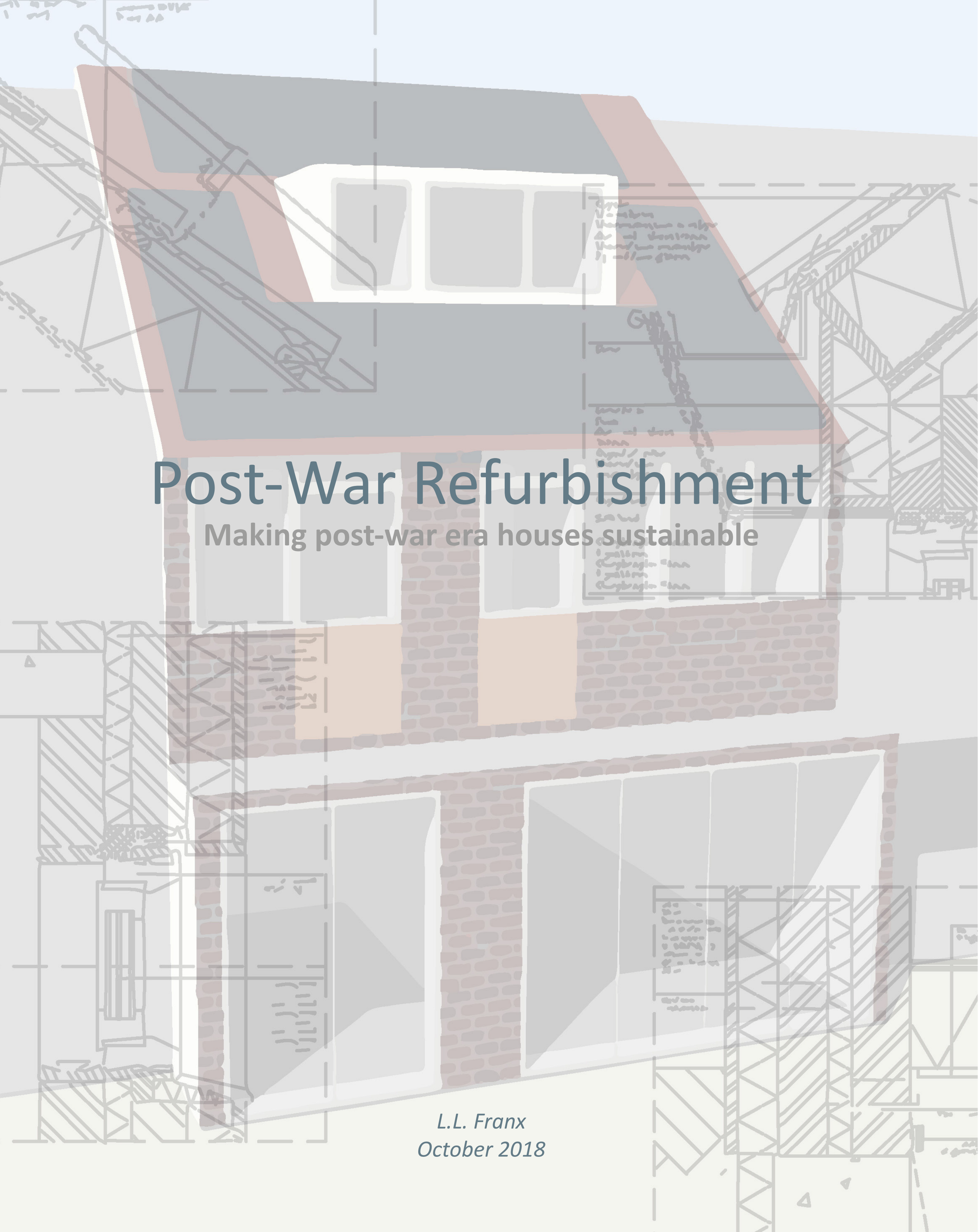

Post-War Refurbishment

Making post-war era houses sustainable

L.L. Franx

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L.L. Franx
Delft, October 2018

Abstract

The Netherlands faces climate change due to global warming and earthquakes due to gas production. To decrease both earthquakes and CO_2 production, the government aims to half the gas production in the coming four years and aims for an entire stop by 2030. Over 80% of Dutch houses are heated with gas; 20% were built in the late post-war era (1960-1974) and these houses consume the most gas due to low levels of insulation. As most of these houses are very similar in construction they have a high potential for large scale refurbishment strategies. Therefore, the aim of this study was to create three strategies with each a different level of improvement, applicable to multiple building types of late post-war era houses.

A row house was used to develop and test the strategies and a semi-detached and a free-standing house were used to test the versatility. Testing was performed with Design Builder and Uniec 2.2, both energy performance programs. Based on a literature review and analysis of the case study, the strategies developed were a basic insulation strategy (A), Energy Performance Coefficient (EPC) ≤ 0,4 strategy (B), and a Net Zero Energy Building (NZEB) strategy (C). Strategy A consists merely of basic insulation techniques and the upgrading of old heating systems, which lowers gas consumption with roughly 50% and has a payback time of roughly 15 years. The second strategy aims to lower the EPC to 0,4 or less as is required for newly built houses and consists of higher-level insulation techniques and the use of solar power for heating and electricity. This decreases gas consumption with roughly 75%, electricity consumption with over 45%, has a payback time of roughly 15 years, and a better balanced investment vs. yearly savings. Strategy C adds exterior insulation and installs a hybrid electric boiler, an air heat pump, and solar collectors resulting in a (nearly) NZEB and gas-free house. A very large investment is required for this strategy but the approximate 20 year payback time makes it worthwhile.

The free-standing house was very similar in construction and the three strategies can easily be applied. Strategy A showed similar results, and remarkably both B and C showed both a higher reduction and shorter payback time than with the row house. With strategy C a NZEB could easily be achieved. The semi-detached house has an a-typical construction, monumental status, and air heating system and would require a specific strategy focussing on internal insulation and complete replacement of the heating and ventilation system.

In conclusion, typical post-war era houses can easily be refurbished with these three strategies whereas a-typical houses will require a specific strategy. From a long-term societal perspective, I recommend the NZEB strategy. From the homeowner's perspective, the EPC ≤ 0,4 strategy is probably the best achievable given the required investments. If we really want to reduce global warming and reduce gas consumption, major steps still have to be taken by the government and industry.

Contents

1. Introduction

Global warming is becoming an increasing issue of the modern world. The burning of fossil fuels produces greenhouse gasses, causing temperatures to rise. In turn, this rise in temperatures leads to the melting of polar ice and snow, causing sea levels to rise. According to R. Lindsey (2016) the global sea level has risen with 6,7cm between 2014-1993 and will continue to rise with a yearly rate of 3,2mm. For low lying countries such as the Netherlands this rise in sea levels can have devastating effects. However, this is not the only effect. Rising air and water temperatures are causing drastic climate change which may spiral out of control. According to Bintanja and Andry (2017) the lack of polar ice will strongly increase the amount of precipitation in the Arctic region. However, due to higher temperatures this will mainly fall as rain, speeding up the melting process of the permafrost layer. This might not sound dangerous but greenhouse gasses have been trapped in the frozen permafrost for thousands of years. When the permafrost melts, these gasses are released into the atmosphere, adding to global warming. In other regions climate change is causing an increasing number of extreme droughts, endangering water supplies and causing devastating fires.

For the Netherlands global warming is not the only problem. Since the discovery of natural gas in the province of Groningen, the Dutch have come to rely heavily on this gas for heating and electricity production. However, the rising number of earthquakes in Groningen has become a major concern in the past decade. In March the government finally decided to take action. Based on the recent advice given by the 'Staatstoezicht op de Mijnen' the government decided to reduce the gas extraction from 21 billion cubic metres to 12 billion cubic metres in the coming four years and stop entirely by 2030 (Santen & Walle, 2018). The majority of Dutch houses rely heavily on this gas for heating, warm water and cooking. Therefore, homeowners can help the government in this process by reducing their energy demand and switching to sustainable energy sources.

Luckily over the past years new techniques have been developed to produce energy with the use of safe and sustainable sources. These techniques rely on wind power, earth heat, water power or sunlight to produce energy in the form of electricity or warm water. Yet, the first and most effective step is simple reducing our overall energy demand, starting with the energy demand of our homes. Until the oil crisis in 1973 fuel was cheap and therefore houses were hardly insulated. The oil crisis finally created energy awareness, increasing ever since. In 1995 a minimum thermal resistance (R_c) was finally included in Dutch building laws and since its introduction the amount of thermal resistance has doubled. Nevertheless, in 2015 only 20% of all Dutch houses were built between 1995 and 2015 (Rijksoverheid, 2016). By refurbishing old houses with insulation and new efficient installations the energy demand of these houses can be reduced drastically. The largest portion of houses, roughly 33%, was built with little to no insulation during the post-war era between 1945 and 1974. As this is the largest portion of houses in the Netherlands, the largest potential for demand reduction can be found within this group. This research will focus on the houses built between 1960 and 1974 as this constitutes roughly 65% of all houses built in the post-war era.

In the world of refurbishment many different possibilities are available. This can make it difficult for homeowners to choose the right techniques and solutions. Luckily houses built between 1960 and 1974 share many similar characteristics.

This provides the possibility for the creation of strategies with different levels of improvement. Homeowners can then choose the desired strategy based on their wishes and budget. Therefore, the aim of this study was to answer the following question:

"Which strategies are possible to reduce energy consumption to different levels for multiple building types built between 1960-1974?"

Within this study the focus will be on Dutch houses built between 1960 and 1974. Therefore, only Dutch regulations, insulation techniques, and installations will be taken into account. However, most of these regulations, techniques, and installations are quite similar to those used in other countries or can easily be adjusted to local preferences.

To answer the set question a row-house in Haarlem, built in 1963, was used as the main case study. The house is located within the Ramplaankwartier neighbourhood where a refurbishment project is underway. The aim of the project is to make the neighbourhood energy neutral and ultimately disconnect it from the national gas network. Three different strategies were created based on this case study, each with a different improvement level. To assess the versatility of the strategies they were tested on two other building types.

This report contains all the gathered information, research and drawn conclusions. First a literary review is given to provide information including characteristics and known problems of houses built in 1960-1974, different types of sustainable designs, possible upgrading techniques, a number of reference projects and a main overview of prices. After a description of the methodology used, detailed information on Dutch refurbishment techniques is given. Next the analysis of the case study is discussed. Subsequently the three different strategies are thoroughly discussed and compared. This is followed by the applicability of the strategies on two other houses, including possible alternatives, and the technical application of the strategies on the main case study. Following the research are the final conclusion and recommendations. The report ends with a reflection on the performed research.

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2. Literature review

This chapter contains the background information gathered at the start and during the research project. It provides a knowledge basis for the rest of this thesis.

2.1. Haarlem

At the start of the research project a row house in Haarlem was set as the main case study. This part contains background information about the city and neighbourhood.

2.1.1. Cultural history

Haarlem is a city in the Netherlands, situated in the province of North-Holland of which it is also the capital, close to Amsterdam, see figure 1. The city was built along the river Spaarne on an old dune ridge and it received its city rights in 1245 (Wikipedia contributors, 2017c). Until the end of the Middle Ages Haarlem played an important role due to its excellent connections with other cities by road and waterway. During the 16th and beginning of the 17th century, after some difficult times, the city grew again as it became the epicentre of the tulip trade and the textile industry was boosted by Flemish and French immigrants. This also brought famous painters such as Frans Hals to the city, see figure 2. In the 1630's a so called period of 'Tulip mania' occurred in the Netherlands, with at its epicentre Haarlem.

During the end of the 17th century the economy gradually decreased as the textile industry decreased and people started moving to Amsterdam, the new economic centre. As Amsterdam expanded rapidly, Haarlem became a slumbering suburb for rich merchants and business owners. A positive side-effect was that a lot of buildings from the Middle Ages and Golden Age have remained intact.

Figure 1: In red the city of Haarlem (Google Maps, 2017).

Figure 2: Wedding portrait by Frans Hals, finished in 1666.

2.1.2. Ramplaankwartier

South-West of the city centre is the neighbourhood Ramplaankwartier, see figure 3. This neighbourhood is situated on an old sand excavation site. In the 15th century the family Ramp acquired the land and a house accompanying it (Wijkraad Ramplaankwartier, 2013). Before the Dutch Reformation the Roman Catholic Ramp family occupied important functions in Haarlem, among which mayor. After the Reformation the still Catholic family was shunned from society and ran into debt. The house was demolished and the land was divided and sold to farmers. At the beginning of the 20th century Bloemendaal built a so-called 'Tuindorp' on part of the land, which is still part of the Ramplaankwartier today. A few years later Haarlem annexed the land and further expanded the 'Tuindorp' and officially created the Ramplaankwartier. After World War II the neighbourhood kept

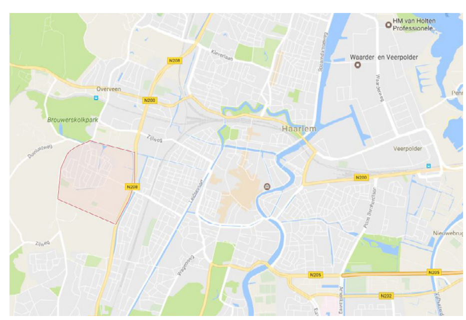

Figure 3: In red the Ramplaankwartier neighbourhood (Google Maps, 2017).

expanding with the last big expansion in the 1960's.

As a result, the majority of houses in the Ramplaankwartier were built between 1920 and 1970. Due to the low amount of energy awareness during this time these houses have a high level of gas consumption. Houses built between 1965 and 1974 have an average gas consumption of 1500m^3, whereas modern day houses have an average gas consumption of only 1000m^3 (Milieu Centraal, 2017). Based on the information provided by a group of inhabitants, the average consumption of the 1960's houses in the Ramplaankwartier is almost 1800m^3. This is significantly higher than the average gas consumption of a vast majority of the other houses in the neighbourhood. Furthermore, the construction methods used for the houses built in the 1960's, 1970's and also 1950's in the neighbourhood are very similar. This makes it very feasible that the developed strategies can be applied to an even larger group of houses.

2.1.3. Conclusion

The old city of Haarlem plays an important historical role within the development of the Netherlands. Not only as an important economic centre but also culturally. The Ramplaankwartier neighbourhood is a relatively new neighbourhood of this city. A portion of the houses in the neighbourhood were built in the 1960's and 70's. Based on the information provided by inhabitants these houses have a higher gas consumption than other houses in the neighbourhood. Furthermore the 1960's and 70's in the neighbourhood are very similar in style making the development of strategies feasible. They are also very similar to the early post-war era houses in the which means that the strategies can possible be applied to these houses as well, if needed with slight alterations.

2.2. Houses from 1960-1974

When handling upgrading projects of late post-war houses there are some general characteristics and problems that have to be considered. A question that also has to be answered is why we would even take the trouble to keep these houses: why not just demolish and replace them with new houses that meet modern requirements?

2.2.1. Characteristics

During the late post-war era, standard row houses were built in the outer neighbourhoods of cities, see figure 4, and large semi-detached and free-standing houses in affluent regions. These houses have certain characteristics that can be divided into three categories, namely: construction technique, exterior appearance, and the floor plan. These will now be described along with photos.

Figure 4: Typical post-war era row houses (Funda.nl, 2017).

Figure 5: An example of houses with dormers (Google Street View, 2016).

During the 1960's concrete became very popular and the use drastically increased over the years. This use of concrete made large expansions possible, creating very flexible floor plans. In the beginning of the 60's ground floors were sometimes still made from wood, but precast concrete or cast-in-situ floors soon gained popularity. The concrete floors often continue into balconies or window lintels creating a cold bridge. Loadbearing floors were always cast-in-situ with steel reinforcement to create larger expansions. Only attic floors were still made from wood. For the outer walls cavity wall structures were always used and sometimes concrete elements were added for extra stability. Concrete bricks were used for interior walls, a double layer being used for loadbearing walls. Roofs were still made of wooden structures in the 60's and 70's with predominately standard Dutch roof tiles as roof covering. Often wooden dormers were added to the roof structure to increase floor space cheaply.

Figure 6: An example of a large green border between the street and houses (Google Street View, 2016).

One main exterior characteristic that sets late post-war houses apart, is the large amount of glazing. Due to the large use of concrete, larger openings could be made in walls resulting in more and bigger windows, see figures 4 and 5. Fixed and openable windows were applied allowing a lot of natural light and fresh air into homes and having a positive effect on inhabitants' wellbeing. Row houses from 1960 to 1974 commonly have pitched roofs with dormers or skylights, see figure 5. Semi-detached and free-standing houses are freer in form and a larger percentage of these houses have slanting or flat roofs.

Figure 7: The living room of a semi-detached house (Franx, 2018).

A change on urban scale was the increase in popularity of the front yard during the 60's. In contrast to before, standard row houses were no longer built close to the side walk but front yards were added to make streets greener and create some distance between the street and the houses, see figure 6.

Figure 8: The small kitchen of a semi-detached house (Franx, 2018).

The floor plans of these houses are characterized by large living rooms, small kitchens, and comfortable sized bedrooms, see figures 7 and 8. Living rooms in standard row houses run the entire depth of the house, allowing light to enter from both sides. In the Netherlands houses with this characteristic are also known as 'Doorzonwoningen', which had their building peak around 1970. Ventilation in these houses is mostly ensured by openable windows and ventilation grills in living areas and extraction points in the kitchen and bathrooms.

2.2.2. Problems

As mentioned before one of the main problems of 1960's and 70's houses is the high energy consumption. Almost 80% of this consumption is used for heating (Milieu Centraal, 2017). This is mainly due to low thermal resistance of the outer surface due to a lack of insulation. The quality and performance of the outer surfaces of a dwelling are essential for the heating consumption of a dwelling as this defines the heat loss and gain of the house (Konstantinou, 2014). This lack of insulation is mainly due to the lacking of insulation regulations during this time period and project managers often wanted to keep the building costs as low as possible.

Exterior walls commonly only have an air cavity which has over time often lost its function as debris has collected in it, lowering the thermal resistance or R_c-value. Exterior panels beneath windows are thin and therefore hardly insulated. Single glazing was still installed during 60's although double glazing did become popular in the 70's, especially after the oil crisis in 1973.

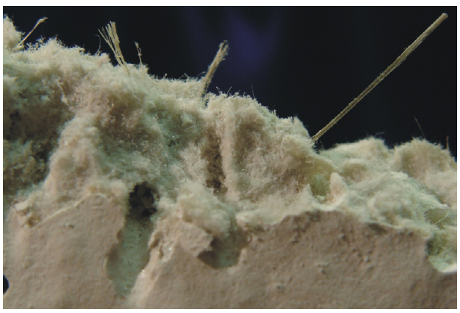

Figure 9: An example of processed asbestos (Flickr, 2017).

A major problem when renovating 1960's and 70's houses is the presence of asbestos, see figure 9. Asbestos building materials were very popular in this period and therefore many houses contain asbestos in some form. Most of these materials are not dangerous when left alone but during a fire or the removal process dangerous particles can come free which can lead to lung tumours (mesothelioma). Therefore, the asbestos has to be removed by specialised workers using special equipment.

Figure 10: An example of cracked concrete (Franx, 2017).

Also, certain building methods have to be taken into account. During the 1960's and 70's the so called 'Kwaaitaal' and 'Manta' floors were used. Calcium chloride had been added to these floors to speed up the hardening process of the concrete (Wikipedia contributors, 2017d). Over time the calcium chloride can cause corrosion of the steel enforcement causing concrete parts to break free and the floor to lose its strength, see figure 10. Furthermore, balconies and a large portion of widow lintels were directly connected to the internal floor, creating large cold bridges.

In this period thicker walls and floors were used in constructions decreasing airborne noise. However, the concrete floors often span multiple houses increasing structural-borne noise. What is more, sometimes metal elements, for example staircases, were directly attached to the concrete. Structural-borne noise disturbance is therefore often an issue in these houses.

Figure 11: An example of eroded pointing work (Franx, 2017).

During the 1960's and 70's Spruce wood was commonly used for window frames. However, this type of wood requires high maintenance because it tends to rot fast. Spruce wood frames placed in this period nowadays commonly have to be replaced because they have disintegrated beyond repair.

Due to the use of a different kind of mortar during the 1960's and 70's, the pointing of brick walls has often eroded, see figure 11. This can easily be restored by repointing the brickwork. When repointing the correct mortar has to be chosen to ensure that water inside the brickwork can still evaporate. This is easily done wrong, causing pointing or even bricks to become damaged in the future.

The last areas of concern are the electricity networks and plumbing fixtures. A standard thing to do when upgrading a 1960's and 70's house is redoing the whole electricity network and creating new electricity groups. This is important because the network has often been extended over the years in an unsafe way, often causing a lot of high energy consuming appliances to be in the same group. The plumbing fixtures aren't as big of a problem as plumbers take this into account, therefore it is more something to keep in mind. Nowadays a different standard diameter is used for water pipes. When replacing for example a boiler, the old pipes will not fit on the new boiler and special connecting pieces can be used to solve this.

2.2.3. Why keep these houses?

If there are so many problems with 1960's and 70's houses, one may wonder why we should not just replace them with modern houses. There are, however, certain reasons to maintain these houses.

For one, these houses were built during the peak of the 'Doorzonwoningen'. During this peak the widest expansion was used when building row houses which, in part, led to the characteristic large windows. This combination of characteristics created very comfortable houses as they are light and often very spacious. Due to the low building costs these houses were, and still are, very popular, especially in the lower price segment.

Another positive effect of large windows is that less artificial lighting is needed during the day and it has a positive effect on a person's health. When indoors it helps to retain a healthy sleep rhythm, which is very important for a person's wellbeing. Houses with large amounts of natural light therefore have happier, healthier, and more productive inhabitants. This is therefore a characteristic that should certainly be retained.

Especially on the level of sustainability there is a very good reason to retain these houses. The building materials of these houses mainly consist of bricks and concrete which are both materials that are very difficult to reuse in the same way. Of these materials bricks are the easiest to reuse, however, this does require careful handling during demolition to keep the bricks intact. Concrete is more difficult to reuse and almost impossible to reuse as a building material for houses again, especially when steel reinforcement and additives are present in the concrete. After demolition the concrete rubble often ends up in a landfill which is a waste of material as the concrete is often still in good condition. Moreover, cement, a major component of concrete, is a major producer of CO_2 emissions (Dhami, Reddy, & Mukherjee, 2012).

Upgrading houses gives the concrete structure a second life and reduces CO_2 production.

Another reason to choose for upgrading instead of replacement is very simply the total cost. When upgrading houses, the costliest elements such as the main structure are maintained. This means only smaller elements are replaced and new elements are added. In most cases these new elements would also have been placed if the old house had been replaced which means these costs are the same. Demolishing a house also creates other costs as the debris of the old house has to be disposed of and the site requires preparing for the new house. All these factors make upgrading a better option when the main structure is still in good condition.

2.2.4. Conclusion
Due to the large living spaces and windows but mostly the relatively low prices of 1960's and 1970's houses, these houses are still very popular today. However, to achieve these low prices some corners were cut resulting in some well-known problems which can occur. Most of these problems can easily be solved by renovating these houses with the use of modern techniques. As the main structure of these houses is often still in good condition renovation is a more sustainable and also cheaper solution than demolition.

2.3. Sustainable design definitions
Over the past few years many types of sustainable design terms have developed. This large amount of terms can often cause confusion when talking about sustainable designs as people often use the wrong terms when talking about sustainability. Below are a few popularly used terms and their precise meaning.

2.3.1. Energy neutral design
This is a collective term used for any type of project that focusses on the environment and low energy consumption during all planning and production stages (Wikipedia contributors, 2017a). Most people in the Netherlands however use this term to refer to buildings that consume no to hardly any fossil fuel-based energies.

2.3.2. Green/Sustainable building
A green or sustainable building refers to any building that is environmentally responsible and resource-efficient during its entire lifecycle (Wikipedia contributors, 2017b). This includes design, construction, maintenance, and demolition of the building. LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) are both rating systems for sustainable buildings. BREEAM

can also be applied to large scale developments.

2.3.3. Net Zero Energy Building

A Net Zero Energy Building or NZEB produces the same amount of sustainable energy as the total amount of energy, building and user-related, it consumes during one year (Wikipedia contributors, 2017a). When its production of renewable energy is not enough to meet the households demand, non-renewable energy is consumed. This is compensated by supplying renewable energy when production is higher than the demand. Houses that produce more energy than needed in a year are called Energy-Plus Buildings, when a house produces slightly less it is a Near Net Zero Energy Building.

2.3.4. Off-the-grid

True off-the-grid buildings or communities are self-sufficient and are therefore independent of public utilities. These buildings or communities have their own energy and water supply and sewer system (Wikipedia contributors, 2017e). These types of buildings or communities can already be found in remote places where public utilities cannot be provided, often also supplying most of their own food. However, over the past few years off-grid has been promoted as a lifestyle and more people in populated areas are constructing homes that are self-sufficient in one or more of these utilities. Partial off-the-grid houses only supply one or two utilities themselves, in the Netherlands these houses commonly do not require gas.

2.3.5. Passive House Principle

The Passive House Principle, or PHP, is a design process which aims to massively decrease the heating demand. To achieve this, multiple techniques are applied. Passive houses are often compact in size to reduce outer surface area and orientated towards the sun. Especially in colder climates passive solar gain is maximized with principal windows facing the sun and limited windows in the dark façade. Superinsulation is applied to reduce heat loss through walls, floor and roof and special attention is given to thermal bridges. Special windows with remarkably low thermal conductivity (U-values) for the entire window, including the frame, are installed. Ventilating passive houses can be done by passive natural ventilation or, more commonly, by mechanical ventilation with efficient heat recovery. This can be combined with earth tubes to passively preheat or precool intake air. To prevent heat escaping through air leaks extreme airtightness is required, during construction this can be tested with a blower door test. The primary source of space heating is provided by passive solar gain and waste heat from internal sources whereas for cooling external features are applied such as trees, green roofs, and passive shading. To ensure heating and/or cooling on extreme days a heating and/or cooling element can be integrated in the ventilation system. The element can be heated by a heat pump or using solar energy. The passive house principle can be applied to achieve a partial or total off-the-grid building.

2.3.6. Conclusion

The term that applies best to the goal of the Ramplaankwartier neighbourhood of becoming a Sustainable Neighbourhood by removing itself from the gas network, is partial off-grid. This means an alternative has to be provided for cooking and heating for which gas is currently being used.

2.4. Upgrading dwellings

A house can be upgraded by a number of different techniques, each with its own aim. To choose the best suitable upgrading technique, first an inventory of all the available techniques and their aims have to be defined. Based on each aim the best upgrading technique can be chosen.

2.4.1. Restoration

When restoring a building it is returned to its original state or design (Cambridge Dictionary, 2018c). Restoration is commonly applied to monumental buildings e.g. churches and old town halls which are not allowed to be altered in appearance. According to Zijlstra (2012) the term restoration ranges from bringing a building back to the state which it had when first completed to preserving the building in the state in which it was found.

2.4.2. Renovation/Modification

In the Cambridge Dictionary (2018b) renovation is described as "the process of repairing and improving a building so that it is in good condition again". According to Giebeler et al. (2009) this only implies replacement and repair of defect building components. No new components are added to the building but existing component are maintained and upgraded in value and function (Zijlstra, 2012).

2.4.3. Refurbishment

The Cambridge Dictionary (2018a) describes refurbishment as any work done on a building which makes it new again. This includes the replacement of outdated components which are still intact, in contrast to renovation/modification which focusses on defect components (Giebeler et al., 2009).

There are three types of refurbishment: partial, normal, and total refurbishment (Giebeler et al., 2009). Partial renovation is only applied to one component or part of a building, for example the façade or ground floor. When the refurbishment measures encompass the whole building, normal refurbishment is applied. Total refurbishment includes large scale demolition to reduce the building commonly to its loadbearing skeleton.

A more extreme form of refurbishment is conversion. The conversion process includes refurbishing a building in combination with changing the load bearing structure and/or interior layout. This requires inspection of the existing structure and structural calculations for the changes. Often total refurbishment projects include some form of conversion work meaning that these projects can better be described as "total refurbishment plus conversion" (Giebeler et al., 2009).

2.4.4. Intervention
An intervention is performed when only one part of a building is changed e.g. the west wing or roof (Zijlstra, 2012). The term intervention only refers to the location and not the process which is applied e.g. refurbishment.

2.4.5. Transformation
When a building undergoes a transformation, it is significantly improved by completely changing its appearance and function (Cambridge Dictionary, 2018d). The existing building is drastically changed to house a new function and comply to new requirements. This can be done on two levels: by only changing the interior of the building, which is often applied to monumental buildings e.g. the old TU Delft library, or by changing both the interior and exterior.

2.4.6. Addition/Extension
As the word suggests addition refers to adding a new structure to a building. This can be for example a second façade or an extra floor space. At the connection with the existing building some form of conversion work is always required and therefore structural issues always play a part (Giebeler et al., 2009). Addition/extension can be performed in combination with other processes.

2.4.7. Conclusion
For the Ramplaankwartier project the term 'refurbishment' is best suited since defective elements, but also outdated elements, have to be replaced during the upgrading processes. As the whole house will be changed while the function stays the same, the terms intervention and transformation are not applicable. The term addition/extension could be added to the refurbishment term if

during the design and testing process an extra space is deemed beneficial.

2.5. Refurbishment strategies

According to Konstantinou (2014) all refurbishment projects are based on one or more of five main strategies. The main strategies are replace, add-in, wrap-it, add-on, and cover-it. All five have their own benefits, limitations and variations.

2.5.1. Replace

A common strategy to improve a building is to replace the old façade, or parts of it, with a new one, see figure 12. This increases the thermal and acoustic performance of the façade. Removing the entire façade allows the creation of a new façade which meets all the current requirements but also gives the opportunity to redesign the layout and utilities. When applying this strategy extra attention must be given to connections to the old façade and thermal bridges.

Figure 12: Before and after facades of the GAK-gebouw in Amsterdam (rufusdevries.nl).

2.5.2. Add-in

The second option is insulating a building on the inside, this option is often used when handling a monumental building. This is done by adding insulation internally to external surfaces and replacing windows, see figure 13. This method of adding insulation however does not solve thermal bridges, which can cause moisture problems if these connections are not handled with extra care. The main negative aspect of this strategy is the decrease in space due to the fact that a new layer is added to the inside of the walls.

Figure 13: An internally insulated attic (bedi.nl).

2.5.3. Wrap-it

The reverse option is to add a second layer to the outside of the building or 'wrapping'. With this method a new layer is added to the existing façade, consisting of insulation and new cladding. This method can also include wrapping balconies, see figure 14, or creating a buffer zone by installing a second façade. Wrapping a façade solves thermal bridges, gives the façade a nice facelift, and protects the old walls from further damage.

Figure 14: Before and after facades of an externally insulated building (buildup.eu).

2.5.4. Add-on

A good approach to increase floor space as well as insulation is by adding a completely new structure to the building. These new structures can vary extremely in size, from balconies to extra floors to entire buildings, see figure 15, mostly depending on the available space surrounding the building and the structural abilities of the existing structure. If the existing structures allow it, the new structure can be attached to it, on top or suspended in front. An alternative solution is to add a secondary structure to the existing one. By adding a new structure, the thermal barrier will move from the old façade to the new façade creating the opportunity to improve the climate by adding new installations. Thermal bridges in the old façade will be eliminated in the façade where the new structure is added. Other parts of the building that are not connected to the new structure should be updated according to one of the other strategies.

Figure 15: New elements were added to the building to increase space, improve indoor climate and produce electricity (buildup.eu).

2.5.5. Cover-it

The final strategy is covering a courtyard or atrium. This is most commonly done with a glass structure which allows light infiltration and increases heat gains, see figure 16. The new structure creates a buffer zone between the outside and the façade of the building. An additional benefit is that often functional space is added to the building. However, the appearance of the building often changes significantly. Special attention must be given to the climate of the new space as it can overheat easily in direct sunlight.

Figure 16: The glass covered courtyard of the Scheepvaartmuseum in Amsterdam (scheepvaartmuseum.nl, 2017).

2.5.6. Conclusion

The strategies replace, add-in, wrap-it, and add-on can be applied to the 70's houses. Dividing walls and the internal layer of cavity walls often provide the structural stability in 70's houses, which makes it possible to replace the outer brick layer with a new façade. When the outer appearance of the house must remain intact or the budget is lower, insulation can be added on the inside. If the structure of the building does not allow the outer layer of the façade to be replaced a new layer can be added to the existing façade. Finally, as kitchens are often small, there is a potential to combine the add-on strategy with one of the other strategies.

2.6. Dutch refurbishment practices

In the 1990's the philosophy of 'Trias Energetica' was introduced. This included a three-step strategy to promote sustainable design (BOOM-SI, 2006). The first step of the strategy is reducing the energy demand of a building as much as possible. Secondly utilize renewable energy sources to their full extent. And finally, when exhaustible sources are needed, exploit them as efficiently as possible. This strategy can also be applied when refurbishing an existing building by insulating the building, adding new installations to utilize renewable sources, and replacing old installations with efficient installations. For each step different methods are already available in the Netherlands. The most suitable methods for small scale refurbishment are discussed below. Once a method has been chosen, keep in mind that prices can vary drastically between companies and always obtain at least two quotations. Information on all techniques, including prices was gathered from milieucentraal.nl and isolatie-weetjes.nl.

2.6.1. Insulation techniques

As mentioned above, step one for any sustainable design is reducing the energy demand of a building. On average, heating is accountable for 80% of a building's energy demand. Thus, the best starting point is reducing the heat loss. This can be achieved by insulating the building to a high level. There are many insulation techniques already available in the Netherlands, each with their own pro's and con's. The advised minimum thermal resistance or R_c-values for a normal refurbishment are 3,5(m^2*K)/W for the ground floor and 4(m^2*K)/W for the roof and cavity wall insulation for the façade. When aiming for an energy neutral building the advised minimum values are 5(m^2*K)/W for the ground floor, 4,5(m^2*K)/W for the façade, and 6(m^2*K)/W for the roof.

2.6.1.1. Cavity Wall Insulation

When applying cavity wall insulation, the cavity between the two brick layers of the outer walls is filled with insulation material. A number of insulation materials are possible, each have a relatively similar thermal resistance. The precise material is determined after a thorough inspection of the cavity wall by a specialized company. The material is then blown into the cavity through holes made in the outer brick wall and these holes are sealed off afterwards. This only takes a day's work and causes minimal disturbance to inhabitants. No permit is needed to apply cavity wall insulation.

The cavity wall must be in good condition before applying the insulation material, otherwise cold bridges and moisture problems can occur. Debris filled cavities can sometimes still be insulated after cleaning the cavity. The outer brick layer of the wall may not have a vapor retarding finish and this can cause moisture problems as vapor will be trapped in the wall. The cavity must have a minimum depth of 3cm, but for the best results a depth of 5cm is advised. Walls that are less than 24cm in depth never have an air cavity whereas thicker walls may one.

There are a number of insulation materials from which can be chosen. The most common are: glass wool, stone wool, and polystyrene grains (minimum depth of 5cm). For narrow cavities (3-5cm) PUR foam can be applied. These materials all have a similar U-value making the depth of the cavity the decisive factor for the final R_c-value of the insulated wall. The R_c-value of an outer wall with an air cavity of 6cm can on average be increased from 0,4(m^2*K)/W to 1,7(m^2*K)/W.

During the 70's and 80's some houses where already insulated with the use of this method. The cavity insulation of these houses has often sunk down. These cavities can often be refilled by adding the same material where holes have appeared. A second solution is first cleaning the entire cavity and then refilling it with new insulation material. Houses built in the 70's and 80's often already have a thin layer of insulation, if the air cavity is deep enough extra material can be added to increase the R_c-value of the wall.

Ventilation

The ventilation of the house also deserves attention when insulating a naturally ventilated house. By filling the cavity with insulation, seams and crevices are closed. To provide enough ventilation extra grills above windows may need to be added if these are not yet present. Another issue is the crawl space underneath the ground floor. This is often ventilated through the cavity wall, when insulating the cavity this is stopped. To ensure the removal of harmful gasses and moisture in the crawl space special ventilation ducts will have to made, this can be done by the insulation company.

Bats

Bats sometimes make cavity walls their home. As the bat is a protected species in the Netherlands a special dispensation has to be obtained before filling the cavity. An expert will also have to research the type of bat and when during the year it sleeps in the cavity. Next special measures will have to be taken to give the bats a new home. Be careful, moving bats can take a lot of time.

Price

The average price for cavity insulation is €15,- to €30,- per m^2 (isolatie-weetjes.nl), this depends on the chosen material. On average, cavity wall insulation has a short payback period of only 4 years due to a lower heating demand.

2.6.1.2. Wall insulation

Outer walls without a cavity or requiring a higher R_c-value than can be reached with cavity insulation alone, can be insulated externally or internally.

External insulation

The best method is external insulation as it prevents possible cold bridges, does not decrease internal space and provides the opportunity for a new façade finish. A thick layer of insulation material is placed against the old façade wall. Next a new finish is applied, this can be any type of finish to mimic the old façade or to create an entirely new look. For this technique special thin brick strips have been developed to reduce the thickness of the added layer. Windows for example do not have to be replaced as special elements are available for such connections. A more drastic version of this technique that can sometimes be applied on cavity walls, is removing the entire outer layer of the cavity wall. This way a thick layer of insulation can be placed directly against the inner wall and any kind of new finish can be applied. However, this method is more expensive and less practical for a single row house.

Internal insulation

Houses whose façade may not be changed can be insulated internally. A frame work with insulation is placed against the inside of the walls and a finish layer is added. As a layer is added on the inside of the walls there will automatically be a loss of internal space, for small houses this can be a problem. Furthermore, cold bridges can arise and therefore precautions must be taking to prevent moisture problems within the new layer. A correctly placed moisture repellent foil can prevent this.

Price

External insulation is more expensive than internal insulation, but the achievable thermal resistance is significantly higher. The price for external insulation depends on the thickness of the insulation and the type of finish material. For a R_c-value of 4(m^2*K)/W the average price is €100 - €150,- per m^2 and is always done by a professional company. Professionally placed internal insulation costs €90,- per m^2 on average, but the achievable R_c-value is only 2,5(m^2*K)/W. Internal insulation can also be placed by a home owner: the materials cost on average €40,- per m^2 (isolatie-weetjes. nl).

2.6.1.3. Roof Insulation

Insulating a roof significantly decreases the heating demand of a house and is, in the case of a pitched roof, quite easily applied. A high percentage of houses already has some form of roof insulation, but this is often only a thin layer. By adding or replacing insulation material the Rc-value of the roof can easily be increased to 4(m^2*K)/W. Especially for heated attics with bedrooms this can have a big impact.

Pitched roof

A pitched clay tile roof can easily be insulated on the inside by placing insulation material between the wooden beams of the roof. This can even be done by the home-owner to reduce costs. First check the construction of the roof: a vapor retarding foil on the outside requires a second vapor retarding foil on the inside of the construction to prevent the wood from rotting. For a R_c-value of 4(m²*K)/W, the thickness of the insulation depends on the U-value of the material. For most materials a thickness of 13cm is required to achieve a R_c-value of 4(m²*K)/W.

When insulating pitched roofs with a different cladding, it is advisory to check the exact construction of the roof. A clay tile construction has a secondary structure for the cladding which allows air to ventilate underneath the cladding. This prevents moisture from penetrating the construction as vapor is removed. Similar cladding constructions can be insulated with the same techniques. Cladding constructions without this ventilation layer, require ventilation on the inside of the main construction and are therefore more similar to flat roof constructions. This means more care should be taken when insulating on the inside as moisture problems can occur. To prevent this the natural ventilation between the cladding and insulation material most be retained. To prevent vapor from entering the construction from the inside, a vapor retarding foil should be applied on the warm side of the insulation material.

Insulating a roof on the outside is also possible. There are two different methods that can be applied, both have to be performed by a specialised company. The most effective method is removing the roof tiles and placing insulation material on the outside of the construction. This can easily be combined with the retiling of the roof. A disadvantage of this method is that the roof will become higher which means new connections have to made between the roof and gutters. Secondly when insulating only a single row house special connections with neighbouring roofs have to be made and the increase in height will be noticeable.

The second method uses the same techniques as the cavity wall insulation. The cavity between the roof tiles and the roof construction is filled with insulation material. However due to the thin layer of insulation material this method only marginally increases the thermal resistance of the roof. Therefore, it should only be applied if no other method is possible. Furthermore, when performing future repairs, this form of insulation can cause large amounts of debris.

Attic floor

For an attic that is not used as living space and can be sealed with a hatch the best option is to insulate the floor of the attic. This will reduce the heat loss of the rooms below the attic. The type of material is mainly determined by the floor construction and whether the floor has to remain walkable. Insulation material can be placed on top of the floor or in case of a wooden floor it can also be placed between the floor beams. If necessary floorboards can temporarily be removed. To prevent moisture in the construction a vapor retarding layer must be placed on the warm side of the insulation material. The hatch to the attic should also be insulated and cracks sealed off.

Flat roof

Insulating a flat roof should always be done by a specialised company because of the high risk of moisture problems. The best moment to insulate a roof is when the roof cladding has to be replaced. After removing the cladding, insulation material can be placed on top of the roof structure and can be sealed with new roof cladding. To prevent water from gushing over the edge during strong winds a minimum edge height of 10cm is required. As the added insulation increases the height of the roof it might be necessary to increase the height of the roof edge.

If the roof cladding is still in good condition a different option is placing special pressure and water-resistant insulation on top of the roof cladding. Gravel or tiles can be placed on top of the insulation to keep it in place. This will also increase the height, which might make it necessary to increase the height of the roof edge.

A third option is insulating the roof on the inside, for example between the wooden beams of the roof construction. When using this method, a so-called ‘cold roof’ is created. As mentioned before moisture problems are possible. Due to higher risk of moisture problems and other easier solutions, this method is not advised. If applied, this should only be done by a specialised company and after consultation with specialists.

Dormers

Most dormers have a flat roof and these can therefore be insulated in the same way as a flat roof. As with a flat roof this should always be done by a specialised company. When renovating a very old dormer it might be more cost effective to replace the entire dormer, especially when the dormer is seriously worn or mouldy. By doing this the walls, windows, and roof are drastically improved in one go, saving money and time.

Green roof

A green roof or roof with vegetation does not provide enough insulation on its own in the winter. The real advantage is in the summer as the grass will heat up slightly slower than a standard roof. However, this type of roof still requires a thick layer of insulation material to reach a R_c-value of $4(m^2*K)/W$. Therefore, on its own it is not an adequate replacement for insulation material. It does, however, decrease noise disturbance from the surroundings and acts as a buffer for rainwater, decreasing the peak load on the sewers during heavy rainfall. Due to this water buffering effect it a good option for garages or sheds. As a green roof is heavier than a normal roof, not all existing buildings and materials can bear this increased load. The precise weight of a green roof depends on the type of vegetation. A lightweight sedum roof can sometimes be placed but special materials and foils have to be used to prevent leakages. Therefore, this should always be done by a specialised company that is certified.

