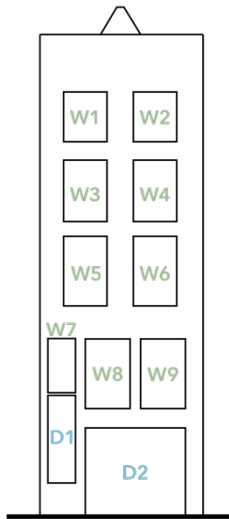
*Dimensions building blocks. Own work.*

- **Dormer windows:** See table for dimensions
  - Dormer 1: front house, North roof
  - Dormer 2: back house, North roof
  - Dormer 3: front house, South roof
  - Dormer 4: back house, South roof

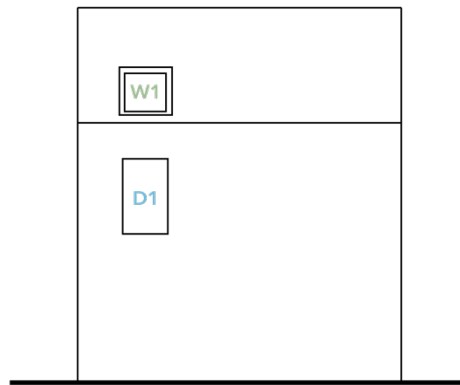
	Height (m)	Width (m)	Location
<b>Dormer 1</b>	2.7	1.3	Front house, North
<b>Dormer 2</b>	1.7	1.2	Back house, North
<b>Dormer 3</b>	1.7	1.8	Front house, South
<b>Dormer 4</b>	1.4	1.5	Back house, South

*Dimensions dormer windows. Own work.*

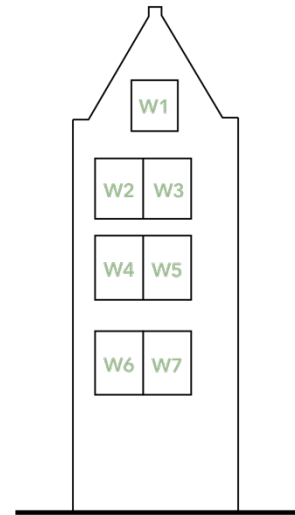
- **Zones:** As per building block
- **Openings:** See drawings and tables for dimensions and specifications openings



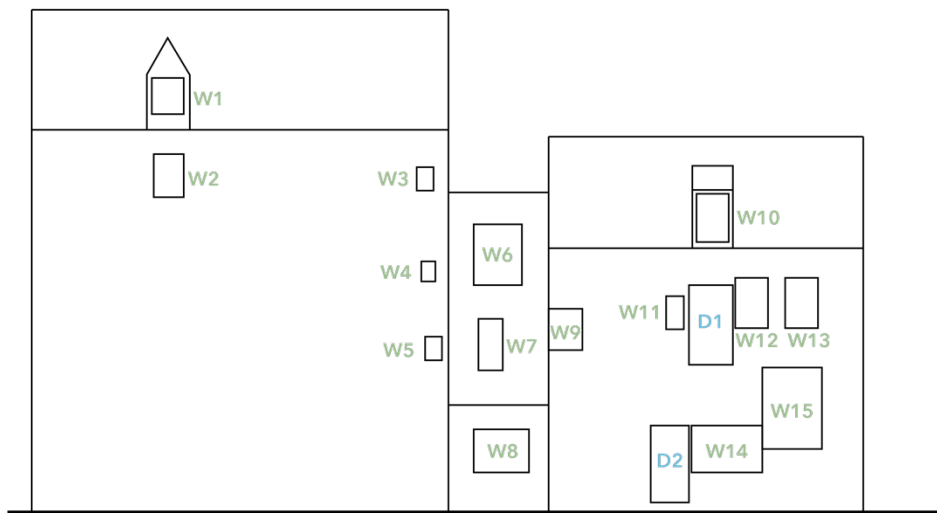
EAST ELEVATION FRONT HOUSE



SOUTH ELEVATION BACK HOUSE



WEST ELEVATION FRONT HOUSE



NORTH ELEVATION

*Windows. Own work.*

	Height (m)	Width (m)	Glazing type
<b>W1</b>	1.5	1.3	Single glazing (6 mm)
<b>W2</b>	1.5	1.3	Single glazing (6 mm)
<b>W3</b>	1.8	1.3	Single glazing (6 mm)
<b>W4</b>	1.8	1.3	Single glazing (6 mm)
<b>W5</b>	2.0	1.3	Single glazing (6 mm)
<b>W6</b>	2.0	1.3	Single glazing (6 mm)
<b>W7</b>	1.7	0.8	Single glazing (6 mm)
<b>W8</b>	2.1	1.4	Single glazing (6 mm)
<b>W9</b>	2.1	1.4	Single glazing (6 mm)
<b>D1</b>	2.3	0.8	N.A.
<b>D2</b>	3.6	3.0	N.A.

*Openings East elevation front house. Own work*

	Height (m)	Width (m)	Glazing type
<b>W1</b>	1.2	1.1	Single glazing (6 mm)
<b>D1</b>	2.1	1.3	N.A.

*Openings South elevation back house. Own work.*

	Height (m)	Width (m)	Glazing type
<b>W1</b>	1.4	1.3	Single glazing (6 mm)
<b>W2</b>	1.8	1.3	Single glazing (6 mm)
<b>W3</b>	1.8	1.3	Single glazing (6 mm)
<b>W4</b>	1.8	1.3	Single glazing (6 mm)
<b>W5</b>	1.8	1.3	Single glazing (6 mm)
<b>W6</b>	1.8	1.3	Single glazing (6 mm)
<b>W7</b>	1.8	1.3	Single glazing (6 mm)

*Openings West elevation front house. Own work.*

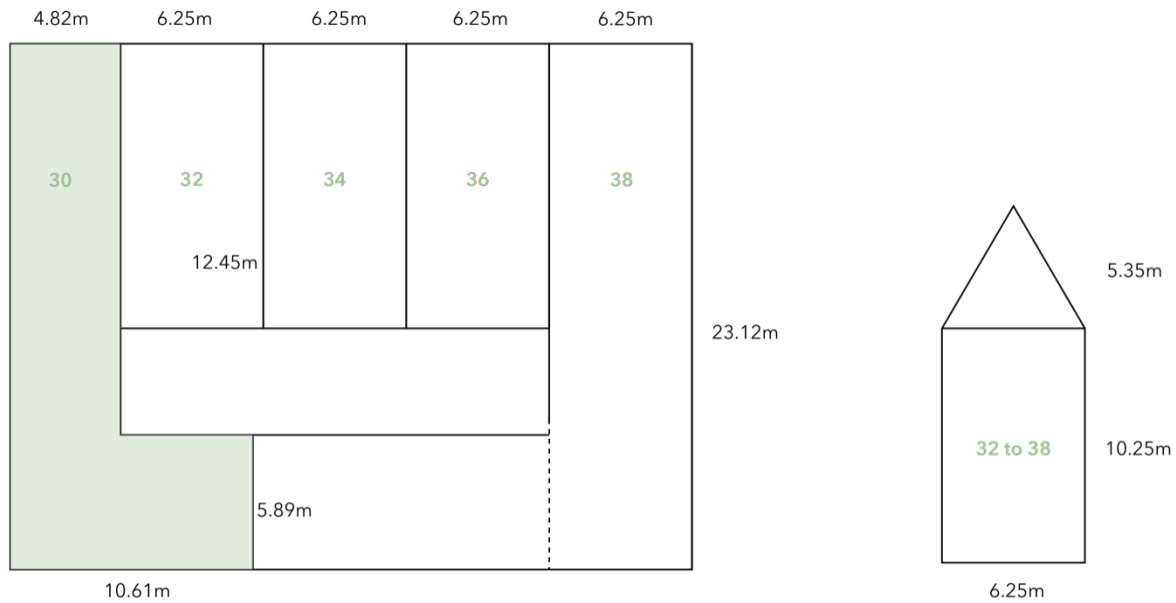
	Height (m)	Width (m)	Glazing type
<b>W1</b>	0.9	1.0	Single glazing (6 mm)
<b>W2</b>	1.2	0.9	Single glazing (6 mm)
<b>W3</b>	0.7	0.5	Single glazing (6 mm)
<b>W4</b>	0.7	0.4	Single glazing (6 mm)
<b>W5</b>	0.7	0.5	Single glazing (6 mm)
<b>W6</b>	1.7	1.3	Single glazing (6 mm)
<b>W7</b>	1.5	0.6	Single glazing (6 mm)
<b>W8</b>	1.3	1.6	Single glazing (6 mm)
<b>W9</b>	1.2	0.9	'Achterzet raam'
<b>W10</b>	1.5	1.1	Single glazing (6 mm)
<b>W11</b>	1.0	0.5	'Achterzet raam'
<b>W12</b>	1.4	0.9	'Achterzet raam'
<b>W13</b>	1.4	0.9	'Achterzet raam'
<b>W14</b>	1.4	2.0	'Achterzet raam'
<b>W15</b>	2.4	1.6	'Achterzet raam'
<b>D1</b>	2.2	1.3	N.A.
<b>D2</b>	2.2	1.1	N.A.