Price

The price for roof insulation depends on many factors, the major two being the type of roof and material used. For internally insulating a pitched roof or an attic floor prices are €20 - €50,- per m^2, not including the finish. Prices for external insulation are €40 - €60,- per m^2, not including new cladding. For a flat roof external insulation ranges between €70,- and €115,- per m^2, finish included (isolatie-weetjes.nl).

2.6.1.4. Ground floor insulation

A ground floor can be insulated on the outside or inside of the house. This depends on the floor structure and the presence of a crawl space underneath the floor.

Crawl space insulation

The easiest and most efficient method is insulating the underside of the floor through the crawl space underneath the house. This is done by applying insulation material on the underside of the floor or in between the beams of a wooden floor structure. To apply the insulation material the crawl space must be easily accessible and have a minimum height of 35cm, the ideal height being 50cm. To prevent moisture from decaying the insulation material, a vapor retarding foil is placed on the earthy floor of the crawl space and against the walls up to a height of 20cm. Sometimes a layer of water can be present in a crawl space, in this case a special foil that can float or Styrofoam chips can be applied. Ventilation of the crawl space is very important as Radon gas will otherwise build up and moisture problems could occur. It is therefore important that enough ventilation holes are present to let air naturally ventilate the crawl space.

Crawl spaces less than 35cm in height can be excavated to reach the required height and not-accessible crawl can sometimes be made accessible. In case of a wooden floor with a low crawl space, floor boards can be removed to place the foil on the ground and insulation material between the floor beams. Finally, the floor boards can be placed back again. An alternative solution for low crawl spaces is ground insulation. This is done by partly filling the space with Styrofoam chips or insulation shells. Ground insulation is a very cheap but nevertheless effective form of insulating a floor. The insulation material will at the same time prevent moisture problems and, as it floats, it can even be applied in regions with high groundwater levels.

Interior floor insulation

The alternative for crawl space insulation is insulating the floor on the inside of the house. A layer of insulation material is placed on top of the main floor structure and a new finish layer is applied. This method requires a lot of work as the old finish needs to be removed and pipes might need to be moved. The extra layer of material will decrease the height of the rooms meaning doorposts may need to be heightened. The insulation material and new finish can also be placed on top of the existing floor finish but this will cause an even greater loss of height. As such this is a very expensive method of floor insulation and not as effective as exterior insulation.

Price

The average price for crawl space insulation with an R_c-value of 3,5(m^2*K)/W is €30,- per m^2, this includes the lower tax rate of 6%. Crawl space insulation can also be applied by the home owner, costing on average €20,- per m^2. Due to possible moisture problems it is however advisory to hire a specialised company. Ground insulation on average costs €20,- per m^2, including the lower tax rate. Interior floor insulation varies between the €20,- and €35,- per m^2, excluding the price of the new finish layer (isolatie-weetjes.nl).

2.6.1.5. Windows and frames

Replacing single or even old double pain glass with HR++ glass or triple glass is a very efficient method to reduce heat loss and increase indoor comfort. Replacing windows is easy and does not take much time or effort. Single or double pain glass can easily be replaced by HR++ glass, frames do not require much alteration. Triple glass however is much heavier and thicker therefore often requiring new frames, especially for openable windows. It is therefore advisory when window frames need replacing to choose for triple glass as the increase in price is only 20% and the benefit is higher. When replacing frames any type of material can be used for triple glass but it is essential to choose a frame with a maximum U-value of 1,3W/(m^2*K).

Even in unheated rooms single pane glass should be replaced. For double pain glass in unheated rooms it is often more efficient to wait until the frames have to be replaced and choose for triple glass. The only exception to this rule is an unheated conservatory on the sun-ward side of the house. To prevent overheating in summer due to the large amount of glass, single glass is the best option for an unheated conservatory. Windows between the conservatory and inside of the house should however also be replaced with HR++ glass as the conservatory can be cold in winter. This method does not apply for heated conservatories, these should be fitted with highly insulating glass and frames. Ventilation and shading can be applied to prevent overheating in summer.

2.6.1.6. Ventilation

Good ventilation is essential for the health of inhabitants. When insulating a naturally ventilated house special attention should therefore be given to the ventilation of the house. This is because old, naturally ventilated houses often rely on these seams and crevices for ventilation. When a house is insulated these seams and crevices are largely sealed off. Therefore, ventilation grills have to be placed to reassure a good level of ventilation. When replacing windows in a naturally ventilated house, ventilation grills can easily be added above windows to increase ventilation.

An alternative solution is to install complete mechanical ventilation. Modern mechanical ventilation systems, also known as balance ventilation, preheat the fresh air with the outgoing air. This reduces heat loss as the fresh air entering the house is warmer but also requires major changes to the house as new ducts have to be placed to supply each room with fresh air. This is therefore a costly intervention which requires space for the ducts and ventilation unit.

2.6.2. Renewable energy

In the Netherlands electricity is provided by an energy company and distributed via the national network. By using renewable energy sources, a household can also provide its own electricity. There are multiple renewable energy sources, including solar, wind, water, earth, and biomass. For small scale production such as a house, the sun or solar energy is the best source. Solar energy can be used in two ways, to produce electricity or to heat water. The use of hot water is discussed in subchapter 1.6.3.1.1. Hybrid installations.

2.6.2.1. Photovoltaic panels

Solar energy can be transformed into electricity by photovoltaic panels, also known as PV or solar panels. There are two types of PV panels available in the Netherlands, the main differences being the colour and price of the panel. Aesthetically most people prefer the black monocrystalline panel above the blue polycrystalline panel. However, the polycrystalline panel is slightly cheaper making

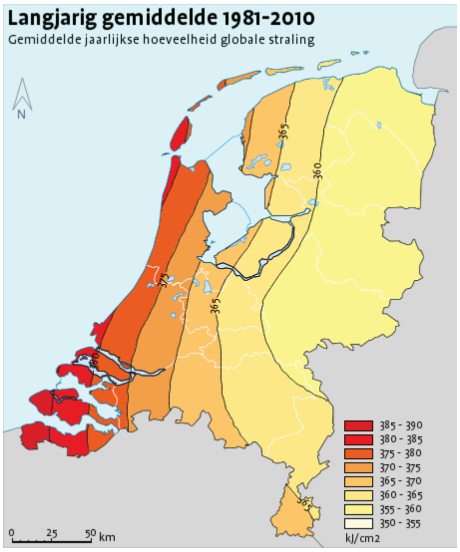

Figure 17: The average solar radiation in the Netherlands (KNMI, 2010).

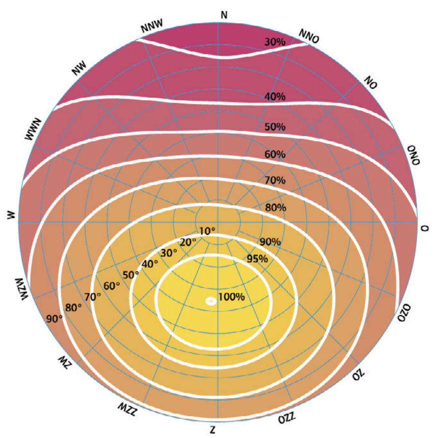

Figure 18: The solar radiation diagram for the Netherlands (westlandsolar.nl, 2012).

the overall distribution about 50/50. A PV-panel system has an average efficiency of 13%, which is significantly lower than the 45% efficiency of solar collectors. Solar collectors use sunlight to heat water, see the paragraph on hybrid installations. In most cases PV-panels can be placed without the need of a permit. For monumental buildings or buildings with the ‘beschermd stadsgezicht’-status a special permit is almost always needed.

Location

The amount of sun radiation in an area determines the electricity production. Due to weather and sun-hour differences, the location on earth greatly influences the average yearly sun radiation. Even within the Netherlands there is a noticeable difference in average yearly radiation between the west and east side of the country, see figure 17. On cloudy days PV-panels still produce electricity, only less than on clear days as the amount of sun radiation is lower. Due to slightly more hours of clear skies, the average yearly radiation is higher in the west provinces.

Orientation

Correct orientation of a PV-panel is very important as this significantly influences the amount of sun radiation on a panel. As can be concluded from figure 18, the optimal orientation for the Netherlands is 36° angle southwards facing. However, southwards facing PV panels have a peak production around noon, when most people are at work. The past few years it has almost been an obsession to place PV panels southwards facing to achieve the optimal efficiency. In off-grid neighbourhoods this obsession has even led to problems as there are not enough people at home to use the electricity. Due to an overload of electricity at noon, PV panels sometimes have to be switched off. By placing panels east- and westwards the energy production is more evenly spread over the day. Practical tests have even shown that the decrease in efficiency is negligible.

In series or parallel connected

PV-panels produce direct current, with a converter this first has to be turned into alternating current before it can be used. A PV-panel system can be connected to a converter in two different ways. The cheapest is the in series-connected system, all the panels are linked together and finally linked to one converter. In the parallel system each panel is a separate system with its own micro-converter, making it more expensive. However, the parallel system has a slight advantage. In a series-connected system, the production is determined by the weakest panel. A shaded or damaged panel will lower the production of the entire system. In a parallel system only the shaded or damaged panel will produce less electricity, it will not influence the production of the other panels. Therefore, when moments of partial shade are inevitable, a parallel system is more efficient.

Overheating

High temperature can also decrease the efficiency of a PV-panel system. Temperatures under the panels can rise quickly on clear summer days. It is therefore important that air can circulate under the panels to remove the hot air. High amounts of sun radiation will cause a converter to rise in temperature. Similar to the PV-panels this will decrease the efficiency of the converter. A converter should therefore be placed in a well-ventilated room.

Price

An in series-connected system with 10 PV-panels will, on average, produce 2360kWh per year. The average price for such a system, including installation, is €4400,- but can vary significantly per company (Milieu Centraal, 2018). The current payback period is 9 years on average, the minimum life-expectancy of a system is 25 years. Due to ongoing development, the price and efficiency is constantly improving. Since 2008 the price for a PV-panel system halved, although the price reduction has become smaller in the last few years.

Salderingsregeling

Currently a special regulation allows Dutch homeowners to sell electricity to the national grid when a surplus of electricity is produced. At the end of the year the produced electricity is deducted from the delivered electricity. This means homeowners receive the same fare for their electricity as they have to pay their electricity company. When more electricity was produced than consumed a lower fare is applied to the surplus amount (Milieu Centraal, 2018). This fare can vary between companies. An example: a household consumes 2000kWh and produces 2500kWh in a year. Of the total amount produced the normal price is applied to the 2000kWh, and a lower fare is applied to the extra 500kWh. Recently it was announced that the new government wants to replace this so called 'salderingsregeling' with a special subsidy by 2020. With this new regulation a household will receive a subsidy for each kWh produced by the PV-panels (Essent, 2018).

2.6.3. Efficient installations

After insulating a house, the remaining energy demand can be supplied by renewable energy sources. However, in some cases this is not possible or not enough. By using highly efficient installations the consumption of fossil fuels can be reduced.

2.6.3.1. Heating installation

Water for radiators and tap water is heated with a HR combi boiler or, in old houses, with a heating boiler and dedicated boiler for tap water. Modern day HR combi boilers are much more efficient than 15 years ago. Especially when warm tap water is still provided by a dedicated boiler it is highly recommended to replace the heating boiler and hot water boiler with a modern HR combi boiler. This significantly reduces gas usage but also reduces maintenance costs.

Hybrid installations

To further reduce fuel consumption, a hybrid installation can also be installed. A hybrid installation is either a solar boiler or heat pump combined with a HR combi boiler. The system will primarily rely on the solar boiler or heat pump but at peak moments the combi boiler will help to answer the demand.

A solar boiler uses sun light to heat water with the use of solar collectors, which are quite similar in appearance to PV-panels. In a standard solar boiler, the pre-heated water is then stored in a tank until needed. An average family of 4 requires 3,5m^2 solar collectors and a 150L tank. Similar to PV-panels, the collectors should be placed anywhere from south-east to south-westward facing, south being the best. The collectors should be placed at a 20° to 60° angle, 40° being the optimum for solar collectors in the Netherlands. Keep in mind that the storage tank will require space. Standard solar boilers are only used to preheat tap water but bigger combi solar boilers can also be installed. A combi solar boiler can be used for tap water and for low-temperature heating, floor heating or radiators. As combi systems provide tap water and heating, larger collectors and a bigger tank are needed. However, the reduction in gas consumption will be much greater.

A heat pump removes heat from a medium, air, earth or groundwater, and turns this into usable heat. For existing houses an air-based heat pump is the best option, as the others require drilling. A ventilation unit, quite similar to an air-conditioning unit, is placed outside in the garden or on the roof. Via pipes the unit is connected to the actual heat pump which is placed next to the HR combi boiler. In houses with mechanical ventilation the extracted air can also be used as heat source, which will reduce the heat loss. To eliminate gas consumption an electric heat pump can be installed. These heat pumps are designed to prevent peak moments and can be combined with solar boilers.

Installation settings

By choosing the optimum settings unnecessary energy consumption can be prevented. The three main adjustable factors are the maximum water temperature, the minimum amount of hot water, and the water distribution of the radiators.

To satisfactorily heat a well-insulated house a maximum water temperature or flow temperature of 60°C can often be sufficient, instead of the standard 80°C. For special low-temperature radiators a temperature of 40-55°C is even enough, there are also very low-temperature version for 35°C. However, drinking water will still have to be heated to 60°C to prevent bacteria growth in the pipes.

Secondly, a combi boiler can keep a minimum amount of water heated at all times. This can be prevented by switching the combi boiler to eco-mode which will save up to 40m3 gas per year. However, in this setting it will take slightly longer to get hot water from faucets.

Finally, by adjusting the water distribution over the radiators the heat distribution throughout the house can be improved. This will improve the comfort level and increase the efficiency of the combi boiler.

Price

The average price for a standard HR combi boiler is €2.100,-. A hybrid system is more expensive, an average solar powered system for 4 people being €5.400,- and an average air-based heat pump system €6.700,-, excluding possible subsidies (milieu-centraal.nl).

2.6.3.2. Modern electric appliances

Finally, a very easy and effective improvement that can be done by home owners without professional help, is replacing old electric appliances with new, energy efficient appliances. Good examples are energy consuming appliances such as refrigerators, freezers, washing machines, dryers, electric stoves, etc. but also lightbulbs. Especially incandescent light bulbs should be replaced immediately with LED lamps. Compact fluorescent or energy-saving lamps are already better, but even more energy can be saved by replacing them with LED lamps. Significant advantages of LED lamps are their high energy efficiency, extremely long life-span, and the large range of colour choices.

2.6.4. Summary costs

Sadly, money is an important part of everything in our life, including refurbishing a house. Every described method has its own price tag. Due to differences in materials and applications a price range has been established for each method. To create an overview for further use a table was made of all the methods with their corresponding price ranges, see table 1 on page 38. For the 'salderingsregeling' an average electricity price of €0,20 per kWh was used and a selling price of €0,03 to €0,11 per kWh. For gas a price of €0,63 per m^3 was used. The finish level was included in the prices. All prices were based on information on the websites milieucentraal.nl and isolatie-weetjes.nl.

Measure	Min. Price	Max. Price
Wall	[/m2]	[/m2]
Cavity wall insulation	€ 15,00	€ 30,00
External wall insulation	€ 100,00	€ 150,00
Internal wall insulation	€ 40,00	€ 90,00
Roof	[/m2]	[/m2]
Internal pitched roof or attic floor insulation	€ 30,00	€ 70,00
External pitched roof insulation	€ 60,00	€ 100,00
External flat roof insulation	€ 70,00	€ 115,00
Dormers	[/m]	[/m]
Complete replacement	€ 1.000,00	€ 2.500,00
Ground floor	[/m2]	[/m2]
Crawl space insulation	€ 20,00	€ 45,00
Internal floor insulation	€ 35,00	€ 70,00
Windows	[/m2]	[/m2]
HR++ glazing	€ 130,00	€ 230,00
HR+++ glazing	€ 160,00	€ 280,00
Window frames	€ 170,00	€ 270,00
Insulated external (glass) doors	€ 200,00	€ 700,00
Heating installation		
HR combi boiler	€ 1.500,00	€ 3.500,00
Solar boiler 1 panel with tank (excl. kettle)	€ 2.000,00	€ 3.000,00
Solar boiler 2 panels with tank (excl. kettle)	€ 2.750,00	€ 4.000,00
Solar boiler 3 panels with tank (excl. kettle)	€ 4.500,00	€ 5.500,00
Solar boiler < 5m2 subsidy	€ 500,00	€ 2.500,00
Solar boiler 5 < m2 < 10 subsidy	€ 1.500,00	€ 3.000,00
Air heat pump gas fuelled system	€ 4.500,00	€ 8.500,00
Air heat pump electricly fuelled system	€ 5.000,00	€ 12.000,00
Air heat pump subsidy	€ 1.250,00	€ 2.600,00
Ground source heat pump	€ 8.500,00	€ 19.500,00
Ground source heat pump subsidy	€ 2.650,00	€ 3.400,00
LT radiators / floor heating	€ 2.500,00	€ 5.000,00
PV-panels	[/Wp]	[/Wp]
PV-panels incl. installation and Tax [/Wp]	€ 1,50	€ 1,74
Tax refund [/Wp]	€ 0,22	€ 0,26
Electricity	[/kWh]	[/kWh]
Salderingsregeling	€ 0,20	€ 0,20
Selling surplus electricity	€ 0,03	€ 0,11
Electric appliances		
LED bulb	€ 1,00	€ 10,00
Induction stove	€ 300,00	€ 1.000,00
A+ oven	€ 500,00	€ 1.000,00
A++ fridge-freezer combi	€ 500,00	€ 1.000,00
A+++ dishwasher	€ 300,00	€ 800,00
A+++ washing machine	€ 300,00	€ 800,00
A+++ dryer	€ 600,00	€ 1.000,00

Table 1: Summary of the price ranges for each improvement measurement (miliucentraal.nl and isolatie-weetjes.nl).

2.6.5. Conclusion

A whole array of options is available, each with their own price tag and improvement level. This information is a basis for the rest of the project. Keep in mind that not all options are suitable for each house and sometimes some alterations might be necessary. Furthermore, price ranges can be very large due to material differences and large differences between contractors. Once a method has been chosen always obtain at least three quotations before deciding. Consult milieucentraal.nl for more information on a method, this website is an excellent knowledge base.

2.7. Reference projects

Two similar projects were analysed for recommendations.

2.7.1. Project Stroomversnelling

Figure 19: Project stroomversnelling in progress (flickr.com).

Stroomversnelling is a project of the Dutch government to facilitate the building companies and corporations in refurbishing especially 60's and 70's houses to Net-Zero Energy Buildings (stroomversnelling.nl, 2017). All involved parties are brought together to exchange knowledge and create the best result. Multiple projects have already been finished, two examples are in Arnhem and Stadskanaal, see figure 19.

In Arnhem a new pre-fabricated façade was applied to an existing façade to provide the houses with a highly insulated outer shell. The natural ventilation was replaced by complete mechanical ventilation. Special heat exchange elements were installed in the façade to preheat the fresh air, see figure 20. A new pre-fabricated roof was installed, fully covered with PV-panels and a solar collector.

In Stadskanaal a test house was first completed and tested, see figure 21. Based on the results from the test house, the plan was slightly altered before applying it to the other houses. An extra pre-fabricated layer was added to the existing façade to increase insulation. The new roof has a different angle to optimize the energy production of the PV-panels added to the roof. Mechanical ventilation was installed with a heat exchanger. A heat-pump was installed to heat or cool the ventilation air, eliminating any other heating devices. The gas connection was removed from the house as it had become redundant.

As almost all the houses in these projects were inhabited, good communication between all parties was vital. A similar project in Tilburg concluded that inhabitants were disappointed about the level of communication about their personal wishes and what they could expect but that they were nevertheless very happy with the result. Their advice for future projects was to concentrate on a good line of communication between inhabitants and builders. Furthermore, ensure that the inhabitants know what to expect and give them the chance to express their own wishes.

Figure 20: A detailed model of the prefabricated facades (flickr.com).

Figure 21: The test house in Stadskanaal (flickr.com).

2.7.2. Prêt-à-Loger

A more ambitious project is the Prêt-à-Loger concept devised by students of the Technical University Delft which is aimed at row houses from the 1960's. The refurbishment in combination with extension concept involves adding a second façade to the building to increase living space, produce solar energy, and improve insulation (Prêt-à-Loger, 2017).

In the plan a second glass façade with integrated photovoltaic panels is added to the south façade and acts as a greenhouse, see figure 22. The north façade is wrapped in insulation and the north facing roof is replaced by a green roof to insulate in winter and cool in summer. A ground tube is installed to provide the house with cool air in summer. In summer the warm air rises to the top of the green house, due to the stack effect, and is let out through an openable window, see figure 23. In winter the greenhouse works as a buffer zone between the outside and inside. A computer constantly monitors the electricity usage of the household and the amount being produced by the PV-panels. It advises the household when to use certain appliances such as the washing machine. This will most commonly be in the middle of the day when people are at work as south facing PV-panels produce the most electricity at this point of the day. In this concept the house is

Figure 22: The greenhouse extension of the Prêt-à-Loger (thegreenvillage.org).

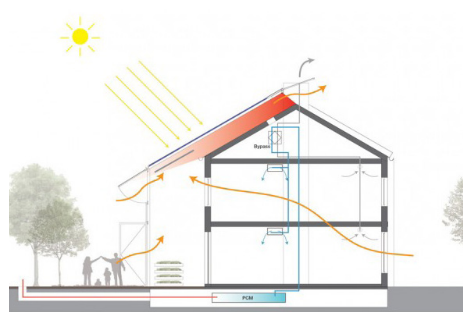

Figure 23: Summer situation climate scheme (asserts.inhabitat.com).

not disconnected from the electricity network as to ensure that the electricity demand can be met when the PV-panels do not produce enough.

This is still a concept as it has never been applied to a real house. At the moment it has only been applied to a specially built test house on the TU Delft campus which can be visited. Therefore, it is still unclear if this concept is really suitable for a 1960's house. Furthermore, the effect of the concept depends greatly on the orientation of a house which might mean that it only suitable for north-south orientated houses.

2.7.3. Conclusion

Apart from individual refurbishments, a number of medium scale refurbishment projects have already been applied on 1960's and 70's houses. However, these projects do still focus on identical row houses as this allows the creation of one plan which can be applied on all houses. No plan has yet been made which, with only small alterations, can be applied to multiple types of houses on a large scale. An important conclusion from the Stroomversnelling projects which should always be considered during a project, is that good communication with inhabitants is vital for a good result. The level of communication can really make or break a refurbishment project.

2.8. Conclusion

The Ramplaankwartier is a relatively new neighbourhood in Haarlem with most houses built between the 1920's and 1970's. To achieve their goal of becoming a Sustainable Neighbourhood and eliminate the gas consumption of the neighbourhood all houses will require improvements. Of the houses in the neighbourhood the 1960's and 70's consume the highest average amount of gas. These houses are very similar in construction and the high gas consumption is due to the low amount of insulation. As these houses are still very comfortable and popular upgrading is a better choice than demolition. The best way to achieve the goal of a partially off-grid neighbourhood is to refurbish the houses, to do this multiple options are available. In the Netherlands a number of refurbishment methods are already available, each with their own benefits and price tags. As not everyone has the same budget and different wishes, the goal of three different strategies was set.

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3. Methodology

After the literature review was performed a fitting testing format was chosen. The methodology that will be used during this research project is described below.

3.1. Method

During this research project three test houses will be used to answer the set research question. These test houses are a row house in Haarlem, semi-detached house in Wassenaar and free-standing house in Gorssel. All three houses were built between 1960 and 1974. The row house will serve as the main test house for the development of the multiple strategies. After development, the strategies will be applied to the other two houses to test the versatility and generalizability. During the development two energy-efficiency simulation programs will be used to simulate the fuel consumption after application of the strategies. This will be done to test the effectiveness of techniques and help make decisions.

For the project I chose to develop three refurbishment strategies, each with a different level of improvement and budget. These strategies are based on the different levels of refurbishments Dutch homeowners already tend to choose. The three strategies are the following:

Basic insulation strategy (A)

This is a simple strategy which focusses on improving the insulation level of the house and replacing outdated heating installations. The main goal of this strategy is to reduce the heating demand. This strategy is aimed at homeowners with a small budget who wish to reduce their gas consumption.

EPC ≤ 0,4 strategy (B)

The second strategy aims to reach an Energy Performance Coefficient or EPC of 0,4 or less which is the current requirement for new houses. Insulation is not enough to reach this goal and therefore the use of renewable energy sources has been included in this strategy. This strategy is aimed at homeowners with a medium budget who wish to include the use of renewable energy sources in their refurbishment strategy.

Net Zero Energy Building (NZEB) strategy (C)

The last strategy is aimed at homeowners who wish to significantly lower their energy bills and most importantly live gas-free. This strategy involves extreme insulation and a focus on renewable energy sources instead for heating and electricity. This strategy is aimed at homeowners who want to make a difference, help fight global warming, make the Netherlands gas-free, and are willing to make a substantial investment to achieve these goals.

Before starting with the development of the strategies the test houses will be analysed and a detailed list of requirements will be made for each strategy.

3.2. Simulations

As this research project focusses on lowering the energy demand of houses through refurbishment, the main aim for using simulation programs is to simulate the energy consumption after application of each strategy. Two software programs will be used to simulate the energy consumption: Design Builder and Uniec. Both these programs provide an energy-efficiency simulation, but differ significantly in the level of detail.

Design Builder is a multipurpose program which allows many input parameters and can make very detailed simulations of indoor climates and energy-efficiency. For this project Design Builder version 4.7.0.027 will be used for the simulations. As this project focusses on Dutch houses, the Netherlands will be used as the location and Dutch weather data will be used for each model. With the use of the built-in interface a representative model will be created for each test house. By performing a simulation of a year, the annual fuel consumption will be calculated.

Uniec is a more basic solely energy-efficiency simulation program which is based on Dutch regulations. This makes it slightly harder to make a true representation of a situation but makes the program much easier. Uniec version 2.2 will be used during this project. It will be used to calculate the annual fuel consumption, Energy Prestation Coefficient or EPC, and BENG label of each situation. For modern buildings regulations require a maximum EPC of 0,4 currently. Houses built between 1960-1974, which have not been updated since, commonly have an EPC of 1,5 or higher. The BENG label is probably going to replace the EPC in 2020 but the guide lines are still in development. This label consists of three categories: energy demand, primary energy consumption, and percentage renewable energy. For each category respectively, the government currently has the following requirements in mind: a maximum of 25kWh/m^2, a maximum of 25kWh/m^2, and a minimum of 50%.

To measure the effectiveness of each strategy four model variations will be made for each test house. These models will simulate the four different situations: current, after application of strategy A, after application of strategy B, and after application of strategy C. The simulation of the current situation will allow calibration of the base model: inputs will be adjusted until the results are consistent with the observed energy consumption. With the base model each new situation will be modelled by changing the model according to the improvement techniques. Next, each new strategy will be evaluated by calculating the new consumption and comparing it to that of the current situation. In addition, the EPC and BENG label will be added to the results in the simulations performed with Uniec.

3.3. Cost calculation

As costs play an important role for homeowners the required investment and payback time will be calculated for each strategy. To calculate the required investment table 1 (p. 24), depicting the estimated minimum and maximum costs for each improvement, will be used. The minimum and maximum investment will be calculated for each strategy with the use of the prices in this table.

Based on the required investment and reduction in yearly costs the payback time will be calculated. This will be done by calculating a best- and worst-case scenario based on the simulation results. The minimum investment will be divided by best-case reduction to calculate the best-case scenario for the payback time. The maximum investment will be divided by the worst-case reduction to calculate the worst-case scenario for the payback time. For this calculation the average prices of €0,20 per kWh electricity and €0,63 per m^3 gas will be used.

3.4. Predictions

Before starting the development of the strategies and simulations I set the following predictions. I expect that the three developed strategies will reach the requirements and that it will be possible to change the row house into a Net Zero Energy Building and gas-free house. Furthermore, I expect that the three strategies can easily be applied to the free-standing house and will show similar simulation results. As it is already clear that the semi-detached house is quite different from the other two houses, I expect that more difficulties will arise during the testing of this house. I hope that at least one of the strategies can be applied but do not exclude the possibility that all three might be unsuitable.

4. Analysis row house Haarlem

4.1. Situation

As main test house a row house in Haarlem was chosen. The house is a typical Dutch row house with neighbours on either side. It was built around 1963 and has the characteristics of a typical late post-war house. It is situated on a rough 20° angle, the front side facing North and the back of the house facing South.

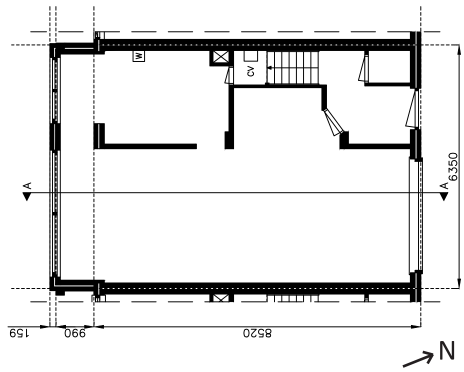

Figure 24: Floorplan of the first floor.

4.2. Program

The house has a typical ‘Doorzonwoning’ floorplan. The first floor consists of a large living room which spans the entire depth of the house, a small entrance with adjacent toilet, and a small kitchen opening onto the garden, see figure 24. A few years ago, an expansion was added at the back, increasing the size of the living room and kitchen. A staircase in the entrance hall leads to the second floor. Leading off the landing on the second floor are two large bedrooms, two small bedrooms, and a small bathroom, see figure 25. The two bedrooms at the back of the house share a balcony overlooking the garden. The staircase continues upward to the attic. The attic consists of four rooms and has dormers on each side of the house. A large bedroom overlooks the garden, the other rooms are small and in use as storage rooms.

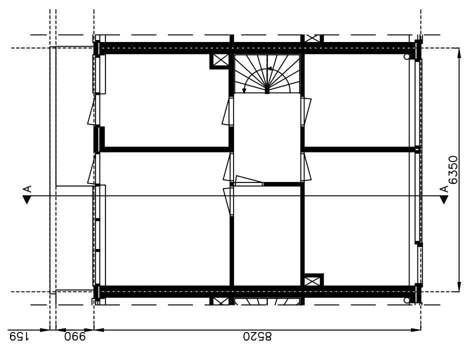

Figure 25: Floorplan of the second floor.

4.3. Façade

The façade consists of typical Dutch bricks and large windows characteristic for the building era, see figure 26. Especially the second floor has a high percentage of glass as the windows span the entire width of the façade. The garden facing façade has a particularly high percentage of glass. From this we can conclude that the front and back façades are not loadbearing.

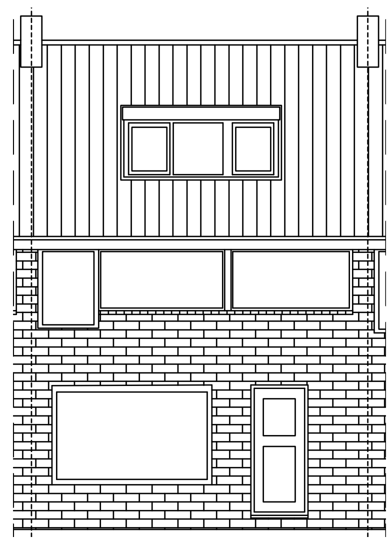

Figure 26: Front façade.

4.4. Construction

The construction of the house is quite simple. All outer walls consist of cavity walls from top to bottom without any insulation. Four walls act as loadbearing walls: the house-dividing walls and two internal walls placed parallel to the dividing walls. The loadbearing walls consist of thick concrete masonry blocks (kalkzandsteen). Other internal dividing walls consist of thin aerated concrete bricks (drijfsteen).

The ground floor has two different constructions. A wooden floor in the living room and a MUWI-element floor in the hallway and kitchen. A MUWI-element floor is a prefab concrete floor system developed in the 1960’s and was the predecessor of the modern-day ‘Broodjesvloer’. The second floor is a cast-in-place concrete floor with a special loadbearing element above the opening in the loadbearing wall on the ground floor. The floor directly continues into the balcony and a concrete strip which is visible in the back façade, creating a significant cold bridge. The recent expansion at the back slightly reduces the cold bridge as the balcony and strip have been integrated into the roof of the extension. The concrete floor only spans the test house and does not continue into the neighbouring houses as is sometimes the case in 1960's houses. This means that structurally-borne noise will not be an issue in this house. The attic floor is a simple wooden beam construction with wooden floorboards on top. The roof has a 40° angle and has a loadbearing construction of wooden beams, cladded with boards, waterproofing foils, and Dutch clay roof tiles. The dormers are made of sandwich boards, windows and a flat roof with asphalt felting.

Throughout the passing years a large portion of the windows has been replaced some form of double glazing. Newly replaced windows have been replaced with HR++ glass, older replacements have been performed with HR glass and there are also still some old double and single glazed windows.

4.5. Energy consumption

The current owners consumed 4000kWh of electricity and 2260m^3 of gas in 2016. Electricity is used for the main appliances such as lights, computers, fridge, washing machine, etc. Gas is used for heating, hot water and cooking. Heating is provided by hot water radiators in each room. These are supplied by a compact HR combi boiler which also provides hot water for the bathroom. Hot water in the kitchen is provided by a small dedicated electric boiler. Both the HR combi boiler and electric boiler are relatively new.

4.6. Simulations

A Design Builder and Uniec model of the current situation were created as a basis for the further simulations. Below both programs are explained and the entered parameters are presented.

4.6.1. Design Builder

Design Builder is an advanced modelling tool which can be used to develop a comfortable and energy-efficient building design. It can calculate a range of outputs concerning the indoor climate of building and also its annual consumption. An entire building can be simulated in the program with the use of its built-in interface. With the use of Design Builder, the comfort levels and energy consumption were calculated.

4.6.1.1. Simulation inputs

In Design Builder characteristics regarding local climate, geometry, zones, construction, installations, and indoor climate are entered under different tabs. Since the completion of the test house, slight alterations have been applied. Therefore, a Design Builder model of the current situation was made. The parameters for this model were based on the original drawings, information given by the inhabitants, and a number of assumptions.

Climate

The test house is located in Haarlem, near Amsterdam. As Design Builder does not have any standard climate information for Haarlem, the information for Amsterdam Schiphol was entered as this was the nearest location available.

Geometry

The test house was entirely modelled in Design Builder with the use of the built-in interface. Each floor was modelled as a block and a pitched roof block with dormers was added on top, see figure 27 and 28. The outer shapes of the neighbouring houses were also added to provide the right conditions. The balconies and supporting walls of the neighbouring houses were included as surfaces. Based on information given by the inhabitants a garden facing extension and an extra dormer were added to the original construction. For both dormers the same measurements and materials were used.

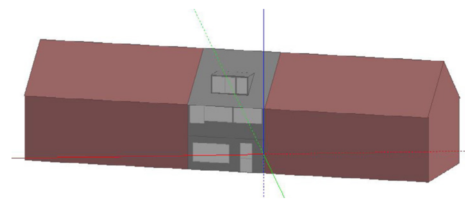

Figure 27: Front of the Design Builder model.

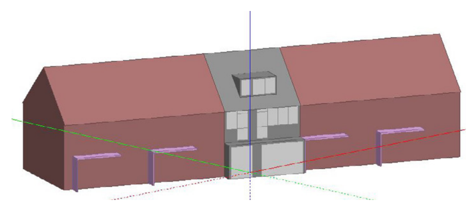

Figure 28: Back of the Design Builder model.

Zones

Rooms are simulated as zones in Design Builder. For each zone different parameters can be entered in the Activity, Construction, Openings, Lighting, and HVAC tabs. Based on these parameters the program is able to determine all internal gains and losses and calculate the energy consumption of a building. Design Builder has a number of standard parameters which can be chosen. To create the most realistic situation the standard template most applicable for each room was chosen and slightly edited. An occupancy schedule was made based on standard Dutch working hours.

Based on the provided building plans the construction materials were entered and windows were added to the model. It was assumed that the new extension has an entirely glass façade with glass doors. In Design Builder glass doors have to be simulated as openable glass, resulting in a larger glass façade. As all the windows differ in quality, an average situation was used.

Parameters

Table 2, page 50, displays a summary of the main parameters such as the thermal resistance of the outer shell, the airtightness and systems. See Appendix 1 for a more detailed overview.

	Current situation		
Construction	Structure type	Rc-value [m2*K/W]	U-value [W/m2*K]
External wall	Brick cavity wall	1,02	0,98
Ground floor 1	Wooden floor	1,33	0,75
Ground floor 2	MUWI concrete floor	0,57	1,75
Pitched roof	Wooden roof structure	0,79	1,26
Flat roof	Wooden roof structure	0,74	1,36
Dormer wall	Wooden structure	1,84	0,55
Dormer roof	Wooden roof structure	0,74	1,36
Doors	Low standard doors		2,82
Glazing	Low standard double glazing		2,76
Frames	Wooden frames		2,62
Airtightness			
Infiltration rate [ac/h]	0,7		
Installations			
Ventilation	Natural ventilation		
Heating and HW installation	HR combi-boiler		
Kitchen HW installation	Electric boiler 10 L		
PV-panels			
Solar collectors			

Tabel 2: Summary of the main parameters.

4.6.1.2. Results

Based on the entered parameters and set time frames, Design Builder calculates the energy consumption for multiple categories in kWh. These categories are generally Room Electricity, Lighting, System Fans, System Pumps, Heating, DHW or hot water and Generation. The only thing Design Builder does not calculate is energy consumption for cooking. When the consumption of a category is 0kWh it will not be included in the results. To calculate all these consumptions Design Builder uses the entered parameters and set time frame.

In the current situation gas is used for heating and hot water which means the resulting amount of kWh has to be converted to m^3 for the comparison. There are two different types of gas, high and low calorific gas. In the Netherlands low calorific gas or 'Gronings aardgas' is distributed to households. One cubic metre low calorific gas equals 9,77kWh on average. Based on the information provided by the inhabitants this means roughly 22,1MWh of gas was consumed in 2016. As Design Builder will never be able to reproduce the exact same result due to differences in average data and the reality, a deviation of 10% between the simulated and observed energy consumption is allowed. Thus, I estimated the annual gas usage at 22,1MWh, ±2,2MWh.

The Room Electricity and Lighting categories are based on averages and were only used to simulate the heat production of these categories. The fuel consumption of these categories was not taken into account. Instead a set amount was used based on the actual consumption provided by the inhabitants.

Heating and cooling design

To ensure a comfortable indoor climate the heating and cooling design simulations were performed. Figure 29 depicts the heating design for the building, a comfortable average air temperature of 20°C was achieved. The cooling design, see figure 30, simulated a maximum average air temperature of 29°C on a hot summer day. When evaluating the temperatures for each separate room it was concluded that this is mostly due to slight overheating of the south facing rooms, especially the kitchen and attic.

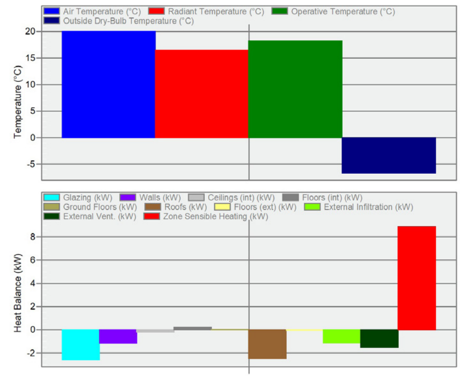

Figure 29: Heating design.

Annual consumption

As this report focuses on reducing the energy consumption of the building, the annual fuel usage was the most important result. By performing a full-scale simulation of the building, the annual fuel usage was calculated. The results were 17710kWh for heating, 373kWh for hot water in the kitchen and another 3100kWh for hot water in the bathroom, see figure 31. No consumption was calculated for the installations themselves as a basic HVAC model was used. In this situation this consumption cannot be calculated by Design Builder. The results add up to a total of 2130m^3 of gas and 373kWh of electricity. The simulated gas consumption is slightly lower than expected but well within range. As the total gas consumption is based on the heating and hot water demand slight differences in any of these two consumption groups can be responsible. It might even be due to a slight difference in the gas consistency resulting in a different amount of kWh per m^3 of gas.

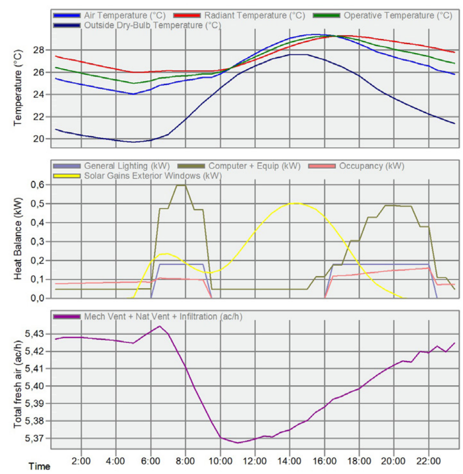

Figure 30: Cooling design on July 15th.

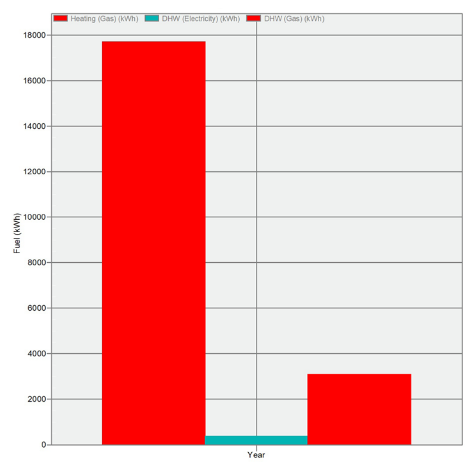

Figure 31: Annual fuel consumption breakdown.

4.6.2. Uniec

Uniec is a very simple web-based program which calculates the energy consumption, EPC and BENG label of a house. This program and the calculations are based on the Dutch building regulation NEN 7120. To calculate the results a number of parameters must be entered, these include the heated living area, infiltration, the size and heat resistance or heat conductivity of all the outer surface areas, the hot water installations, the ventilation system, and when present the PV-panel installations.

4.6.2.1. Results

Uniec calculates the annual energy consumption for heating, the heating installation, hot water, the hot water installation, cooling, the cooling installation, summer comfort, ventilation, lighting, and on-site energy production. These separate consumptions are all defined in MJ. To calculate the total gas and electricity consumption, the results of multiple categories are added together and then converted to either m^3 for gas or kWh for electricity. In situations where gas is used the primary heating and hot water consumptions are added and converted to m^3 gas. The other categories, except the on-site energy production, are added to calculate the site-bound installations consumption. In situations where electricity is used for heating and hot water this is also added to the site-bound installations consumption. The category on-site energy production is directly converted to kWh. Furthermore, the electricity consumption of appliances is calculated based on a set amount per m^2. As this set amount does not adequately represent the real situation it was not taken into account. Lastly Uniec also calculates total amount of CO_2-emmission, EPC and BENG label of the building. similar to Design Builder Uniec does not calculate the energy consumption of cooking.

To make the Uniec results comparable to the Design Builder results the following categories were used: heating, heating installation, hot water, hot water installation, ventilation and on-site energy production. Cooling, cooling installation, summer comfort and lighting were not included as there is no cooling installation present in any of the situation, summer comfort is not an actual consumption, and lighting is based on a fixed amount per m^2 of living area. All the categories are defined in MJ. To convert to m^3 the amount of 35,17MJ/m^3 was used as specified by Uniec. For the conversion to kWh the amount of 9,2186MJ/kWh was used, taking a generation efficiency of 40% into account as required by the NEN7120. Similar to Design Builder a set amount of kWh was used for the electricity consumption of appliances and lighting.

Annual consumption

The final results for the current situation were 6090 MJ for heating, 731MJ for the heating installation, and 13300MJ for hot water. The total amount was 1988m^3 of gas and 544kWh of electricity. Based on these amounts the hot water consumption was split according to the amount produced with electricity and the amount produced with gas. This resulted in 1732m^3 for heating, 253m^3 for hot water, 465kWh for hot water and 79kWh for the heating installation. This is lower than expected and is probably due to the fact that Uniec used averages for the calculations such as average outdoor temperature, heating temperatures and hot water usage. It is therefore less situation specific and larger deviations can be expected.

Additionally, Uniec calculated an EPC of 1,129 for the current situation. This is already slightly better than the average 1,5 or higher for 1960's and 70's houses due to slight improvements such as double glass and more efficient installations. However, it is still nowhere near the 0,4 which is standard for modern houses and major improvements are certainly possible. The BENG label consists of three categories: energy demand, primary energy consumption, and percentage renewable energy. For the current situation these were respectively 115,4kWh/m^2, 157,4kWh/m^2, and 0%. This is nowhere near the current requirements of 25kWh/m^2, 25kWh/m^2, and 50%.

4.6.3. Comparison

The Design Builder and Uniec results were combined in a table for comparison, see table 3. As was mentioned above Design Builder did not calculate the installation consumption, therefore a correction was added based on the amount calculated by Uniec. Additionally, a fixed amount of electricity was added to both results for the electricity consumption of appliances and lighting. For the current situation this was set to 3500kWh based on the real consumption. As gas is used for cooking in the current situation, a set amount of 37m^3 for cooking was included. This amount is based on the average consumption stated by Milieu Centraal (2018).

	Current situation					
Program	DesignBuilder		Uniec		Measurements	
Elec installations	0	kWh	79	kWh		
Elec installations correction	79	kWh				
Elec heating						
Elec hot water	373	kWh	465	kWh		
Elec cooking						
Elec appliances	3500	kWh	3500	kWh		
Electricity production	0	kWh	0	kWh		
Electricity total	3952	kWh	4044	kWh	3984	kWh
Gas heating	1813	m3	1732	m3		
Gas hot water	317	m3	256	m3		
Gas cooking	37	m3	37	m3		
Gas total	2167	m3	2025	m3	2260	m3
Totaal CO2-emission			4646	kg		
EPC			1,129			
BENG energiebehoefte			115,4	kWh/m2		
BENG primair			157,4	kWh/m2		
BENG hernieuwbaar			0	%		

Table 3: Results comparison for the current situation.

4.7. Conclusion

By analysing the row house, the construction methods and materials were identified. With these and other parameters a Design Builder and Uniec model of the current situation were made. Based on the simulated results it can be concluded that the models are an adequate representation of the current situation. Both final models were used as a basis for the testing and comparison of the three strategies.

4.8. References

Milieu Centraal. (2018). Kookplaat en keukenapparaten. Retrieved 09-04-2018 from https://www.milieucentraal.nl/energie-besparen/apparaten-en-verlichting/huishoudelijke-apparaten/kookplaat-en-keukenapparaten/

5. Refurbishment strategies

Three different refurbishment strategies were developed, each with a different improvement level as aim. The boundary conditions for the strategies were based on reference projects and advise given by Milieu Centraal. As with the analysis of the test house, Design Builder and Uniec 2.2 were used to simulate the comfort levels, fuel usage and the EPC. By comparing the results of the simulations, the improvement level of each strategy was measured.

5.1. Basic insulation strategy (A)

The first refurbishment strategy is a basic insulation strategy. The aim of this strategy is to provide a significant improvement without major costs or disturbances. To achieve this, the strategy mainly focusses on decreasing the heat loss of the house, by applying insulation. The second step is replacing old heating installations. For the majority of houses no permit is required for the application of this strategy.

5.1.1. Boundary conditions

This strategy is best suited for homeowners with a small budget whom only wish to improve the insulation level of their house. Main advantages of this strategy are a low investment and the small disturbance.

Requirements

- Simple insulation techniques
- Payback time: 10 years
- Minimal disturbance level
- R_c-values:
  - Wall > 2,0 (m^2*K)/W
  - Floor > 3,5 (m^2*K)/W
  - Roof > 4,0 (m^2*K)/W
  - Dormers > 2,5 (m^2*K)/W
- Windows: HR++
- Frames: U-value < 1,4 W/(m^2*K)
- Heating and hot water installation < 15 years old
- LED lighting

Optional extra's

- Efficient electric appliances
- Electric cooking

5.1.2. Insulation techniques

For this strategy common Dutch insulation techniques were compared and the best suitable were chosen. To achieve the set goals the following insulation techniques are recommended. See chapter 2 for more detailed information on all the techniques. All the chosen techniques have a short payback time, the lowest level of disturbance during application and can be applied fast.

- *Cavity wall insulation*

This is an easy and cheap technique that can be applied in a day without any disturbance for the inhabitants.

- *Internally insulated pitched roof*

This insulation technique will cause some slight disturbance as room will have to be made in the attic to place the insulation. Luckily this technique is not difficult to apply will therefor only take one to two weeks.

- *Externally insulated flat roof*

As this is done on the outside of the house the disturbance level is low. Due to the small flat roof area of the house this will probably only take a few days, slightly depending on the chosen material.

- *Insulating dormers*

By insulating the walls and flat roof the level of thermal resistance for the dormers can easily be increased.

- *Crawl space insulation*

For the test house this technique will cause some slight inconveniences as openings have to be made to reach the crawl spaces. Based on the information provided by homeowners of similar houses in the neighbourhood, it can be concluded that this technique is definitely possible.

- *Window and door replacement*

Windows that do not have HR++ glazing must be replaced. The frames of fixed windows can easily be altered, openable windows might require new frames. As a number of windows of the test house have already been upgraded we assumed that the north facing living room window and all second-floor windows have to be upgraded. Furthermore, we assumed that the openable windows will require new frames.

- *Extra ventilation grills*

The test house is currently naturally ventilated via openable windows and infiltration. To provide enough fresh air after insulation extra ventilation grills have be placed in the façade. This can easily be done when replacing windows by placing the grills in the window frame above the glazing.

5.1.3. Heating and hot water installations

The HR combi boiler which provides heating and hot water for the bathroom is currently only 6 years old. A small dedicated electric boiler provides hot water in the kitchen and is currently 10 years old. Both installations are less than 15 years old which means replacement is not yet required.

5.1.4. LED-lighting

No information was provided regarding the type of lighting so an average situation with mostly energy-saving light bulbs was assumed. Although these are already significantly better than incandescent light bulbs LED lights are still better and have a much longer life span. Therefore, I assumed that all light bulbs will have to be replaced.

5.1.5. Extra options

These extra options are recommended to further decrease the electricity consumption and prepare the house for the future. They were not taken into account in the simulation.

- *Efficient electric appliances*

To decrease electricity use, replacement of electric appliances older than 20 years is recommended. This can be done step-by-step to spread costs. Examples of appliances recommended for replacement are fridges, electric stoves and ovens, microwaves, washing machines and dryers. Modern appliances have energy labels, appliances with a label A++ or A+++ are recommended.

- *Electric cooking*

Replacing the gas stove with an induction stove will prepare the house for a gas-free future. Of all electric alternative induction is the best option. These stoves work with magnetism which means the stove does not became hot like other types of electric stoves, only the pan becomes warm. This makes them highly efficient, easy in use, and very safe. Some old houses also have a gas oven, these should also be replaced with an electric alternative.

5.1.6. Simulations

To simulate the decrease in fuel usage, the original construction properties, infiltration level, and lighting system were changed according to the described techniques, see table 4 on page 60 for a summary of the parameters. The infiltration level was lowered as the application of the mentioned insulation techniques automatically causes a slight decrease in infiltration. The heating and ventilation systems were not altered as these do not require replacement. In appendix 2 the precise parameters can be found.

5.1.7. Cost calculation

The minimum and maximum costs for each improvement were calculated and added up to calculate the minimum and maximum costs of the strategy, see table 5 on page 60. The optional extras were not taking into account for this calculation.

	Current situation			Basic insulation strategy		
Construction	Structure type	Rc-value [m2*K/W]	U-value [W/m2*K]	Improvement	Rc-value [m2*K/W]	U-value [W/m2*K]
External wall	Brick cavity wall	1,02	0,98	Cavity wall insulation	2,21	0,45
Ground floor 1	Wooden floor	1,33	0,75	Crawl space insulation	3,81	0,262
Ground floor 2	MUWI concrete floor	0,57	1,75	Crawl space insulation	3,57	0,28
Pitched roof	Wooden roof structure	0,79	1,26	Internal insulation	4,22	0,24
Flat roof	Wooden roof structure	0,74	1,36	External insulation	4,17	0,24
Dormer wall	Wooden structure	1,84	0,55	Internal insulation	2,63	0,38
Dormer roof	Wooden roof structure	0,74	1,36	External insulation	4,17	0,24
Doors	Low standard doors		2,82	New insulated doors		1,25
Glazing	Low standard double glazing		2,76	HR++ glass		1,51
Frames	Wooden frames		2,62	Wooden frames / with thermal break		1,39
Airtightness						
Infiltration rate [ac/h]	0,7			0,4		
Installations						
Ventilation	Natural ventilation			Natural ventilation		
Heating and HW installation	HR combi-boiler			HR combi-boiler		
Kitchen HW installation	Electric boiler 10 L			Electric boiler 10 L		
PV-panels						
Solar collectors						

Table 4: Summary of the changed parameters.

Required improvements	Min. Price		Max. Price			Min. Price		Max. Price	
Wall		[/m2]		[/m2]	[m2]				
Cavity wall insulation	€	15,00	€	30,00	25	€	375,00	€	750,00
Internal wall insulation dormer	€	40,00	€	90,00	5	€	200,00	€	450,00
Roof		[/m2]		[/m2]	[m2]				
Internal pitched roof insulation	€	30,00	€	70,00	60	€	1.800,00	€	4.200,00
External flat roof insulation	€	70,00	€	115,00	16	€	1.120,00	€	1.840,00
Ground floor		[/m2]		[/m2]	[m2]				
Crawl space insulation	€	20,00	€	45,00	60	€	1.200,00	€	2.700,00
Windows		[/m2]		[/m2]	[m2]				
HR++ glass	€	130,00	€	230,00	17	€	2.210,00	€	3.910,00
Window frames	€	170,00	€	270,00	8	€	1.360,00	€	2.160,00
Insulated external (glass) doors	€	200,00	€	700,00	6	€	1.200,00	€	4.200,00
Electric appliances									
LED bulb	€	1,00	€	10,00	15	€	15,00	€	150,00
Total						€	9.480,00	€	20.360,00

Table 5: Minimum and maximum costs calculation.

5.1.8. Results

After applying the changes, a new simulation was performed using Design Builder and Uniec, see table 6 for the results. Based on the results, a 3% reduction in gas consumption and 39-56% reduction in electricity consumption is likely. An EPC level of 0,765 was reached.

In addition, the total price for application of this strategy on the test house was calculated. Based on the investment and yearly savings the payback time of the strategy was calculated. In contrast to what was expected a relatively long payback time was calculated. Even the best-case scenario payback time is more than 10 years for this house. This is a bit strange as only insulation techniques with a payback time below the 10 years were chosen for this strategy. Possible explanations might be that the investment was overestimated and/or the improvement level was underestimated by the simulation programs.

	Current situation						Basic insulation strategy					
Program	DesignBuilder		Uniec		Measurements		DesignBuilder		Difference	Uniec		Difference
Elec installations	0	kWh	79	kWh			0	kWh		56	kWh	-29%
Elec installations correction	79	kWh					56	kWh				
Elec heating												
Elec hot water	373	kWh	465	kWh			373	kWh	0%	458	kWh	-2%
Elec cooking												
Elec appliances	3500	kWh	3500	kWh			3400	kWh	-3%	3400	kWh	-3%
Electricity production	0	kWh	0	kWh			0	kWh		0	kWh	
Electricity total	3952	kWh	4044	kWh	3984	kWh	3829	kWh	-3%	3914	kWh	-3%
Gas heating	1813	m3	1732	m3			601	m3	-67%	947	m3	-45%
Gas hot water	317	m3	256	m3			317	m3	0%	252	m3	-2%
Gas cooking	37	m3	37	m3			37	m3	0%	37	m3	0%
Gas total	2167	m3	2025	m3	2260	m3	955	m3	-56%	1236	m3	-39%
Totaal CO2-emission			4646	kg						3140	kg	-32%
EPC			1,129							0,765		-32%
BENG energiebehoefte			115,4	kWh/m2						68,9	kWh/m2	-40%
BENG primair			157,4	kWh/m2						103,8	kWh/m2	-34%
BENG hernieuwbaar			0	%						0	%	
Cost							Minimum			Maximum		
Investment							€		9.480,00	€		20.360,00
Yearly savings							€		521,67	€		789,56
Payback time [years]							12			39		

Table 6: Fuel consumption comparison and payback time.

5.2. EPC ≤ 0,4 strategy (B)

The main goal of the second strategy is to reach an EPC of 0,4 or lower. Insulating a building is not enough to reach this EPC level which means that renewable energy sources will also have to be used. This means new installations such as solar panels will have to be added to the building.

5.2.1. Boundary conditions

This second strategy is suited for homeowners who aim for a good insulation level of their homes and want to use renewable sources for part of their energy consumption. This second strategy has a longer payback time and might cause somewhat more disturbance than the first strategy.

Requirements

- Maximum EPC of 0,4
- Use of renewable energy sources
- Payback time: 10-25 years
- Medium disturbance level
- R_c-values:
  - Wall > 2,0 (m^2*K)/W
  - Floor > 5,0 (m^2*K)/W
  - Roof > 6,0 (m^2*K)/W
  - Dormer > 4,5 (m^2*K)/W
- Windows: HR+++
- Frames: U-value < 1,4 W/ (m^2*K)
- LED lighting

Optional extra's

- Efficient electric appliances
- Electric cooking

5.2.2. Insulation techniques

The insulation techniques are similar to those in the first strategy. The main difference being that a higher level of thermal resistance is required for a number of techniques.

- *Cavity wall insulation*
- *Internally insulated pitched roof*

For this strategy a higher level of thermal resistance is required for this technique.

- *Externally insulated flat roof*

For this strategy a higher level of thermal resistance is required for this technique.

- *Insulating dormers*

For this strategy a higher level of thermal resistance is required for this technique.

- *Crawl space insulation*

For this strategy a higher level of thermal resistance is required for this technique.

- *Window and door replacement*

For this strategy a higher level of thermal resistance is required for this technique.

- *Lowering infiltration*

The application of the insulation will cause slight lowering of the infiltration but this can be increased even further by sealing cracks and crevasses in the outer shell.

- *Extra and/or larger ventilation grills*

I decided to retain the natural ventilation instead of replacing it with complete mechanical ventilation as intermediate simulations indicated a drastic increase in electricity consumption and only a small decrease in the heating demand. As the infiltration is lowered drastically with this strategy extra or larger ventilation grills will have to be placed to ensure that enough fresh air enters the house.

5.2.3. Installations

By using available renewable energy sources, the fossil fuel consumption of the house can be lowered. A popular and easily accessible renewable energy source is the sun.

- *Hybrid HR++ combi boiler with solar collectors*

For the test house a solar boiler installation with a 120L tank and 3,2m^2 of solar collectors was chosen due to the limited space on the roof and in the house. For this test house two PV-panel sized solar collectors with each a surface area of 1,6m^2 were chosen. This was done because the regular sized solar collectors did not fit on the roof in combination with the required number of PV-panels and because it created a more uniform and thus more aesthetically pleasing result. It is unclear if the current combi boiler is compatible with solar collectors so I assumed that a new one will have to placed. To increase effectiveness of the new installation the dedicated electric boiler in the kitchen must be removed and the kitchen tap connected to the combi boiler installation. This means that the new combi boiler will provide hot water for the heating system and hot water taps in the bathroom and kitchen. To achieve this new piping will have to be placed to connect the combi boiler to the kitchen.

- *Photovoltaic panels*

To reach an EPC lower than 0,4 a total of 8 PV-panels with a 275Wp production each are required. These panels are 1,67m^2 on average and based on the Design Builder model and other houses in the neighbourhood, I deemed it possible to place 8 of these panels on the roof in addition to the two solar collectors. See figure 32 for a simple visualization of the 10 solar panels on the roof of the house.

Figure 32: Simple garden façade visualization of situation after application of strategy B.

5.2.4. LED-lighting

As with strategy A I assumed a situation with mostly energy-saving light bulbs. Although these are already significantly better than incandescent light bulbs LED lights are still better and have a much longer life span.

5.2.5. Extra options

These extra options are recommended to further decrease the electricity consumption and prepare the house for the future. They were not taken into account in the simulation.

- *Efficient electric appliances*

To decrease electricity use, replacement of electric appliances older than 20 years is recommended. This can be done step-by-step to spread costs. Examples of appliances recommended for replacement are fridges, electric stoves and ovens, microwaves, washing machines and dryers. Modern appliances have energy labels, appliances with a label A++ or A+++ are recommended.

- *Electric cooking*

Replacing the gas stove with an induction stove will prepare the house for a gas-free future. Of all electric alternatives, induction is the best option. These stoves work with magnetism which means the stove does not become hot like other types of electric stoves, only the pan becomes warm. This makes them highly efficient, easy to use, and very safe. Some old houses also have a gas oven, these should also be replaced with an electric alternative.

5.2.6. Simulations

To simulate the decrease in fuel usage, the original construction properties were changed according to the insulation techniques and the infiltration level was lowered. Additionally, a detailed HVAC system was created to simulate the heating demand, including solar collectors on the roof, see table 7 for a summary of the changes. For the renewable energy production photovoltaic panels were added to the roof. Furthermore, the lighting scheme was changed to LED lighting. See the added excel for the precise parameters and calculations. See appendix 3 for a detailed overview of the parameters.

5.2.7. Costs

The minimum and maximum costs for each improvement were calculated and added up to calculate the minimum and maximum costs of the strategy, see table 8. The optional extras were not taken into account for this calculation.

5.2.8. Results

After applying the changes, a new simulation was performed using Design Builder and Uniec, see table 9 on page 66 for the results. The main aim of an EPC of 0,4 or less was reached. Based on the results a 54-84% reduction in gas consumption and 47-48% reduction in electricity consumption is probable. The vast difference between the gas consumption results of the two programs is quite strange. This can be due to the fact that Design Builder allows a more specific situation to be created. Another possibility is that an error

	Current situation			EPC ≤ 0,4 strategy		
Construction	Structure type	Rc-value [m2*K/W]	U-value [W/m2*K]	Improvement	Rc-value [m2*K/W]	U-value [W/m2*K]
External wall	Brick cavity wall	1,02	0,98	Cavity wall insulation	2,21	0,45
Ground floor 1	Wooden floor	1,33	0,75	Crawl space insulation	5,25	0,19
Ground floor 2	MUWI concrete floor	0,57	1,75	Crawl space insulation	5,24	0,19
Pitched roof	Wooden roof structure	0,79	1,26	Internal insulation	6,19	0,16
Flat roof	Wooden roof structure	0,74	1,36	External insulation	6,17	0,16
Dormer wall	Wooden structure	1,84	0,55	Internal insulation	4,58	2,2
Dormer roof	Wooden roof structure	0,74	1,36	External insulation	6,17	0,16
Doors	Low standard doors		2,82	New insulated doors		1,25
Glazing	Low standard double glazing		2,76	HR+++ glass		0,77
Frames	Wooden frames		2,62	Wooden frames / with thermal break		1,39
Airtightness						
Infiltration rate [ac/h]	0,7			0,2		
Installations						
Ventilation	Natural ventilation			Natural ventilation		
Heating and HW installation	HR combi-boiler			HR combi-boiler with solar collectors		
Kitchen HW installation	Electric boiler 10 L					
PV-panels				8 monocrystalline 275 Wp panels (each 1,67 m2)		
Solar collectors				2 solar collectors (each 1,67 m2) + 120 L tank		

Table 7: Summary of the changed parameters.

Required improvements	Min. Price		Max. Price			Min. Price		Max. Price	
Wall	[/m2]		[/m2]		[m2]				
Cavity wall insulation	€	15,00	€	30,00	25	€	375,00	€	750,00
Internal wall insulation dormer	€	40,00	€	90,00	5	€	200,00	€	450,00
Roof	[/m2]		[/m2]		[m2]				
Internal pitched roof insulation	€	30,00	€	70,00	60	€	1.800,00	€	4.200,00
External flat roof insulation	€	70,00	€	115,00	16	€	1.120,00	€	1.840,00
Ground floor	[/m2]		[/m2]		[m2]				
Crawl space insulation	€	20,00	€	45,00	60	€	1.200,00	€	2.700,00
Windows	[/m2]		[/m2]		[m2]				
HR+++ glass	€	160,00	€	280,00	24	€	3.840,00	€	6.720,00
Window frames	€	170,00	€	270,00	24	€	4.080,00	€	6.480,00
Insulated external (glass) doors	€	200,00	€	700,00	19	€	3.800,00	€	13.300,00
Heating installation									
HR Combi-boiler					1	€	1.500,00	€	3.500,00
Solar boiler 2 panels with tank					1	€	2.750,00	€	4.000,00
Solar boiler < 5m2 subsidy					1	€	-500,00	€	-2.500,00
PV-panels	[/Wp]		[/Wp]		[Wp]				
PV-panels incl. installation and tax	€	1,50	€	1,74	2200	€	3.300,00	€	3.828,00
Tax refund	€	-0,22	€	-0,26	2200	€	-484,00	€	-572,00
Electric appliances									
LED bulb	€	1,00	€	10,00	15	€	15,00	€	150,00
Total						€	22.996,00	€	44.846,00

Table 8: Minimum and maximum costs calculation.

was made in the HVAC settings in Design Builders or in the Uniec parameters. Lastly the predicted payback time ranges between the 15 and 42 years. The wide range in this payback time is due to the large range in the estimated gas reduction as this directly effects the yearly savings. The best-case scenario payback time is well within the boundary conditions of this strategy.

	Current situation			EPC ≤ 0,4 strategy			
Program	DesignBuilder	Uniec	Measurements	DesignBuilder	Difference	Uniec	Difference
Elec installations	0 kWh	79 kWh		31 kWh		440 kWh	457%
Elec installations correction	79 kWh			409 kWh			
Elec heating							
Elec hot water	373 kWh	465 kWh		0 kWh	-100%	0 kWh	-100%
Elec cooking							
Elec appliances	3500 kWh	3500 kWh		3400 kWh	-3%	3400 kWh	-3%
Electricity production	0 kWh	0 kWh		-1769 kWh		-1696 kWh	
Electricity total	3952 kWh	4044 kWh	3984 kWh	2071 kWh	-48%	2144 kWh	-47%
Gas heating	1813 m3	1732 m3		222 m3	-88%	774 m3	-55%
Gas hot water	317 m3	256 m3		96 m3	-70%	128 m3	-50%
Gas cooking	37 m3	37 m3		37 m3	0%	37 m3	0%
Gas total	2167 m3	2025 m3	2260 m3	355 m3	-84%	939 m3	-54%
Totaal CO2-emission		4646 kg				1402 kg	-70%
EPC		1,129				0,373	-67%
BENG energiebehoefte		115,4 kWh/m2				51 kWh/m2	-56%
BENG primair		157,4 kWh/m2				55,9 kWh/m2	-64%
BENG hernieuwbaar		0 %				31 %	
Cost				Minimum		Maximum	
Investment				€ 22.996,00		€ 44.846,00	
Yearly savings				€ 1.064,18		€ 1.517,76	
Payback time [years]				15		42	

Table 9: Fuel consumption comparison and payback time.

5.3. Net Zero Energy Building strategy (C)

The last refurbishment strategy is aimed at homeowners who really want to make a difference and live gas-free. This can be achieved by making the house a (near) Net Zero Energy Building and eliminating gas consumption. This ultimately means that the annual electricity consumption is equal to the annual electricity production of the building and that no gas is consumed. This strategy requires major changes including insulation, a new heating system, use of renewable energy, and efficient electrical appliances.

5.3.1. Boundary conditions

The last strategy is aimed at homeowners who are willing to make a large investment in order to drastically lower their energy consumption and live gas-free. The main goal for a NZEB is to produce as much electricity as is consumed in one year. Furthermore, the house will be prepared for the future by replacing gas fuelled installation with new installation based on other sources.

Requirements

- A (nearly) NZEB
- Gas-free
- Use of renewable energy sources
- No budget limits
- R_c-values:
  - Wall > 4,5 (m^2*K)/W
  - Floor > 5,0 (m^2*K)/W
  - Roof > 6,0 (m^2*K)/W
  - Dormer > 4,5 (m^2*K)/W
- Windows: HR+++
- Frames: U-value < 1,4 W/ (m^2*K)
- LED lighting
- Efficient electric appliances

5.3.2. Insulation techniques

For a (near) NZEB and gas-free house a high level of thermal resistance is required to eliminate heat loss as much as possible. To achieve this other insulation techniques are recommended than with the previous two strategies. The aim of the insulation techniques is to entirely encase the building in insulation on the outside. This will highly insulate the building and prevent cold bridges.

- *Cavity wall insulation and external insulation*

Cavity wall insulation is not enough to reach a high level of thermal resistance which means that the outer walls will require extra insulation. By externally insulating the house this can be achieved without decreasing the available floor space inside and with a lower disturbance level than with internal insulation. External insulation also requires a new finish layer for the house which means that the appearance of the house can be changed if this is desired. For the test house I chose to retain the current appearance so as to lower the difference with the neighbouring houses. As this technique creates an entirely new finish layer, possible pointing work problems are immediately solved.

- *Externally insulated roof*

Externally insulating the pitched and flat roofs allows a high level of thermal resistance to be reached without decreasing the internal space of the house.

- *New highly insulated dormers*

Replacing the old dormers with new, highly insulated dormers is cheaper and faster than insulating the existing dormers. For the test house slightly different sized dormers were chosen to increase the amount of roof area which can be used for PV-panels.

- *Crawl space insulation*
- *Window and door replacement*

As new connections will have to be made between the windows and doors and the outer wall, the easiest solution to completely replace all windows, doors and frames.

- *Lowering infiltration*

The application of these techniques will cause lowering of the infiltration but this can be increased even further by sealing cracks and crevasses in the outer shell.

- *Extra and/or larger ventilation grills*

I decided to retain the natural ventilation instead of replacing it with complete mechanical ventilation as intermediate simulations indicated a drastic increase in electricity consumption and only a small decrease in the heating demand.

5.3.3. Installations

By using the available renewable energy sources, the fossil fuel consumption of the house can be lowered. A popular and easily accessible renewable energy source is the sun.

- *Electric boiler with air heat pump and solar collectors*

For this specific case study, a solar boiler installation with a 120L tank and 3,2m^2 of solar collectors was chosen due to limited amount of space on the roof and in the house. For this house two PV-panel sized collectors were chosen to allow more PV-panels to be placed on the roof and create a more uniform view. The solar collectors can easily be placed on the pitched roof. The tank will require space in the house. For the air-based heat pump a unit has to be placed: this can be done in the garden or on the flat roof of the extension. This new system will provide low-temperature heating and can also provide cooling. New low-temperature radiators need to be placed, LT floor heating is also possible. Replacing radiators is quite easy and does not require major changes. Low-temperature floor heating will require a new floor with insulation, piping and special flooring. Furthermore, the ceiling height will become lower and new doors and doorposts will have to be placed. However, floor heating will provide a higher comfort level, the ultimate choice lies with the homeowners. For the simulation low-temperature radiators were used.

- *Photovoltaic panels*

To reach a NZEB a high level of electricity production is required. As with the solar collectors the roof is ideal for PV-panels. With these panels electricity can be produced to be used by the inhabitants and sold to the national grid when the demand is lower than the production. This will ultimately lower the electricity bill for the inhabitants. Monocrystalline panels are recommended over polycrystalline due to their higher aesthetical quality and slightly higher production rate. Due to the new electrically based heating system, the electricity consumption will be higher. However, the new south-facing pitched roof structure only provides room for a maximum of 11 large monocrystalline panels next to the solar collectors. To maximize production a high-power type with a production of 305Wp per panel was chosen.

5.3.4. LED-lighting

As with strategy A and B I assumed a situation with mostly energy-saving light bulbs. Although these are already significantly better than incandescent light bulbs, LED lights are still better and have a much longer life span.

5.3.5. Electric appliances

The optional extra options of the first two strategies is mandatory for this third strategy.

- *Efficient electric appliances*

To decrease electricity use, replacement of electric appliances older than 15 years is required. Modern appliances have energy labels, appliances with a label A++ or A+++ are recommended.

- *Electric cooking*

As the house will be disconnected from the gas-grid, the gas stove needs to be replaced with an induction stove. Of all electric alternatives, induction is the best option. These stoves work with magnetism which means the stove does not become warm like other types of electric stoves, only the pan becomes warm. This makes them highly efficient, easy to use, and very safe. Some old houses also have a gas oven, these also need to be replaced with an electric alternative.

5.3.6. Simulations

To simulate the decrease in fuel usage, the original construction properties were changed, the infiltration level was lowered, and the LED lighting and new appliances were applied. A detailed HVAC system was created to simulate the heating demand, including solar collectors on the roof. For the renewable energy production photovoltaic panels were added to the roof. A simple visualization was made of the building after application of the strategy, for this visualization the current appearance was maintained, see figures 33 and 34. See table 10 on page 70 for a summary of the changes, see appendix 4 for a detailed overview.

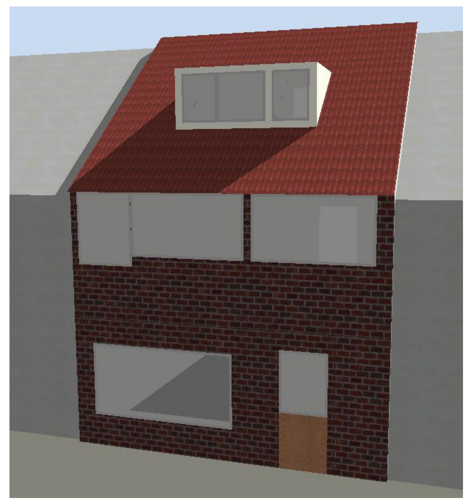

Figure 33: Simple front façade visualization of situation after application of strategy C.

Figure 34: Simple garden façade visualization of situation after application of strategy C.

5.3.7. Costs

The minimum and maximum costs for each improvement were calculated and added up to calculate the minimum and maximum costs of the strategy, see table 11.

	Current situation			NZEB strategy		
Construction	Structure type	Rc-value [m2*K/W]	U-value [W/m2*K]	Improvement	Rc-value [m2*K/W]	U-value [W/m2*K]
External wall	Brick cavity wall	1,02	0,98	External and cavity wall insulation	4,55	0,22
Ground floor 1	Wooden floor	1,33	0,75	Crawl space insulation	6,29	0,16
Ground floor 2	MUWI concrete floor	0,57	1,75	Crawl space insulation	5,24	0,19
Pitched roof	Wooden roof structure	0,79	1,26	External insulation	6,22	0,16
Flat roof	Wooden roof structure	0,74	1,36	External insulation	6,17	0,16
Dormer wall	Wooden structure	1,84	0,55	Internal insulation	4,58	0,22
Dormer roof	Wooden roof structure	0,74	1,36	External insulation	6,22	0,16
Doors	Low standard doors		2,82	New insulated doors		1,25
Glazing	Low standard double glazing		2,76	HR+++ glass		0,77
Frames	Wooden frames		2,62	Wooden frames / with thermal break		1,39
Airtightness						
Infiltration rate [ac/h]	0,7			0,2		
Installations						
Ventilation	Natural ventilation			Natural ventilation		
Heating and HW installation	HR combi-boiler			LT radiator heating, Hybrid electric combi-boiler with heat pump and solar collectors		
Kitchen HW installation	Electric boiler 10 L					
PV-panels				11 monocrystalline 305 Wp panels (each 1,67 m2)		
Solar collectors				2 solar collectors (each 1,67 m2) + 120 L tank		

Table 10: Summary of the changed parameters.

Required improvements	Min. Price	Max. Price		Min. Price	Max. Price
Wall	[/m2]	[/m2]	[m2]		
Cavity wall insulation	€ 15,00	€ 30,00	25	€ 375,00	€ 750,00
External wall insulation	€ 100,00	€ 150,00	35	€ 3.500,00	€ 5.250,00
Roof	[/m2]	[/m2]	[m2]		
External pitched roof insulation	€ 60,00	€ 100,00	60	€ 3.600,00	€ 6.000,00
External flat roof insulation	€ 70,00	€ 115,00	6	€ 420,00	€ 690,00
Dormers	[/m]	[/m]	[m]		
Complete replacement	€ 1.000,00	€ 2.500,00	6	€ 6.000,00	€ 15.000,00
Ground floor	[/m2]	[/m2]	[m2]		
Crawl space insulation	€ 20,00	€ 45,00	60	€ 1.200,00	€ 2.700,00
Windows	[/m2]	[/m2]	[m2]		
HR+++ glass	€ 160,00	€ 280,00	17	€ 2.720,00	€ 4.760,00
Window frames	€ 170,00	€ 270,00	17	€ 2.890,00	€ 4.590,00
Insulated external (glass) doors	€ 200,00	€ 700,00	19	€ 3.800,00	€ 13.300,00

Table 11a: Minimum and maximum costs calculation.

Required improvements	Min. Price	Max. Price		Min. Price	Max. Price
Heating installation					
Air heat pump electricly fuelled system			1	€ 5.000,00	€ 12.000,00
Heat pump subsidy			1	€ -1.250,00	€ -2.600,00
Solar boiler 2 panels with tank			1	€ 2.750,00	€ 4.000,00
Solar boiler < 5m2 subsidy			1	€ -500,00	€ -2.500,00
LT radiators / floor heating			1	€ 2.500,00	€ 5.000,00
PV-panels	[/Wp]	[/Wp]	[Wp]		
PV-panels incl. installation and tax	€ 1,50	€ 1,74	3355	€ 5.032,50	€ 5.837,70
Tax refund	€ -0,22	€ -0,26	3355	€ -738,10	€ -872,30
Electric appliances					
LED bulb	€ 1,00	€ 10,00	15	€ 15,00	€ 150,00
Induction stove			1	€ 300,00	€ 1.000,00
A+ oven			1	€ 500,00	€ 1.000,00
A++ fridge-freezer combi			1	€ 500,00	€ 1.000,00
A+++ dishwasher			1	€ 300,00	€ 800,00
A+++ washing machine			1	€ 300,00	€ 800,00
A+++ dryer			1	€ 600,00	€ 1.000,00
Total				€ 39.814,40	€ 79.655,40

Table 11b: Minimum and maximum costs calculation continued.

5.3.8. Results

After applying the changes, a new simulation was performed using Design Builder and Uniec, see table 12 on page 72 for the results. The gas consumption was completely eliminated as required for this strategy. This means that the goal of a gas-free house is reached. However, as can be concluded from the results it is not possible for this house to produce enough electricity to eliminate the electricity consumption. This means that the goal of a NZEB is not achievable for this test house. This is simply due to the small roof area of the house. Houses with a large roof area will have a higher chance of reaching the NZEB goal. The predicted decrease in the electricity demand is 13-39%. This large range is mostly due to the large difference in the predicted heating demands of the two programs. As with strategy B this can be due to the fact that Design Builder allows a more specific situation to be created or because certain errors were unintentionally made. Lastly a payback time of 24 to 58 years was calculated. The large range in this payback time is mostly due to the large differences in the available finish levels for each technique and slightly due to the differences in the predicted electricity reduction. However, the best-case scenario payback time is better than I had expected.

	Current situation			NZEB strategy			
Program	DesignBuilder	Uniec	Measurements	DesignBuilder	Difference	Uniec	Difference
Elec installations	0 kWh	79 kWh		28 kWh		644 kWh	715%
Elec installations correction	79 kWh			616 kWh			
Elec heating				275 kWh		1518 kWh	
Elec hot water	373 kWh	465 kWh		550 kWh	47%	804 kWh	73%
Elec cooking				175 kWh		175 kWh	
Elec appliances	3500 kWh	3500 kWh		3000 kWh	-14%	3000 kWh	-14%
Electricity production	0 kWh	0 kWh		-2244 kWh		-2621 kWh	
Electricity total	3952 kWh	4044 kWh	3984 kWh	2400 kWh	-39%	3520 kWh	-13%
Gas heating	1813 m3	1732 m3		0 m3	-100%	0 m3	-100%
Gas hot water	317 m3	256 m3		0 m3	-100%	0 m3	-100%
Gas cooking	37 m3	37 m3		0 m3	-100%	0 m3	-100%
Gas total	2167 m3	2025 m3	2260 m3	0 m3	-100%	0 m3	-100%
Totaal CO2-emission		4646 kg				698 kg	-85%
EPC		1,129				0,147	-87%
BENG energiebehoefte		115,4 kWh/m2				47,4 kWh/m2	-59%
BENG primair		157,4 kWh/m2				9,2 kWh/m2	-94%
BENG hernieuwbaar		0 %				88 %	
Cost				Minimum		Maximum	
Investment				€ 39.814,40		€ 79.655,40	
Yearly savings				€ 1.380,55		€ 1.675,61	
Payback time [years]				24		58	

Table 12: Fuel consumption comparison and payback time.

5.4. Results comparison

After application of each strategy a comparison was made of the results, see table 13, and the visualisations of each strategy and the current situation were compared, see figures 35, 36, 37, and 38. The most significant result is that the payback time of strategy B is only 3 years longer than that of strategy A. Therefore, strategy B achieves a substantial reduction in energy consumption while providing a favourable balance between investment and yearly savings. To

	Basic insulation strategy				EPC ≤ 0,4 strategy				NZEB strategy			
Program	DB	Diff.	Uniec	Diff.	DB	Diff.	Uniec	Diff.	DB	Diff.	Uniec	Diff.
Elec installations	0 kWh		56 kWh	-29%	31 kWh		440 kWh	457%	28 kWh		644 kWh	715%
Elec installations corr.	56 kWh				409 kWh				616 kWh			
Elec heating									275 kWh		1518 kWh	
Elec hot water	373 kWh	0%	458 kWh	-2%	0 kWh	-100%	0 kWh	-100%	550 kWh	47%	804 kWh	73%
Elec cooking									175 kWh		175 kWh	
Elec appliances	3400 kWh	-3%	3400 kWh	-3%	3400 kWh	-3%	3400 kWh	-3%	3000 kWh	-14%	3000 kWh	-14%
Electricity production	0 kWh		0 kWh		-1769 kWh		-1696 kWh		-2244 kWh		-2621 kWh	
Electricity total	3829 kWh	-3%	3914 kWh	-3%	2071 kWh	-48%	2144 kWh	-47%	2400 kWh	-39%	3520 kWh	-13%
Gas heating	601 m3	-67%	947 m3	-45%	222 m3	-88%	774 m3	-55%	0 m3	-100%	0 m3	-100%
Gas hot water	317 m3	0%	252 m3	-2%	96 m3	-70%	128 m3	-50%	0 m3	-100%	0 m3	-100%
Gas cooking	37 m3	0%	37 m3	0%	37 m3	0%	37 m3	0%	0 m3	-100%	0 m3	-100%
Gas total	955 m3	-56%	1236 m3	-39%	355 m3	-84%	939 m3	-54%	0 m3	-100%	0 m3	-100%
Totaal CO2-emission			3140 kg	-32%			1402 kg	-70%			698 kg	-85%
EPC			0,765	-32%			0,373	-67%			0,147	-87%
BENG energiebeh.			68,9 kWh/m2	-40%			51 kWh/m2	-56%			47,4 kWh/m2	-59%
BENG primair			103,8 kWh/m2	-34%			55,9 kWh/m2	-64%			9,2 kWh/m2	-94%
BENG hernieuwbaar			0 %				31 %				88 %	
Cost	Minimum		Maximum		Minimum		Maximum		Minimum		Maximum	
Investment	€ 9.480,00		€ 20.360,00		€ 22.996,00		€ 44.846,00		€ 39.814,40		€ 79.655,40	
Yearly savings	€ 521,67		€ 789,56		€ 1.064,18		€ 1.517,76		€ 1.380,55		€ 1.675,61	
Payback time [years]	12		39		15		42		24		58	

Table 13: Result comparison of the three strategies.

achieve zero gas consumption would require the (nearly) NZEB strategy (C) which implies a far larger investment. Additionally, this strategy would have the largest impact on the aesthetics of the house, see figure 38, as it requires the application of outer insulation, new different sized dormers, and a large number of solar panels. As strategy A is a basic strategy only focused on increasing the insulation with easy insulation techniques, this strategy has no significant effect on the aesthetics of the house. Strategy B can be seen as more of an in-between state as does have some solar panel similar to strategy C but the insulation techniques are, in the sense of aesthetic impact, more similar to strategy A.

Figure 35: Visualisation of the current situation.

Figure 36: Visualisation of the Basic insulation strategy.

Figure 37: Visualisation of the EPC ≤ 0,4 strategy.

Figure 38: Visualisation of the NZEB strategy.

5.5. Conclusion

Based on the literature review and analysis of the test house three refurbishment strategies were developed, each with a different level of improvement. Each strategy was tested on the main test house for improvements and the final results. For the main test house, the first two strategies reached nearly all their set goals and an EPC of 0,4 or less can be achieved with strategy B. Additionally a gas-free house is possible with a nearly Net Zero Energy Building. However, a truly Net Zero Energy Building is not possible for this test house due to the small surface area of the roof.

With the three different strategies the main problem of 1960's and 1970's, a high heating demand, can be lowered in different levels. As asbestos, 'Kwaaitaal' or 'Manta' floors, and structural-borne noise were not a problem in this house these problems did not require addressing. The problem of spruce wood frames can easily be solved with these strategies as replacement of the windows is required and new frames might be necessary for HR++ or HR+++ glazing. Strategy C includes external insulation which automatically solves the problems of eroded pointing work. As both strategy B and C require new installations and PV-panels, changes will have to be made to the plumbing fixtures and electricity network. The changes to the electricity network have to be performed by a certified technician to ensure a safe electricity network, providing the opportunity to solve any existing problems.