*Openings North elevation. Own work.*

**Note:** 'achterzet raam' is not available in Design Builder and thus modelled as double glazed, clear windows (6 mm & 13 mm air).

#### **Step 4: Adjoining buildings**

- **New building (standard component block):** See drawing for dimensions
  - Block 1 & 2: Oudezijdsvoorburgwal 32
  - Block 3 & 4: Oudezijdsvoorburgwal 34
  - Block 5 & 6: Oudezijdsvoorburgwal 36
  - Block 7 to 9: Oudezijdsvoorburgwal 38



*Dimensions adjoining buildings. Own work.*

## **Step 5: Activity (different for residential & retail)**

### **5.1 Residential:** Building block 3 to 8

- **Detailed occupancy template:** married couple
- **Occupancy density:** 0.025 people/m<sup>2</sup>
- **Metabolic rate:** light office work
- **Metabolic factor:** 0.93 (average woman/man)
- **Occupancy schedule (pre-covid, residents to workplace):**
  - Weekdays
    - 6:30 to 7:00: 50%
    - 7:00 to 8:00: 100%
    - 8:00 to 18:00: 0%
    - 18:00 to 18:30: 50%
    - 18:30 to 22:00: 100%
    - 22:00 to 23:00: 50%
    - 23:00 to 6:30: 0%
  - Weekend
    - 9:00 to 9:30: 50%
    - 9:30 to 16:00: 100%
    - 16:00 to 16:30: 50%
    - 16:30 to 20:30: 0%
    - 20:30 to 21:00: 50%
    - 21:00 to 22:30: 100%
    - 22:30 to 23:00: 50%
    - 23:00 to 9:00: 0%
- **Computers:** 2.8 W/m<sup>2</sup> (= one laptop and one desktop)
  - Weekdays
    - 6:30 to 7:00: 50%
    - 7:00 to 8:00: 100%
    - 8:00 to 18:00: 0%

- 18:00 to 18:30: 50%
    - 18:30 to 22:00: 100%
    - 22:00 to 23:00: 50%
    - 23:00 to 6:30: 0%
  - Weekends
    - 8:00 to 18:00: 100%
    - 18:00 to 8:00: 0%
- **Miscellaneous:** 3.0 W/m<sup>2</sup>
  - Schedule same as computers
- **General lighting on:**
  - October to March (weekdays & weekend)
    - 7:00 to 7:30: 50%
    - 7:30 to 9:00: 100%
    - 9:00 to 10:00: 50%
    - 10:00 to 17:00: 0%
    - 17:00 to 17:30: 50%
    - 17:30 to 22:00: 100%
    - 22:00 to 23:00: 50%
    - 23:00 to 7:00: 0%
  - April to September
    - 7:00 to 8:00: 100
    - 8:00 to 18:00: 0%
    - 18:00 to 18:30: 50%
    - 18:30 to 22:00: 100%
    - 22:00 to 23:00: 50%
    - 23:00 to 7:00: 0%
- **DHW:** 1.125 l/m<sup>2</sup>/day (= 45 l hot water per day per person)
  - Schedule same as occupancy
- **Heating:**
  - **Setpoint temperature:** 19 °C (as mentioned by residents of 30B)
  - **Setback temperature:** 12 °C (as mentioned by residents of 30B)
  - Weekday & SummerDesignDay:
    - Until 07:00: 0.5
    - Until 08:00: 1
    - Until 18:00: 0.5
    - Until 22:00: 1
    - Until 24:00: 0.5
  - WinterDesignDay
    - Until 24:00: 1
  - Saturday,
    - Until 09:00: 0.5
    - Until 16:00: 1
    - Until 24:00: 0.5
  - Sunday,
    - Until 9:00: 0.5
    - Until 22:00: 1
    - Until 24:00: 0.5
  - Holidays,
    - Until 24:00: 0.5
  - AllOtherDays,
    - Until 24:00: 0

- **Natural ventilation:**
  - **Setpoint temperature:** 24 °C
  - **Schedule:** Always on
- **Lighting:**
  - **Target illuminance:** 200 lx
- **Ventilation fresh air:** 7 l/s/person

## 5.2 Retail: Building block 1 and 2

- **Detailed occupancy template:** office workers
- **Occupancy density:** 0.0208 people/m<sup>2</sup> (3 people in store)
- **Metabolic rate:** Standing/walking
- **Metabolic factor:** 0.93 (average woman/man)
- **Occupancy schedule:**
  - Monday & Tuesday
    - off
  - Wednesday to Sunday
    - 12:30 to 13:00: 50%
    - 13:00 to 20:00: 100%
    - 20:00 to 20:30: 50%
- **Computers:** 5.2 W/m<sup>2</sup> (= one laptop and one desktop)
  - Schedule same as occupancy
- **Miscellaneous:** 3.0 W/m<sup>2</sup>
  - Schedule same as occupancy
- **General lighting on:**
  - Schedule same as occupancy
- **DHW:** Off
- **Heating:**
  - **Setpoint temperature:** 17 °C (as mentioned by user of 30A)
  - **Setback temperature:** 12 °C (as mentioned by user of 30A)
  - Wednesday to Sunday & SummerDesignDay,
    - Until 13:00: 0.5
    - Until 20:00: 1
    - Until 24:00: 0.5
  - Monday & Tuesday,
    - Until 24:00: 0.5
  - For: WinterDesignDay,
    - Until 24:00: 1
  - For: AllOtherDays,
    - Until 24:00: 0
- **Natural ventilation:**
  - **Setpoint temperature:** 24 °C
  - **Schedule:** Always on
- **Lighting:**
  - **Target illuminance:** 300 lx
- **Ventilation fresh air:** 7 l/s/person

## Step 6: Construction (identical for residential & retail)

- **External walls:** Solid brick walls, 225mm, uninsulated, pre-1919 (U-value = 1.7 W/m<sup>2</sup>\*K)
- **Below grade walls:** Solid brick walls, 225mm, uninsulated, pre-1919 (U-value = 1.7 W/m<sup>2</sup>\*K)

- **Flat roof** (U-value = 0.398 W/m<sup>2</sup>\*K):
  - 0.02m concrete tiles
  - 0.008m bitumen
  - 0.065 PUR
- **Pitched roof occupied** (U-value = 0.256 W/m<sup>2</sup>\*K):
  - 0.025m clay tile
  - 0.12m rockwool
  - 0.065m gypsum plaster board
- **Pitched roof unoccupied** (U-value = 0.256 W/m<sup>2</sup>\*K):
  - Same as pitched roof, occupied
- **Internal partitions:** 230mm single leaf brick, plastered on both sides (U-value = 1.650 W/m<sup>2</sup>\*K):
- **Ground floor** (U-value = 0.354 W/m<sup>2</sup>\*K):
  - 0.06m PUR
  - 0.1m cast concrete
  - 0.07m floor/roof screed
  - 0.03m timber flooring
- **Internal floors** (U-value = 0.420 W/m<sup>2</sup>\*K):
  - 0.01m timber flooring
  - 0.065m rockwool
  - 0.05m Cement plaster board
- **Airtightness:**
  - 0.7 ac/h
  - **Crack template:** poor

### **Step 7: Openings**

- **Building level:** Single glazing, clear, no shading
- **Block level:** Several double glazing, clear, no shading due to presence of "achterzetramen"
  - See step 3, create building, for specifications of openings
- **Painted wooden window dividers and frames**
  - **Divider width:** 0.04m
  - **Frame width:** 0.1m

### **Step 8: Lighting**

#### **8.1 Residential:** Building block 3 to 8

- **Template:** Lamp type unknown
- **General lighting:** 3.0 W/m<sup>2</sup>/100 lx
- **Lighting control:** on
- **Task lighting:** 1.0 W/m<sup>2</sup>

#### **8.2 Retail:** Building block 1 & 2

- **Template:** lamp type unknown
- **General lighting:** 5.0 W/m<sup>2</sup>/100 lx
- **Lighting control:** on

### **Step 9: HVAC (identical for residential and retail)**

#### **9.1 In HVAC tab:**

- **Template:** radiator heating, boiler HW, natural ventilation

- **Heating:** according to activity template (different for residential and retail)
- **Natural ventilation:** according to activity template (different for residential and retail)