The results of the Design Builder and Uniec simulation for both strategies B and C varied significantly. This is probably due to the differences between the two programs, Design Builder being very situation specific with many parameters and Uniec very general and based on averages. The large price differences between insulation materials, finish levels and installation cause a large difference between the minimum and maximum calculated investments. Together with the differences between the reduction results this gives a large range in the calculated payback times. To reach a low level of investment it is very important to acquire multiple quotations for each improvement. Another way to reduce the costs is having the owners do the work themselves: for certain techniques this is definitely possible.

Based on the results, I would advise strategy B for this particular house because this strategy resulted in the best balance between the investment and yearly savings. Furthermore, it must be noted that the payback time calculations were performed with the current electricity and gas prices. An increase in the gas price and decrease in the electricity price have been announced for 2019, the exact amount is still unclear. This change will probably increase the yearly savings and lower the predicted payback times, especially for the NZEB strategy.

6. Versatility testing

The developed strategies were next tested on versatility by applying them on the two other test houses, each a different building type: a semi-detached and free-standing house. These two houses were both built towards the end of the late post-war era. After a quick assessment of the two houses I decided to test the free-standing house first because the semi-detached house has very a-typical characteristics.

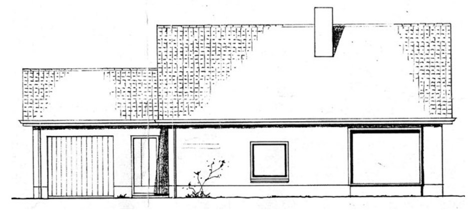

Figure 39: Front façade.

6.1. Free-standing house

A reasonable large free-standing house in Gorssel was assessed for this research project. The house was built in 1972 and the original drawings were provided by the previous owners. The current state of the house is unknown.

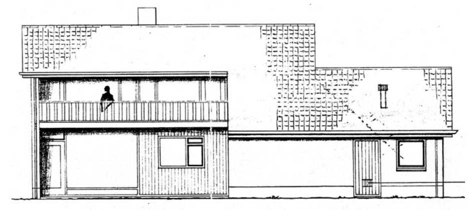

Figure 40: Garden façade.

6.1.1. Analysis

The free-standing house has a main part with two floors and a secondary part with one floor, see figures 39, 40, 41, and 42. Although the layout of the house is very unique, the sizes of the room are very standard for the time. The main living spaces such as the living room and bedrooms are large, whereas the kitchen and bathrooms are small.

The applied construction techniques are also typical for post-war era houses. The main floors are made of concrete and the ground floor has a crawl space. The attics have a wooden floor construction. The house has a garden facing balcony which is part of the concrete floor creating a cold bridge. The house has a pitched roof consisting of a wooden beam construction with clay tile cladding. The house is heated with radiators connected to a combi boiler which also provides hot water and located in the garage. Ventilation occurs naturally via openable windows and extraction points in the kitchen and bathrooms.

As the information concerning this house was provided by the previous owners the amount of information was quite limited. Therefore, the simulations were based on the original building drawings and possible changes were not taken into account. Furthermore, the worst-case scenario was assumed when information was lacking.

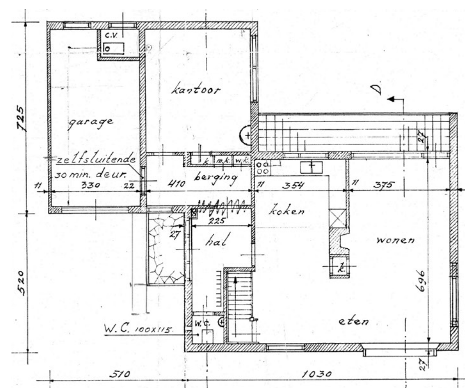

Figure 41: First floor.

6.1.1.1. Simulations

Similar to the test house a Design Builder and Uniec model of the current situation were created as a basis for the further simulations. See table 14 on page 78 for a summary of the main parameters and see appendix 5 for more details.

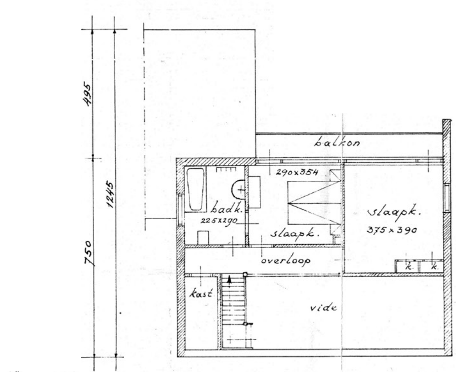

Figure 42: Second floor.

	Current situation		
Construction	Structure type	Rc-value [m2*K/W]	U-value [W/m2*K]
External wall	Brick cavity wall	0,718	1,392
Ground floor	Concrete floor	0,674	1,483
Pitched roof	Wooden roof structure	1,993	0,502
Doors	Low standard doors		2,823
Glazing	Low standard double glazing		3,157
Frames	Wooden frames		2,628
Airtightness			
Infiltration rate [ac/h]	0,7		
Installations			
Ventilation	Natural ventilation		
Heating and HW installation	Combi-boiler		
PV-panels			
Solar collectors			

Table 14: Summary of the main parameters for the current situation.

6.1.1.2. Results

The simulations gave the following consumption results: 4049kWh of electricity, 4705/4832m^3 of gas, and an EPC of 2,019, see table 15. The measurements are a rough estimate by the previous homeowners of their consumption.

	Current situation					
Program	DesignBuilder		Uniec		Measurements	
Elec installations	0	kWh	349	kWh		
Elec installations correction	349	kWh				
Elec heating						
Elec hot water						
Elec cooking						
Elec appliances	3700	kWh	3700	kWh		
Electricity production	0	kWh	0	kWh		
Electricity total	4049	kWh	4049	kWh	4000	kWh
Gas heating	4152	m3	4245	m3		
Gas hot water	516	m3	550	m3		
Gas cooking	37	m3	37	m3		
Gas total	4705	m3	4832	m3	4500	m3
Totaal CO2-emission			9357	kg		
EPC			2,019			
BENG energiebehoefte			196,2	kWh/m2		
BENG primair			383,4	kWh/m2		
BENG hernieuwbaar			0	%		

Table 15: Results comparison for the current situation.

6.1.2. Application basic insulation strategy

The first strategy can easily be applied to this house as the construction is very similar to the row house. Each step was applied to the house, techniques requiring slight adjustments are explained in more detail.

- *Cavity wall insulation*
- *Internal pitched roof and attic insulation*

The attic in the lower part of the house is not heated and only in use as storage. Therefore, this part only requires attic floor insulation. The small attic space in the main part of the house can also be insulated with attic floor insulation.

- *Crawl space insulation*
- *Window and door replacement*
- *Ventilation grills*

As the ventilation is only provided by openable windows, ventilations grills have to be placed to ensure enough fresh air.

- *Heating and hot water installations*

No information was provided concerning the heating and hot water installation. Therefore, I assumed it is older than 15 years, requiring replacement.

- *LED-lights*

As no information was provided I assumed that all lightbulbs require replacement.

- *Extra options*

This is up to the owners to decide.

6.1.2.1. Simulations & cost calculation

Both models were adjusted according to the used insulation techniques, see table 16 for a summary of the changed parameters.

	Current situation			Basic insulation strategy		
Construction	Structure type	Rc-value [m2*K/W]	U-value [W/m2*K]	Improvement	Rc-value [m2*K/W]	U-value [W/m2*K]
External wall	Brick cavity wall	0,718	1,392	Cavity wall insulation	1,669	0,599
Ground floor	Concrete floor	0,674	1,483	Crawl space insulation	3,531	0,283
Pitched roof	Wooden roof structure	1,993	0,502	Internal insulation	4,172	0,240
Doors	Low standard doors		2,823	New insulated doors		1,245
Glazing	Low standard double glazing		3,157	HR++ glazing		1,514
Frames	Wooden frames		2,628	Wooden frames / with thermal break		1,393
Airtightness						
Infiltration rate [ac/h]	0,7			0,4		
Installations						
Ventilation	Natural ventilation			Natural ventilation		
Heating and HW installation	Combi-boiler			HR combi-boiler		
PV-panels						
Solar collectors						

Table 16: Summary of the changed parameters.

See appendix 6 for a detailed overview. Additionally, a cost calculation was done for the strategy, see table 17 for the results.

Required improvements	Min. Price	Max. Price		Min. Price	Max. Price
Wall	[/m2]	[/m2]	[m2]		
Cavity wall insulation	€ 15,00	€ 30,00	130	€ 1.950,00	€ 3.900,00
Roof	[/m2]	[/m2]	[m2]		
Internal pitched roof and attic insulation	€ 30,00	€ 70,00	143	€ 4.290,00	€ 10.010,00
Ground floor	[/m2]	[/m2]	[m2]		
Crawl space insulation	€ 20,00	€ 45,00	129	€ 2.580,00	€ 5.805,00
Windows	[/m2]	[/m2]	[m2]		
HR++ glass	€ 130,00	€ 230,00	35	€ 4.550,00	€ 8.050,00
Window frames	€ 170,00	€ 270,00	35	€ 5.950,00	€ 9.450,00
Insulated external (glass) doors	€ 200,00	€ 700,00	19	€ 3.800,00	€ 13.300,00
Heating installation					
HR combi-boiler			1	€ 1.500,00	€ 3.500,00
Electric appliances					
LED bulb	€ 1,00	€ 10,00	20	€ 20,00	€ 200,00
Total				€ 24.640,00	€ 54.215,00

Table 17: Minimum and maximum costs calculation.

6.1.2.2. Results

Next the main results were combined and compared to the results of the current situation and the payback time was calculated, see table 18. This strategy resulted in a 11% reduction in electricity and a 50-52% reduction in gas. An EPC of 1,043 was reached and this strategy has a payback time of 15 to 34 years.

	Current situation			Basic insulation strategy			
Program	DesignBuilder	Uniec	Measurements	DesignBuilder	Difference	Uniec	Difference
Elec installations	0 kWh	349 kWh		0 kWh		86 kWh	-75%
Elec installations correction	349 kWh			86 kWh			
Elec heating							
Elec hot water							
Elec cooking							
Elec appliances	3700 kWh	3700 kWh		3500 kWh	-5%	3500 kWh	-5%
Electricity production	0 kWh	0 kWh		0 kWh		0 kWh	
Electricity total	4049 kWh	4049 kWh	4000 kWh	3586 kWh	-11%	3586 kWh	-11%
Gas heating	4152 m3	4245 m3		1796 m3	-57%	1963 m3	-54%
Gas hot water	516 m3	550 m3		419 m3	-19%	432 m3	-21%
Gas cooking	37 m3	37 m3		37 m3	0%	37 m3	0%
Gas total	4705 m3	4832 m3	4500 m3	2252 m3	-52%	2432 m3	-50%
Totaal CO2-emission		9357 kg				4864 kg	-48%
EPC		2,019				1,043	-48%
BENG energiebehoefte		196,2 kWh/m2				126,1 kWh/m2	-36%
BENG primair		383,4 kWh/m2				191,9 kWh/m2	-50%
BENG hernieuwbaar		0 %				0 %	
Cost				Minimum		Maximum	
Investment				€ 24.640,00		€ 54.215,00	
Yearly savings				€ 1.604,60		€ 1.637,99	
Payback time [years]				15		34	

Table 18: Fuel consumption comparison and payback time.

6.1.3. Application EPC ≤ 0,4 strategy

Similar to the first strategy, this second strategy can easily be applied. Each step was applied to the house, techniques requiring slight adjustments are explained in more detail.

- *Cavity wall insulation*
- *Internal pitched roof and attic insulation*

The attic in the lower part of the house is not heated and only in use as storage. Therefore, this part only requires attic floor insulation. The small attic space in the main part of the house can also be insulated with attic floor insulation.

- *Crawl space insulation*
- *Window and door replacement*
- *Ventilation grills*

As the ventilation is only provided by openable windows, ventilations grills have to be placed to ensure enough fresh air.

- *Heating and hot water installations*

No information was provided concerning the heating and hot water installation. Therefore, I assumed it is older than 15 years, requiring replacement. As the house has enough unused attic space and roof space a 4,8m^2 solar with a 200L tank was chosen for this house. Similar to the row house PV-panel sized solar collectors were chosen to achieve a more aesthetically pleasing view.

- *PV-panels*

To reach an EPC ≤ 0,4 a total of 24 275Wp PV-panels are required. The house has a large west-east orientated pitched roof which makes this possible. An integrated type of PV-panel, for example the Solesia PV-panels sold by Eternit in combination with their Domino tiles, can even be chosen to achieve a more aesthetically pleasing view. Due to the west-east orientation the production is more evenly spread over the day while the total production is only slightly lower.

- *LED-lights*

As no information was provided I assumed that all lightbulbs require replacement.

- *Extra options*

This is up to the owners to decide.

6.1.3.1. Simulations & cost calculation

Both models were adjusted according to the used insulation techniques, see table 18 on page 82 for a summary of the changed parameters. See appendix 7 for a detailed overview of the parameters. Additionally, a cost calculation was done for the strategy, see table 19 on page 82 for the results.

	Current situation			EPC ≤ 0,4 strategy		
Construction	Structure type	Rc-value [m2*K/W]	U-value [W/m2*K]	Improvement	Rc-value [m2*K/W]	U-value [W/m2*K]
External wall	Brick cavity wall	0,718	1,392	Cavity wall insulation	1,669	0,599
Ground floor	Concrete floor	0,674	1,483	Crawl space insulation	5,246	0,191
Pitched roof	Wooden roof structure	1,993	0,502	Internal insulation	6,172	0,162
Doors	Low standard doors		2,823	New insulated doors		1,245
Glazing	Low standard double glazing		3,157	HR+++ glass		0,786
Frames	Wooden frames		2,628	Wooden frames / with thermal break		1,393
Airtightness						
Infiltration rate [ac/h]	0,7			0,2		
Installations						
Ventilation	Natural ventilation			Natural ventilation		
Heating and HW installation	Combi-boiler			HR combi-kettle with solar collector		
PV-panels				24 monocrystalline 275 Wp panels (each 1,67 m2)		
Solar collectors				4,8 m2 solar collector (3x 1,6 m2) + 200 L tank		

Table 19: Summary of the changed parameters.

Required improvements	Min. Price	Max. Price		Min. Price	Max. Price
Wall	[/m2]	[/m2]	[m2]		
Cavity wall insulation	€ 15,00	€ 30,00	130	€ 1.950,00	€ 3.900,00
Roof	[/m2]	[/m2]	[m2]		
Internal pitched roof and attic insulation	€ 30,00	€ 70,00	143	€ 4.290,00	€ 10.010,00
Ground floor	[/m2]	[/m2]	[m2]		
Crawl space insulation	€ 20,00	€ 45,00	129	€ 2.580,00	€ 5.805,00
Windows	[/m2]	[/m2]	[m2]		
HR+++ glass	€ 160,00	€ 280,00	35	€ 5.600,00	€ 9.800,00
Window frames	€ 170,00	€ 270,00	35	€ 5.950,00	€ 9.450,00
Insulated external (glass) doors	€ 200,00	€ 700,00	19	€ 3.800,00	€ 13.300,00
Heating installation					
HR combi-boiler			1	€ 1.500,00	€ 3.500,00
Solar boiler 3 panels with tank			1	€ 4.500,00	€ 5.500,00
Solar boiler < 5m2 subsidy			1	€ -500,00	€ -2.500,00
PV-panels	[/Wp]	[/Wp]	[Wp]		
PV-panels incl. installation and tax	€ 1,50	€ 1,74	6600	€ 9.900,00	€ 11.484,00
Tax refund	€ -0,22	€ -0,26	6600	€ -1.452,00	€ -1.716,00
Electric appliances					
LED bulb	€ 1,00	€ 10,00	20	€ 20,00	€ 200,00
Total				€ 38.138,00	€ 68.733,00

Table 20: Minimum and maximum costs calculation.

6.1.3.2. Results

The main results were combined and compared to the results of the current situation and the payback time was calculated, see table 21 on page 83. This strategy resulted in a 113-121% reduction in electricity and a 60-71% reduction in gas. An EPC of 0,378 was reached as required for this strategy and a payback time of 13 to 26 years was calculated.

	Current situation			Basic insulation strategy			
Program	DesignBuilder	Uniec	Measurements	DesignBuilder	Difference	Uniec	Difference
Elec installations	0 kWh	349 kWh		0 kWh		86 kWh	-75%
Elec installations correction	349 kWh			86 kWh			
Elec heating							
Elec hot water							
Elec cooking							
Elec appliances	3700 kWh	3700 kWh		3500 kWh	-5%	3500 kWh	-5%
Electricity production	0 kWh	0 kWh		0 kWh		0 kWh	
Electricity total	4049 kWh	4049 kWh	4000 kWh	3586 kWh	-11%	3586 kWh	-11%
Gas heating	4152 m3	4245 m3		1796 m3	-57%	1963 m3	-54%
Gas hot water	516 m3	550 m3		419 m3	-19%	432 m3	-21%
Gas cooking	37 m3	37 m3		37 m3	0%	37 m3	0%
Gas total	4705 m3	4832 m3	4500 m3	2252 m3	-52%	2432 m3	-50%
Totaal CO2-emission		9357 kg				4864 kg	-48%
EPC		2,019				1,043	-48%
BENG energiebehoefte		196,2 kWh/m2				126,1 kWh/m2	-36%
BENG primair		383,4 kWh/m2				191,9 kWh/m2	-50%
BENG hernieuwbaar		0 %				0 %	
Cost				Minimum		Maximum	
Investment				€ 24.640,00		€ 54.215,00	
Yearly savings				€ 1.604,60		€ 1.637,99	
Payback time [years]				15		34	

Table 21: Fuel consumption comparison and payback time.

6.1.4. Application NZEB strategy

This third strategy can easily be applied, only requiring minor changes to fit the size of the house and household.

- *Cavity wall insulation and external insulation*
- *Externally insulated roof*
- *Crawl space insulation*
- *Window and door replacement*
- *Lowering infiltration*
- *Ventilation grills*
- *Electric boiler with air heat pump and solar collectors*

As the house has enough unused attic space and roof space a 4,8m^2 solar with a 200L tank was chosen for this house. Similar to the row house PV-panel sized solar collectors were chosen to achieve a more aesthetically pleasing view. For the air-based heat pump a unit can easily be placed in the garden next to the garage without giving any disturbance.

- *Photovoltaic panels*

With 39 275Wp PV-panels a totally NZEB can be achieved. The house has a large west-east orientated pitched roof which makes this possible. An integrated type of PV-panel, for example the

Solesia PV-panels sold by Eternit in combination with their Domino tiles, can even be chosen to achieve a more aesthetically pleasing view. Due to the west-east orientation the production is more evenly spread over the day while the total production is only slightly lower.

- *LED-lights*

As no information was provided I assumed that all lightbulbs require replacement.

- *Induction stove*

As no information was provided I assumed that the stove requires replacement and will be replaced with an induction stove.

- *Efficient electronic appliances*

As no information was provided I assumed that all electronic appliances require replacement and will be replaced with efficient appliances.

6.1.4.1. Simulations & cost calculation

Both models were adjusted according to the used insulation techniques, see table 22 for a summary of the changed parameters. See appendix 7 for a detailed overview of the parameters. Additionally, a cost calculation was done for the strategy, see table 23 for the results.

6.1.4.2. Results

The main results were combined and compared to the results of the current situation and the payback time was calculated, see table 24 on page 86. This strategy resulted in a 110-121% reduction in electricity and a 100% reduction in gas, making it a NZEB and gas-free house. An EPC of -0,322 was reached and a payback time of 17 to 31 years was calculated.

6.1.5. Results comparison

After each strategy was applied all the results were combined into one table for a comparison, see table 25 on page 86. Compared to the results of the row house the result for the free-standing house are better and a shorter payback time is predicted. Furthermore, the range between the Design Builder and Uniec results is much smaller than for the row house. This might be due to a better consistency between the entered parameters.

	Current situation			NZEB strategy		
Construction	Structure type	Rc-value [m2*K/W]	U-value [W/m2*K]	Improvement	Rc-value [m2*K/W]	U-value [W/m2*K]
External wall	Brick cavity wall	0,718	1,392	Cavity wall insulation	1,669	0,599
Ground floor	Concrete floor	0,674	1,483	Crawl space insulation	5,246	0,191
Pitched roof	Wooden roof structure	1,993	0,502	Internal insulation	6,172	0,162
Doors	Low standard doors		2,823	New insulated doors		1,245
Glazing	Low standard double glazing		3,157	HR+++ glass		0,786
Frames	Wooden frames		2,628	Wooden frames / with thermal break		1,393
Airtightness						
Infiltration rate [ac/h]	0,7			0,2		
Installations						
Ventilation	Natural ventilation			Natural ventilation		
Heating and HW installation	Combi-boiler			Air-heatpump and solar collector hybrid system with electrical post-heating		
PV-panels				39 monocrystalline 275 Wp panels (each 1,67 m2)		
Solar collectors				4,8 m2 solar collector (3x 1,6 m2) + 200 L tank		

Table 22: Summary of the changed parameters.

Required improvements	Min. Price		Max. Price			Min. Price		Max. Price	
Wall	[/m2]		[/m2]		[m2]				
Cavity wall insulation	€	15,00	€	30,00	130	€	1.950,00	€	3.900,00
External wall insulation	€	100,00	€	150,00	160	€	16.000,00	€	24.000,00
Roof	[/m2]		[/m2]		[m2]				
External pitched roof insulation	€	60,00	€	100,00	156	€	9.360,00	€	15.600,00
Ground floor	[/m2]		[/m2]		[m2]				
Crawl space insulation	€	20,00	€	45,00	60	€	1.200,00	€	2.700,00
Windows	[/m2]		[/m2]		[m2]				
HR+++ glass	€	160,00	€	280,00	35	€	5.600,00	€	9.800,00
Window frames	€	170,00	€	270,00	35	€	5.950,00	€	9.450,00
Insulated external (glass) doors	€	200,00	€	700,00	19	€	3.800,00	€	13.300,00
Heating installation									
Air heat pump electricly fuelled system					1	€	5.000,00	€	12.000,00
Heat pump subsidy					1	€	-1.250,00	€	-2.600,00
Solar boiler 3 panels with tank					1	€	2.750,00	€	4.000,00
Solar boiler < 5m2 subsidy					1	€	-500,00	€	-2.500,00
LT radiators / floor heating					1	€	2.500,00	€	5.000,00
PV-panels	[/Wp]		[/Wp]		[Wp]				
PV-panels incl. installation and tax	€	1,50	€	1,74	10725	€	16.087,50	€	18.661,50
Tax refund	€	-0,22	€	-0,26	10725	€	-2.359,50	€	-2.788,50
Electric appliances									
LED bulb	€	1,00	€	10,00	20	€	20,00	€	200,00
Induction stove					1	€	300,00	€	1.000,00
A+ oven					1	€	500,00	€	1.000,00
A++ fridge-freezer combi					1	€	500,00	€	1.000,00
A+++ dishwasher					1	€	300,00	€	800,00
A+++ washing machine					1	€	300,00	€	800,00
A+++ dryer					1	€	600,00	€	1.000,00
Total						€	68.608,00	€	116.323,00

Table 23: Minimum and maximum costs calculation.

	Current situation			NZEB strategy			
Program	DesignBuilder	Uniec	Measurements	DesignBuilder	Difference	Uniec	Difference
Elec installations	0 kWh	349 kWh		345 kWh		618 kWh	77%
Elec installations correction	349 kWh			273 kWh			
Elec heating				2116 kWh		2176 kWh	
Elec hot water				977 kWh		925 kWh	
Elec cooking				175 kWh		175 kWh	
Elec appliances	3700 kWh	3700 kWh		3000 kWh	-19%	3000 kWh	-19%
Electricity production	0 kWh	0 kWh		-7288 kWh		-7742 kWh	
Electricity total	4049 kWh	4049 kWh	4000 kWh	-402 kWh	-110%	-848 kWh	-121%
Gas heating	4152 m3	4245 m3		0 m3	-100%	0 m3	-100%
Gas hot water	516 m3	550 m3		0 m3	-100%	0 m3	-100%
Gas cooking	37 m3	37 m3		0 m3	-100%	0 m3	-100%
Gas total	4705 m3	4832 m3	4500 m3	0 m3	-100%	0 m3	-100%
Totaal CO2-emission		9357 kg				-1783 kg	-119%
EPC		2,019				-0,322	-116%
BENG energiebehoefte		196,2 kWh/m2				88,9 kWh/m2	-55%
BENG primair		383,4 kWh/m2				-29,7 kWh/m2	-108%
BENG hernieuwbaar		0 %				125 %	
Cost				Minimum		Maximum	
Investment				€ 68.608,00		€ 116.323,00	
Yearly savings				€ 3.786,01		€ 3.947,24	
Payback time [years]				17		31	

Table 24: Fuel consumption comparison and payback time.

	Basic insulation strategy				EPC ≤ 0,4 strategy				NZEB strategy			
Program	DB	Diff.	Uniec	Diff.	DB	Diff.	Uniec	Diff.	DB	Diff.	Uniec	Diff.
Elec installations	0 kWh		86 kWh	-75%	11 kWh		431 kWh	23%	345 kWh		618 kWh	77%
Elec installations corr.	86 kWh				420 kWh				273 kWh			
Elec heating									2116 kWh		2176 kWh	
Elec hot water					kWh		kWh		977 kWh		925 kWh	
Elec cooking									175 kWh		175 kWh	
Elec appliances	3500 kWh	-5%	3500 kWh	-5%	3500 kWh	-5%	3500 kWh	-5%	3000 kWh	-19%	3000 kWh	-19%
Electricity production	0 kWh		0 kWh		-4451 kWh		-4771 kWh		-7288 kWh		-7742 kWh	
Electricity total	3586 kWh	-11%	3586 kWh	-11%	-520 kWh	-113%	-840 kWh	-121%	-402 kWh	-110%	-848 kWh	-121%
Gas heating	1796 m3	-57%	1963 m3	-54%	1234 m3	-70%	1716 m3	-60%	0 m3	-100%	0 m3	-100%
Gas hot water	419 m3	-19%	432 m3	-21%	104 m3	-80%	160 m3	-71%	0 m3	-100%	0 m3	-100%
Gas cooking	37 m3	0%	37 m3	0%	37 m3	0%	37 m3	0%	0 m3	-100%	0 m3	-100%
Gas total	2252 m3	-52%	2432 m3	-50%	1375 m3	-71%	1913 m3	-60%	0 m3	-100%	0 m3	-100%
Totaal CO2-emission			4864 kg	-48%			1383 kg	-85%			-1783 kg	-119%
EPC			1,043	-48%			0,378	-81%			-0,322	-116%
BENG energiebeh.			126,1 kWh/m2	-36%			108,9 kWh/m2	-44%			88,9 kWh/m2	-55%
BENG primair			191,9 kWh/m2	-50%			111,5 kWh/m2	-71%			-29,7 kWh/m2	-108%
BENG hernieuwbaar			0 %				32 %				125 %	
Cost	Minimum		Maximum		Minimum		Maximum		Minimum		Maximum	
Investment	€ 24.640,00		€ 54.215,00		€ 38.138,00		€ 68.733,00		€ 68.608,00		€ 116.323,00	
Yearly savings	€ 1.604,60		€ 1.637,99		€ 2.664,37		€ 3.000,10		€ 3.786,01		€ 3.947,24	
Payback time [years]	15		34		13		26		17		31	

Table 25: Result comparison of the three strategy.

6.1.6. Conclusion

All three strategies can easily be applied to the free-standing house due to its technical similarity to the row house. The strategies are more effective than on the row house and have a shorter payback time. This is because a large portion of the row house's facade consists of glass in contrast to the free-standing house. As brick walls can be insulated to much a higher level than windows the strategies, especially C, are more effective.

6.2. Semi-detached house

This house is located in Wassenaar and as mentioned before has very a-typical characteristics. The house was built in 1973-1974 exactly during the fuel crisis. However most of the drawings were already made in 1972 and the building standards had not yet been changed.

6.2.1. Analysis

This is a large house consisting of three floors. The first floor is raised about 1m above ground level with underneath a basement which can be reached either via the slanting driveway or an indoor staircase, see figure 43. The second floor is situated directly under the slanting roof, see figure 44. The lowest point of the second-floor rooms at the front of the house is about 1m, the highest point at the back about 4 m. The front of the house and the slanting roof face the north-east, the back side and garden face south-west. Especially the garden façade has a very high percentage of glazing, see figure 45, providing a nice view over the garden but also causing overheating in summer. The neighbouring house was originally an exact mirror reflection but was drastically modified in 2005.

The construction of both houses is quite simple. All main floors consist of cast-in-situ concrete without a break between the houses, see figure 46. The floors are supported by thick basement walls, the outer walls, a concrete internal wall and the thick house dividing wall. Other internal walls are thin brick walls. The balconies on the first and second floor are part of the floors and create large cold bridges, see figure 47. Concrete elements in the façade support the large window openings, but also create extra cold bridges. A bay-window on the first floor is supported by a concrete slab connected to the brick wall, creating yet another cold bridge, see figure 46.

Unfortunately, the area where the house is situated is marked as monumental cityscape. This means special permission is required for exterior changes. This limits the possibilities for external insulation as a special board has to first approve any exterior changes. To increase the possibility of any refurbishment plans involving changes to the exterior, both houses would need to be refurbished. As the neighbours have already performed simple insulation measures it is unlikely that they would agree to such a drastic refurbishment project. Furthermore, the house is one of three sets of semi-detached houses (six houses in total), making approval of exterior changes highly unlikely.

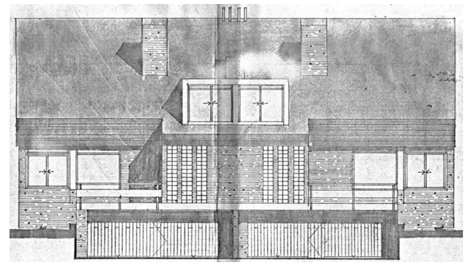

Figure 43: Front façade.

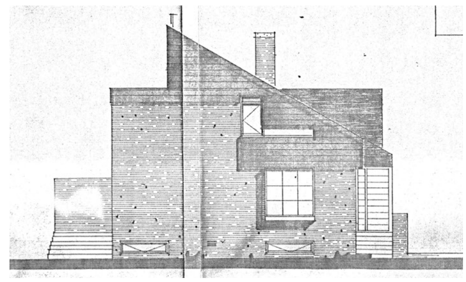

Figure 44: Side façade.

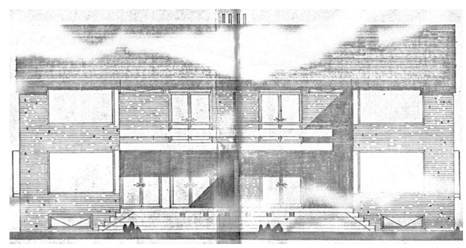

Figure 45: Garden façade.

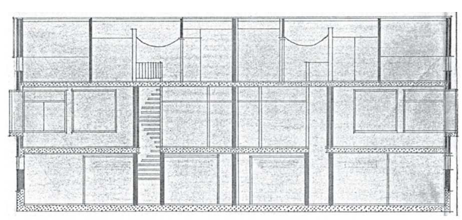

Figure 46: Cross section 1.

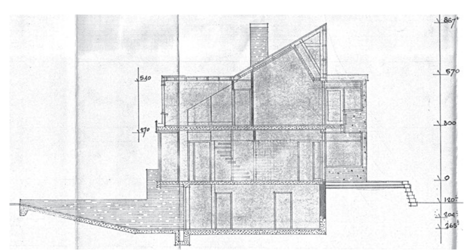

Figure 47: Cross section 2.

6.2.1.1. Simulations

Regrettably due to the strange characteristics of the house I was unable to make a Design Builder model which adequately reflected the current situation within the available time. The main problems arose in the cellar where the temperature simulation showed unrealistic high temperatures in summer and low temperatures in winter which do not reflect the real situation. Due to the mechanics of the program, creating an adequate model would have required using advanced features and special modelling techniques, which was beyond the scope of this graduation thesis.

6.2.2. Application basic insulation strategy

The basic insulation strategy can easily be applied to a large extent. A number of measures have already been applied by the homeowners in the past decade, these have a green check mark.

✔ *Cavity wall insulation*

The outer walls consist of cavity walls and have already been insulated to meet the requirements.

- *Internal pitched roof insulation*

The slanted roof does not consist of the typical Dutch clay tile cladding but an asphalt shingle cladding. The shingles are nailed onto wooden roof boards. Ventilation under these roof boards is required to prevent moisture problems or overheating. A thin layer of insulation, about 3cm, is already present on the inside of the construction at the moment. By replacing this insulation material with new and thicker material the thermal resistance can easily be increased. As the construction resembles a flat roof construction the ventilation under the roof boards must be maintained to prevent moisture problems.

- *External flat roof insulation*

The small flat roof at the back of the house has to be insulated externally. As an unpleasant draft is currently present in the room below it is advisable to first inspect the construction. To improve comfort levels, it might be better to internally insulate the flat roof.

- *Insulating dormer*

The dormer at the front of the house can be insulated quite easily. We would recommend simultaneously insulating the neighbouring dormer to improve aesthetic results. The dormer windows have already been replaced with HR++ glass a few years ago. The dormer roof can be insulated externally and the walls can be insulated internally, demanding extra care to prevent condensation.

✘ *Crawl space insulation*

In contrast to the case study house, the basement floor does not have a crawl space but was placed directly on the soil when cast. This makes crawl space insulation impossible. As the basement is only semi-heated and not used as living space, insulating its floor is not necessary. An alternative solution is insulating the floor of the first floor to decrease heat loss from the living areas to the basement. However, this heat loss might not be very bad as it slightly improves comfort in the basement.

- *Window and door replacement*

A large portion of the windows have already been replaced with HR++ double glazing, as well as the sliding doors at the back of the house. Extra reduction in heat loss can be achieved by replacing the front door and balcony door with well insulated doors. Replacing the garage doors with better insulating doors might also help.

- *New ventilation grills*

The house is naturally ventilated via grills above windows, new and old. The old grills in the two largest bedrooms still require replacement. For the front-facing bedroom a special noise dampening grill might be advisory.

✔ *Heating and hot water installations*

The heating installation consists of a hot air heater and dedicated boiler. Both have been replaced roughly 10 years ago and do not require replacement yet.

- *LED-lights*

Old lightbulbs have to be replaced with LED lightbulbs, especially those of frequently used lamps.

- *Extra options*

It is strongly advised to replace the fridge, freezer, oven and dishwasher within the coming years as these are all over 20 years old.

6.2.3. Application EPC ≤ 0,4 strategy

Unfortunately, several techniques of this strategy cannot be applied to this house. This is in part due to the construction and heating installation of the house, but mostly due to the monumental status which restricts changes to the exterior of the house. The most important improvements, changes to the heating and hot water installations and the placement of PV-panels, cannot be applied. This means that an EPC of 0,4 or less cannot be achieved.

✔ *Cavity wall insulation*

- *Internal pitched roof and attic insulation*

❌ *Crawl space insulation*

- *Window and door replacement*
- *New ventilation grills*

❌ *Heating and hot water installations*

❌ *PV-panels*

- *LED-lights*

- *Extra options*

6.2.4. Application NZEB strategy

Even more techniques than with the previous strategy cannot be applied unfortunately. As with the previous strategy this is due to the construction, heating installation and mostly monumental status.

❌ *Cavity wall insulation and external insulation*

❌ *Externally insulated roof*

❌ *Crawl space insulation*

- *Window and door replacement*
- *Lowering infiltration*
- *Ventilation grills*

❌ *Electric boiler with air heat pump and solar collectors*

❌ *Photovoltaic panels*

- *LED-lights*
- *Induction stove*
- *Efficient electronic appliances*

6.2.5. Conclusion

Although the basic insulation strategy can be applied, a house specific strategy is more suitable for this house to create real improvement. This is due to the unconventional construction and heating installation, but also the monumental status of the house. Such a specific strategy would mostly consist of internal changes, retaining the exterior to obtain a building permit.

A possible house specific strategy could consist of the following techniques:

- *Internal insulation*

This will prevent major external changes, cold bridges, and reduce noise disturbance.

- *Window and door replacement*

HR+++ glazing with new frames will reduce heat loss. Additionally, an integrated vertical sunscreen is advisory for the south-west orientated façade to reduce overheating in summer.

- *Complete mechanical ventilation with heat exchange*

This will reduce heat loss in winter, improve the indoor climate, decrease overheating in summer, and indirectly warm the basement.

- *Low temperature floor heating and radiators*

This will increase the comfort level of the house and allow the application of an air heat pump and solar collectors.

- *Electric boiler with air heat pump and solar collectors*

To fuel the heating system a new electric-fuelled boiler which is connected to a heat pump can be installed. If possible, with solar collectors on the small flat roof at the back of the house.

- *Possibly integrated photovoltaic panels*

It might even be possible to place an integrated type of PV-panel system on the slanted roof when the roof cladding of both houses is replaced. It is possible that the neighbours would participate in this part of the plan as it allows them to place PV-panels as well without having to join in with the whole strategy. Furthermore, one of the other sets of houses already has a differently coloured roof which increases chance of such a modification being permitted.

- *Reduce moisture problems basement*

Repointing the house will decrease the moisture problems in the basement. It might also be advisable to place a drainage system around the house and/or exterior insulation material against the basement's outer walls below ground level to further reduce the moisture problems.

- *LED-lights*

Old lightbulbs have to be replaced with LED lightbulbs, especially those of frequently used lamps.

- *Induction stove*

This will allow the house to be disconnected from the gas network.

- *Efficient electronic appliances*

Appliances over 20 years old have to be replaced, this will drastically decrease the electricity consumption.

Sadly, the thorough development, testing, and technical design of such a strategy is beyond the scope of this research project. Therefore, this is an excellent subject for further research.

6.3. Conclusion

For most houses with the same characteristics, application of all three strategies is certainly possible. Favourable results can be achieved with strategy B for similar houses as the row house. Strategy C can achieve a zero-gas consumption and high reduction of electricity consumption but at a high investment. However, as with almost everything, a more unique situation such as the case of the semi-detached house will always require a specific design to reach the desired results.

7. Technical application

After simulating the results of each strategy, the technical applications needed to reach these results were designed. This was only done for the row-house, but due to the technical similarities they are, to a large extent, also applicable to the free-standing house. To create the current and new details for each strategy, the real drawings as well as SBR-reference details (SBRCURnet, 2018) for renovation and new constructions were used.

7.1. Current situation

Based on the provided information an AutoCAD file was made to allow the creation of different drawings, see appendix 9 for the true to scale drawings. As the floorplans did not include the current extension some assumptions were made regarding the size and detailing, see figure 48. Next a detailed version of the section was made to allow the creation of details of important points in the façade, see figure 49.

Six points in the façade were chosen to highlight the changes due to the application of the three strategies. The first point is the connection between the ground floor and the façade, see figure 70 in appendix 9. This detail was based on the original drawings which provided detailed information on this point. Based on the original drawings the space between the floor beams and crawl space floor is roughly 450mm which is enough for crawl space floor insulation. The second and third details depict the connection between ground floor window, the facade and second level floor, see figure 50. As no detailed information on this point was provided in the original drawings, an SBR-reference detail for a bay window was used as reference. The fourth detail depicts the connection between the second-floor window, roof and third level floor, see figure 51 on the next page. The original drawings provided a 1:5 detail for this point which was used as the basis for this detail. The fifth detail depicts the connection between the dormer window and roof, see figure 74 in the appendix. As no detailed information was available in the original drawings an SBR-reference renovation detail for a dormer was used as reference. The same goes for detail 6 which depicts the connect between the dormer roof and window, see figure 75 in the appendix.

The heating and hot water installations were also included in the floorplans. Based on the original drawings I assumed that the HR combi boiler (CV) is located underneath the staircase on the ground floor and the dedicated electric boiler (W) is above the sink in the kitchen. The brand types of both installations were provided by the inhabitants and these were used to establish the sizes of both installations. As the space underneath the staircase is very small the owners have a Nefit ProLine NxT HR30 CW5 boiler which is an exceptionally compact HR combi boiler. The dedicated kitchen

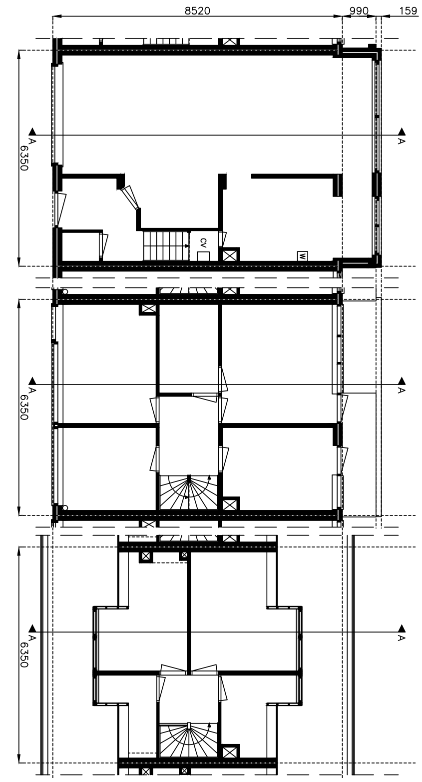

Figure 48: Floorplans current situation.

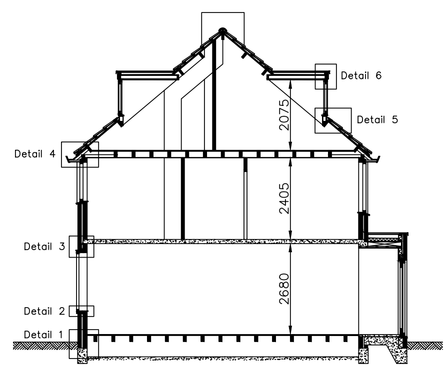

Figure 49: Section A-A current situation.

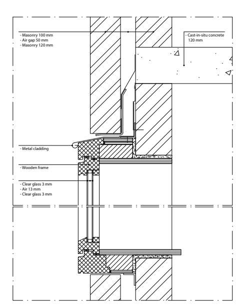

Figure 50: Details 2 and 3 current situation.

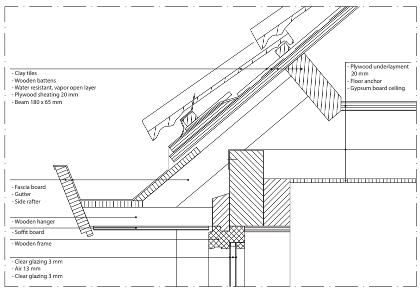

Figure 51: Detail 4 current situation.

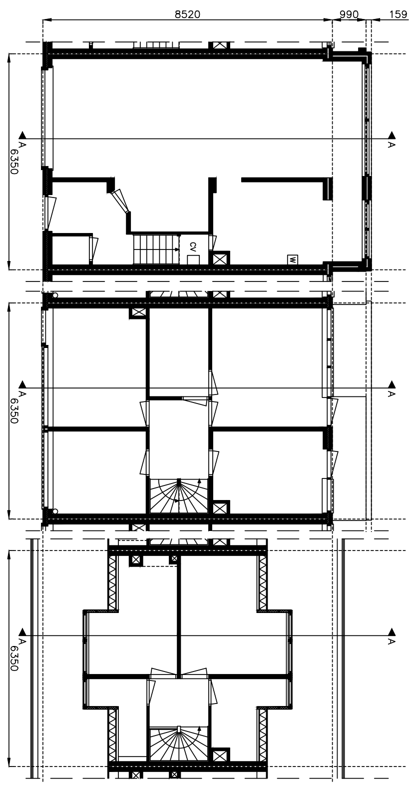

Figure 52: Floorplans strategy A.

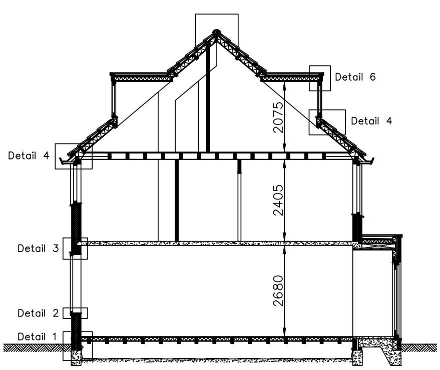

Figure 53: Section A-A strategy A.

boiler is an Itho Daalderop Close-in 10L electric boiler which is small enough to place in a kitchen cabinet. As strategies B and C require much larger installations some concessions as to space will have to be made.

7.2. Strategy A

Next the drawings were changed to represent the situation after application of strategy A, the basic insulation strategy. In the case of Haarlem this means insulating the house, the installations do not require any changes. As can be seen in the floorplans and section, see figures 52 and 53, the effect that this strategy has on useable space is negligible. After application the only thing that will be visible on the inside is the insulation between the roofbeams and this is only minimal. The same points in the façade as for the current situation were chosen to show the changes in detail, see figure 53 and appendix 10 for the details in the true scale.

As can be seen in figure 80 in appendix 10 the cavity in the façade and the underside of the ground floor are insulated. A special water and vapor resistant layer on the floor of the crawl space will prevent against water and vapor coming up through the floor of the crawl space. To ensure that vapor coming through the walls and wooden floor can still leave the crawl space, ventilation holes have been created with special tubes in the façade. As this strategy requires HR++ glazing, the glazing of all windows with low standard double glazing have to be replaced. This replacing does not have a great effect on the frames that are still in a good condition as the glazing is not that much thicker, see figure 54. Some frames might require slight adjustments but this will be minimal and a majority of the frames can be retained. I assumed that all the frames are in a good condition and that the windows of the extension already have HR++ glazing which means that these do not require replacement. Next the attic is insulated internally with 13cm insulation material, a vapor resistant layer on the inside to prevent moisture problems, and a gypsum board finish layer. Special attention must be given to the connection between the second-floor windows and the roof, see figure 83 in appendix 10. As the windows also connect directly to the floor construction of the attic, insulation must be placed in the floor construction to prevent a cold bridge in this point. Initially I planned on insulating the dormer roofs externally but after studying the construction I chose to use a combination of internal and external insulation. I chose this to prevent cold bridges where the roof construction connects to the window and pitched roof and also to prevent drastic changes to the ledge of the dormer. However, in this situation it is very moisture problems can easily occur in the construction if not done well. To prevent this an extra vapor resistant layer was added on the inside. The roof of the extension was insulated externally, as some insulation was already present in this point no drastic changes are required here.

As this strategy only requires basic insulation the changes are small and the detailing was relatively straight forward. No big problems occurred during the design process. From this it can be concluded that strategy A can easily be applied and as it does not require much changes. It can probably be accomplished well within a month. As the free-standing house is very similar in construction the detailing will not be very different. The only extra point of interest for the free-standing house is the balcony of this house which creates a cold bridge but this can easily be solved.

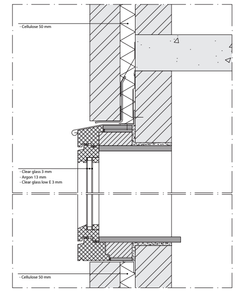
Figure 54: Detail 2 and 3 strategy A.

7.3. Strategy B

The second strategy combines a high level of insulation with the use of solar energy for electricity and heating. For this strategy the same type of insulation techniques as with strategy A are used but to a much higher level which means that changes are more visible. Additionally, new technical installations have to be placed on the outside and inside of the house for the use of solar energy. These changes are more visible inside the house, see figures 55 and 56, and will require some space, especially in the attic.

Similar to strategy A the cavity in the façade is insulated. The crawl space is insulated to a higher level to reduce heat loss as much as possible, see figure 90 in appendix 11. To minimize heat loss through the windows HR+++ glazing is required. To place this type of glazing I concluded that all the frames will have to be replaced as they are not broad enough to be adapted to fit the required thickness of glazing, see figure 57 on the next page. In the details I used frames with a U-value ≤ 1,4 as required for this strategy. In figures 91, 92, and 93 in the appendix a fixed window is depicted, figures 94 and 95 show the openable window of the dormer. The slanting roof is insulated with 200mm insulation and the line of insulation is continued in a similar way as for the previous strategy, see figure 58 on the next page. As can be seen in figure 95 in appendix 11 the dormer roof is insulated with a total of 190mm, to prevent water problems on the roof the ledges will have to be increased in height.

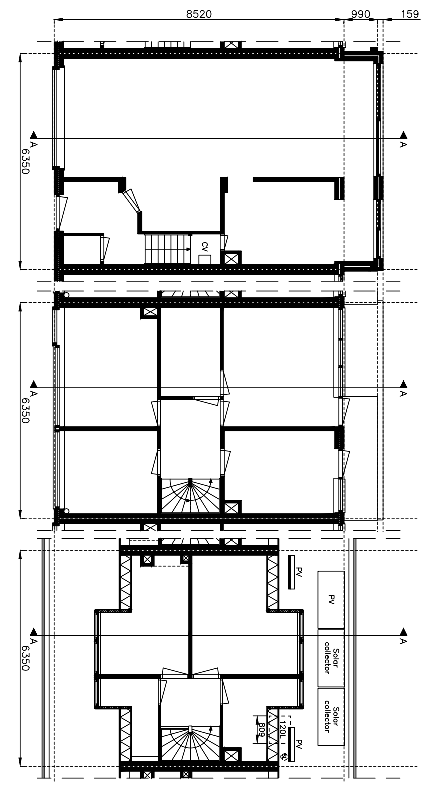

Figure 55: Floorplans strategy B.

As mentioned before new installations have to be installed for this strategy to allow the use of solar energy for electricity and heating. In this specific situation six PV-panels and two solar collector panels are placed on the roof, see figure 59 on the next page. In this situation I applied six Solarwatt 60M 285Wp panels, sized 1680mm by 990mm. A transformer will have to be placed to transform the produced electricity to the correct current and voltage. Additionally, an extra group has to be placed in the fuse box, at the same time the electrical system can be checked for any

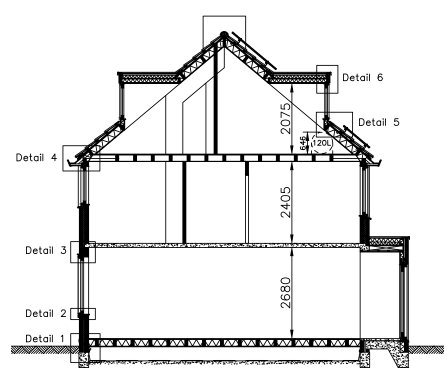

Figure 56: Section A-A strategy B.

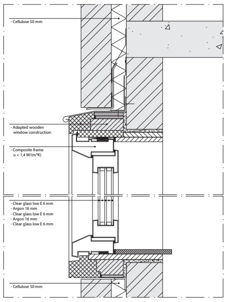

Figure 57: Detail 2 and 3 strategy B.

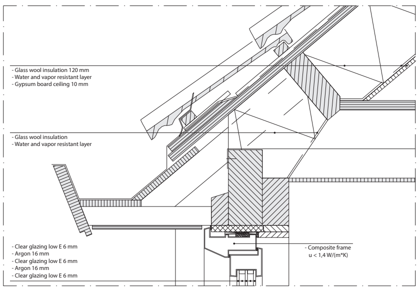

Figure 58: Detail 4 strategy B.

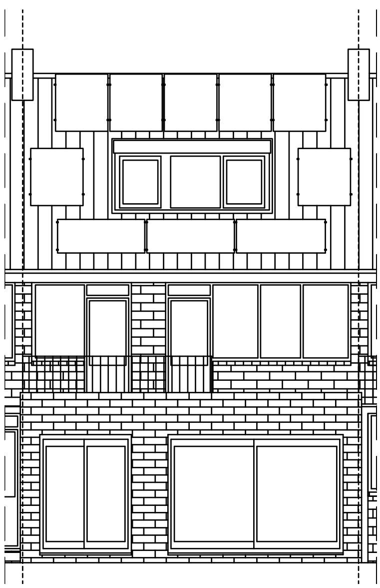

Figure 59: Back view strategy B

problem as mentioned in chapter 2. For the solar boiler installation, I chose the ATAG EcoNorm II 120L with two 1,6m^2 solar collectors. This installation was chosen for its PV-panel sized solar collectors and small boiler tank which can be placed in a lying position. The two solar collectors are 1650mm by 990mm and can easily be placed next to the PV-panels on the roof due to their similar size. The tank has a diameter of 624mm and is only 809mm high, in a lying position it can easily be placed underneath the slanting roof in the small south facing bedroom, see figures 55 and 56. The installation also includes a small 8L expansion tank and a control unit which can be placed next to the tank. Two new pipes will have to be installed to connect the solar boiler to the already present HR combi boiler. Based on the information on the Nefit website (Nefit, 2017) it is possible that the boiler does not require replacement. As I assumed in chapter 5 that it does have to be replaced, this could lower the price of the strategy with €1.500,- to €3.500,- and would mean an estimated payback time of 14 to 39 years. To increase efficiency of the heating installation and reach an EPC of 0,4 or less the electric boiler in the kitchen has to be removed and the kitchen tap connected to the main HR combi boiler. New pipes will have to be installed to connect the tap. As the combi boiler is located next to the kitchen this can easily be done.

As this strategy has higher requirements the design process was more difficult than for strategy A. Especially the changes to the windows and the placement of the new installation required more attention. Bigger and more changes will have to be made than for strategy A which means that the application will take longer. This strategy will probably take roughly two months to be applied. As with strategy A these details can again be used for the application on the free-standing house, the only extra point being the balcony again.

7.4. Strategy C

As can be expected the last and most extreme strategy was the most difficult to design. Different insulation techniques are used in this strategy and the entire installation is replaced with a gas free alternative, see figures 60, 61. Mostly external insulation is used in this strategy which means that the exterior of the house will change drastically, see figures 64 and 65 on the next page. The only change internally is the placement of a different heating installation which will require some space in the kitchen. This installation also requires solar panels on the roof and a unit outside which have to be placed.

External insulation of the house, including the façade, created multiple new connections which had to be solved. After insulating the cavity with insulation material, the façade is externally insulated and a new exterior façade is created with brick strips, see figure 62 and the details in appendix 12. I chose brick for the new façade to retain the aesthetic expression of the house and decrease the difference between the house and its neighbours. By applying bricks in the form of strips the extra layer is significantly reduced as these are only 2cm thick compared to the 10cm of normal bricks. As the walls of the extension are already insulated to a high level these do not need to be changed. The crawl space is insulated similarly to strategy B, see figure 100 in appendix 12. All windows are removed and the connections were redesigned with HR+++ glazing, see figures 62. The small bay window was redesigned as a normal fixed window similar to the other windows to reduce heat loss and direct sunlight in summer. A whole new highly insulated roof was constructed on the old roof beams, see figure 63 on the next page. By replacing the roof except for the loadbearing structure, a new insulation layer of 190mm can easily be placed externally with new clay tiles on top. To reduce costs the old tiles can also be used provided they are in a good state. To connect the new gutter easily to the gutter of the neighbouring houses the old gutter construction was retained, see figure 63 and 64 on the next page. The fascia of the gutter was increased in height to allow a higher placement of the new gutter while retaining room to connect the new gutter to the neighbouring gutters with a small pipe. The two dormers were replaced with two new prefabricated and highly insulated dormers. This was more effective and cost efficient than insulating the old dormers. To allow a more efficient use of roof space slightly lower and broader dormers were chosen, see figures 65 on the next page. Lastly the flat roof of the extension was externally insulated, requiring a higher ledge which can easily be achieved.

The entire heating installation was replaced with an electric fuelled boiler with air-based heat pump and solar collectors. Additionally, eleven high power PV-panels were placed. In this situation I chose for a Nefit EnviLine TowerSolar Monoblock 9.0 TS-S which has an inside and outside unit, see figures 60 and 61 (Nefit, 2017a). I assumed that the inside unit, sized 1800mm by 600mm by 660mm, is too high for underneath the stairs which means that it will have to be placed in the kitchen. The benefit of this inside unit is that the solar collectors can be connected directly to the unit due to its large integrated tank and therefore the 120L tank in the attic is not required. The 8L expansion tank and controller still have to placed, but these are luckily very small. To limit noise pollution the Monoblock 9.0 outside unit was chosen which is an efficient, silent but also more expensive model. To reduce noise, it is advised to place the unit in the garden, the outlet not facing a wall and with plants around it. An additional noise dampening hood has been developed by Nefit to reduce noise even further and can be

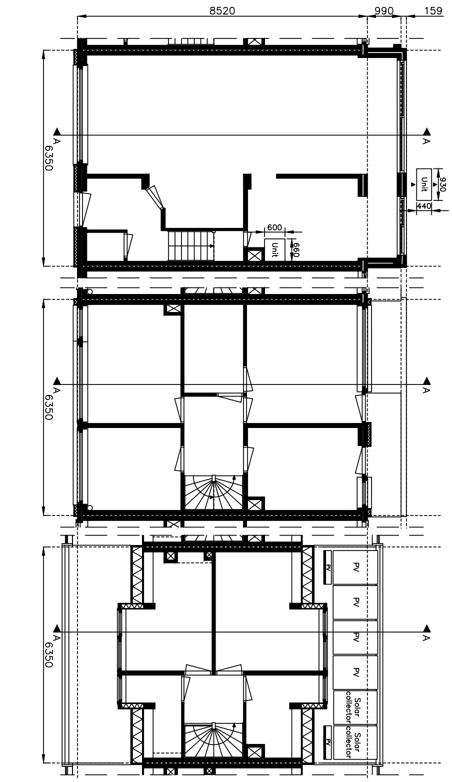

Figure 60: Floorplans strategy C.

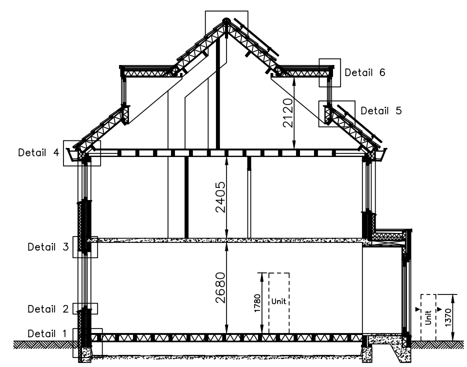

Figure 61: Section A-A strategy C.

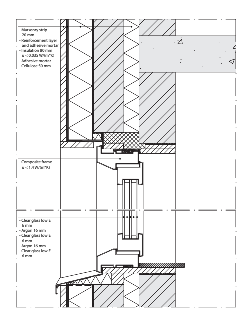
Figure 62: Detail 2 and 3 strategy C.

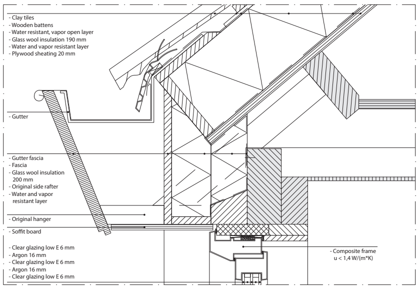

Figure 63: Detail 4 strategy C.

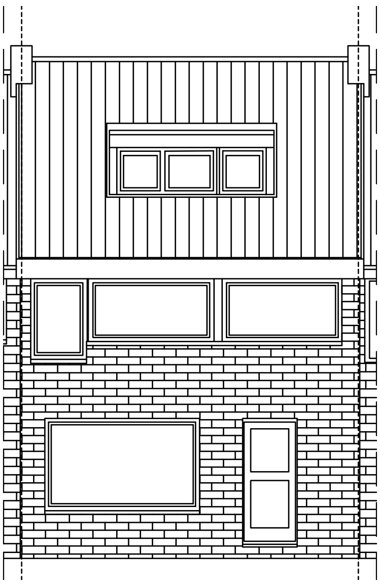

Figure 64: Front view strategy C.

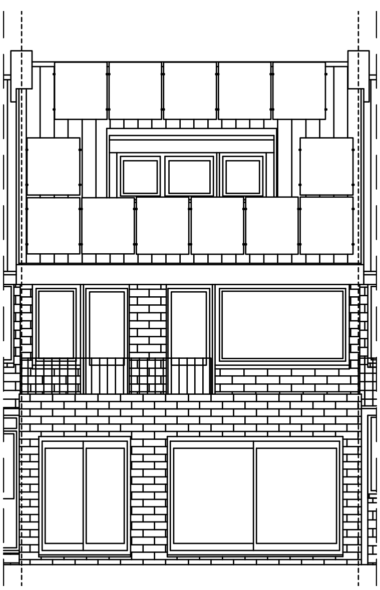

Figure 65: Back view strategy C.

purchased separately. The solar collectors are the same PV-panel sized collectors as mentioned in paragraph 7.3. To maximize the electricity production, I chose eleven Solarwatt High Power 60M 305Wp panels. As mentioned before, a transformer will have to be placed and an extra group made in the fuse box. The installation of the induction stove will also require the placement of an extra group in fuse box. Furthermore, as gas is no longer consumed the entire connection can be closed and removed which will increase the yearly savings calculated in chapter 5, the precise amount depends on the provider.

Due to the drastic changes and creation of new connections between all the elements, this last strategy was the hardest to design. Especially the connection between the roof and the wall took some time as many options were possible. I finally chose for this solution as I thought it to be the most elegant and practical to connect to the neighbouring houses. The application of this strategy will also take much longer than strategy A and B, I suspect roughly four to six months. As with the previous strategies these details can again be used for the free-standing house. Due to the fact that the free-standing house does not connect to other houses more liberties can be taken for the creation of the details. This means that more drastic changes can be made to the aesthetic expression of the house if the owners want this. A different detail can for example be created for the connection between the façade and the roof as no neighbouring gutters have to be taken into account. An extra point for this house is again the balcony which creates a cold bridge and also has to insulated externally.

7.5. Conclusion

Real technical applications were designed that can be used to realise the application of the strategies. This was hardest for strategy C as this strategy required major changes to the outer shell to achieve the required level of insulation. For this strategy most of the details had to be redesigned, a new outer shell was created around the original loadbearing structure which is at the same time aesthetically pleasing and practical to apply. As this strategy is the most invasive it will also take the longest to apply.

These details can also be used to apply the strategies to other types of late post-war houses such as the free-standing house, provided that they are structurally similar. I would recommend using them as a reference and adapting them to the situation, especially when applying the third strategy to a free-standing house as this situation provides much more design freedom for the aesthetic expression of the house.

7.6. References

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Nefit. (2017b). ProLine NxT. Retrieved 21-09-2018 from https://www.nefit.nl/professioneel/producten_pro/product_detail_pro/product-detail-pro_18560

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8. Conclusion and recommendations

During this study three different refurbishment strategies were developed, each with a different level of improvement and aimed at late post-war houses. These are a Basic insulation strategy (A), an Energy Performance Coefficient or EPC of 0,4 or less strategy (B), and a Net Zero Energy Building or NZEB strategy (C). These were tested on a row house, semi-detached and freestanding house.

As the name indicates strategy A consists of easy insulation techniques and only minor updates to the installations, see table 26. This strategy aims to decrease the energy consumption with a minimum investment. Strategy B aims for an EPC of 0,4 or less and similar insulation techniques are used as in strategy A but to a higher level, see table 26. Additionally, solar energy is used for the heating system and production of electricity by placing solar collectors and PV-panels on the roof. Remarkable is that, for the row house, the predicted payback time of strategy B is only 3 years more than that of strategy A. This is due to a better balance between investment and yearly savings. The third and last strategy has the highest aim, the creation of a (nearly) NZEB and gas-free house. To achieve the high level of insulation required for this strategy, different insulation techniques are used, see table 26. The entire outer shell of the house is insulated externally which means major changes are made to the exterior of the house. A hybrid electric boiler with air heat pump and solar collector is used as alternative for the old gas-fuelled combi-boiler. PV-panels on the roof will power this boiler and provide electricity for appliances. By replacing the gas-stove with an electric alternative the gas consumption is completely eliminated. Unfortunately, the simulations showed that it is not possible to achieve a completely NZEB for the row house. This is due to the small roof area which can be used for PV-panels. Fortunately, a gas-free house is definitely possible and the payback time is, with 24 years, shorter than I had initially expected.

	Strategy A	Strategy B	Strategy C
Outer wall	Cavity	Cavity	Cavity + External
Ground floor	Crawl space	Crawl space	Crawl space
Pitched roof	Internal	Internal	External
Flat roof	External	External	External
Window frames	Retained	New	New
Glazing	HR++	HR+++	HR+++
Radiators	Normal	Normal	Low-temperature
Boiler	Gas	Gas	Electric
Solar collectors	No	Yes	Yes
PV-panels	No	Yes	Yes

Table 26: Summary of the three strategies.

After developing the strategies and testing them on the row house, the three strategies were tested on the semi-detached and free-standing house. As the free-standing house is very similar in construction to the row house, all three strategies can easily be applied. The results for strategy A were very similar to those for the row house although the payback time is slightly longer, 15 years. Remarkably both strategy B and C had much better results for the free-standing house than for the row house. A payback time of 13 is expected for strategy B which is shorter than strategy A's. Secondly the free-standing house can be changed into a completely NZEB and gas-free house with a predicted payback time of only 17 years. Especially this last result was very remarkable and unexpected. This is probably due to the lower percentage of glazing for the free-standing house and the much larger roof. Unfortunately though, for the semi-detached house only strategy A is possible and even this strategy is not advisable. This is due to the very different construction of the house, the heating installation and monumental status which really make it an a-typical house. Therefore, a house-specific strategy with internal insulation and replacement of the heating and ventilation systems is required for this house to reach similar results.

After all the testing, the real technical application of the strategies was designed in detail for the row house. The resulting details can be used for the real application of a strategy. As the row house is so similar in construction to the free-standing house, these details can also be used for the free-standing house. I would recommend using the applications as a reference, especially for strategy C, as the free-standing house allows much more design freedom for the aesthetic expression of the house.

To recap, at the beginning of this study the following research question was set: "Which strategies are possible to reduce energy consumption to different levels for multiple building types built between 1960-1974?". Based on the results mentioned above it can be concluded that three strategies, a Basic insulation, EPC ≥ 0,4 and NZEB strategy are possible. The three strategies that I developed each have a different level of reduction in energy consumption, required investment, and can be applied to multiple building types with a typical late post-war era construction. Houses with an a-typical construction require a case-specific strategy to reach similar results. As early and late post-war era houses do not differ much in construction, it might be possible to apply these three strategies to early post-war houses as well.

From a long-term societal perspective, I would highly recommend strategy C as this strategy has a reasonable payback time and will help make the Netherlands gas-free and lower CO2 production. However, the required investment of this strategy is high and not all homeowners will be able or willing to pay this. A house-linked mortgage has been opted as a possible solution for this problem. In this scenario the mortgage also changes owner when a house is sold which means that the beneficiary of the investment also pays for the investment while he/she occupies the house. This way homeowners do not have to be afraid of losing their investment when selling their house or the risk of having to pay for investment from which they can no longer benefit.

Another important subject is the production of electricity. As long as the largest portion of electricity is still produced with gas, the effect of strategy C will be limited. Other sources such as wind and solar power are very unpredictable and if we really want to rely solely on these sources, sufficient energy storage, locally and on a big scale, is critical. At the moment the best methods to store energy are huge battery storages or reservoirs with a Hydro dam. Of these, batteries are the only possibility in the Netherlands, which means that major investments are needed in this technique. Furthermore, development of new and better solutions is needed in order to make wind and solar energy practical energy sources. To conclude, there is a lot that can be done by homeowners but the government and industry need to act if we really want to reduce the gas production and global warming.

9. Reflection

Sustainable design has already played a role within the entire Architecture programme for over a decade. It is particularly relevant to the master track Building Technology since developing sustainable buildings depends in large part on the use of technical installations. As the demand for sustainable building designs, such as Net Zero Energy Buildings and passive buildings has drastically increased in the past few years, this role has become ever more important. Within the Building Technology programme, sustainable design has always interested me, especially sustainable refurbishment.

In the last years an increasing number of research papers have been published within this field. Most of these papers focus on one or multiple application case studies which have actually been refurbished in reality. The real results after refurbishment play an important role in this field as this really proves how successful the refurbishment was. In contrast, in this graduation thesis I took a theoretical approach by reviewing completed projects and performing simulations. I reviewed and analysed multiple refurbishment projects performed in the past based on research papers of completed case studies and I performed simulations of three strategies with two energy performance programs. Furthermore, I also aimed to provide a clear overview of all the available techniques possible when refurbishing a building thereby providing relevant information and laying the groundwork for future research and projects in this field.

During my research I used Design Builder and Uniec for the simulations. Design Builder is a very useful program for building development and I had used this program before during other courses and projects in the Master programme. Uniec was a new program for me but due to its simplicity very easy to learn. By simulating the models during the development process, I was able to locate problems easily and immediately apply improvements. My first mentor had a good understanding of the programs and helped me solve a number of problems encountered during the development process.

By making Design Builder and Uniec models of all the different situations, I was able to compare the models and test the reliability of the models. Having undertaken this task, I now appreciate the complexity and the time needed to make the initial model of the current situation of a house. Especially the free-standing and semi-detached houses were difficult as these houses had very unique forms. Due to the limited possibilities in Design Builder it was difficult to make models of the houses which adequately represented the form of the houses: the roofs were the most challenging. For the semi-detached house the second issue was the heating installation for which none of the pre-sets could be used as with the other houses and unfortunately, I was never able to achieve an output which was consistent with the observed energy consumption for this house. Luckily, once the initial model was made for the row and free-standing house, I was able to improve this model very easily as I had predicted.

During the project I had regular meetings with my mentors to discuss my progress and help me with difficulties. My mentors helped me to focus my research and see new possibilities when I encountered problems. Furthermore, the regular meetings helped me to set intermediate deadlines for myself which helped me plan my work, and the meetings led to new insights. After simulating the strategies my mentors motivated me to design the technical application of the strategies. I find creating the technical details one of the most challenging parts of any project. Nevertheless, once I get started I often find this the most interesting part. Once started, I can work for hours on the details with dedication and passion to make sure that everything connects correctly and no unresolved issues remain in a design.

As my research was based on case study houses, the building plans were an important information source. Unfortunately, the plans I received of the row house were not entirely accurate, forcing me to make a number of assumptions. Furthermore, I did not have direct contact with the inhabitants so I did not know their wishes. This was better for the semi-detached house as I have a good relationship with the inhabitants. Observation and discussion provided me with accurate information on their heating habits and improvement wishes for the house. The plans of the free-standing house were provided by the previous inhabitants so no information of the current state was available. Therefore, the approaches were tested on the old state of the house and it is unclear if this is still the state of the house. From my experience during this project I was able to conclude that good contact with the inhabitants and accurate information on the house is crucial to achieve a suitable result.

Throughout this graduation project I have learned many things, not only in the field of sustainable design and refurbishment but also about myself and what motivates me. As I already knew before starting the project planning and especially sticking to a plan is challenging for me, especially when working alone. When working in a group I feel more motivated to work as I don't want to let down the group by not doing my share of the work. In a group there is always some pressure to work which I really miss when working alone. Another benefit of working together is that you can easily motivate each other by discussing your work with one another. Although I did at first work at the faculty, I found it difficult to discuss my work with others as they were working on completely different topics. Finally, I have really enjoyed this graduation project and after performing all the simulations and designing the technical details I am really interested what the real results of the strategies would be. Hopefully I will be able to test this during my career.

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Appendix 1. Parameters Haarlem

The following parameters were used for the creation of the Design Builder and Uniec models of the current situation of the row house in Haarlem.

Location	
Location Template	Amsterdam AP Schiphol
Hourly Weather Data	NLD_AMSTERDAM_IWEC
Winter Design	Heating 99.6% coverage
Summer Design	99.6% coverage

Table 27: Location data.

Construction materials	Thickness [mm]	R-value [m*K/W]	U-value [W/m2*K]
External Wall			
Brick	100	1,02	0,980
Air gap	50		
Concrete blocks lightweight	120		
Plaster lightweigth	10		
House Dividing Wall			
Plaster lightweigth	10	-	-
Concrete blocks lightweight	120		
Air gap	20		
Concrete blocks lightweight	120		
Plaster lightweigth	10		
Internal Loadbearing Wall			
Plaster lightweigth	10	-	-
Concrete blocks lightweight	70/90/120		
Plaster lightweigth	10		
Internal Wall			
Plaster lightweigth	10	-	-
Aerated Concrete Block	50/70/90/120		
Plaster lightweigth	10		
Pitched Roof			
Clay tiles	25	0,794	1,26
Air gap with frame	20		
Hardboard	10		
Wooden beams	100		
Gypsum Plasterboard	10		
Flat Roof			
Asphalt roofing	5	0,738	1,355
Roof screed	5		
Hardboard	10		
Wooden beams	100		
Gypsum Plasterboard	10		

Table 28a: Construction parameters.

Construction materials	Thickness [mm]	R-value [m*K/W]	U-value [W/m2*K]
Dormer Wall			
Glass fibre board	20	1,836	0,545
fibre board	30		
wood particle panel	40		
Plaster lightweigth	10		
Ground Floor Wood			
Timber Flooring	30	1,332	0,751
Wooden beams	200		
Air gap	400		
Ground Floor MUWI element			
Cast Concrete	30	0,572	1,749
Cast Concrete - dense, reinforced	200		
Air gap	400		
Internal Concrete Floor			
Cast Concrete	120	0,376	2,658
Internal Wood Floor			
Timber Flooring	20	1,13	0,885
Wooden beams	180		
Gypsum Plasterboard	10		
External Door			
Painted Oak	35	-	2,823
Glazing			
Clear glazing	3	-	2,761
Air gap	13		
Clear glazing	3		
Frame			
Wooden window frame	40	-	2,628

Table 28b: Construction parameters continued.

Zone	Entry	Toilet	Living	Kitchen
Template	Domestic Circulation	Domestic Toilet	Domestic Lounge	Domestic Kitchen
Zone type	Standard, conditioned			
Floor area [m2]	6,07	0,92	35,39	10,43
Density [people/m2]	0,0155	0,0243	0,0188	0,0237
Schedule	5: 7-10 and 17-23; 2: 9-23			
Activity	Standing/walking		Eating/drinking	Cooking
Heating				
Template	Radiator heating, HR combi-boiler, electric hot water boiler kitchen, Natural Ventilation			
Schedule	5: 7-10 and 17-23; 2: 9-23			
Heating [C]	19,5		21	
Heating set back [C]	17,5			
HW consumption [L/day]				8
Ventilation				
Mechanical Ventilation [ac/h]	0,5			
Natural Ventilation [ac/]	5			
Summer min outdoor temperature	18			
Summer max outdoor temperature	28			
Min fresh air [L/s-person]	7			21
Office Equipment				
Gain [W/m2]	1,57	1,61	3,9	30,28
Schedule	Dwell_DomCirc_Equip	Dwell_DomToilet_Equip	Dwell_DomLounge_Equip	Dwell_DomKitchen_Equip
Lighting				
Power density [W/m2-100 lux]	5			
Lighting type	Low standard			
Schedule	Dwell_DomCirc_Light	Dwell_DomToilet_Light	Dwell_DomLounge_Light	Dwell_DomKitchen_Light
Shading	Inside drapes - close weave light			
Airtightness				
Infiltration rate [dm3/s per m2]	0,7			

Table 29: Zone parameters floor 1.

Zone	Landing	Bedroom 1	Bedroom 2	Bedroom 3	Bedroom 4	Bathroom
Template	Domestic Circulation	Domestic Bedroom				Domestic Bathroom
Zone type	Standard, conditioned					
Floor area [m2]	6,07	11,36	9,63	7,97	6,79	6,07
Density [people/m2]	0,0155	0,0229				0,0187
Schedule	5: 7-10 and 17-23; 2: 9-23	5: 23-7; 2: 23-9				5: 7-10 and 16-23; 2: 9-23
Activity	Standing/walking	Bedroom				Standing/walking
Heating						
Template	Radiator heating, HR combi-boiler, electric hot water boiler kitchen, Natural Ventilation					
Schedule	5: 7-10 and 17-23; 2: 9-23					
Heating [C]	19,5					
Heating set back [C]	17,5					
HW consumption [L/day]						120
Ventilation						
Mechanical Ventilation [ac/h]	0,5					
Natural Ventilation [ac/]	5					
Summer min outdoor temperature	18					
Summer max outdoor temperature	28					
Min fresh air [L/s-person]	7					14
Office Equipment						
Gain [W/m2]	1,57	3,58				1,67
Schedule	Dwell_DomCirc_Equip	Dwell_Bed_Equip				Dwell_DomBath_Equip
Lighting						
Power density [W/m2-100 lux]	5					
Lighting type	Low standard					
Schedule	Dwell_DomCirc_Light	Dwell_DomBed_Light				Dwell_DomBath_Light
Shading		Inside drapes - close weave light				
Airtightness						
Infiltration rate [dm3/s per m2]	0,7					

Table 30: Zone parameters floor 2.

Zone	Landing	Bedroom 5	Bedroom 6	Attic 1	Attic 2	Attic space 1	Attic space 2
Template	Domestic Circulation	Domestic Bedroom		Domestic Circulation			
Zone type	Standard, conditioned						
Floor area [m2]	4,37	12,54	10,81	6,58	5,36	2,47	2,47
Density [people/m2]	0,0155	0,0229		0,0155			
Schedule	5: 7-10 and 17-23; 2: 9-23	5: 23-7; 2: 23-9		5: 7-10 and 17-23; 2: 9-23			
Activity	Standing/walking	Bedroom		Standing/walking			
Heating							
Template	Radiator heating, HR combi-boiler, electric hot water boiler kitchen, Natural Ventilation						
Schedule	5: 7-10 and 17-23; 2: 9-23						
Heating [C]	19,5						
Heating set back [C]	17,5						
HW consumption [L/day]							
Ventilation							
Mechanical Ventilation [ac/h]	0,5						
Natural Ventilation [ac/]	5						
Summer min outdoor temperature	18						
Summer max outdoor temperature	28						
Min fresh air [L/s-person]	7						
Office Equipment							
Gain [W/m2]	1,57	3,58		1,57			
Schedule	Dwell_DomCirc_Equip	Dwell_Bed_Equip		Dwell_DomCirc_Equip			
Lighting							
Power density [W/m2-100 lux]	5						
Lighting type	Low standard						
Schedule	Dwell_DomCirc_Light	Dwell_DomBed_Light		Dwell_DomCirc_Light			
Shading		Inside drapes - close weave light					
Airtightness							
Infiltration rate [dm3/s per m2]	0,7						

Table 31: Zone parameters floor 3.

Appendix 2. Parameters Haarlem: strategy A

The following parameters were used for the creation of the Design Builder and Uniec models of the situation after application of strategy A on the row house in Haarlem.

Location	
Location Template	Amsterdam AP Schiphol
Hourly Weather Data	NLD_AMSTERDAM_IWEC
Winter Design	Heating 99.6% coverage
Summer Design	99.6% coverage

Table 32: Location data.

Construction materials	Thickness [mm]	Rc-value [m*K/W]	U-value [W/m2*K]
External Wall			
Brick	100	**2,209**	**0,453**
glass fibre/wool - fibre slab	**50**		
Concrete blocks lightweight	120		
Plaster lightweigh	10		
House Dividing Wall			
Plaster lightweigth	10	-	-
Concrete blocks lightweight	120		
Air gap	20		
Concrete blocks lightweight	120		
Plaster lightweigth	10		
Internal Loadbearing Wall			
Plaster lightweigth	10	-	-
Concrete blocks lightweight	70/90/120		
Plaster lightweigth	10		
Internal Wall			
Plaster lightweigth	10	-	-
Aerated Concrete Block	50/70/90/120		
Plaster lightweigth	10		
Pitched Roof			
Clay tiles	25	**4,217**	**0,237**
Air gap	20		
Hardboard	10		
Wood beams with insulation	**130**		
Gypsum Plasterboard	10		
Flat Roof			
Asphalt roofing	5	**4,167**	**0,240**
Insulation	**120**		
Roofscreed	5		
Hardboard	10		
Wood beams	100		
Gypsum Plasterboard	10		
Dormer Wall			
Glass fibre board	20	**2,598**	**0,385**
fibre board	30		
Wood frame with insulation	**40**		
Plaster lightweigth	10		

Table 33a: Construction parameters.

Construction materials	Thickness [mm]	Rc-value [m*K/W]	U-value [W/m2*K]
Ground Floor Wood			
Timber Flooring	30	**3,810**	**0,262**
Wood beams with insulation	**100**		
Wooden beams	**100**		
Air gap	400		
Ground Floor MUWI element			
Cast Concrete	30	**3,572**	**0,28**
Cast Concrete - dense, reinforced	200		
Insulation	**90**		
Air gap	**310**		
Internal Concrete Floor			
Cast Concrete	120	0,376	2,658
Internal Wood Floor			
Timber Flooring	20	1,13	0,885
Wooden beams	180		
Gypsum Plasterboard	10		
External Door			
Wood	**10**	-	**1,245**
Door insulation	**20**		
Wood	**10**		
Glazing			
Clear glazing	**3**	-	**1,514**
Argon	**13**		
Clear glazing low E	**3**		
Frame			
Polyvinylchloride	**20**	-	**1,393**
Rubber	**10**		
Polyvinylchloride	**20**		

Table 33b: Construction parameters continued.

Zone	Entry	Toilet	Living	Kitchen
Template	Domestic Circulation	Domestic Toilet	Domestic Lounge	Domestic Kitchen
Zone type	Standard, conditioned			
Floor area [m2]	6,07	0,92	35,39	10,43
Density [people/m2]	0,0155	0,0243	0,0188	0,0237
Schedule	5: 7-10 and 17-23; 2: 9-23			
Activity	Standing/walking		Eating/drinking	Cooking
Heating				
Template	Radiator heating, HR combi-boiler, electric hot water kettle kitchen, Natural Ventilation			
Schedule	5: 7-10 and 17-23; 2: 9-23			
Heating [C]	19,5		21	
Heating set back [C]	17,5			
HW consumption [L/day]				8
Ventilation				
Mechanical Ventilation [ac/h]	0,5			
Natural Ventilation [ac/]	5			
Summer min outdoor temperature	18			
Summer max outdoor temperature	28			
Min fresh air [L/s-person]	7			21
Office Equipment				
Gain [W/m2]	1,57	1,61	3,9	30,28
Schedule	Dwell_DomCirc_Equip	Dwell_DomToilet_Equip	Dwell_DomLounge_Equip	Dwell_DomKitchen_Equip
Lighting				
Power density [W/m2-100 lux]	2,5			
Lighting type	LED lamps			
Schedule	Dwell_DomCirc_Light	Dwell_DomToilet_Light	Dwell_DomLounge_Light	Dwell_DomKitchen_Light
Shading	Inside drapes - close weave light			
Airtightness				
Infiltration rate [dm3/s per m2]	0,4			

Table 34: Zone parameters floor 1.

Zone	Landing	Bedroom 1	Bedroom 2	Bedroom 3	Bedroom 4	Bathroom
Template	Domestic Circulation	Domestic Bedroom				Domestic Bathroom
Zone type	Standard, conditioned					
Floor area [m2]	6,07	11,36	9,63	7,97	6,79	6,07
Density [people/m2]	0,0155	0,0229				0,0187
Schedule	5: 7-10 and 17-23; 2: 9-23	5: 23-7; 2: 23-9				5: 7-10 and 16-23; 2: 9-23
Activity	Standing/walking	Bedroom				Standing/walking
Heating						
Template	Radiator heating, HR combi-boiler, electric hot water kettle kitchen, Natural Ventilation					
Schedule	5: 7-10 and 17-23; 2: 9-23					
Heating [C]	19,5					
Heating set back [C]	17,5					
HW consumption [L/day]						120
Ventilation						
Mechanical Ventilation [ac/h]	0,5					
Natural Ventilation [ac/]	5					
Summer min outdoor temperature	18					
Summer max outdoor temperature	28					
Min fresh air [L/s-person]	7					14
Office Equipment						
Gain [W/m2]	1,57	3,58				1,67
Schedule	Dwell_DomCirc_Equip	Dwell_Bed_Equip				Dwell_DomBath_Equip
Lighting						
Power density [W/m2-100 lux]	2,5					
Lighting type	LED lamps					
Schedule	Dwell_DomCirc_Light	Dwell_DomBed_Light				Dwell_DomBath_Light
Shading		Inside drapes - close weave light				
Airtightness						
Infiltration rate [dm3/s per m2]	0,4					

Table 35: Zone parameters floor 2.

Zone	Landing	Bedroom 5	Bedroom 6	Attic 1	Attic 2	Attic space 1	Attic space 2
Template	Domestic Circulation	Domestic Bedroom		Domestic Circulation			
Zone type	Standard, conditioned						
Floor area [m2]	4,37	12,54	10,81	6,58	5,36	0,43	0,43
Density [people/m2]	0,0155	0,0229		0,0155			
Schedule	5: 7-10 and 17-23; 2: 9-23	5: 23-7; 2: 23-9		5: 7-10 and 17-23; 2: 9-23			
Activity	Standing/walking	Bedroom		Standing/walking			
Heating							
Template	Radiator heating, HR combi-boiler, electric hot water kettle kitchen, Natural Ventilation						
Schedule	5: 7-10 and 17-23; 2: 9-23						
Heating [C]	19,5						
Heating set back [C]	17,5						
HW consumption [L/day]							
Ventilation							
Mechanical Ventilation [ac/h]	0,5						
Natural Ventilation [ac/]	5						
Summer min outdoor temperature	18						
Summer max outdoor temperature	28						
Min fresh air [L/s-person]	7						
Office Equipment							
Gain [W/m2]	1,57	3,58		1,57			
Schedule	Dwell_DomCirc_Equip	Dwell_Bed_Equip		Dwell_DomCirc_Equip			
Lighting							
Power density [W/m2-100 lux]	2,5						
Lighting type	LED lamps						
Schedule	Dwell_DomCirc_Light	Dwell_DomBed_Light		Dwell_DomCirc_Light			
Shading		Inside drapes - close weave light					
Airtightness							
Infiltration rate [dm3/s per m2]	0,4						

Table 36: Zone parameters floor 3.