## 9.2 In navigator (HVAC):

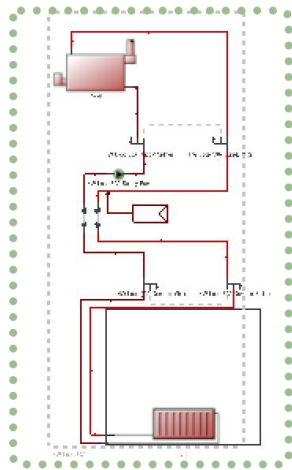
- **Zone groups (see table for specifications):**
  - **30A:** Block 1 & 2
    - Add hot water loop
    - Add radiators
  - **30B:** Block 3 & 4
    - Add hot water loop
    - Add radiators
    - Add DHW loop (& water outlet)
  - **30C:** Block 5 & 6
    - Add hot water loop
    - Add radiators
    - Add DHW loop (& water outlet)
  - **30D:** Block 7 & 8
    - Add hot water loop
    - Add radiators
    - Add DHW loop (& water outlet)

	Block	HW loop	Radiators	DHW loop
<b>30A</b>	Block 1	Boiler:	260 W/m <sup>2</sup>	Not present
	Block 2	<ul style="list-style-type: none"> <li>• Nominal capacity: 23 kW</li> <li>• Flow rate: 0.00208 m<sup>3</sup>/s</li> </ul>	500 W/m <sup>2</sup>	
<b>30B</b>	Block 3	Boiler:	260 W/m <sup>2</sup>	No alterations
	Block 4	<ul style="list-style-type: none"> <li>• Nominal capacity: 23 kW</li> <li>• Flow rate: 0.00208 m<sup>3</sup>/s</li> </ul>	210 W/m <sup>2</sup>	
<b>30C</b>	Block 5	Boiler:	200 W/m <sup>2</sup>	No alterations
	Block 6	<ul style="list-style-type: none"> <li>• Nominal capacity: 23 kW</li> <li>• Flow rate: 0.00208 m<sup>3</sup>/s</li> </ul>	170 W/m <sup>2</sup>	
<b>30D</b>	Block 7	Boiler:	210 W/m <sup>2</sup>	No alterations
	Block 8	<ul style="list-style-type: none"> <li>• Nominal capacity: 23 kW</li> <li>• Flow rate: 0.00208 m<sup>3</sup>/s</li> </ul>	230 W/m <sup>2</sup>	No alterations

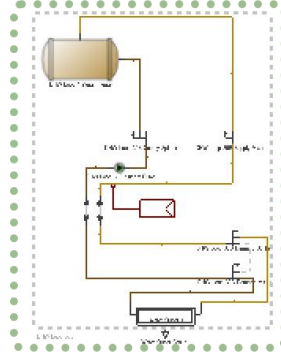
*Specifications detailed HVAC system. Own work.*

**Note:** Capacity of radiators is calculated with 85 W per m<sup>3</sup> of the space, as specified by Joost de Vree ([https://www.joostdevree.nl/shtmls/capaciteit\\_cv\\_en\\_radiators.html](https://www.joostdevree.nl/shtmls/capaciteit_cv_en_radiators.html)) for minimal insulated buildings with a desired temperature of around 20 degrees Celsius.

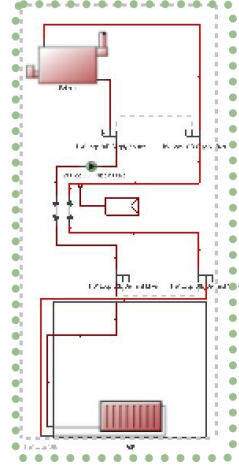
Heating 30A



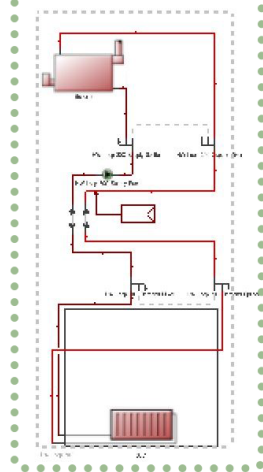
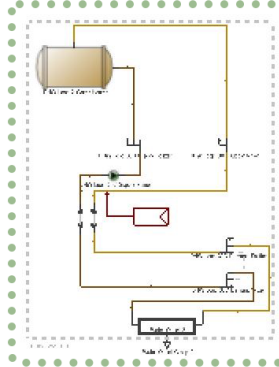
DHW 30B



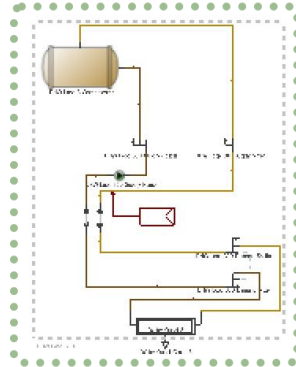
Heating 30B



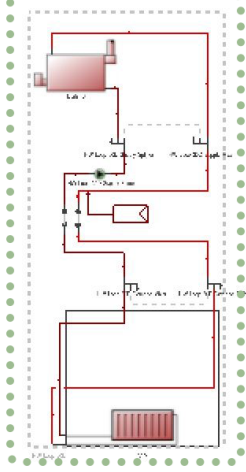
DHW 30C Heating 30C



DHW 30D



Heating 30D



HVAC system. Own work.

## C.2 Input renovation model

### **Step 1: New file**

- Copy of base model file
- Alterations to base model are specified underneath

### **Step 2: Model options**

- No alterations

### **Step 3: Create building**

- Partitions drawn between front and back house to create separate zones for intermediate member.
  - Block 1
    - Zone 1: Front house
    - Zone 2: Intermediate member
  - Block 3
    - Zone 1: Intermediate member
    - Zone 2: Front house
  - Block 5
    - Zone 1: Intermediate member
    - Zone 2: Front house
- No further alterations

	Block	Zone	Function/location
<b>Front house</b>	Block 1	Zone 1	Ground floor, 30A
	Block 3	Zone 2	1 <sup>st</sup> floor, 30B
	Block 5	Zone 2	2 <sup>nd</sup> floor, 30C
	Block 7	Zone 1	3 <sup>rd</sup> floor, 30C
	Block 8	Zone 1	4 <sup>th</sup> floor, 30D
<b>Back house</b>	Block 1	Zone 2	GF, intermediate member, 30A
	Block 2	Zone 1	Ground floor, 30A
	Block 3	Zone 1	1 <sup>st</sup> floor, intermediate member, 30B
	Block 4	Zone 1	1 <sup>st</sup> floor, 30B
	Block 5	Zone 1	2 <sup>nd</sup> floor, intermediate member, 30C
	Block 6	Zone 1	2 <sup>nd</sup> floor, 30C

*Blocks & zones. Own work.*

### **Step 4: Adjoining buildings**

- No alterations

### **Step 5: Activity (different for residential & retail)**

#### **5.1 Residential:** Building block 3 to 8

- **Computers:** 2.5 W/m<sup>2</sup> (was 2.8 W/m<sup>2</sup>)
- **Miscellaneous:** 2.0 W/m<sup>2</sup> (was 3.0 W/m<sup>2</sup>)
- **DHW:** due to water reducing faucets & showerhead 20% less DHW = 0.9 l/m<sup>2</sup>/day = 36 l hot water per day per person (was 1.125 l/m<sup>2</sup>/day)
- **Heating:**
  - **Setpoint temperature:** 20 °C (was 19 °C)
  - **Setback temperature:** 15 °C for B3Z1, B4Z1, B5Z1 & B6Z1, 18 °C for B3Z2, B5Z2, B7Z1, B8Z1 (was 12 °C)

#### **5.2 Retail:** Building block 1 and 2

- **Office equipment:** 3.5 W/m<sup>2</sup> (was 5.2 W/m<sup>2</sup>)
- **Miscellaneous:** 2.0 W/m<sup>2</sup> (was 3.0 W/m<sup>2</sup>)

- **Heating:**
  - **Setpoint temperature:** 19 °C (was 17 °C)
  - **Setback temperature:** 15 °C for B1Z2 & B2Z1, 18 °C for B1Z1 (was 12 °C)

## **Step 6: Construction (different for front & back house)**

### **6.1 Back house (B1Z2, B2Z1, B3Z1, B4Z1, B5Z1 & B6Z1)**

- **External walls:** Solid brick walls, 225mm, uninsulated, pre-1919 (U-value = 0.243 W/m<sup>2</sup>\*K)
  - Added 0.14m EPS (standard)
  - Added 0.01m exterior plaster (dense)
- **Below grade walls:** Solid brick walls, 225mm, uninsulated, pre-1919 (U-value = 0.243 W/m<sup>2</sup>\*K)
  - Added 0.14m EPS (standard)
  - Added 0.01m exterior plaster (dense)
- **Flat roof** (U-value = 0.218 W/m<sup>2</sup>\*K):
  - 0.02m concrete tiles
  - 0.008m bitumen
  - 0.132 foam polyisocyanate (was 0.065m PUR)
- **Pitched roof, occupied** (U-value = 0.218 W/m<sup>2</sup>\*K):
  - 0.025m clay tile
  - 0.132 polyisocyanate (was 0.12m rockwool)
  - 0.065m gypsum plaster board
- **Pitched roof, unoccupied** (U-value = 0.218 W/m<sup>2</sup>\*K):
  - Same as pitched roof, occupied
- **Ground floor** (U-value = 0.235 W/m<sup>2</sup>\*K):
  - 0.1m PUR (was 0.06m PUR) Thermocushions were not available in DB
  - 0.1m cast concrete
  - 0.07m floor/roof screed
  - 0.03m timber flooring
- **Airtightness:**
  - 0.02 ac/h
  - **Crack template:** good

### **6.2 Front house (B1Z1, B3Z2, B5Z2, B7Z1 & B8Z1)**

- **External walls:** Solid brick walls, 225mm, uninsulated, pre-1919 (U-value = 1.6 W/m<sup>2</sup>\*K):
  - Added 0.021m plaster (dense)
  - Added internal source (for wall heating, not for B8Z1, check under construction of specific wall)
  - Added 0.01m plaster (dense)
- **Below grade walls:** Solid brick walls, 225mm, uninsulated, pre-1919 (U-value = 1.6 W/m<sup>2</sup>\*K):
  - Added 0.021m plaster (dense)
  - Added internal source (check under construction under construction of specific wall)
  - Added 0.01m plaster (dense)
- **Flat roof** (U-value = 0.218 W/m<sup>2</sup>\*K):
  - 0.02m concrete tiles
  - 0.008m bitumen
  - 0.132 foam polyisocyanate (was 0.065m PUR)

- **Pitched roof, occupied** (U-value = 0.218 W/m<sup>2</sup>\*K):
  - 0.025m clay tile
  - 0.132 polyisocyanate (was 0.12m rockwool)
  - 0.065m gypsum plaster board
- **Pitched roof, unoccupied** (U-value = 0.218 W/m<sup>2</sup>\*K):
  - Same as pitched roof, occupied
- **Ground floor** (U-value = 0.235 W/m<sup>2</sup>\*K):
  - 0.1m PUR (was 0.06m PUR) Thermocushions were not available in DB
  - 0.1m cast concrete
  - 0.07m floor/roof screed
  - 0.03m timber flooring
- **Airtightness:**
  - 0.02 ac/h
  - **Crack template:** good

### Step 7: Openings

- **Building level:** Double glazing, loE, argon filled
- **Frame width:** 0.06
- **Framing:** See table; back house PVC with thermal break (was wood)

	Height (m)	Width (m)	Glazing type	Framing
<b>W1</b>	1.5	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W2</b>	1.5	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W3</b>	1.8	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W4</b>	1.8	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W5</b>	2.0	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W6</b>	2.0	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W7</b>	1.7	0.8	Double (6mm), LoE, Argon (13mm)	Wood
<b>W8</b>	2.1	1.4	Double (6mm), LoE, Argon (13mm)	Wood
<b>W9</b>	2.1	1.4	Double (6mm), LoE, Argon (13mm)	Wood
<b>D1</b>	2.3	0.8	N.A.	N.A.
<b>D2</b>	3.6	3.0	N.A.	N.A.

*Openings East elevation front house. Own work.*

	Height (m)	Width (m)	Glazing type	Framing
<b>W1</b>	1.2	1.1	Double (6mm), LoE, Argon (13mm)	PVC
<b>D1</b>	2.1	1.3	N.A.	N.A.

*Openings South elevation back house. Own work.*

	Height (m)	Width (m)	Glazing type	Framing
<b>W1</b>	1.4	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W2</b>	1.8	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W3</b>	1.8	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W4</b>	1.8	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W5</b>	1.8	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W6</b>	1.8	1.3	Double (6mm), LoE, Argon (13mm)	Wood
<b>W7</b>	1.8	1.3	Double (6mm), LoE, Argon (13mm)	Wood

*Openings West elevation front house. Own work.*

	Height (m)	Width (m)	Glazing type	Framing
<b>W1</b>	0.9	1.0	Double (6mm), LoE, Argon (13mm)	Wood
<b>W2</b>	1.2	0.9	Double (6mm), LoE, Argon (13mm)	Wood
<b>W3</b>	0.7	0.5	Double (6mm), LoE, Argon (13mm)	Wood
<b>W4</b>	0.7	0.4	Double (6mm), LoE, Argon (13mm)	Wood
<b>W5</b>	0.7	0.5	Double (6mm), LoE, Argon (13mm)	Wood
<b>W6</b>	1.7	1.3	Double (6mm), LoE, Argon (13mm)	PVC
<b>W7</b>	1.5	0.6	Double (6mm), LoE, Argon (13mm)	PVC
<b>W8</b>	1.3	1.6	Double (6mm), LoE, Argon (13mm)	PVC
<b>W9</b>	1.2	0.9	Double (6mm), LoE, Argon (13mm)	PVC
<b>W10</b>	1.5	1.1	Double (6mm), LoE, Argon (13mm)	PVC
<b>W11</b>	1.0	0.5	Double (6mm), LoE, Argon (13mm)	PVC
<b>W12</b>	1.4	0.9	Double (6mm), LoE, Argon (13mm)	PVC
<b>W13</b>	1.4	0.9	Double (6mm), LoE, Argon (13mm)	PVC
<b>W14</b>	1.4	2.0	Double (6mm), LoE, Argon (13mm)	PVC
<b>W15</b>	2.4	1.6	Double (6mm), LoE, Argon (13mm)	PVC
<b>D1</b>	2.2	1.3	N.A.	N.A.
<b>D2</b>	2.2	1.1	N.A.	N.A.

Openings North elevation. Own work.

## **Step 8: Lighting**

### **8.1 Residential:** Building block 3 to 8

- **Template:** LED (was unknown)
- **General lighting:** 1.5 W/m<sup>2</sup>/100 lx (was 2.5 W/m<sup>2</sup>/100 lx)

### **8.2 Retail:** Building block 1 & 2

- **Template:** LED (was unknown)
- **General lighting:** 3.5 W/m<sup>2</sup>/100 lx (was 5.0 W/m<sup>2</sup>/100 lx)

## **Step 9: HVAC (tab)**

- **Mechanical ventilation:** Check on
  - **Heat recovery:** On (effectiveness 0.9)
- **Turn off natural ventilation for all blocks**

## **Step 10: Generation: PV panels**

- Draw solar panels on South facing roofs of both back and front house & dormers
  - **Level:** Building
- Under generation tab click include electricity load centers: DC with inverter + AC storage and select all PV panels for electrical unit

## **Step 11: HVAC (in navigator)**

See further in appendix for flow chart HVAC loops

### 11.1 Zone 1 (front house; B1Z1, B3Z2, B5Z2 & B7Z1)

Loop	Adjusted parameters
HW loop (heat pump)	<ul style="list-style-type: none"> <li>○ <b>Flow type:</b> Variable</li> <li>○ <b>Exit T loop:</b> 40 °C</li> <li>○ <b>Boiler:</b> Electricity</li> <li>○ <b>Setpoint:</b> Always 55 °C</li> </ul>
HW loop (electric boiler)	<ul style="list-style-type: none"> <li>○ <b>Flow type:</b> Variable</li> <li>○ <b>Exit T loop:</b> 55 °C</li> <li>○ <b>Boiler:</b> Electricity</li> <li>○ <b>Setpoint:</b> Always 55 °C</li> </ul>
DHW loop	<ul style="list-style-type: none"> <li>○ <b>Setpoint:</b> DHW, always 55 °C</li> <li>○ <b>Water outlet group:</b> B3Z2, B5Z2 &amp; B7Z1</li> </ul>
Air loop	<ul style="list-style-type: none"> <li>○ Added heat recovery</li> <li>○ <b>Effectiveness heat recovery:</b> 0.9</li> </ul>
Zone group equipment	<ul style="list-style-type: none"> <li>○ Radiators, average <math>T_{\text{water}} = 55 \text{ °C}</math></li> <li>○ Radiant surfaces</li> <li>○ Air inlet</li> <li>○ Air outlet</li> </ul>