Appendix 3. Parameters Haarlem: strategy B

The following parameters were used for the creation of the Design Builder and Uniec models of the situation after application of strategy B on the row house in Haarlem.

Location	
Location Template	Amsterdam AP Schiphol
Hourly Weather Data	NLD_AMSTERDAM_IWEC
Winter Design	Heating 99.6% coverage
Summer Design	99.6% coverage

Table 37: Location data.

Construction materials	Thickness [mm]	Rc-value [m2*K/W]	U-value [W/m2*K]
External Wall			
Brick	100	**2,209**	**0,453**
glass fibre/wool - fibre slab	**50**		
Concrete blocks lightweight	120		
Plaster lightweigth	10		
House Dividing Wall			
Plaster lightweigth	10	-	-
Concrete blocks lightweight	120		
Air gap	20		
Concrete blocks lightweight	120		
Plaster lightweigth	10		
Internal Loadbearing Wall			
Plaster lightweigth	10	-	-
Concrete blocks lightweight	70/90/120		
Plaster lightweigth	10		
Internal Wall			
Plaster lightweigth	10	-	-
Aerated Concrete Block	50/70/90/120		
Plaster lightweigth	10		
Pitched Roof			
Clay tiles	25	**6,189**	**0,162**
Air gap	20		
Hardboard	10		
Wood beams with insulation	**200**		
Gypsum Plasterboard	10		
Flat Roof			
Asphalt roofing	5	**6,167**	**0,162**
Insulation	**190**		
Roof screed	5		
Hardboard	10		
Wood beams	100		
Gypsum Plasterboard	10		
Dormer Wall			
Glass fibre board	20	**4,578**	**0,218**
fibre board	30		
Wooden frame with insulation	**110**		
Plaster lightweigth	10		

Table 38a: Construction parameters.

Construction materials	Thickness [mm]	Rc-value [m2*K/W]	U-value [W/m2*K]
Ground Floor Wood			
Timber Flooring	30	**5,251**	**0,19**
Wooden beams with insulation	**160**		
Wooden beams	**40**		
Air gap	400		
Ground Floor MUWI element			
Cast Concrete	30	**5,238**	**0,191**
Cast Concrete - dense, reinforced	200		
Insulation	**140**		
Air gap	**260**		
Internal Concrete Floor			
Cast Concrete	120	-	-
Internal Wood Floor			
Timber Flooring	20	-	-
Wooden beams	180		
Gypsum Plasterboard	10		
External Door			
Wood	**10**	-	**1,245**
Door insulation	**20**		
Wood	**10**		
Glazing			
Clear glazing low E	**6**	-	**0,772**
Argon	**16**		
Clear glazing low E	**6**		
Argon	**16**		
Clear glazing low E	**6**		
Frame			
Polyvinylchloride	**20**	-	**1,393**
Rubber	**10**		
Polyvinylchloride	**20**		

Table 38b: Construction parameters continued.

Zone	Entry	Toilet	Living	Kitchen
Template	Domestic Circulation	Domestic Toilet	Domestic Lounge	Domestic Kitchen
Zone type	Standard, conditioned			
Floor area [m2]	6	0,9	35,25	10,36
Density [people/m2]	0,0155	0,0243	0,0188	0,0237
Schedule	5: 7-10 and 17-23; 2: 9-23			
Activity	Standing/walking		Eating/drinking	Cooking
Heating				
Template	Radiator heating, Hybrid HR++ Combi-boiler with 2x 1,67 m2 solar collectors, Natural Ventilation			
Schedule	5: 7-10 and 17-23; 2: 9-23			
Heating [C]	19,5		21	
Heating set back [C]	17,5			
HW consumption [L/day]				8
Ventilation				
Mechanical Ventilation [ac/h]	0,5			
Natural Ventilation [ac/h]	5			
Summer min outdoor temperature	18			
Summer max outdoor temperature	28			
Min fresh air [L/s-person]	7			21
Office Equipment				
Gain [W/m2]	1,57	1,61	3,9	30,28
Schedule	Dwell_DomCirc_Equip	Dwell_DomToilet_Equip	Dwell_DomLounge_Equip	Dwell_DomKitchen_Equip
Lighting				
Power density [W/m2-100 lux]	2,5			
Lighting type	LED lamps			
Schedule	Dwell_DomCirc_Light	Dwell_DomToilet_Light	Dwell_DomLounge_Light	Dwell_DomKitchen_Light
Airtightness				
Infiltration rate [dm3/s per m2]	0,2			

Table 39: Zone parameters floor 1.

Zone	Landing	Bedroom 1	Bedroom 2	Bedroom 3	Bedroom 4	Bathroom
Template	Domestic Circulation	Domestic Bedroom				Domestic Bathroom
Zone type	Standard, conditioned					
Floor area [m2]	6,02	11,29	9,57	7,91	6,74	4,35
Density [people/m2]	0,0155	0,0229				0,0187
Schedule	5: 7-10 and 17-23; 2: 9-23	5: 23-7; 2: 23-9				5: 7-10 and 16-23; 2: 9-23
Activity	Standing/walking	Bedroom				Standing/walking
Heating						
Template	Radiator heating, Hybrid HR++ Combi-boiler with 2x 1,67 m2 solar collectors, Natural Ventilation					
Schedule	5: 7-10 and 17-23; 2: 9-23					
Heating [C]	19,5					
Heating set back [C]	17,5					
HW consumption [L/day]						120
Ventilation						
Mechanical Ventilation [ac/h]	0,5					
Natural Ventilation [ac/h]	5					
Summer min outdoor temperature	18					
Summer max outdoor temperature	28					
Min fresh air [L/s-person]	7					14
Office Equipment						
Gain [W/m2]	1,57	3,58				1,67
Schedule	Dwell_DomCirc_Equip	Dwell_Bed_Equip				Dwell_DomBath_Equip
Lighting						
Power density [W/m2-100 lux]	2,5					
Lighting type	LED lamps					
Schedule	Dwell_DomCirc_Light	Dwell_DomBed_Light				Dwell_DomBath_Light
Airtightness						
Infiltration rate [dm3/s per m2]	0,2					

Table 40: Zone parameters floor 2.

Zone	Landing	Bedroom 5	Bedroom 6	Attic 1	Attic 2	Attic space 1	Attic space 2
Template	Domestic Circulation	Domestic Bedroom		Domestic Circulation			
Zone type	Standard, conditioned						
Floor area [m2]	4,32	12,47	10,74	6,53	5,32	0	
Density [people/m2]	0,0155	0,0229		0,0155			
Schedule	5: 7-10 and 17-23; 2: 9-23	5: 23-7; 2: 23-9		5: 7-10 and 17-23; 2: 9-23			
Activity	Standing/walking	Bedroom		Standing/walking			
Heating							
Template	Radiator heating, Hybrid HR++ Combi-boiler with 2x 1,67 m2 solar collectors, Natural Ventilation						
Schedule	5: 7-10 and 17-23; 2: 9-23						
Heating [C]	19,5						
Heating set back [C]	17,5						
HW consumption [L/day]							
Ventilation							
Mechanical Ventilation [ac/h]	0,5						
Natural Ventilation [ac/h]	5						
Summer min outdoor temperature	18						
Summer max outdoor temperature	28						
Min fresh air [L/s-person]	7						
Office Equipment							
Gain [W/m2]	1,57	3,58		1,57			
Schedule	Dwell_DomCirc_Equip	Dwell_Bed_Equip		Dwell_DomCirc_Equip			
Lighting							
Power density [W/m2-100 lux]	2,5						
Lighting type	LED lamps						
Schedule	Dwell_DomCirc_Light	Dwell_DomBed_Light		Dwell_DomCirc_Light			
Airtightness							
Infiltration rate [dm3/s per m2]	0,2						

Table 41: Zone parameters floor 3.

Appendix 4. Parameters Haarlem: strategy C

The following parameters were used for the creation of the Design Builder and Uniec models of the situation after application of strategy C on the row house in Haarlem.

Location	
Location Template	Amsterdam AP Schiphol
Hourly Weather Data	NLD_AMSTERDAM_IWEC
Winter Design	Heating 99.6% coverage
Summer Design	99.6% coverage

Table 42: Location data.

Construction materials	Thickness [mm]	R-value [m*K/W]	U-value [W/m2*K]
External Wall			
Brick	20	**4,550**	**0,220**
Insulation	**80**		
Brick	100		
glass fibre/wool - fibre slab	**50**		
Concrete blocks lightweight	120		
Plaster lightweigth	10		
House Dividing Wall			
Plaster lightweigth	10	-	-
Concrete blocks lightweight	120		
Air gap	20		
Concrete blocks lightweight	120		
Plaster lightweigth	10		
Internal Loadbearing Wall			
Plaster lightweigth	10	-	-
Concrete blocks lightweight	70/90/120		
Plaster lightweigth	10		
Internal Wall			
Plaster lightweigth	10	-	-
Aerated Concrete Block	50/70/90/120		
Plaster lightweigth	10		
Pitched Roof			
Clay tiles	25	**6,222**	**0,161**
Air gap with wood frame	20		
Insulation	**190**		
Hardboard	10		
Wooden beams	100		
Gypsum Plasterboard	10		
Flat Roof			
Asphalt roofing	5	**6,167**	**0,162**
Insulation	**190**		
Roof screed	5		
Hardboard	10		
Wood beams	100		
Gypsum Plasterboard	10		

Table 43a: Construction parameters.

Construction materials	Thickness [mm]	R-value [m*K/W]	U-value [W/m2*K]
Dormer Wall			
Glass fibre board	20	**4,578**	**0,218**
fibre board	30		
Wood beams with insulation	**110**		
Plaster lightweigth	10		
Ground Floor Wood			
Timber Flooring	30	**6,288**	**0,159**
Wood beams with insulation	**200**		
Air gap	400		
Ground Floor MUWI element			
Cast Concrete	30	**5,238**	**0,191**
Cast Concrete - dense, reinforced	200		
Insulation	**140**		
Air gap	**260**		
Internal Concrete Floor			
Cast Concrete	120	0,376	2,658
Internal Wood Floor			
Timber Flooring	20	1,13	0,885
Wooden beams	180		
Gypsum Plasterboard	10		
External Door			
Wood	**10**	-	**1,245**
Door insulation	**20**		
Wood	**10**		
Glazing			
Clear glazing low E	**6**	-	**0,772**
Argon	**16**		
Clear glazing low E	**6**		
Argon	**16**		
Clear glazing low E	**6**		
Frame			
Polyvinylchloride	**20**	-	**1,393**
Rubber	**10**		
Polyvinylchloride	**20**		

Table 43b: Construction parameters continued.

Zone	Entry	Toilet	Living	Kitchen
Template	Domestic Circulation	Domestic Toilet	Domestic Lounge	Domestic Kitchen
Zone type	Standard, conditioned			
Floor area [m2]	6,07	0,92	35,39	10,43
Density [people/m2]	0,0155	0,0243	0,0188	0,0237
Schedule	5: 7-10 and 17-23; 2: 9-23			
Activity	Standing/walking		Eating/drinking	Cooking
Heating				
Template	LT radiator heating, Hybrid electric combi-boiler with heat pump and solar collectors, Natural Ventilation			
Schedule	5: 7-10 and 17-23; 2: 9-23			
Heating [C]	19,5		21	
Heating set back [C]	17,5		17,5	
HW consumption [L/day]				8
Ventilation				
Mechanical Ventilation [ac/h]	0,5			
Natural Ventilation [ac/h]	5			
Summer min outdoor temperature	18			
Summer max outdoor temperature	28			
Min fresh air [L/s-person]	7			21
Office Equipment				
Gain [W/m2]	1,57	1,61	3,9	30,28
Schedule	Dwell_DomCirc_Equip	Dwell_DomToilet_Equip	Dwell_DomLounge_Equip	Dwell_DomKitchen_Equip
Lighting				
Power density [W/m2-100 lux]	2,5			
Lighting type	LED lamps			
Schedule	Dwell_DomCirc_Light	Dwell_DomToilet_Light	Dwell_DomLounge_Light	Dwell_DomKitchen_Light
Airtightness				
Infiltration rate [dm3/s per m2]	0,2			

Table 44: Zone parameters floor 1.

Zone	Landing	Bedroom 1	Bedroom 2	Bedroom 3	Bedroom 4	Bathroom
Template	Domestic Circulation	Domestic Bedroom				Domestic Bathroom
Zone type	Standard, conditioned					
Floor area [m2]	6,07	11,36	9,63	7,97	6,79	6,07
Density [people/m2]	0,0155	0,0229				0,0187
Schedule	5: 7-10 and 17-23; 2: 9-23	5: 23-7; 2: 23-9				5: 7-10 and 16-23; 2: 9-23
Activity	Standing/walking	Bedroom				Standing/walking
Heating						
Template	LT radiator heating, Hybrid electric combi-boiler with heat pump and solar collectors, Natural Ventilation					
Schedule	5: 7-10 and 17-23; 2: 9-23					
Heating [C]	19,5					
Heating set back [C]	17,5					
HW consumption [L/day]						120
Ventilation						
Mechanical Ventilation [ac/h]	0,5					
Natural Ventilation [ac/h]	5					
Summer min outdoor temperature	18					
Summer max outdoor temperature	28					
Min fresh air [L/s-person]	7					14
Office Equipment						
Gain [W/m2]	1,57	3,58				1,67
Schedule	Dwell_DomCirc_Equip	Dwell_Bed_Equip				Dwell_DomBath_Equip
Lighting						
Power density [W/m2-100 lux]	2,5					
Lighting type	LED lamps					
Schedule	Dwell_DomCirc_Light	Dwell_DomBed_Light				Dwell_DomBath_Light
Airtightness						
Infiltration rate [dm3/s per m2]	0,2					

Table 45: Zone parameters floor 2.

Zone	Landing	Bedroom 5	Bedroom 6	Attic 1	Attic 2	Attic space 1	Attic space 2
Template	Domestic Circulation	Domestic Bedroom		Domestic Circulation			
Zone type	Standard, conditioned						
Floor area [m2]	4,37	12,54	10,81	6,58	5,36	2,47	2,47
Density [people/m2]	0,0155	0,0229		0,0155			
Schedule	5: 7-10 and 17-23; 2: 9-23	5: 23-7; 2: 23-9		5: 7-10 and 17-23; 2: 9-23			
Activity	Standing/walking	Bedroom		Standing/walking			
Heating							
Template	LT radiator heating, Hybrid electric combi-boiler with heat pump and solar collectors, Natural Ventilation						
Schedule	5: 7-10 and 17-23; 2: 9-23						
Heating [C]	19,5						
Heating set back [C]	17,5						
HW consumption [L/day]							
Ventilation							
Mechanical Ventilation [ac/h]	0,5						
Natural Ventilation [ac/]	5						
Summer min outdoor temperature	18						
Summer max outdoor temperature	28						
Min fresh air [L/s-person]	7						
Office Equipment							
Gain [W/m2]	1,57	3,58		1,57			
Schedule	Dwell_DomCirc_Equip	Dwell_Bed_Equip		Dwell_DomCirc_Equip			
Lighting							
Power density [W/m2-100 lux]	2,5						
Lighting type	LED lamps						
Schedule	Dwell_DomCirc_Light	Dwell_DomBed_Light		Dwell_DomCirc_Light			
Airtightness							
Infiltration rate [dm3/s per m2]	0,2						

Table 46: Zone parameters floor 3.

Appendix 5. Parameters Gorssel

The following parameters were used for the creation of the Design Builder and Uniec models of the current situation of the free-standing house in Gorssel.

Location	
Location Template	Deelen
Hourly Weather Data	NLD_AMSTERDAM_IWEC
Winter Design	Heating 99.6% coverage
Summer Design	99.6% coverage

Table 47: Location data.

Construction materials	Thickness [mm]	R-value [m*K/W]	U-value [W/m2*K]
External Cavity Wall			
Brickwork, outer leaf	110	0,718	1,392
Air gap, 50mm, wall	50		
Brickwoark, inner leaf	110		
External Wall with wood cladding			
Wood siding	10	1,058	0,945
Air gap, 50mm, wall	20		
Brickwork, outer leaf	110		
Air gap, 50mm, wall	50		
Brickwoark, inner leaf	110		
External Brick Wall			
Brick, outer leaf	110	0,301	3,323
Internal Loadbearing Wall			
Brick, inner, 105mm	220		
Internal Wall			
Brick, inner, 105mm	110		
Ground Floor Concrete			
Timber Flooring	30	0,674	1,483
Concrete, cast - mediumweight	30		
Concrete, cast - mediumweight	170		
Pitched Roof			
Clay tiles	25	1,993	0,502
Air gap 10mm	20		
Roofing felt	10		
Sheating, vegetable fiberboard	20		
Glass fibre/wool - fibre quilt	50		
Gypsum Plasterboard	10		
Internal Concrete Floor			
Timber Flooring	30		
Concrete, cast - mediumweight	30		
Concrete, cast - mediumweight	270		
Internal Wood Floor			
Sheating, vegetable fiberboard	20		
Wooden beams	100		
Plywood/wood panels	19		
External Door			
Painted Oak	19	-	2,823
Glazing			
Clear glazing	6	-	3,157
Air gap	6		
Clear glazing	6		
Frame			
Wooden window frame	40	-	2,628

Table 48: Construction parameters.

Zone	Entry	Toilet	Living room	Kitchen	Study	Garage
Template	Domestic Circulation	Domestic Toilet	Domestic Lounge	Domestic Kitchen	Domestic Bedroom	Domestic Circulation
Zone type	Standard, conditioned					
Floor area [m2]	15,56	1,15	39,28	14,06	18,96	22,14
Density [people/m2]	0,0155	0,0243	0,0188	0,0237	0,0229	0,0155
Schedule	5: 7-10 and 17-23; 2: 9-23					
Activity	Standing/walking		Eating/drinking	Cooking	Bedroom	Standing/walking
Heating						
Template	Radiator heating, Combi-boiler, Natural Ventilation					
Schedule	5: 7-10 and 17-23; 2: 9-23					
Heating [C]	19,5		21		19,5	17,5
Heating set back [C]	17,5					15
HW consumption [L/day]				5		
Ventilation						
Mechanical Ventilation [ac/h]	0,5					
Natural Ventilation [ac/]	5					
Summer min outdoor temperature	18					
Summer max outdoor temperature	28					
Min fresh air [L/s-person]	7			21	7	
Office Equipment						
Gain [W/m2]	1,57	1,61	3,9	30,28	3,58	1,57
Schedule	Dwell_DomCirc_Equip	Dwell_DomToilet_Equip	Dwell_DomLounge_Equip	Dwell_DomKitchen_Equip	Dwell_DomBed_Equip	Dwell_DomCirc_Equip
Shading						
Type	Drapes - close weave light					
Position	Inside					
Control type	9-Day cooling and solar + night					
Solar setpoint [W/m2]	120					
Airtightness						
Infiltration rate [dm3/s per m2]	0,7					

Table 49: Zone parameters floor 1.

Zone	Landing	Bedroom 1	Bedroom 2	Bathroom	Closet	Attic space 1	Attic space 2	Attic space 3
Template	Domestic Circulation	Domestic Bedroom		Domestic Bathroom	Domestic Circulation	None		
Zone type	Standard, conditioned					Semi-exterior unconditioned		
Floor area [m2]	4,55	10,21	15,17	7,10	2,85	10,37	27,63	12,40
Density [people/m2]	0,0155	0,0229		0,0187	0,0155			
Schedule	5: 7-10 and 17-23; 2: 9-23					Off 24/7		
Activity	Standing/walking	Bedroom		Standing/walking				
Heating								
Template	Radiator heating, Combi-boiler, Natural Ventilation							
Schedule	5: 7-10 and 17-23; 2: 9-23							
Heating [C]	21	19,5				10		
Heating set back [C]	17,5					10		
HW consumption [L/day]				140				
Ventilation								
Mechanical Ventilation [ac/h]	0,5							
Natural Ventilation [ac/]	5							
Summer min outdoor temperature	18							
Summer max outdoor temperature	28							
Min fresh air [L/s-person]	7			12	7			
Office Equipment								
Gain [W/m2]	1,57	3,58		1,67	1,57			
Schedule	Dwell_DomCirc_Equip	Dwell_DomBed_Equip		Dwell_DomBath_Equip	Dwell_DomCirc_Equip			
Shading								
Type	Drapes - close weave light							
Position	Inside							
Control type	9-Day cooling and solar + night							
Solar setpoint [W/m2]	120							
Airtightness								
Infiltration rate [dm3/s per m2]	0,7							

Table 50: Zone parameters floor 2.

Zone	Attic space 4
Template	None
Zone type	Semi-exterior unconditioned
Floor area [m2]	20,45
Density [people/m2]	
Schedule	Off 24/7
Activity	
Heating	
Template	Radiator heating, Combi-boiler, Natural Ventilation
Schedule	5: 7-10 and 17-23; 2: 9-23
Heating [C]	10
Heating set back [C]	10
HW consumption [L/day]	
Ventilation	
Mechanical Ventilation [ac/h]	0,5
Natural Ventilation [ac/]	5
Summer min outdoor temperature	18
Summer max outdoor temperature	28
Min fresh air [L/s-person]	7
Office Equipment	
Gain [W/m2]	
Schedule	
Lighting	
Type	Drapes - close weave light
Position	Inside
Control type	9-Day cooling and solar + night
Solar setpoint [W/m2]	120
Airtightness	
Infiltration rate [dm3/s per m2]	0,7

Table 51: Zone parameters floor 3.

Appendix 6. Parameters Gorssel: strategy A

The following parameters were used for the creation of the Design Builder and Uniec models of the situation after application of strategy A on the free-standing house in Gorssel.

Location	
Location Template	Deelen
Hourly Weather Data	NLD_AMSTERDAM_IWEC
Winter Design	Heating 99.6% coverage
Summer Design	99.6% coverage

Table 52: Location data.

Construction materials	Thickness [mm]	R-value [m*K/W]	U-value [W/m2*K]
External Cavity Wall			
Brickwork, outer leaf	110	**1,669**	**0,599**
Loose fill/powders - cellulosic insulation	**50**		
Brickwoark, inner leaf	110		
External Wall with wood cladding			
Wood siding	10	**2,009**	**0,498**
Air layer	20		
Brickwork, outer leaf	110		
Loose fill/powders - cellulosic insulation	**50**		
Brickwoark, inner leaf	110		
External Brick Wall			
Brick, outer leaf	110	0,301	3,323
Internal Loadbearing Wall			
Brick, inner, 105mm	220		
Internal Wall			
Brick, inner, 105mm	110		
Ground Floor Concrete			
Timber Flooring	30	**3,531**	**0,283**
Concrete, cast - mediumweight	30		
Concrete, cast - mediumweight	170		
Glass fibre/wool - fibre slab	**100**		
Pitched Roof			
Clay tiles	25	**4,172**	**0,240**
Air gap 10mm	20		
Roofing felt	10		
Sheating, vegetable fiberboard	20		
Glass fibre/wool - fibre slab	**120**		
Gypsum Plasterboard	10		
Internal Concrete Floor			
Timber Flooring	30		
Concrete, cast - mediumweight	30		
Concrete, cast - mediumweight	270		
Internal Wood Floor			
Sheating, vegetable fiberboard	20		
Wooden beams	100		
Plywood/wood panels	19		
External Door			
Wood	**10**	-	**1,245**
Door insulation	**20**		
Wood	**10**		
Glazing			
Clear glazing	**3**	-	**1,514**
Argon	**13**		
Clear glazing low E	**3**		
Frame			
Polyvinlychloride	**20**	-	**1,393**
Rubber	**10**		
Polyvinlychloride	**20**		

Table 53: Construction parameters.

Zone	Entry	Toilet	Living room	Kitchen	Study	Garage
Template	Domestic Circulation	Domestic Toilet	Domestic Lounge	Domestic Kitchen	Domestic Bedroom	Domestic Circulation
Zone type	Standard, conditioned					
Floor area [m2]	15,56	1,15	39,28	14,06	18,96	22,14
Density [people/m2]	0,0155	0,0243	0,0188	0,0237	0,0229	0,0155
Schedule	5: 7-10 and 17-23; 2: 9-23					
Activity	Standing/walking		Eating/drinking	Cooking	Bedroom	Standing/walking
Heating						
Template	Radiator heating, HR-107 combi-boiler, Natural Ventilation					
Schedule	5: 7-10 and 17-23; 2: 9-23					
Heating [C]	19,5		21		19,5	17,5
Heating set back [C]	17,5					15
HW consumption [L/day]				5		
Ventilation						
Mechanical Ventilation [ac/h]	0,5					
Natural Ventilation [ac/]	5					
Summer min outdoor temperature	18					
Summer max outdoor temperature	28					
Min fresh air [L/s-person]	7			21	7	
Office Equipment						
Gain [W/m2]	1,57	1,61	3,9	30,28	3,58	1,57
Schedule	Dwell_DomCirc_Equip	Dwell_DomToilet_Equip	Dwell_DomLounge_Equip	Dwell_DomKitchen_Equip	Dwell_DomBed_Equip	Dwell_DomCirc_Equip
Shading						
Type	Drapes - close weave light					
Position	Inside					
Control type	9-Day cooling and solar + night					
Solar setpoint [W/m2]	120					
Airtightness						
Infiltration rate [dm3/s per m2]	0,4					

Table 54: Zone parameters floor 1.

Zone	Landing	Bedroom 1	Bedroom 2	Bathroom	Closet	Attic space 1	Attic space 2	Attic space 3
Template	Domestic Circulation	Domestic Bedroom		Domestic Bathroom	Domestic Circulation	None		
Zone type	Standard, conditioned					Semi-exterior unconditioned		
Floor area [m2]	4,55	10,21	15,17	7,10	2,85	10,37	27,63	12,40
Density [people/m2]	0,0155	0,0229		0,0187	0,0155			
Schedule	5: 7-10 and 17-23; 2: 9-23					Off 24/7		
Activity	Standing/walking	Bedroom		Standing/walking				
Heating								
Template	Radiator heating, HR-107 combi-boiler, Natural Ventilation							
Schedule	5: 7-10 and 17-23; 2: 9-23							
Heating [C]	21	19,5				10		
Heating set back [C]	17,5					10		
HW consumption [L/day]				140				
Ventilation								
Mechanical Ventilation [ac/h]	0,5							
Natural Ventilation [ac/]	5							
Summer min outdoor temperature	18							
Summer max outdoor temperature	28							
Min fresh air [L/s-person]	7			12	7			
Office Equipment								
Gain [W/m2]	1,57	3,58		1,67	1,57			
Schedule	Dwell_DomCirc_Equip	Dwell_DomBed_Equip		Dwell_DomBath_Equip	Dwell_DomCirc_Equip			
Shading								
Type	Drapes - close weave light							
Position	Inside							
Control type	9-Day cooling and solar + night							
Solar setpoint [W/m2]	120							
Airtightness								
Infiltration rate [dm3/s per m2]	0,4							

Table 55: Zone parameters floor 2.

Zone	Attic space 4
Template	None
Zone type	Semi-exterior unconditioned
Floor area [m2]	20,45
Density [people/m2]	
Schedule	Off 24/7
Activity	
Heating	
Template	Radiator heating, HR-107 combi-boiler, Natural Ventilation
Schedule	5: 7-10 and 17-23; 2: 9-23
Heating [C]	10
Heating set back [C]	10
HW consumption [L/day]	
Ventilation	
Mechanical Ventilation [ac/h]	0,5
Natural Ventilation [ac/]	5
Summer min outdoor temperature	18
Summer max outdoor temperature	28
Min fresh air [L/s-person]	7
Office Equipment	
Gain [W/m2]	
Schedule	
Lighting	
Type	Drapes - close weave light
Position	Inside
Control type	9-Day cooling and solar + night
Solar setpoint [W/m2]	120
Airtightness	
Infiltration rate [dm3/s per m2]	0,4

Table 56: Zone parameters floor 3.

Appendix 7. Parameters Gorssel: strategy B

The following parameters were used for the creation of the Design Builder and Uniec models of the situation after application of strategy B on the free-standing house in Gorssel.

Location	
Location Template	Deelen
Hourly Weather Data	NLD_AMSTERDAM_IWEC
Winter Design	Heating 99.6% coverage
Summer Design	99.6% coverage

Table 57: Location data.

Construction materials	Thickness [mm]	R-value [m*K/W]	U-value [W/m2*K]
External Cavity Wall			
Brickwork, outer leaf	110		
Loose fill/powders - cellulosic insulation	**50**	**1,669**	**0,599**
Brickwoark, inner leaf	110		
External Wall with wood cladding			
Wood siding	10		
Air layer	20		
Brickwork, outer leaf	110	**2,009**	**0,498**
Loose fill/powders - cellulosic insulation	**50**		
Brickwoark, inner leaf	110		
External Brick Wall			
Brick, outer leaf	110	0,301	3,323
Internal Loadbearing Wall			
Brick, inner, 105mm	220		
Internal Wall			
Brick, inner, 105mm	110		
Ground Floor Concrete			
Timber Flooring	30		
Concrete, cast - mediumweight	30	**5,246**	**0,191**
Concrete, cast - mediumweight	170		
Glass fibre/wool - fibre slab	**160**		
Pitched Roof			
Clay tiles	25		
Air gap 10mm	20		
Roofing felt	10	**6,172**	**0,162**
Sheating, vegetable fiberboard	20		
Glass fibre/wool - fibre slab	**190**		
Gypsum Plasterboard	10		
Internal Concrete Floor			
Timber Flooring	30		
Concrete, cast - mediumweight	30		
Concrete, cast - mediumweight	270		
Internal Wood Floor			
Sheating, vegetable fiberboard	20		
Wooden beams	100		
Plywood/wood panels	19		
External Door			
Wood	**10**		
Door insulation	**20**	-	**1,245**
Wood	**10**		
Glazing			
Clear glazing low E	**3**		
Argon	**13**		
Clear glazing	**3**	-	**0,786**
Argon	**13**		
Clear glazing low E	**3**		
Frame			
Polyvinlychloride	**20**		
Rubber	**10**	-	**1,393**
Polyvinlychloride	**20**		

Table 58: Construction parameters.

Zone	Entry	Toilet	Living room	Kitchen	Study	Garage
Template	Domestic Circulation	Domestic Toilet	Domestic Lounge	Domestic Kitchen	Domestic Bedroom	Domestic Circulation
Zone type	Standard, conditioned					
Floor area [m2]	15,56	1,15	39,28	14,06	18,96	22,14
Density [people/m2]	0,0155	0,0243	0,0188	0,0237	0,0229	0,0155
Schedule	5: 7-10 and 17-23; 2: 9-23					
Activity	Standing/walking		Eating/drinking	Cooking	Bedroom	Standing/walking
Heating						
Template	Radiator heating, HR-107 combi-boiler with solar collector, Natural Ventilation					
Schedule	5: 7-10 and 17-23; 2: 9-23					
Heating [C]	19,5		21		19,5	17,5
Heating set back [C]	17,5					15
HW consumption [L/day]				5		
Ventilation						
Mechanical Ventilation [ac/h]	0,5					
Natural Ventilation [ac/]	5					
Summer min outdoor temperature	18					
Summer max outdoor temperature	28					
Min fresh air [L/s-person]	7			21	7	
Office Equipment						
Gain [W/m2]	1,57	1,61	3,9	30,28	3,58	1,57
Schedule	Dwell_DomCirc_Equip	Dwell_DomToilet_Equip	Dwell_DomLounge_Equip	Dwell_DomKitchen_Equip	Dwell_DomBed_Equip	Dwell_DomCirc_Equip
Shading						
Type	Drapes - close weave light					
Position	Inside					
Control type	9-Day cooling and solar + night					
Solar setpoint [W/m2]	120					
Airtightness						
Infiltration rate [dm3/s per m2]	0,2					

Table 59: Zone parameters floor 1.

Zone	Landing	Bedroom 1	Bedroom 2	Bathroom	Closet	Attic space 1	Attic space 2	Attic space 3
Template	Domestic Circulation	Domestic Bedroom		Domestic Bathroom	Domestic Circulation	None		
Zone type	Standard, conditioned					Semi-exterior unconditioned		
Floor area [m2]	4,55	10,21	15,17	7,10	2,85	10,37	27,63	12,40
Density [people/m2]	0,0155	0,0229		0,0187	0,0155			
Schedule	5: 7-10 and 17-23; 2: 9-23					Off 24/7		
Activity	Standing/walking	Bedroom		Standing/walking				
Heating								
Template	Radiator heating, HR-107 combi-boiler with solar collector, Natural Ventilation							
Schedule	5: 7-10 and 17-23; 2: 9-23							
Heating [C]	21	19,5				10		
Heating set back [C]	17,5					10		
HW consumption [L/day]				140				
Ventilation								
Mechanical Ventilation [ac/h]	0,5							
Natural Ventilation [ac/]	5							
Summer min outdoor temperature	18							
Summer max outdoor temperature	28							
Min fresh air [L/s-person]	7			12	7			
Office Equipment								
Gain [W/m2]	1,57	3,58		1,67	1,57			
Schedule	Dwell_DomCirc_Equip	Dwell_DomBed_Equip		Dwell_DomBath_Equip	Dwell_DomCirc_Equip			
Shading								
Type	Drapes - close weave light							
Position	Inside							
Control type	9-Day cooling and solar + night							
Solar setpoint [W/m2]	120							
Airtightness								
Infiltration rate [dm3/s per m2]	0,2							

Table 60: Zone parameters floor 2.

Zone	Attic space 4
Template	None
Zone type	Semi-exterior unconditioned
Floor area [m2]	20,45
Density [people/m2]	
Schedule	Off 24/7
Activity	
Heating	
Template	Radiator heating, HR-107 combi-boiler with solar collector, Natural Ventilation
Schedule	5: 7-10 and 17-23; 2: 9-23
Heating [C]	10
Heating set back [C]	10
HW consumption [L/day]	
Ventilation	
Mechanical Ventilation [ac/h]	0,5
Natural Ventilation [ac/]	5
Summer min outdoor temperature	18
Summer max outdoor temperature	28
Min fresh air [L/s-person]	7
Office Equipment	
Gain [W/m2]	
Schedule	
Lighting	
Type	Drapes - close weave light
Position	Inside
Control type	9-Day cooling and solar + night
Solar setpoint [W/m2]	120
Airtightness	
Infiltration rate [dm3/s per m2]	0,2

Table 61: Zone parameters floor 3.

Appendix 8. Parameters Gorssel: strategy C

The following parameters were used for the creation of the Design Builder and Uniec models of the situation after application of strategy C on the free-standing house in Gorssel.

Location	
Location Template	Deelen
Hourly Weather Data	NLD_AMSTERDAM_IWEC
Winter Design	Heating 99.6% coverage
Summer Design	99.6% coverage

Table 62: Location data.

Construction materials	Thickness [mm]	R-value [m*K/W]	U-value [W/m2*K]
External Cavity Wall			
Brickwork, outer leaf	**20**	**4,693**	**0,213**
EPS expanded polystyrene (standard)	**120**		
Brickwork, outer leaf	110		
Loose fill/powders - cellulosic insulation	**50**		
Brickwoark, inner leaf	110		
External Wall with wood cladding			
Wood siding	**10**	**4,586**	**0,218**
Wood framing with expanded polystyrene	**100**		
Brickwork, outer leaf	110		
Loose fill/powders - cellulosic insulation	**50**		
Brickwoark, inner leaf	110		
External Brick Wall			
Brick, outer leaf	**20**	**4,575**	**0,219**
EPS expanded polystyrene (standard)	**170**		
Brick, outer leaf	110		
Internal Loadbearing Wall			
Brick, inner, 105mm	220		
Internal Wall			
Brick, inner, 105mm	110		
Ground Floor Concrete			
Timber Flooring	30	**5,246**	**0,191**
Concrete, cast - mediumweight	30		
Concrete, cast - mediumweight	170		
Glass fibre/wool - fibre slab	**160**		
Pitched Roof			
Clay tiles	**25**	**6,176**	**0,162**
Air gap 10mm	**20**		
Roofing felt	**5**		
Sheating, vegetable fiberboard	**20**		
Wood framing with expanded polystyrene	**180**		
Sheating, vegetable fiberboard	20		
Gypsum Plasterboard	10		
Internal Concrete Floor			
Timber Flooring	30		
Concrete, cast - mediumweight	30		
Concrete, cast - mediumweight	270		
Internal Wood Floor			
Sheating, vegetable fiberboard	20		
Wooden beams	100		
Plywood/wood panels	19		
External Door			
Wood	**10**	-	**1,245**
Door insulation	**20**		
Wood	**10**		
Glazing			
Clear glazing low E	**3**	-	**0,786**
Argon	**13**		
Clear glazing	**3**		
Argon	**13**		
Clear glazing low E	**3**		
Frame			
Polyvinylchloride	**20**	-	**1,393**
Rubber	**10**		
Polyvinylchloride	**20**		

Table 63: Construction parameters.

Zone	Entry	Toilet	Living room	Kitchen	Study	Garage
Template	Domestic Circulation	Domestic Toilet	Domestic Lounge	Domestic Kitchen	Domestic Bedroom	Domestic Circulation
Zone type	Standard, conditioned					
Floor area [m2]	15,56	1,15	39,28	14,06	18,96	22,14
Density [people/m2]	0,0155	0,0243	0,0188	0,0237	0,0229	0,0155
Schedule	5: 7-10 and 17-23; 2: 9-23					
Activity	Standing/walking		Eating/drinking	Cooking	Bedroom	Standing/walking
Heating						
Template	LT radiator heating, Hybrid electric combi boiler with heat pump and solar collectors, Natural Ventilation					
Schedule	5: 7-10 and 17-23; 2: 9-23					
Heating [C]	19,5		21		19,5	17,5
Heating set back [C]	17,5					15
HW consumption [L/day]				5		
Ventilation						
Mechanical Ventilation [ac/h]	0,5					
Natural Ventilation [ac/]	5					
Summer min outdoor temperature	18					
Summer max outdoor temperature	28					
Min fresh air [L/s-person]	7			21	7	
Office Equipment						
Gain [W/m2]	1,57	1,61	3,9	30,28	3,58	1,57
Schedule	Dwell_DomCirc_Equip	Dwell_DomToilet_Equip	Dwell_DomLounge_Equip	Dwell_DomKitchen_Equip	Dwell_DomBed_Equip	Dwell_DomCirc_Equip
Shading						
Type	Drapes - close weave light					
Position	Inside					
Control type	9-Day cooling and solar + night					
Solar setpoint [W/m2]	120					
Airtightness						
Infiltration rate [dm3/s per m2]	0,2					

Table 64: Zone parameters floor 1.

Zone	Landing	Bedroom 1	Bedroom 2	Bathroom	Closet	Attic space 1	Attic space 2	Attic space 3
Template	Domestic Circulation	Domestic Bedroom		Domestic Bathroom	Domestic Circulation	None		
Zone type	Standard, conditioned					Semi-exterior unconditioned		
Floor area [m2]	4,55	10,21	15,17	7,10	2,85	10,37	27,63	12,40
Density [people/m2]	0,0155	0,0229		0,0187	0,0155			
Schedule	5: 7-10 and 17-23; 2: 9-23					Off 24/7		
Activity	Standing/walking	Bedroom		Standing/walking				
Heating								
Template	LT radiator heating, Hybrid electric combi boiler with heat pump and solar collectors, Natural Ventilation							
Schedule	5: 7-10 and 17-23; 2: 9-23							
Heating [C]	21	19,5				10		
Heating set back [C]	17,5					10		
HW consumption [L/day]				140				
Ventilation								
Mechanical Ventilation [ac/h]	0,5							
Natural Ventilation [ac/]	5							
Summer min outdoor temperature	18							
Summer max outdoor temperature	28							
Min fresh air [L/s-person]	7			12	7			
Office Equipment								
Gain [W/m2]	1,57	3,58		1,67	1,57			
Schedule	Dwell_DomCirc_Equip	Dwell_DomBed_Equip		Dwell_DomBath_Equip	Dwell_DomCirc_Equip			
Shading								
Type	Drapes - close weave light							
Position	Inside							
Control type	9-Day cooling and solar + night							
Solar setpoint [W/m2]	120							
Airtightness								
Infiltration rate [dm3/s per m2]	0,2							

Table 65: Zone parameters floor 2.

Zone	Attic space 4
Template	None
Zone type	Semi-exterior unconditioned
Floor area [m2]	20,45
Density [people/m2]	
Schedule	Off 24/7
Activity	
Heating	
Template	LT radiator heating, Hybrid electric combi boiler with heat pump and solar collectors, Natural Ventilation
Schedule	5: 7-10 and 17-23; 2: 9-23
Heating [C]	10
Heating set back [C]	10
HW consumption [L/day]	
Ventilation	
Mechanical Ventilation [ac/h]	0,5
Natural Ventilation [ac/]	5
Summer min outdoor temperature	18
Summer max outdoor temperature	28
Min fresh air [L/s-person]	7
Office Equipment	
Gain [W/m2]	
Schedule	
Lighting	
Type	Drapes - close weave light
Position	Inside
Control type	9-Day cooling and solar + night
Solar setpoint [W/m2]	120
Airtightness	
Infiltration rate [dm3/s per m2]	0,2

Table 66: Zone parameters floor 3.