*Input HVAC. Own work.*

### 11.2 Zone 2 (back house; B1Z2, B2Z1, B3Z1, B4Z1, B5Z1, B6Z1, & B8Z1)

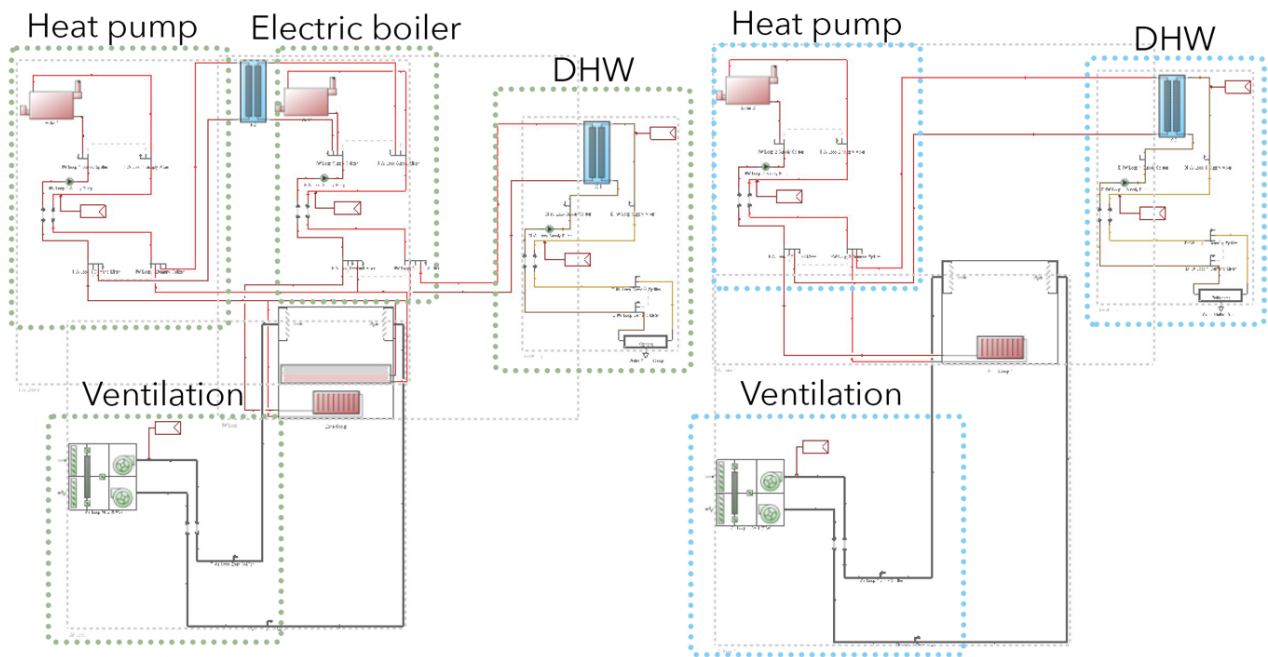
Loop	Adjusted parameters
HW loop (heat pump)	<ul style="list-style-type: none"> <li>○ <b>Flow type:</b> Variable</li> <li>○ <b>Exit T loop:</b> 60 °C</li> <li>○ <b>Boiler:</b> Electricity</li> <li>○ <b>Setpoint:</b> Always 55 °C</li> </ul>
DHW loop	<ul style="list-style-type: none"> <li>○ <b>Setpoint:</b> DHW, always 55 °C</li> <li>○ <b>Water outlet group:</b> B3Z2, B5Z2 &amp; B7Z1</li> <li>○ <b>Drain water exchanger:</b> Ideal, destination equipment</li> </ul>
Air loop	<ul style="list-style-type: none"> <li>○ Added heat recovery</li> <li>○ <b>Effectiveness heat recovery:</b> 0.9</li> </ul>
Zone group equipment	<ul style="list-style-type: none"> <li>○ Radiators (see table below for capacity), average <math>T_{\text{water}} = 55 \text{ °C}</math></li> <li>○ Air inlet</li> <li>○ Air outlet</li> </ul>

*Input HVAC. Own work.*

Zone	Capacity radiator (W)
<b>B1Z2</b>	18.400
<b>B2Z1</b>	33.800
<b>B3Z1</b>	500
<b>B4Z1</b>	10.000
<b>B5Z1</b>	1.000
<b>B6Z1</b>	9.400
<b>B8Z1</b>	11.400

*Input HVAC. Own work.*

**Note:** Capacity of radiators is calculated with 100 W per m<sup>3</sup> of the space, as specified by Joost de Vree ([https://www.joostdevree.nl/shtmls/capaciteit\\_cv\\_en\\_radiator.shtml](https://www.joostdevree.nl/shtmls/capaciteit_cv_en_radiator.shtml)) for insulated buildings with a desired temperature of around 20 degrees Celsius through the use of LT heating.



*Input HVAC (green is front house, blue is back house). Own work.*

### C.3 Results of the base model simulation

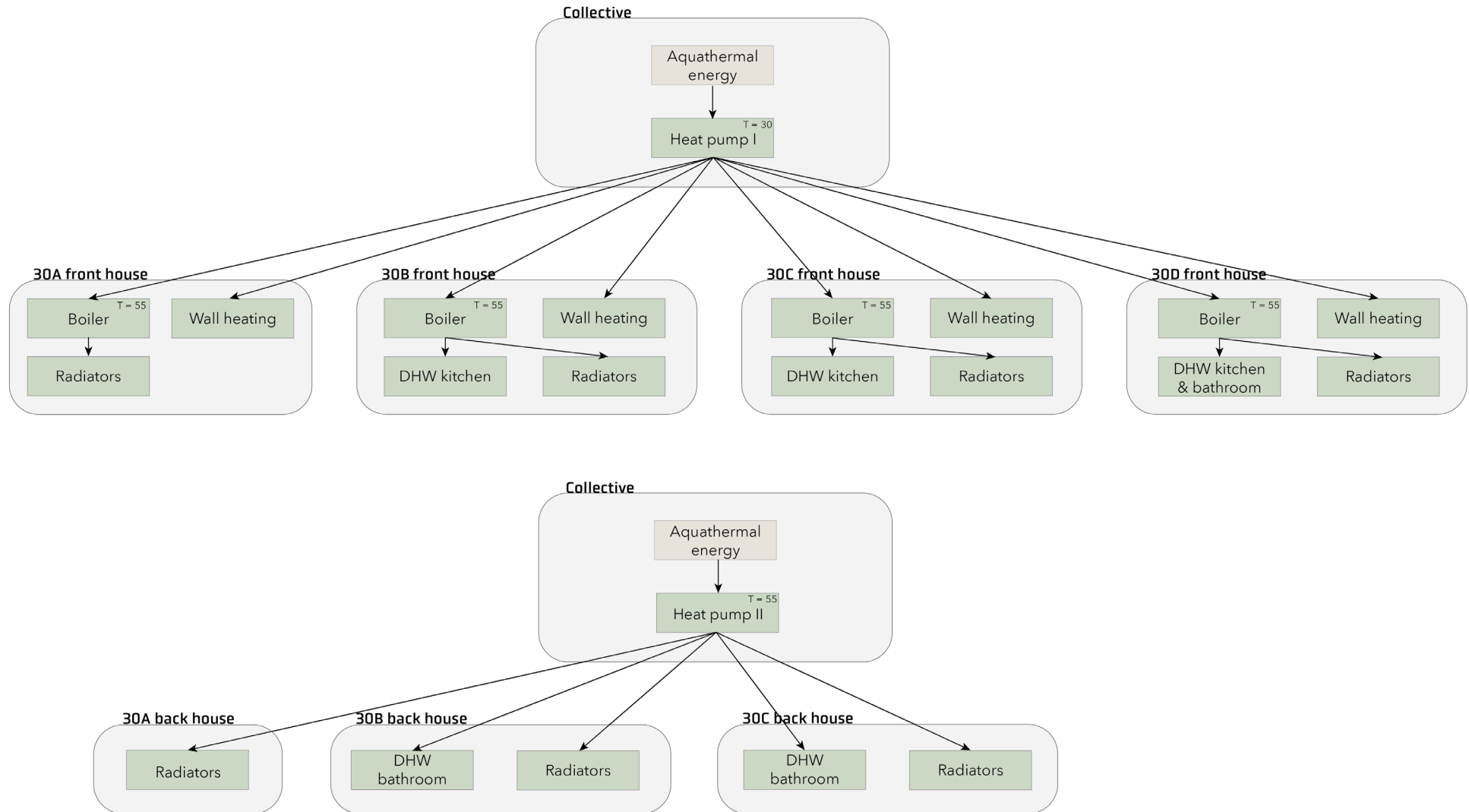
Monthly heat gains and losses																											
	Glazing	Walls	Ceilings (int)	Floors (int)	Ground Floors	Partitions (int)	Roofs	Internal Natural vent.	Mech Vent + Nat Vent + Infiltration	External Infiltration	Radiant + Convective Heating	Task Lighting	General Lighting	Miscellaneous	Computer + Equip	Occupancy	Solar Gains Exterior Windows	Zone Sensible Heating	Air Temperature	Radiant Temperature	Operative Temperature	Room Electricity	Lighting	System Pumps	Heating (Gas)	DHW (Gas)	Outside Dry-Bulb Temperature
	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	ac/h	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	°C	°C	°C	kWh	kWh	kWh	kWh	kWh	°C
01-01-2019	-1199,3	-6346,5	42,0	-14,7	245,5	13,6	-448,1	-111,5	1,78	-5528,1	11272,4	66,1	656,5	263,0	297,4	198,8	346,5	8504,7	13,6	12,1	12,9	560,4	722,5	5,3	11901,5	874,3	3,8
01-02-2019	-838,2	-4440,5	48,2	-62,9	179,3	-9,2	-322,1	-180,8	1,39	-3205,0	6625,5	58,8	565,3	238,2	271,7	179,3	744,3	5008,4	13,9	12,9	13,4	509,9	624,2	3,0	6935,0	790,2	6,3
01-03-2019	-790,4	-3779,3	59,5	-65,5	182,5	-6,2	-275,9	-254,3	2,00	-4315,9	6807,9	63,7	584,1	262,0	301,3	197,3	877,1	5134,0	14,1	13,6	13,8	563,3	647,8	3,3	7184,4	840,9	7,9
01-04-2019	-668,0	-2463,5	83,8	-91,8	84,3	-3,5	-177,2	-210,8	1,42	-2142,8	2425,5	65,5	480,0	264,4	301,1	191,0	1785,0	1834,6	16,4	16,4	16,4	565,4	545,5	1,1	2505,2	830,9	11,0
01-05-2019	-601,2	-2054,0	79,5	-109,7	61,2	-13,7	-140,6	-184,5	1,31	-1938,2	1750,9	63,7	431,4	255,8	290,6	186,6	1855,6	1324,2	16,7	16,9	16,8	546,4	495,1	0,8	1806,9	762,8	11,7
01-06-2019	-451,1	-1115,4	70,4	-111,7	-178,3	-23,3	-70,6	-152,5	1,24	-1155,4	89,7	62,0	393,8	254,0	291,4	145,7	1986,1	68,3	21,9	22,3	22,1	545,5	455,8	0,1	91,4	698,9	17,8
01-07-2019	-480,6	-1069,1	84,2	-69,7	-171,3	5,2	-80,1	-150,8	1,24	-1244,4	34,0	67,1	419,8	269,2	305,6	150,9	1966,4	25,3	22,9	23,3	23,1	574,8	486,8	0,1	33,8	721,1	18,7
01-08-2019	-429,8	-1113,3	71,4	-71,2	-142,0	2,6	-92,4	-132,8	1,30	-1003,1	5,9	63,7	452,8	258,9	296,0	147,3	1723,7	4,5	22,4	22,7	22,5	554,8	516,4	0,1	5,9	673,8	18,8
01-09-2019	-411,6	-1230,3	59,4	-8,0	39,9	24,7	-104,3	-102,2	1,37	-1109,5	344,8	63,1	526,0	257,1	294,3	178,8	1157,3	260,6	18,6	18,8	18,7	551,4	589,0	0,2	351,5	680,9	15,2
01-10-2019	-536,5	-2172,5	58,1	-30,7	165,0	18,2	-166,8	-146,7	1,34	-1686,8	2262,9	66,1	608,0	263,0	297,4	195,4	665,2	1714,8	15,7	15,5	15,6	560,4	674,1	1,1	2335,1	749,7	11,6
01-11-2019	-844,6	-4490,1	41,0	-37,8	195,7	-1,3	-333,1	-118,7	1,33	-3149,3	6711,6	62,0	655,3	254,0	291,4	191,1	396,6	5079,3	13,9	12,8	13,3	545,5	717,3	3,0	6995,8	747,8	6,6
01-12-2019	-952,7	-5150,1	38,0	-49,9	214,3	-1,5	-377,5	-168,9	1,69	-4221,2	8580,7	67,1	693,6	272,3	310,9	205,0	354,7	6480,9	13,8	12,6	13,2	583,2	760,7	3,9	8998,6	856,7	6,1
<b>Total heat losses &amp; gains (kWh)</b>																											
2019	-8204,0	-35424,6	735,5	-723,6	876,0	5,4	-2608,6	-1914,4	1,45	-30699,8	46911,7	768,7	6466,5	3111,9	3549,1	2167,3	13858,6	35439,6				<b>6661,0</b>	<b>7235,2</b>	<b>22,1</b>	<b>49145,1</b>	<b>9228,1</b>	
<b>Total energy usage (kWh)</b>																											
Total elec usage	<b>13918,4</b>																										
Total gas usage	<b>58373,3</b>																										
Total energy usage	<b>72291,6</b>																										

### C.4 Results of the renovation model simulation

Monthly heat gains and losses																																		
	Glazing	Walls	Ceilings (int)	Floors (int)	Ground Floors	Partitions (int)	Roofs	Internal Natural vent.	Mech Vent + Nat Vent + Infiltration	External Infiltration	Radiant + Convective Heating	Task Lighting	General Lighting	Miscellaneous	Process	Computer + Equip	Occupancy	Solar Gains Exterior Windows	Zone Sensible Heating	Zone Sensible Cooling	Air Temperature	Radiant Temperature	Operative Temperature	Heat Recovery Sensible Heating	Heat Recovery Total Heating	Heat Recovery Sensible Cooling	Heat Recovery Total Cooling	Room Electricity	Lighting	System Fans	System Pumps	Heating (Electricity)	Outside Dry-Bulb Temperature	Generation (Electricity)
	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	ac/h	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	°C	°C	°C	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	°C	kWh
01-01-2019	-663,2	-301,6	-21,5	29,5	30,6	9,3	-457,1	-2,7	0,59	-1407,9	9310,5	31,0	328,1	148,5	0,0	203,9	155,2	225,0	1262,8	-9,7	18,1	18,1	648,3	648,3	0,0	0,0	352,4	359,1	67,7	4,0	14832,5	3,8	-178,4	
01-02-2019	-430,8	-675,3	-8,2	5,2	8,4	-4,4	-348,5	-1,4	0,55	-985,2	6390,2	27,6	282,7	134,5	0,0	185,5	139,5	477,6	897,4	-6,4	18,3	18,2	18,2	494,9	494,9	0,0	0,0	320,0	310,3	61,1	2,9	10317,5	6,3	-508,9
01-03-2019	-397,9	-612,8	-10,5	8,3	0,9	-3,2	-326,1	-4,6	0,64	-1195,6	6131,3	29,9	292,7	147,9	0,0	204,8	153,1	562,6	871,2	-4,5	18,4	18,4	18,4	486,4	486,4	0,0	0,0	352,8	322,6	67,7	2,9	9954,8	7,9	-728,3
01-04-2019	-159,3	-1301,1	50,3	-54,3	-26,4	-6,1	-267,9	-3,8	0,52	-622,6	2659,1	30,7	237,9	149,3	0,0	205,7	146,3	1147,9	383,7	-10,6	19,7	19,6	19,7	390,9	390,9	-0,9	-0,9	355,0	268,6	65,5	1,7	4703,5	11,0	-1433,7
01-05-2019	-116,2	-1289,1	48,0	-66,0	-29,8	-6,0	-239,7	-6,5	0,48	-527,7	1950,2	29,9	214,2	144,4	0,0	198,8	142,3	1194,1	258,5	-9,2	19,8	19,8	19,8	380,5	380,5	0,0	0,0	343,2	244,1	67,7	1,5	3581,7	11,7	-1468,9
01-06-2019	23,3	-1394,8	92,2	-134,5	-147,0	-26,0	-158,9	-7,0	0,46	-244,0	121,4	29,1	197,1	143,4	0,0	198,4	110,0	1275,6	75,2	-16,1	23,6	23,5	23,5	266,2	266,2	-4,3	-4,3	341,8	226,2	65,5	0,9	764,5	17,8	-1590,8
01-07-2019	-8,9	-1372,7	109,5	-102,5	-150,3	-2,2	-190,1	-5,1	0,44	-272,7	11,8	31,5	209,4	152,0	0,0	209,1	108,0	1267,9	52,2	-16,0	24,9	24,8	24,8	296,2	296,2	-6,1	-6,1	361,1	240,9	67,7	0,9	614,2	18,7	-1483,7
01-08-2019	-17,7	-1263,0	95,0	-88,5	-125,8	6,5	-190,8	-9,9	0,48	-249,6	4,4	29,9	224,3	146,2	0,0	201,8	108,5	1110,7	51,8	-11,0	24,4	24,2	24,3	265,6	265,6	-3,2	-3,2	348,0	254,2	67,7	0,9	563,6	18,8	-1354,2
01-09-2019	-107,0	-1021,2	62,0	-15,6	-28,1	25,7	-205,9	-5,2	0,49	-329,7	521,6	29,6	261,0	145,2	0,0	200,6	134,6	746,8	96,8	-4,7	21,1	21,0	21,1	275,2	275,2	-0,8	-0,8	345,8	290,6	65,5	1,0	1342,8	15,2	-881,6
01-10-2019	-269,9	-633,0	-1,2	8,5	-0,3	10,9	-237,2	-0,4	0,52	-552,2	3146,8	31,0	302,3	148,5	0,0	203,9	151,5	430,0	316,7	-2,2	19,1	19,0	19,0	354,4	354,4	-0,1	-0,1	352,4	333,3	67,7	1,8	5380,1	11,6	-435,1
01-11-2019	-500,0	-417,5	-19,3	20,1	11,6	0,3	-358,9	4,0	0,53	-947,2	6877,1	29,1	329,8	143,4	0,0	198,4	149,0	256,0	830,8	-5,0	18,3	18,2	18,2	518,8	518,8	0,0	0,0	341,8	358,9	65,5	3,0	11039,0	6,6	-223,1
01-12-2019	-558,0	-387,5	-21,6	17,6	12,2	-1,3	-390,6	3,4	0,61	-1253,4	7963,2	31,5	349,6	153,7	0,0	212,1	159,9	229,0	1084,9	-5,8	18,2	18,2	18,2	557,3	557,3	0,0	0,0	365,9	381,1	67,7	3,5	12758,1	6,1	-172,9
<b>Total heat gains and losses (kWh)</b>																																		
2019	-3205,7	-10669,6	374,8	-372,2	-443,9	3,5	-3371,8	-39,1	0,52	-8587,8	45087,5	360,7	3229,2	1757,2	0,0	2423,0	1657,8	8923,2	6182,1	-101,2				4934,6	4934,6	-15,4	-15,4	<b>4180,3</b>	<b>3589,9</b>	<b>797,0</b>	<b>24,9</b>	<b>21672,1</b>		<b>-10459,6</b>
<b>Total energy usage (kWh)</b>																																		
Total usage	<b>30264,1</b>																																	
Total production	<b>-10459,6</b>																																	
Total demand	<b>19804,5</b>																																	