Appendix 9. Drawings Haarlem

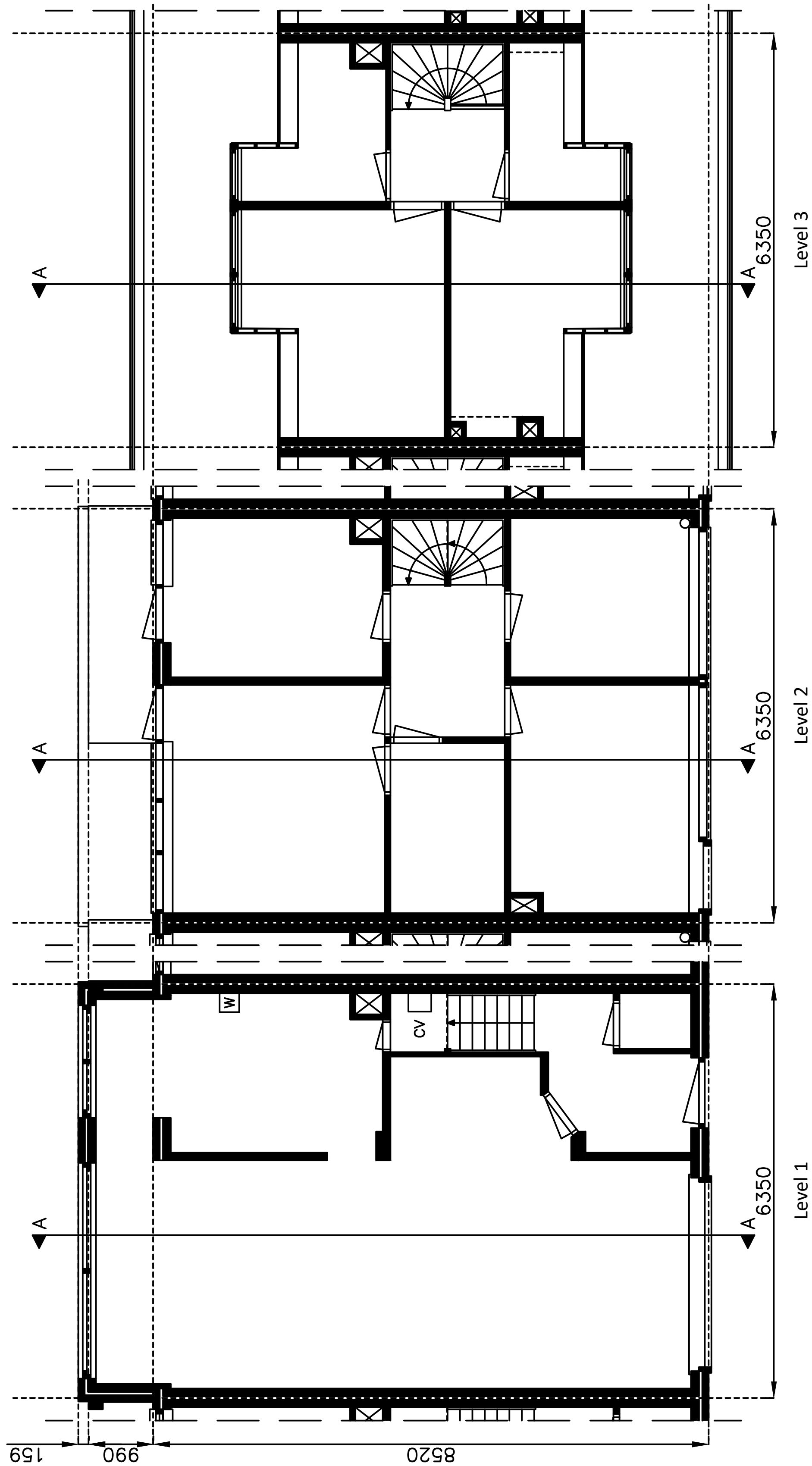


Figure 66: Floorplans current situation
scale 1:100

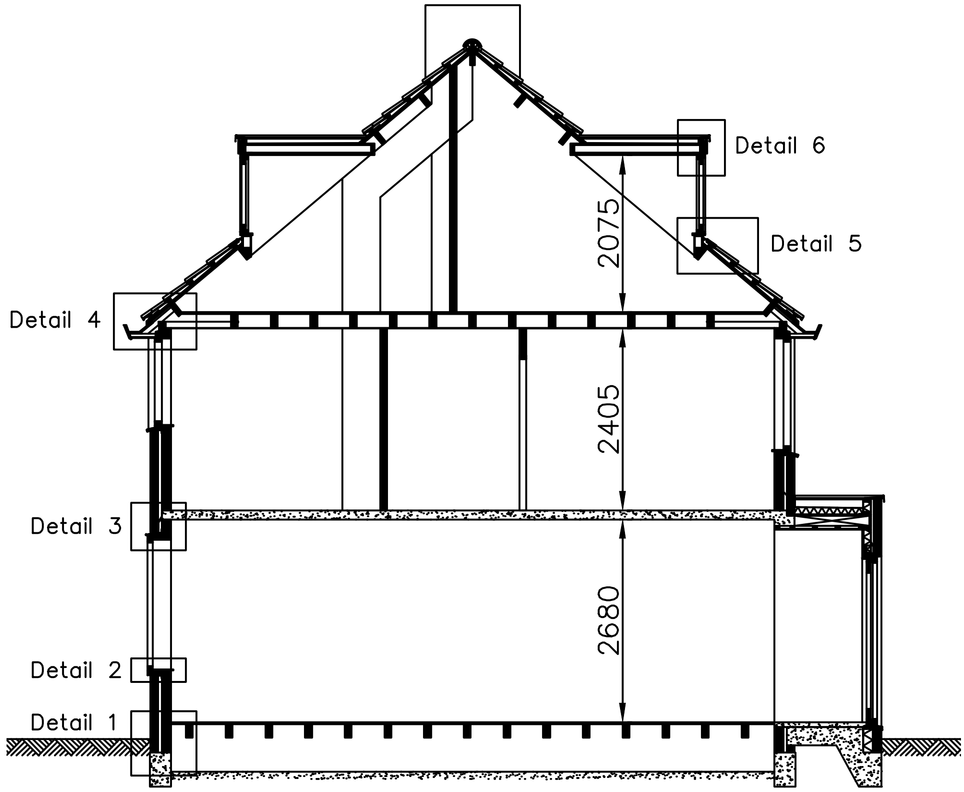


Figure 67: Section A-A current situation scale 1:100

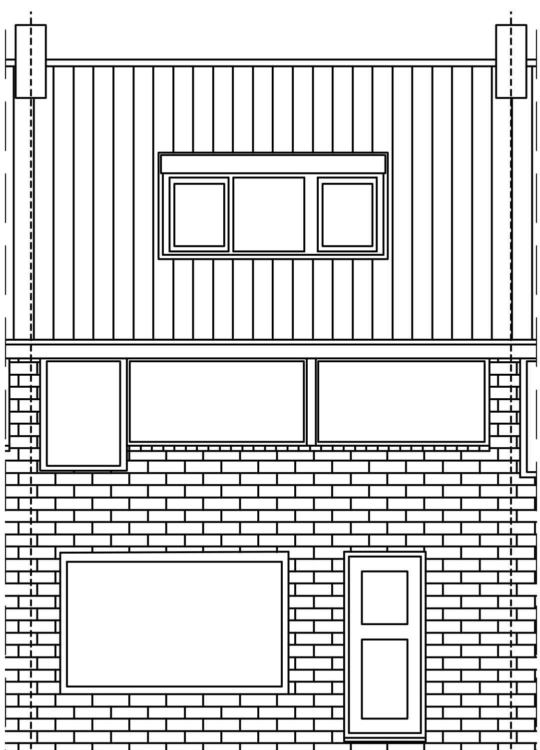


Figure 68: Front view current situation scale 1:100

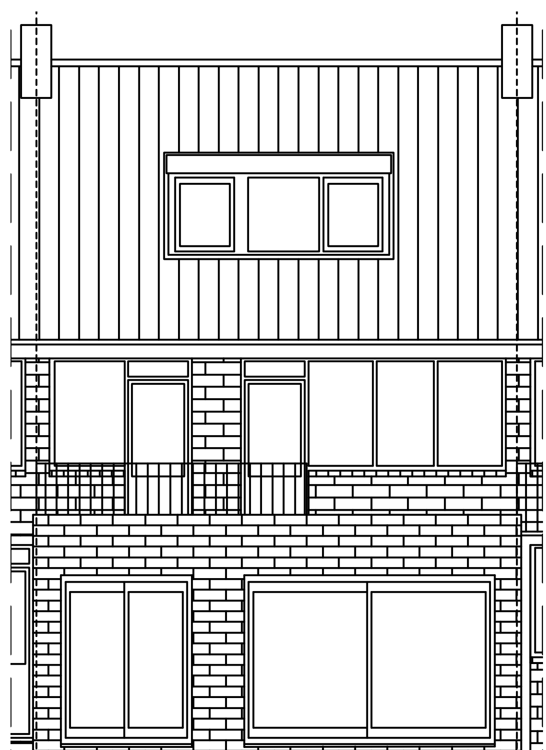


Figure 69: Back view current situation scale 1:100

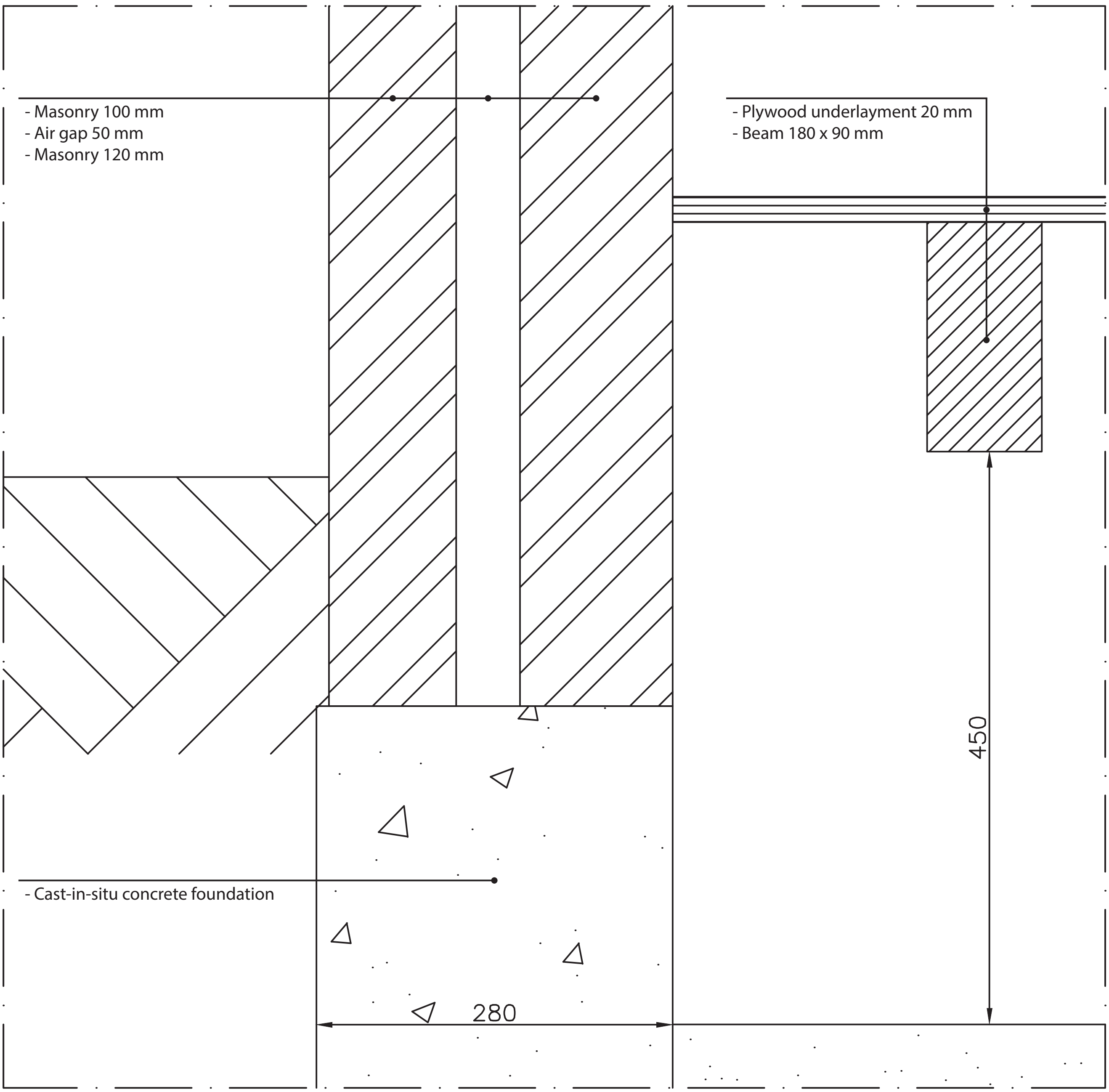


Figure 70: Detail 1 current situation
scale 1:5

Figure 71: Detail 3 current situation
scale 1:5

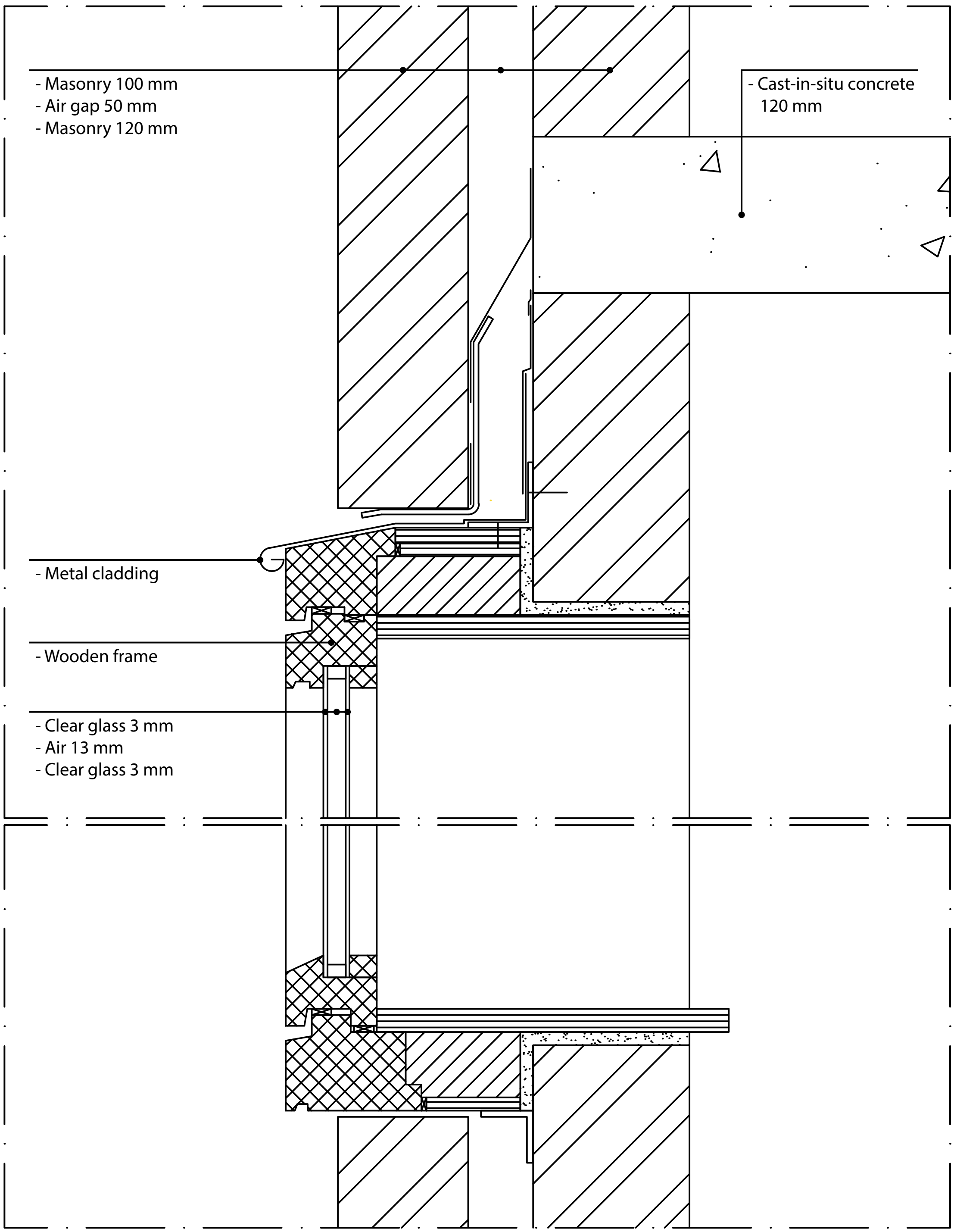


Figure 72: Detail 2 current situation
scale 1:5

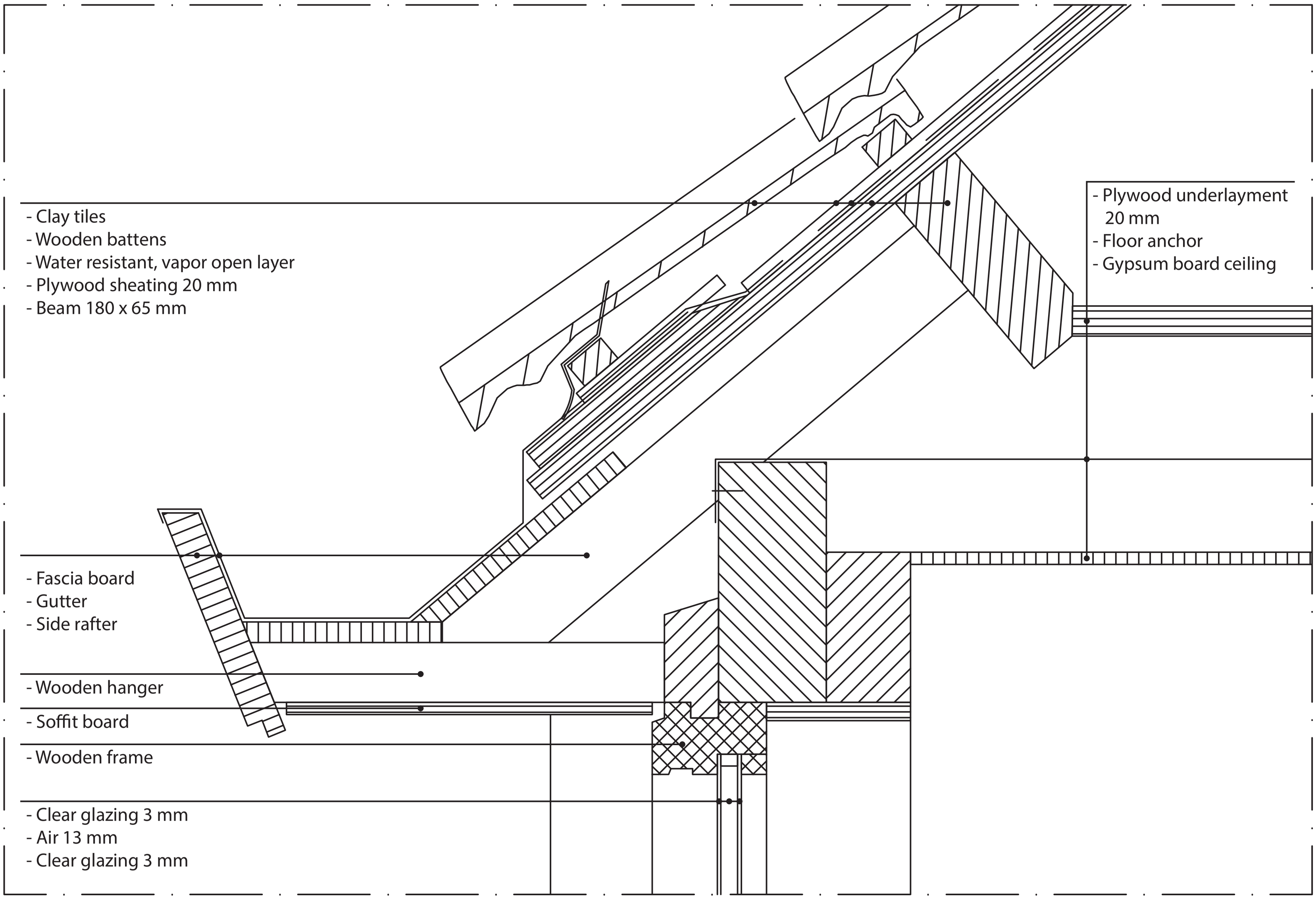


Figure 73: Detail 4 current situation
scale 1:5

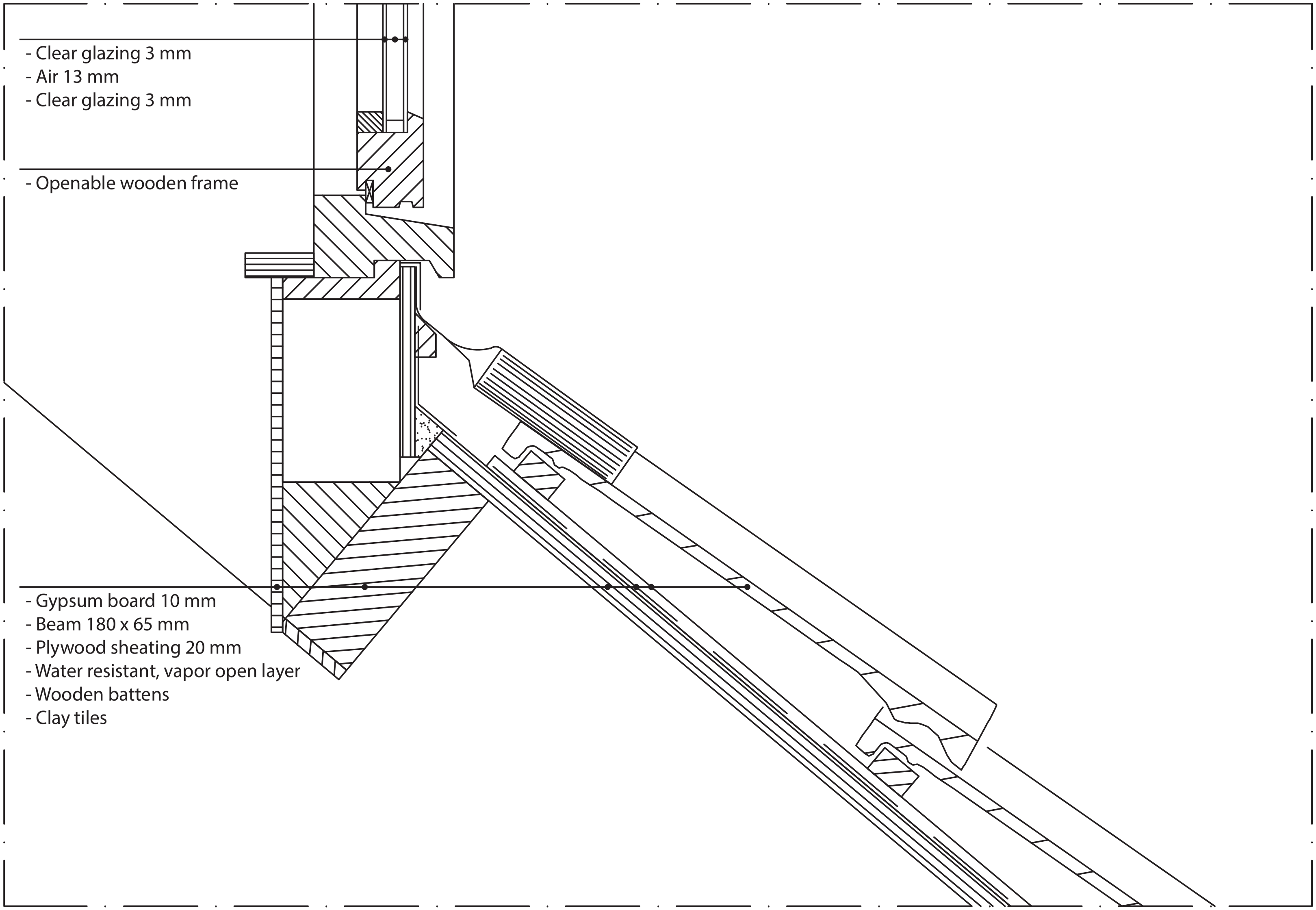


Figure 74: Detail 5 current situation
scale 1:5

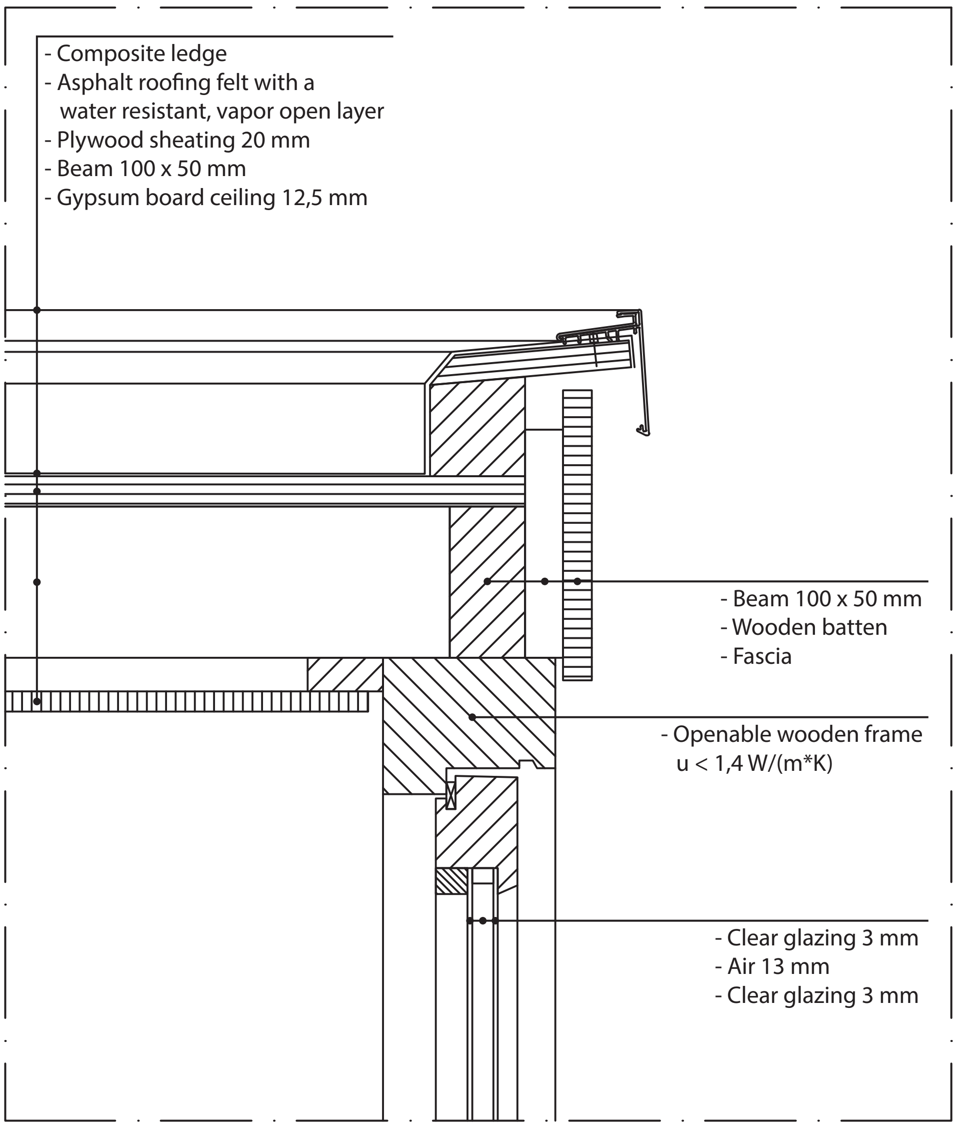


Figure 75: Detail 6 current situation
scale 1:5

Appendix 10. Drawings Haarlem: strategy A

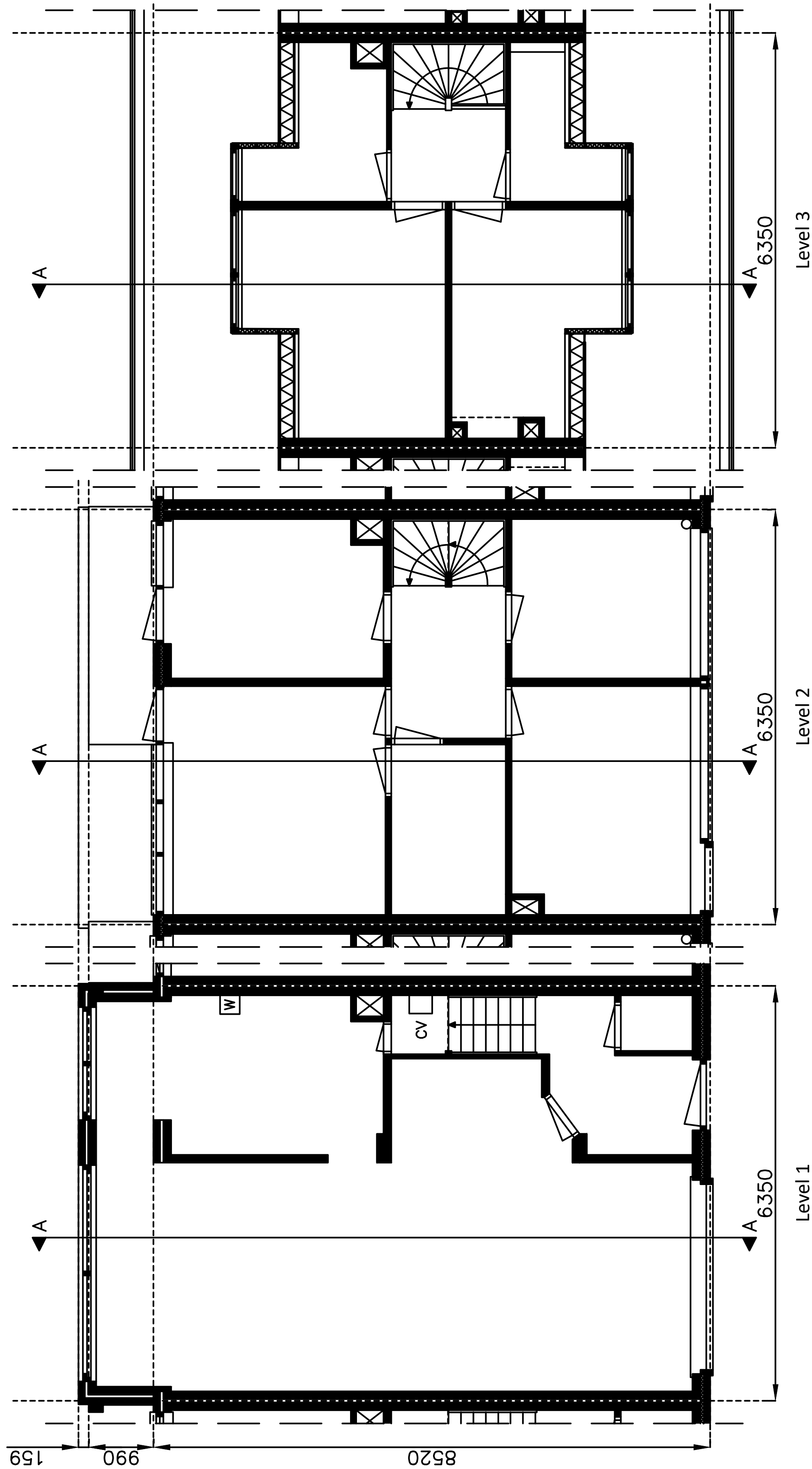


Figure 76: Floorplans strategy A
scale 1:100

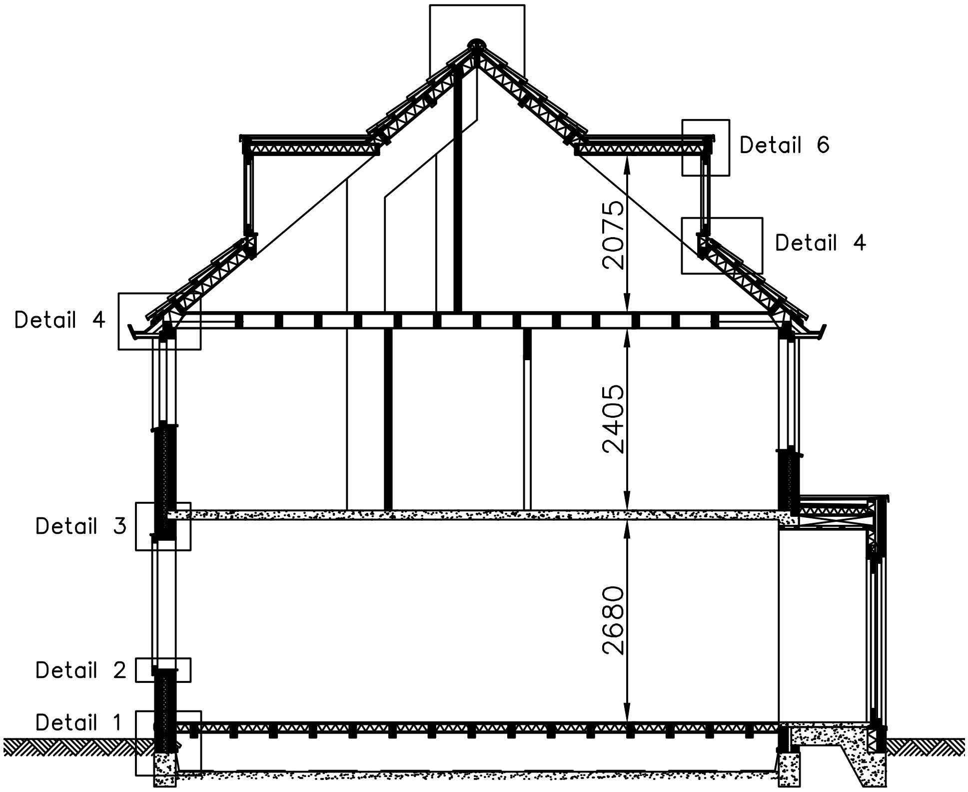


Figure 77: Section A-A strategy A scale 1:100

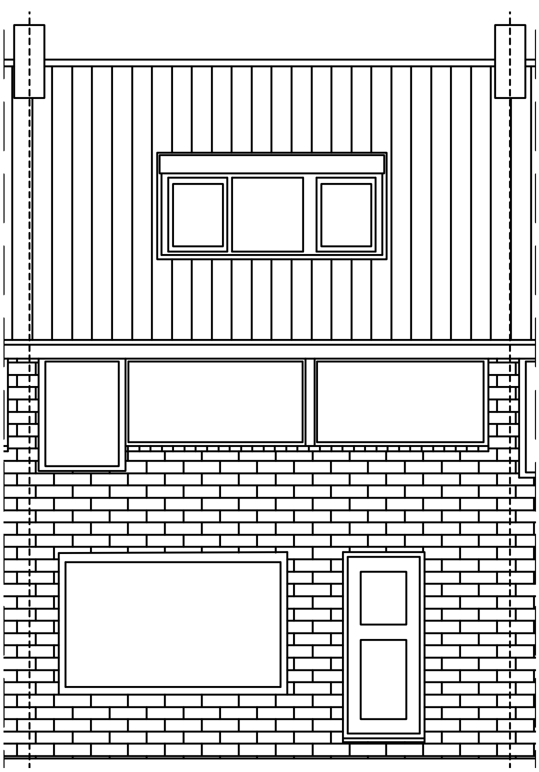


Figure 78: Front view current strategy A 1:100

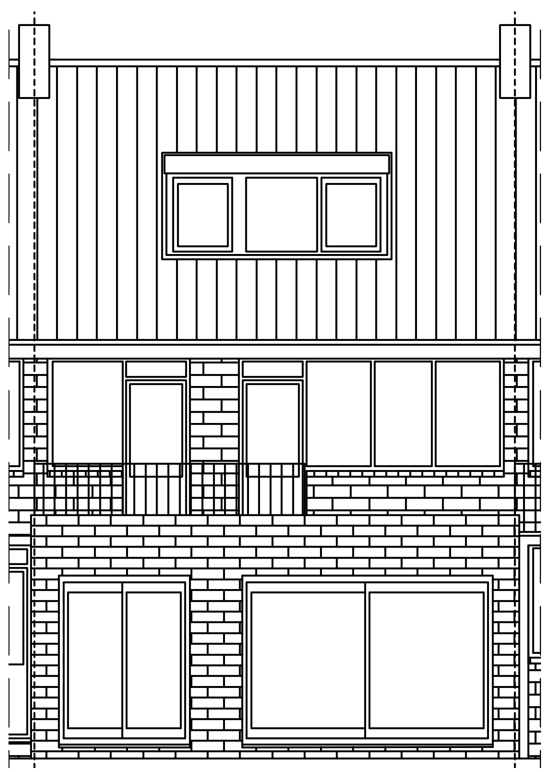


Figure 79: Back view current strategy A 1:100

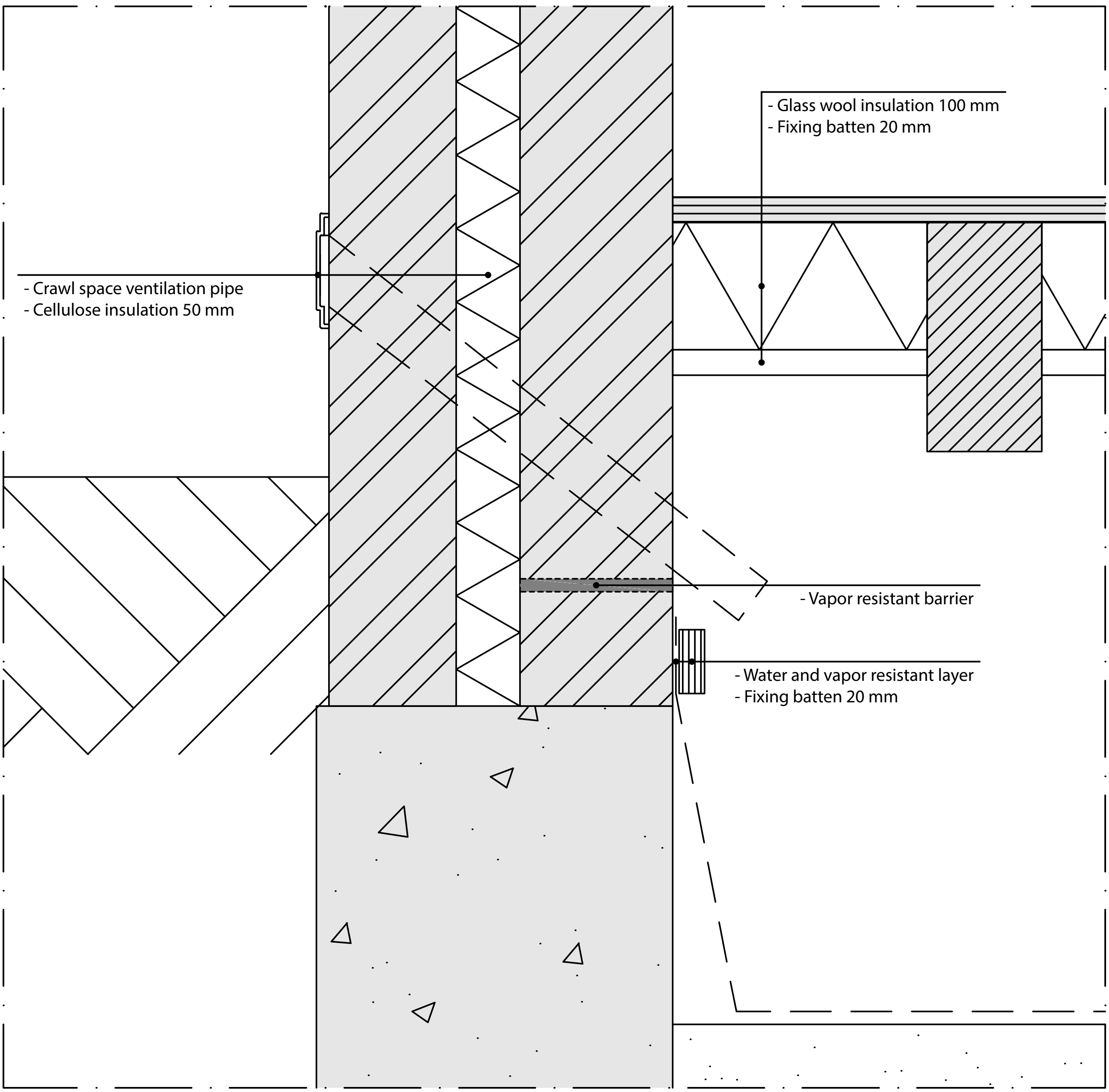
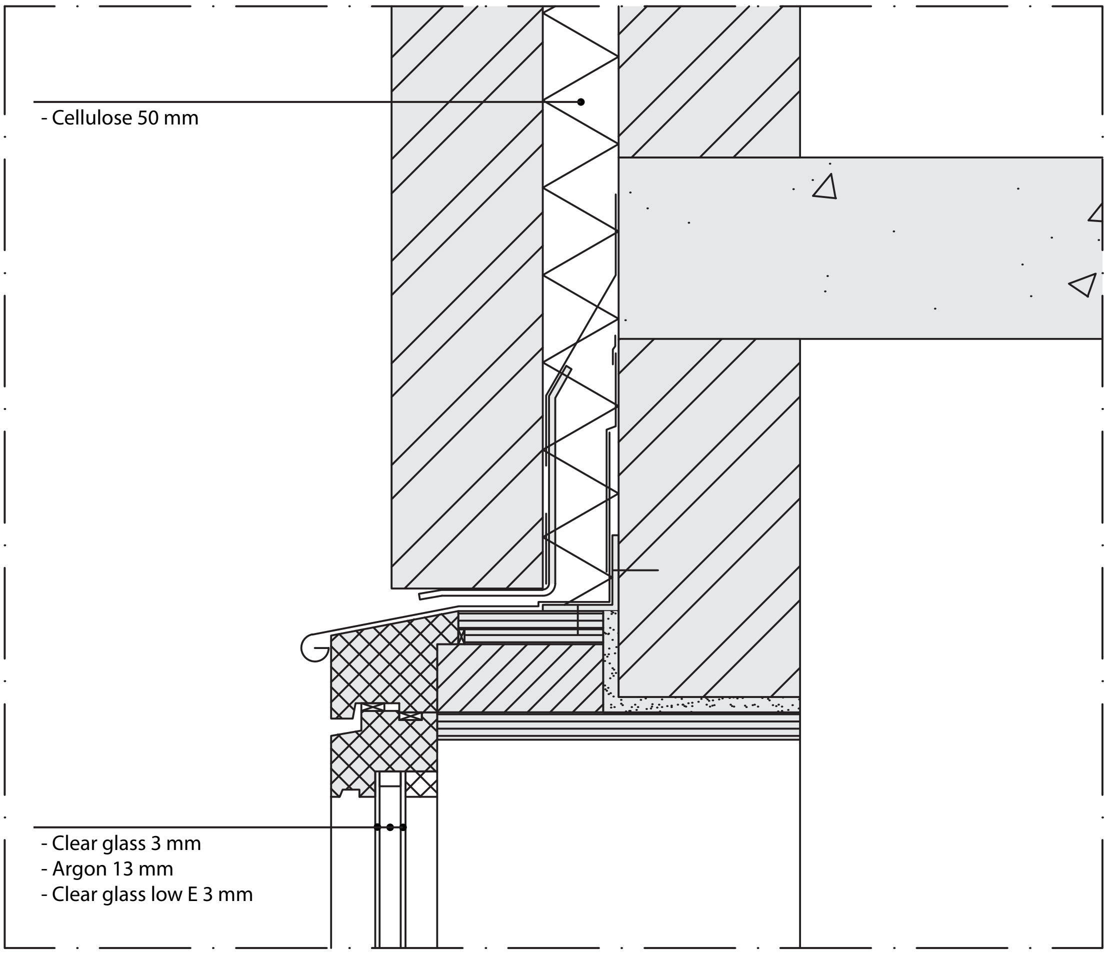


Figure 80: Detail 1 strategy A, in light gray the original construction
scale 1:5

Figure 81: Detail 3 strategy A, in light gray the original construction
scale 1:5