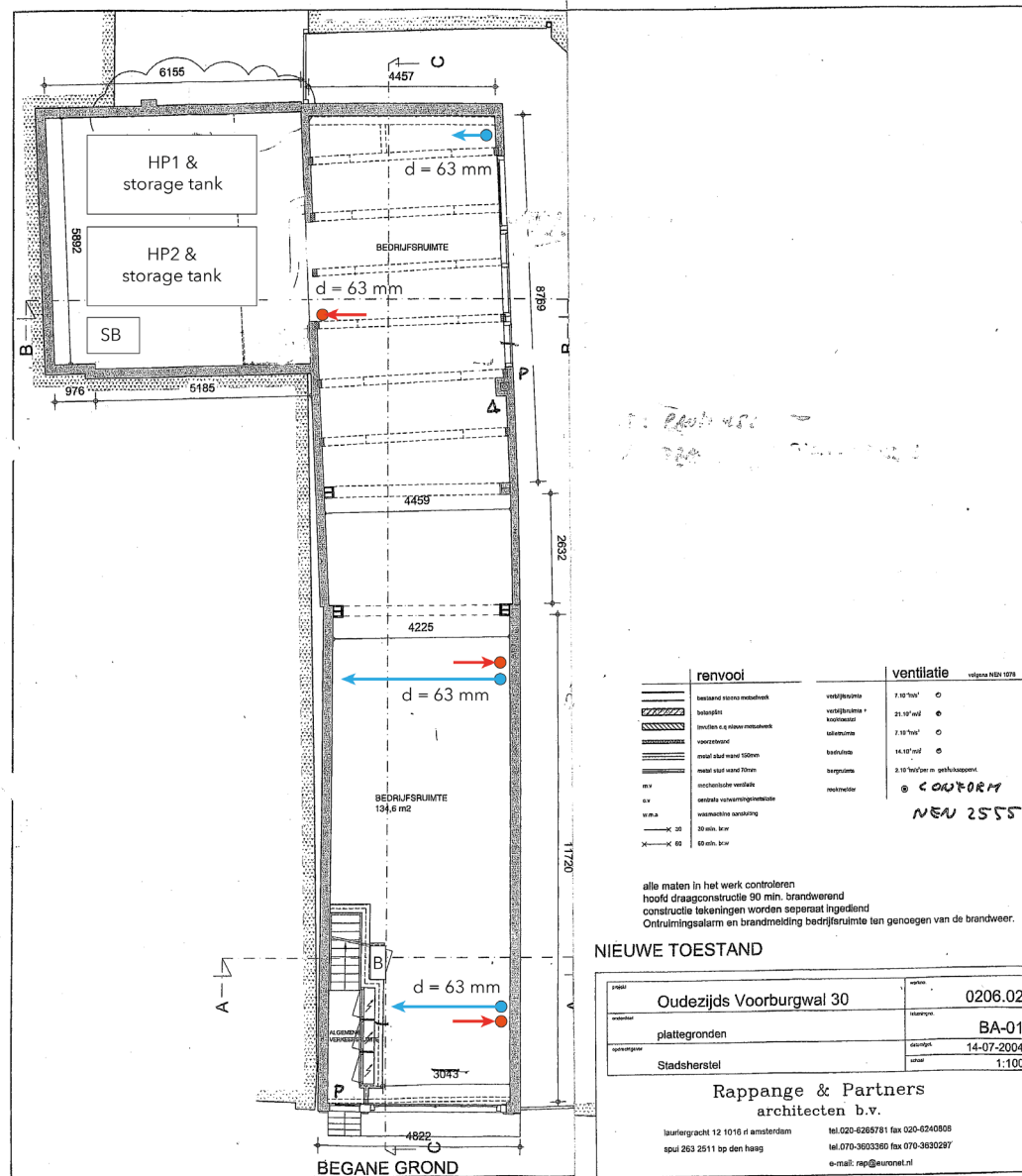
# Appendix D: Specifications of the Design

## D.1 Heating and DHW scheme



Simplified scheme heating & DHW system of proposed design. Own work.

## D.2 Location HVAC installations



Location ventilation ducts ground floor. Adapted from Stadsherstel, 2005.



Location ventilation ducts first and second floor. Adapted from Stadsherstel, 2005.



### D.3 PV panel calculation

Dimensions roofs							
	Length (m)	Height (m)	Area (m2)	Orientation	Inclination	Efficiency	
Roof area back house	8,8	3,8	32,9	SSE	55	95%	
Dormer back house (minus)	1,5	1,9	2,9	SSE	90	N.A.	
Dormer roof (plus)	1,2	1,5	1,8	Flat	0	90%	
<b>Back house total</b>	N.A.	N.A.	31,8	SSE	55	95%	
Front house	11,7	4,8	56,2	SSE	60	95%	
Dormer front house (minus)	1,8	4,0	7,2	SSE	0	N.A.	
Dormer roof (plus)	1,8	2,7	4,9	SSE	55	95%	
<b>Front house total</b>	N.A.	N.A.	53,8	SSE	60	95%	
Back house (never visible from street)							
	Length (m)	Height (m)	Area (m2)	Capacity (Wp)	Capacity location	Amount possible	Production (kWhe)
<b>PV panel (not visible)</b>	1,0	1,6	1,6	320	273,6	15	4104,0
<b>PV roof tile</b>	N.A.	N.A.	1	110	94,1	N.A.	2994,3
<b>PV roof tile Tesla</b>	N.A.	N.A.	1	220	188,1	N.A.	5988,6
Front house							
	Length (m)	Height (m)	Area (m2)	Capacity (Wp)	Capacity location	Amount possible	Production (kWhe)
<b>PV panel (non visible)</b>	1,0	1,6	1,6	320	273,6	13	3556,8
<b>PV panel (visible)</b>	1,0	1,6	1,6	320	273,6	19	5198,4
<b>PV roof tile (non visible)</b>	N.A.	N.A.	1	110	94,1	N.A.	3933,2
<b>PV roof tile (visible)</b>	N.A.	N.A.	1	110	94,1	N.A.	5061,8
<b>PV roof tile Tesla (non visible)</b>	N.A.	N.A.	1	220	188,1	N.A.	7866,3
<b>PV roof tile Tesla (visible)</b>	N.A.	N.A.	1	220	188,1	N.A.	10123,5
Total (kWhe)							
						Production (kWhe)	% of current usage
<b>PV panel (non visible)</b>						7660,8	11,1%
<b>PV panel (visible)</b>						9302,4	13,5%
<b>PV roof tile (non visible)</b>						6927,5	10,1%
<b>PV roof tile (visible)</b>						8056,1	11,7%
<b>PV roof tile Tesla (non visible)</b>						13855,0	20,1%
<b>PV roof tile Tesla (visible)</b>						16112,2	23,4%

Exasun. (2021, March). X-Glass. <https://exasun.com/bestellen/zonnepanelen/x-glass/>

Hanenergy. (2019, March). Hantile solar roof tiles. Hanergy. <https://www.hanergy.eu/hantile-solar-roof-tiles/>

Tesla. (n.d.). Solar Roof Tesla. [https://www.tesla.com/nl\\_nl/solarroof](https://www.tesla.com/nl_nl/solarroof)

#### D.4 Ventilation ducts calculation

Dimensions & occupancy						
	Floor area (m <sup>2</sup> )	Occupancy	Min. Ventilation per person (m <sup>3</sup> /h)	Min. Ventilation per person (l/s)	Needed ventilation (m <sup>3</sup> /h)	
<b>30A</b>	144	± 4	15	4	60	
<b>30B</b>	82	2	25	7	50	
<b>30C</b>	76	2	25	7	50	
<b>30D</b>	79	2	25	7	50	
<b>Total</b>	381	± 10	25	7	210	
Duct sizes total						
	Ventilation (m <sup>3</sup> /h)	Speed in general shaft (m/s)		Diameter shaft (mm)		
<b>30A</b>	60	3,32		80 (2x)		
<b>30B</b>	50	2,76		80 (2x)		
<b>30C</b>	50	2,76		80 (2x)		
<b>30D</b>	50	2,76		80 (2x)		
<b>Total</b>	210	2,9		160 (2x)		
Duct sizes inlet						
	Ventilation (m <sup>3</sup> /h)	# of inlets	Speed in general shaft (m/s)	Diameter shaft (mm)		
<b>30A</b>	60	3	1,78	63		
<b>30B</b>	50	3	1,51	63		
<b>30C</b>	50	3	1,51	63		
<b>30D</b>	50	3	1,51	63		
Duct sizes outlet						
	Ventilation (m <sup>3</sup> /h)	# of inlets	Speed in general shaft (m/s)	Diameter shaft (mm)	Needed	
<b>30A</b>	60	3	1,78	63	2 x 80	
<b>30B</b>	50	4	1,11	63	2 x 80	
<b>30C</b>	50	4	1,11	63	2 x 80	
<b>30D</b>	50	4	1,11	63	2 x 80	

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D.5 Embodied energy calculation

Front house									
Element	Material	Surface area (m2)	Thickness (m)	Volume (m3)	Density (kg/m3)	Weight (kg)	Embodied energy (MJ/kg)	Total embodied energy (MJ)	Total embodied energy (kWh)
Wall heating system	Plastic holders	12,5	0,0	0,2	1380,0	258,3	105,8	27331,9	7592,2
	Aluminium pipes	3120 (m)	0,0000477 (m2/m)	0,1	2700,0	401,8	157,1	63126,7	17535,2
	Plaster	312,0	0,0	6,6	849,0	5562,6	1,8	10012,8	2781,3
Windows	Double glazing	17,4	N.A.	N.A.	N.A.	N.A.	432 (MJ/m2)	7516,8	2088,0
	Wooden frames	4,4	0,1	0,2	520,0	114,4	9,2	1057,1	293,6
Roof insulation (sloped)	PIR	112,4	0,1	14,8	61,6	913,9	92,8	84814,3	23559,5
	Water barrier	112,4	0,0	0,0	89,3	3,0	83,1	250,2	69,5
	Vapor barrier	112,4	0,0	0,0	89,3	1,0	83,1	83,4	23,2
	Tesla roof tiles	53,8	N.A.	N.A.	N.A.	N.A.	4070 (MJ/m2)	218966,0	60823,9
Floor insulation (BH &FH)	Tonzon	145,0	N.A.	N.A.	0,06 (kg/m2)	8,7	80,5	700,4	194,5
<b>Total front house</b>								<b>413859,5</b>	<b>114961,0</b>
Back house									
Element	Material	Surface area (m2)	Thickness (m)	Volume (m3)	Density (kg/m3)	Weight (kg)	Embodied energy (MJ/kg)	Total embodied energy (MJ)	Total embodied energy (kWh)
Exterior insulation	EPS	199,5	0,1	27,9	87,8	2452,3	88,6	217269,7	60352,7
	Plaster	199,5	0,0	4,0	849,0	3387,5	1,8	6097,5	1693,8
Windows	Double glazing	36,7	N.A.	N.A.	N.A.	N.A.	432 (MJ/m2)	15854,4	4404,0
	PVC	9,9	N.A.	N.A.	N.A.	N.A.	2069 (MJ/m2)	96415,4	26782,1
Roof insulation (sloped)	PIR	65,8	0,1	8,7	61,6	535,0	92,8	49651,1	13792,0
	Water barrier	65,8	0,0	0,0	89,3	1,8	83,1	146,5	40,7
	Vapor barrier	65,8	0,0	0,0	89,3	0,6	83,1	48,8	13,6
	Tesla roof tiles	32,4	N.A.	N.A.	N.A.	N.A.	4070 (MJ/m2)	131868,0	36630,0
Roof insulation (terrace)	PIR	34,1	0,1	4,5	61,6	277,3	83,1	23041,5	6400,4
Roof tiles reused	Water barrier	34,1	0,0	0,0	89,3	0,9	92,8	84,8	23,5
	Vapor barrier	34,1	0,0	0,0	89,3	0,3	83,1	25,3	7,0
Roof insulation IM	PIR	3,9	0,1	0,5	61,6	31,7	92,8	2942,8	817,5
Roof tiles reused	Water barrier	3,9	0,0	0,0	89,3	0,1	83,1	8,7	2,4
	Vapor barrier	3,9	0,0	0,0	89,3	0,0	83,1	2,9	0,8
<b>Total back house</b>								<b>543457,4</b>	<b>150960,4</b>
<b>Total (kWh)</b>									
<b>Total</b>								957316,9	265921,4
<b>Total per year (50 years)</b>								19146,3	5318,4
<b>Total per year (25 years)</b>								38292,7	10636,9

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## D.6 Cost calculation

Current energy costs (EUR)					
		Amount	Cost per unity	Total cost	
<b>Gas</b>	Usage	m <sup>3</sup>	5722,9	0,82	4692,8
	Gas supply costs (4x)	days	365	0,129	188,3
	Network management costs (4x)	days	365	0,433	632,2
<b>Electricity</b>	Usage	kWh	13918,4	0,23	3201,2
	Supply costs (4x)	days	365	0,129	188,3
	Management costs (4x)	days	365	0,572	835,1
	Tax reduction (4x)	days	365	-0,706	-1030,8
<b>Total energy costs</b>					<b>8707,2</b>
Renovation energy costs (EUR)					
		Usage	Cost per unity	Total cost	
<b>Gas</b>	Usage	m <sup>3</sup>	0	0,82	0
<b>Electricity</b>	Usage	kWh	14151,9	0,23	3254,9
	Supply costs (4x)	days	365	0,129	188,3
	Network management costs (4x)	days	365	0,554	808,8
	Tax reduction (4x)	days	365	-0,706	-1030,8
<b>Total energy costs</b>					<b>3221,4</b>
Savings (EUR)					
<b>Total savings</b>					<b>5485,873</b>
Investment cost (EUR)					
Investment cost insulation					73864
<b>Total investment cost</b>					<b>168179,0</b>
Payback time (years)					
Payback time insulation					13,5
<b>Total payback time</b>					<b>30,7</b>

Investment cost (EUR)							
	Measures	EUR/m <sup>2</sup>	EUR/piece	m <sup>2</sup>	Amount	Cost (EUR)	
<b>General</b>	Exterior insulation facades BH	150	N.A.	199,5	N.A.	29925	
	Exterior insulation sloped roof BH	175	N.A.	65,8	N.A.	11515	
	Exterior insulation flat roofs BH	125	N.A.	38	N.A.	4750	
	Interior insulation sloped roof FH	85	N.A.	112,4	N.A.	9554	
	Double glazed windows FH & BH	200	N.A.	54,1	N.A.	10820	
	Crack and seam filling	N.A.	1500	N.A.	1	1500	
	Insulation ground floor FH & BH	40	N.A.	145	N.A.	5800	
	Shower heat recovery	N.A.	1505	N.A.	3	4515	
	LED lighting	N.A.	4	N.A.	60	240	
	Radiator fans	N.A.	50	N.A.	24	1200	
	Water reducing faucets & shower heads	N.A.	65	N.A.	12	780	
	<b>Heating</b>	Aquathermal system & heat pumps	N.A.	25000	N.A.	2	35000
		Individual electric boilers	N.A.	1500	N.A.	4	6000
		Wall heating system FH	75	N.A.	312	N.A.	23400
LT radiators		N.A.	800	N.A.	24	19200	
<b>Ventilation</b>	Air handling unit & ducts	N.A.	5500	N.A.	1	5500	
<b>Produce</b>	Tesla PV roof tiles	400	N.A.	86,2	N.A.	34480	
Investment cost (EUR)							
Investment cost insulation						73864	
Investment heating system						83600	
Investment cost PV						34480	
Investment cost other						12235	
<b>Total investment cost</b>						<b>204179</b>	
Subsidies (EUR)							
Heat pump (ISDE)						-8000	
Off natural gas (Municipality Amsterdam)						-3000	
Discount environmental permit due to sustainable renovation (Rijksoverheid)						-25000	
<b>Total subsidy amount</b>						<b>-36000</b>	
Total investment (EUR)							
<b>Total investment cost</b>						<b>168179</b>	

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