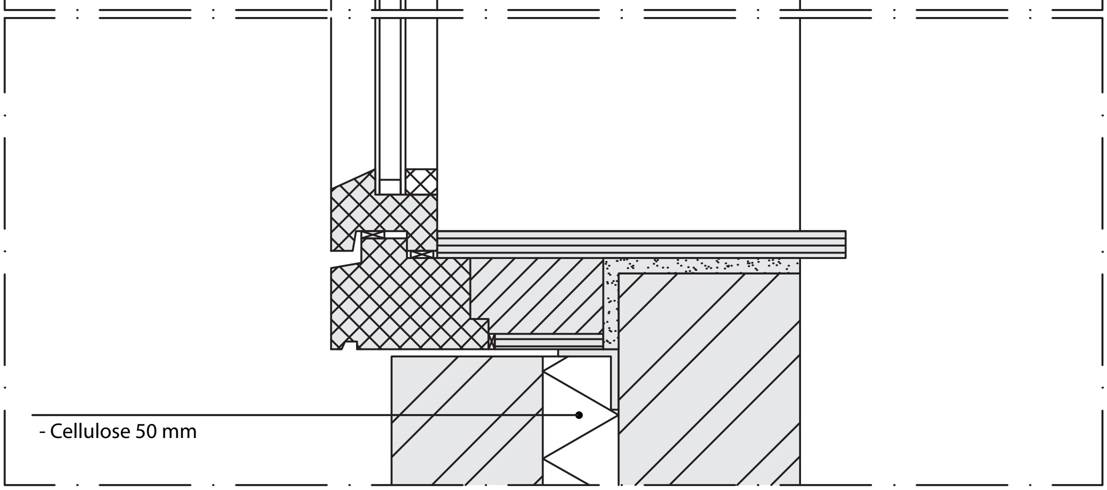


Figure 82: Detail 2 strategy A, in light gray the original construction
scale 1:5

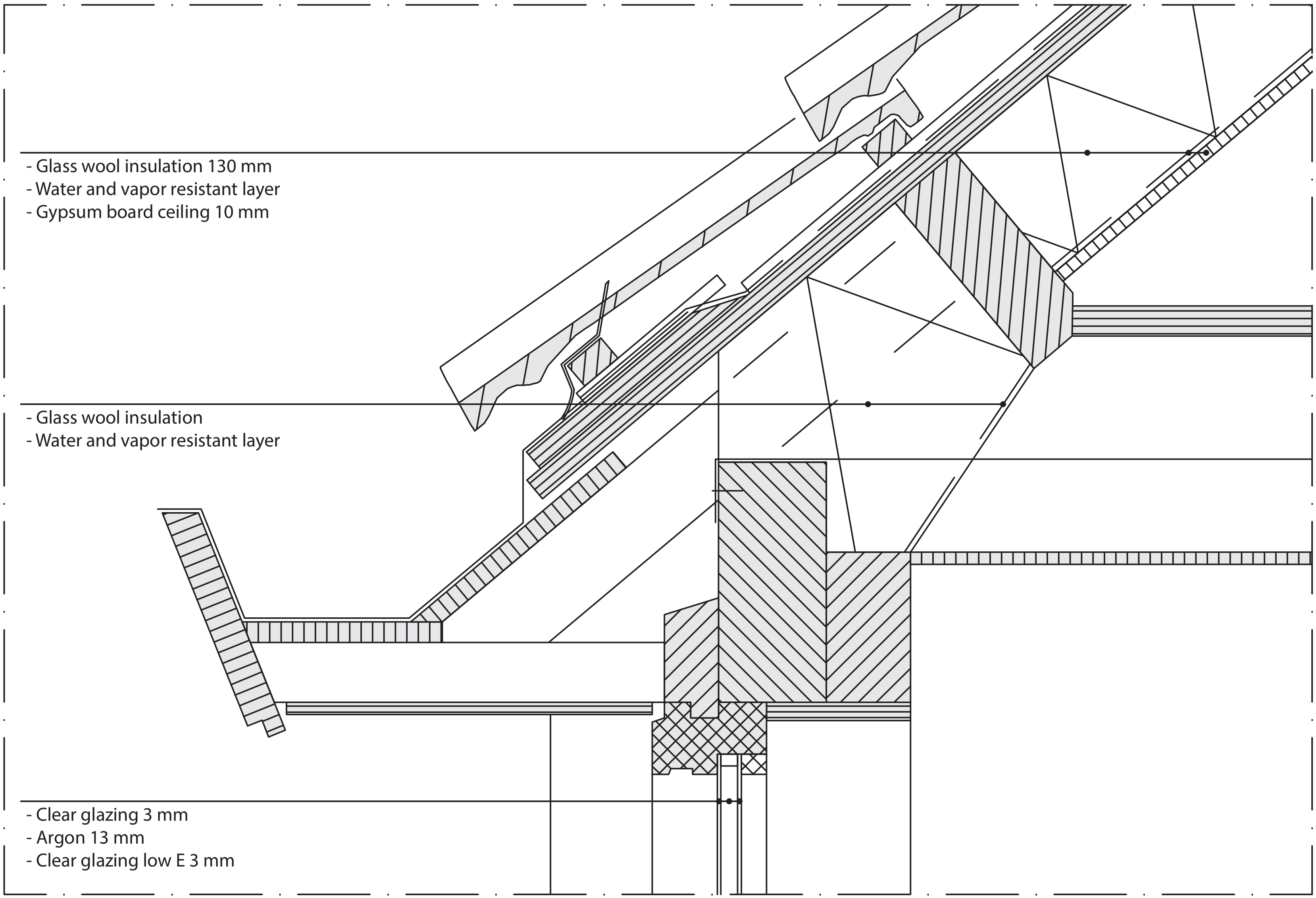


Figure 83: Detail 4 strategy A, in light gray the original construction
scale 1:5

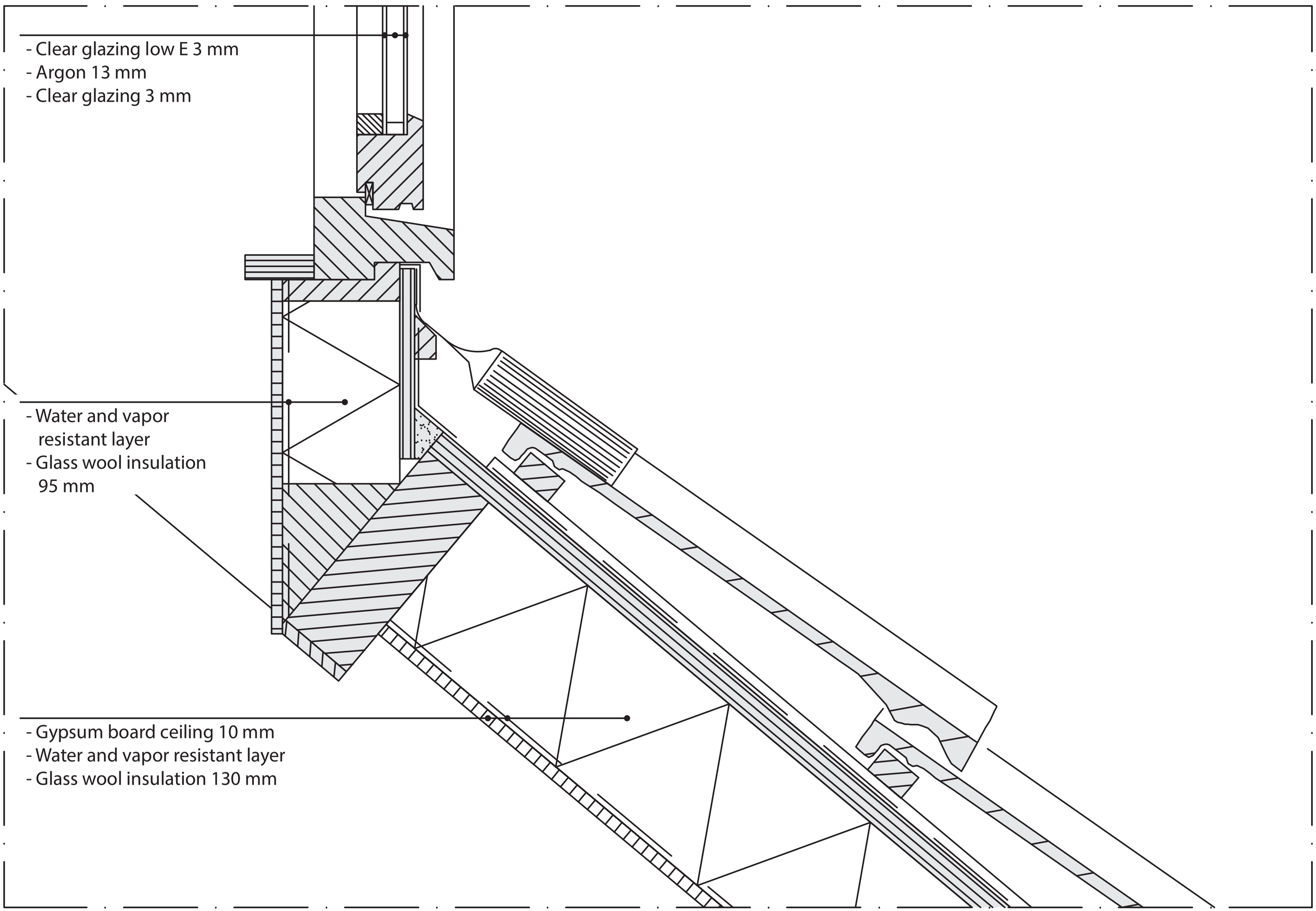


Figure 84: Detail 5 strategy A, in light gray the original construction
scale 1:5

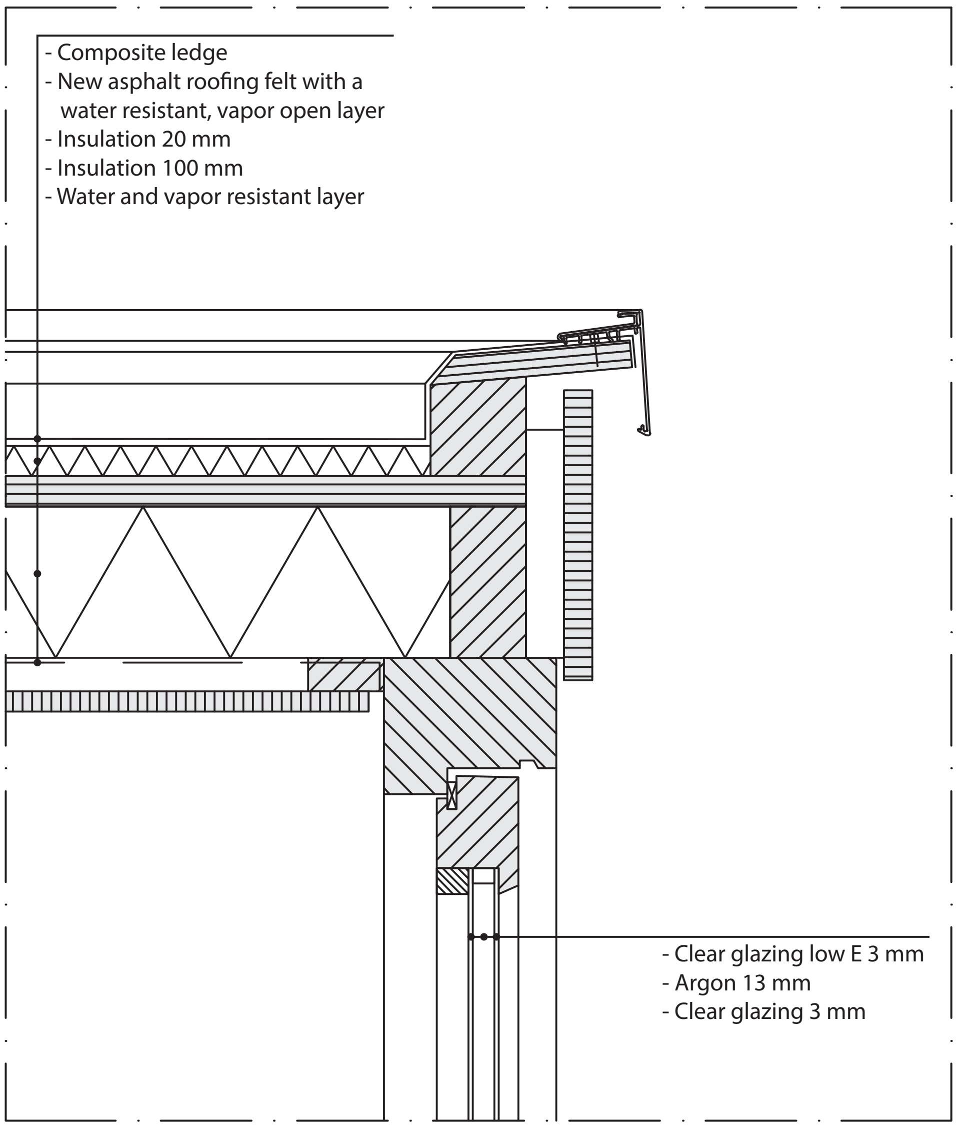


Figure 85: Detail 6 strategy A, in light gray the original construction
scale 1:5

Appendix 11: Drawings Haarlem: strategy B

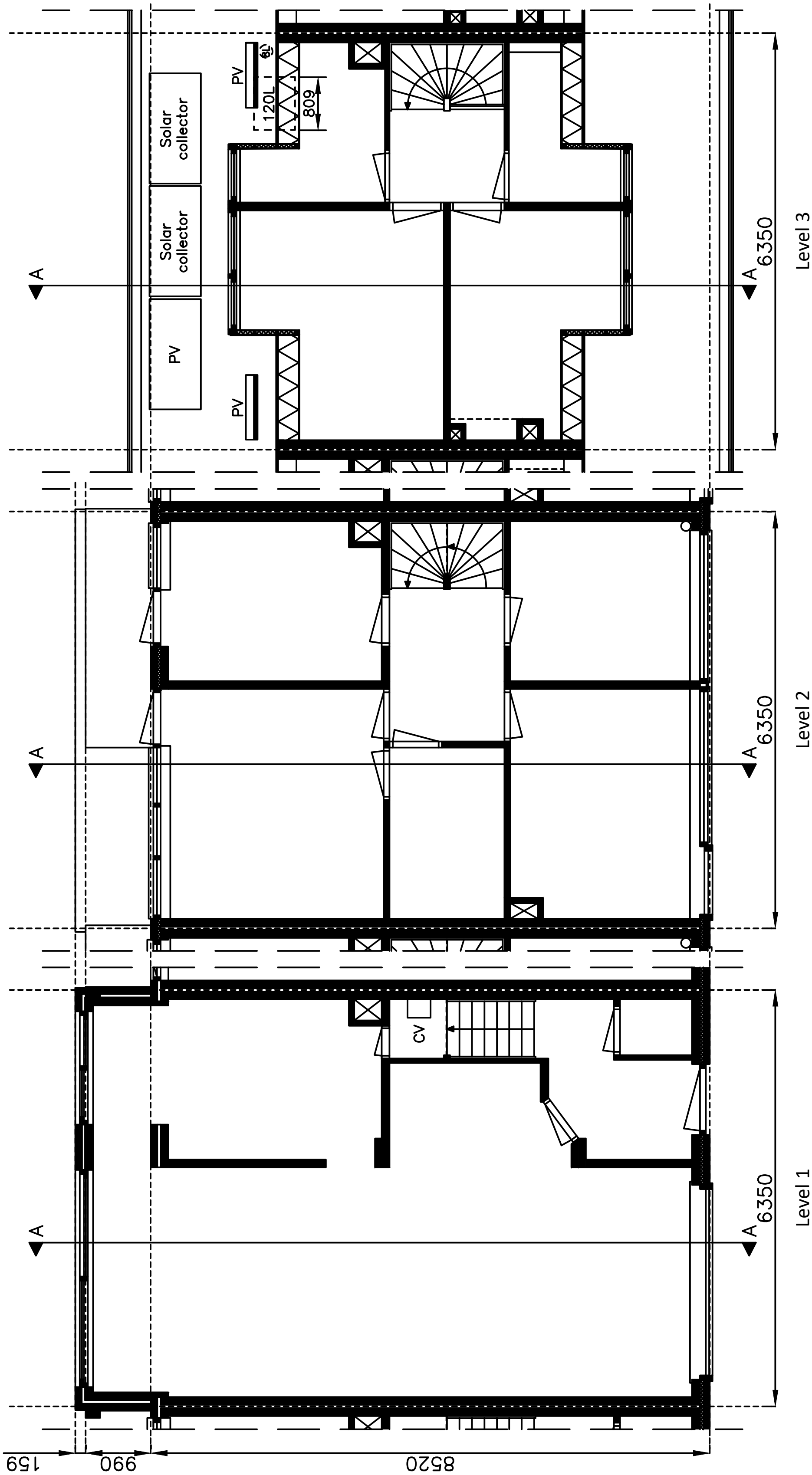


Figure 86: Floorplans strategy B
scale 1:100

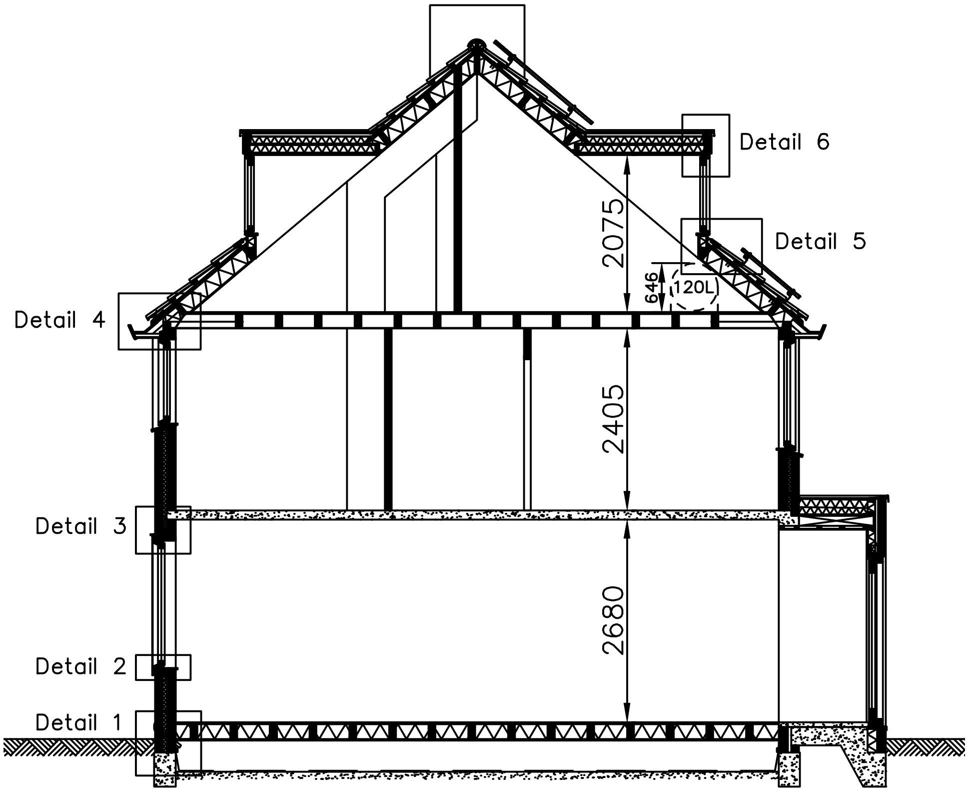


Figure 87: Section A-A strategy B scale 1:100

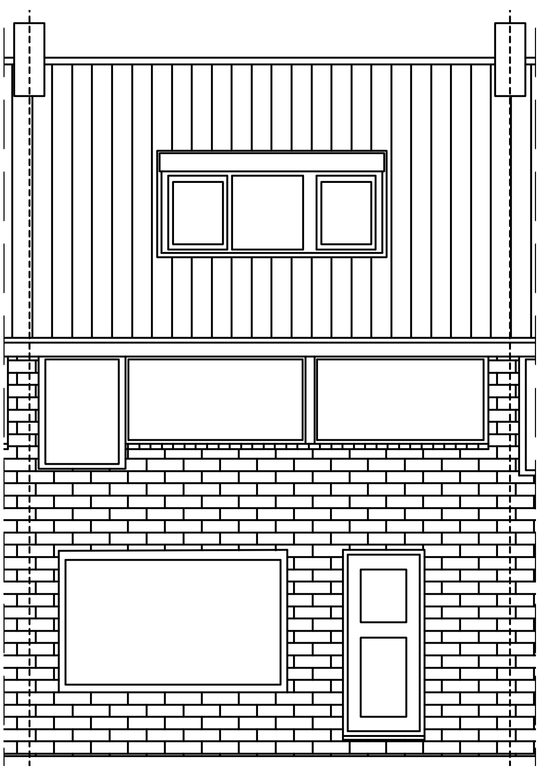


Figure 88: Front view strategy B scale 1:100

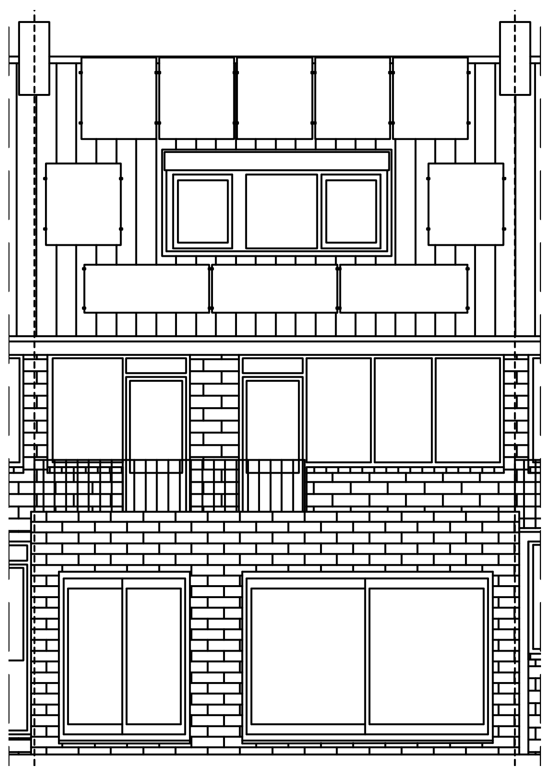


Figure 89: Back view strategy B scale 1:100

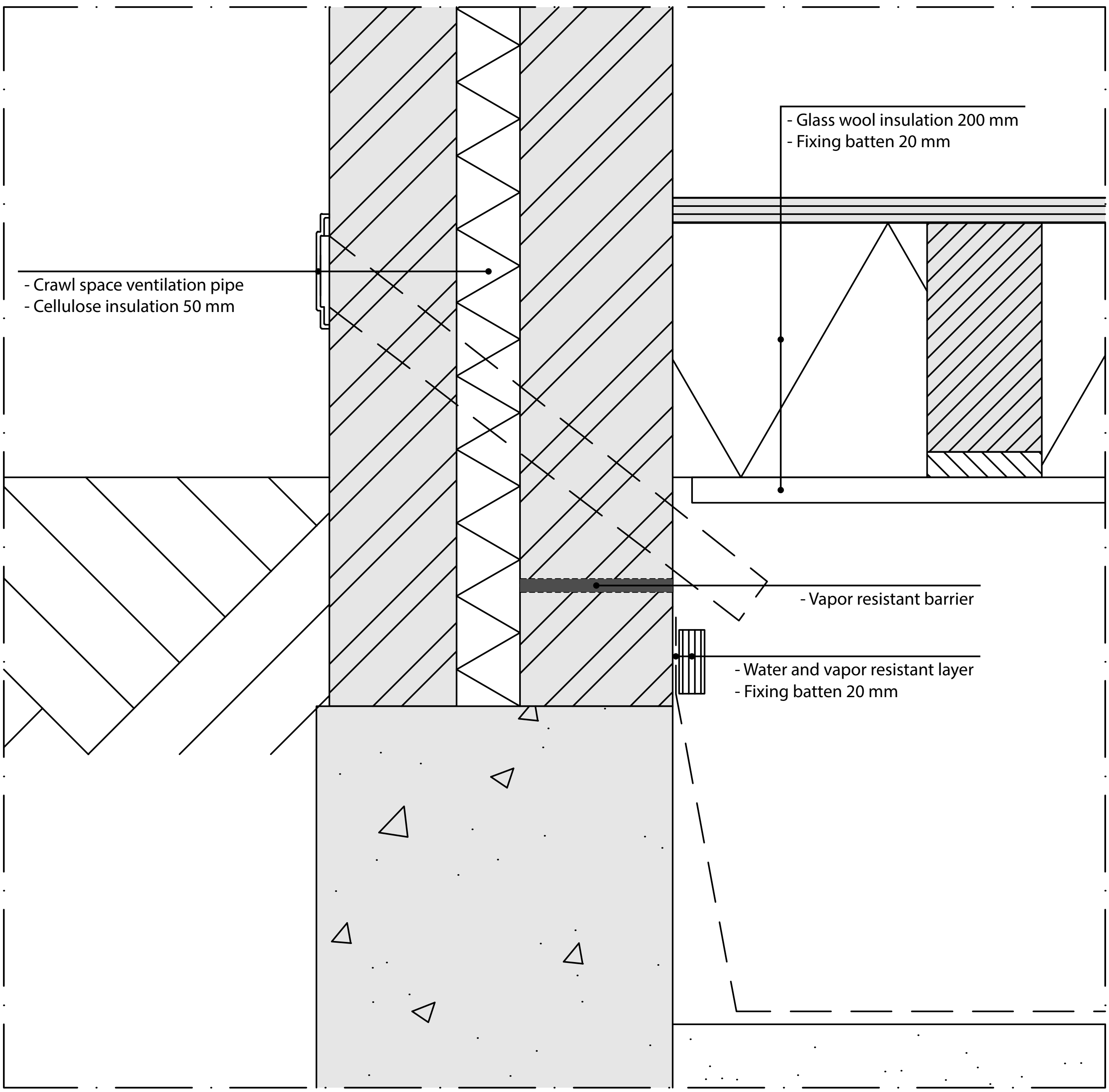
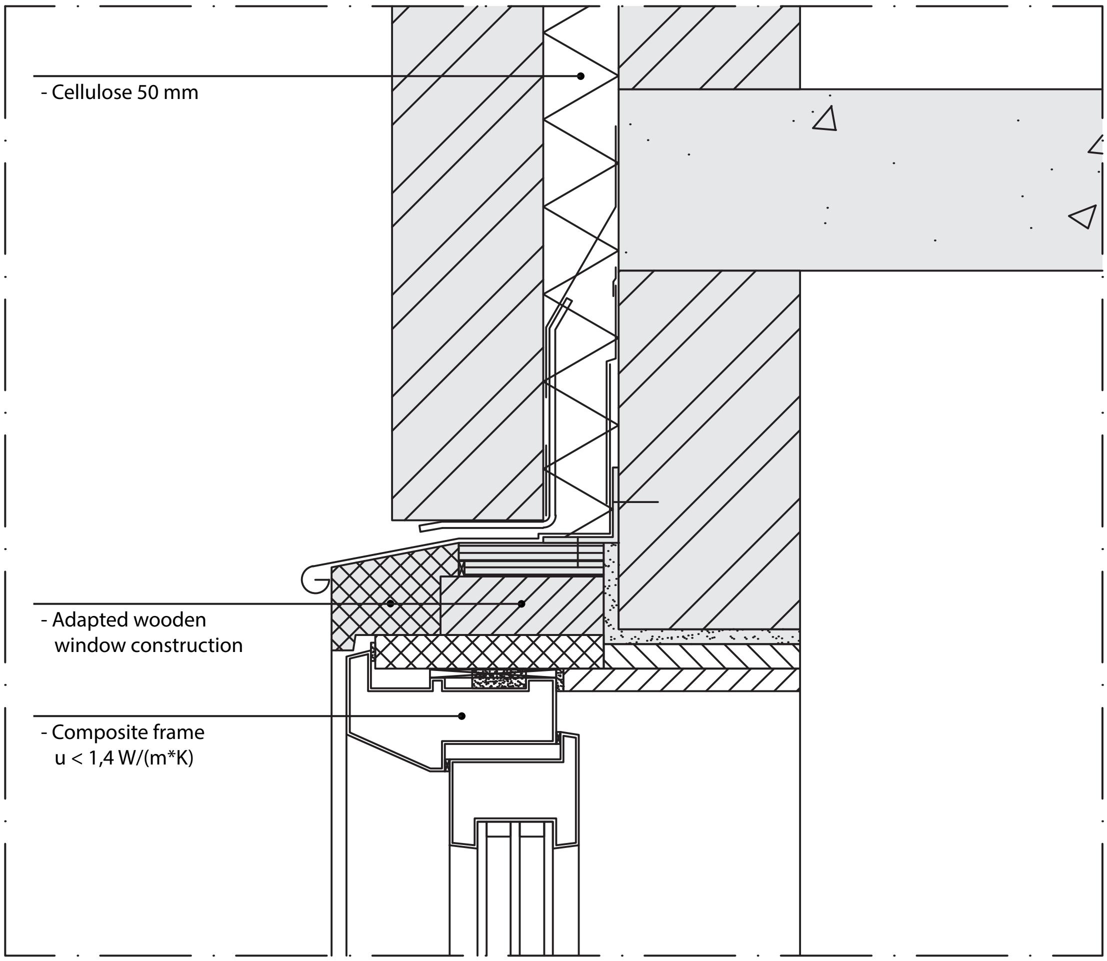


Figure 90: Detail 1 strategy A, in light gray the original construction
scale 1:5

Figure 91: Detail 2 strategy B, in light gray the original construction
scale 1:5



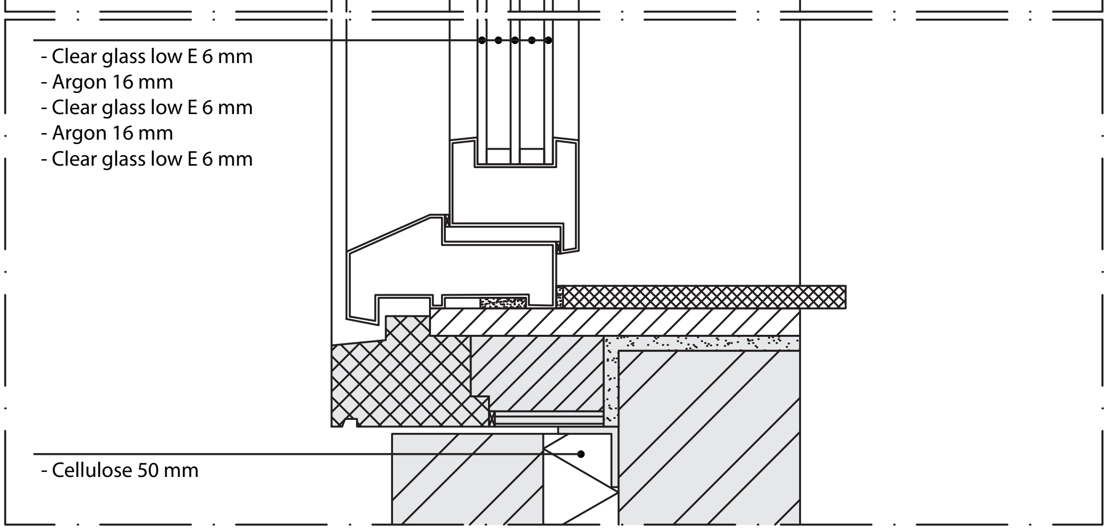


Figure 92: Detail 3 strategy B, in light gray the original construction
scale 1:5

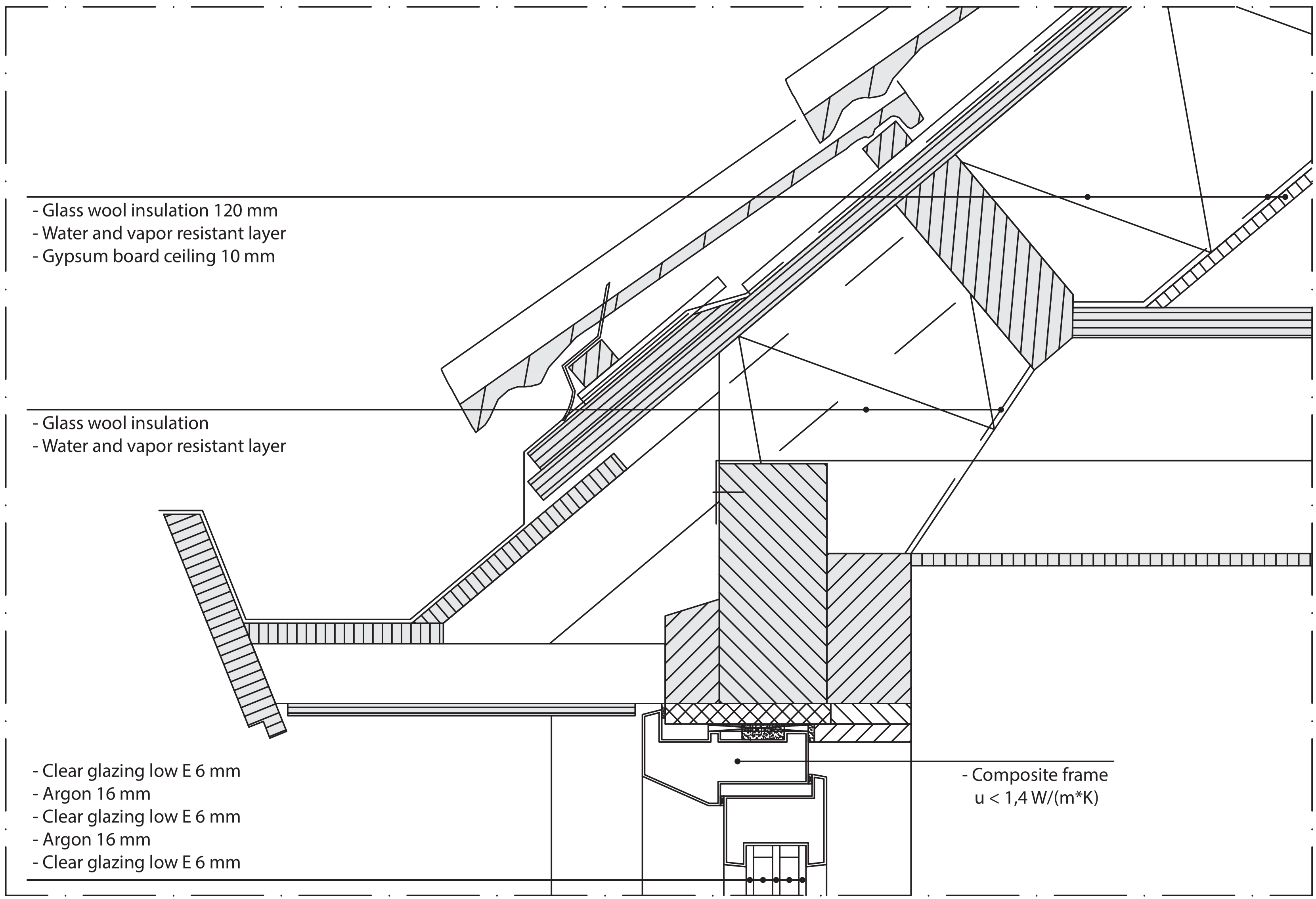


Figure 93: Detail 4 strategy B, in light gray the original construction
scale 1:5

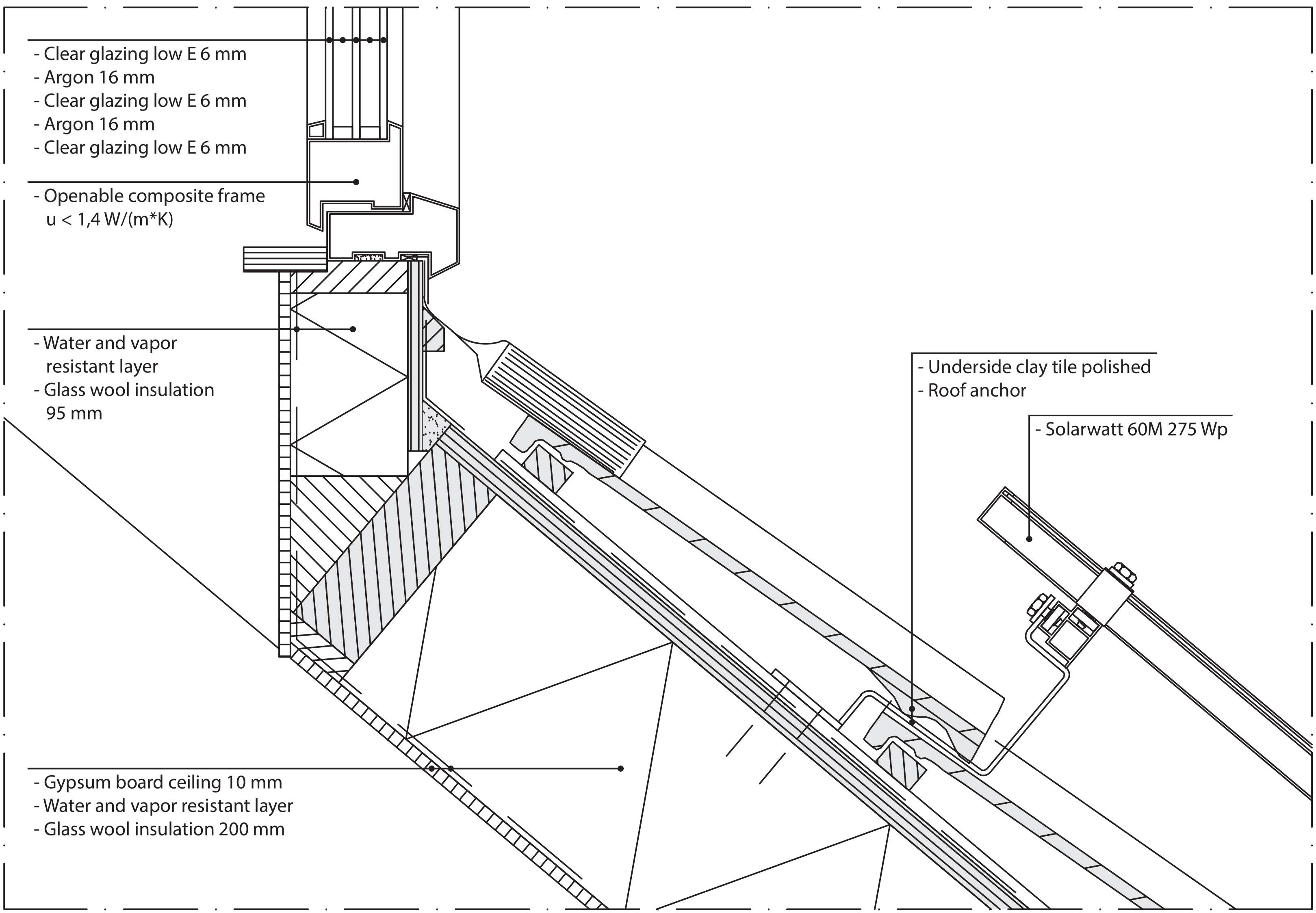


Figure 94: Detail 5 strategy B, in light gray the original construction
scale 1:5

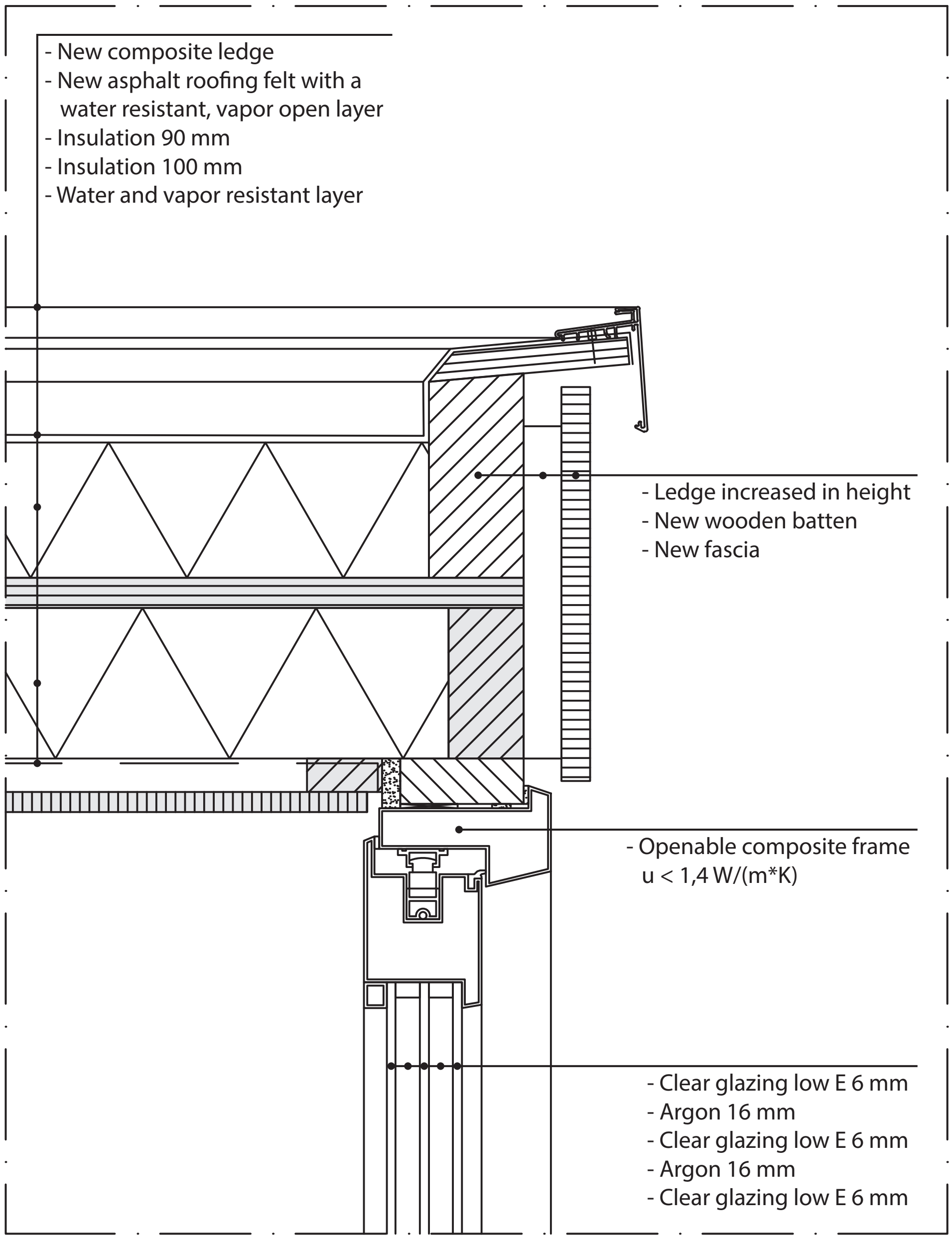


Figure 95: Detail 6 strategy B, in light gray the original construction
scale 1:5

Appendix 12: Drawings Haarlem: strategy C

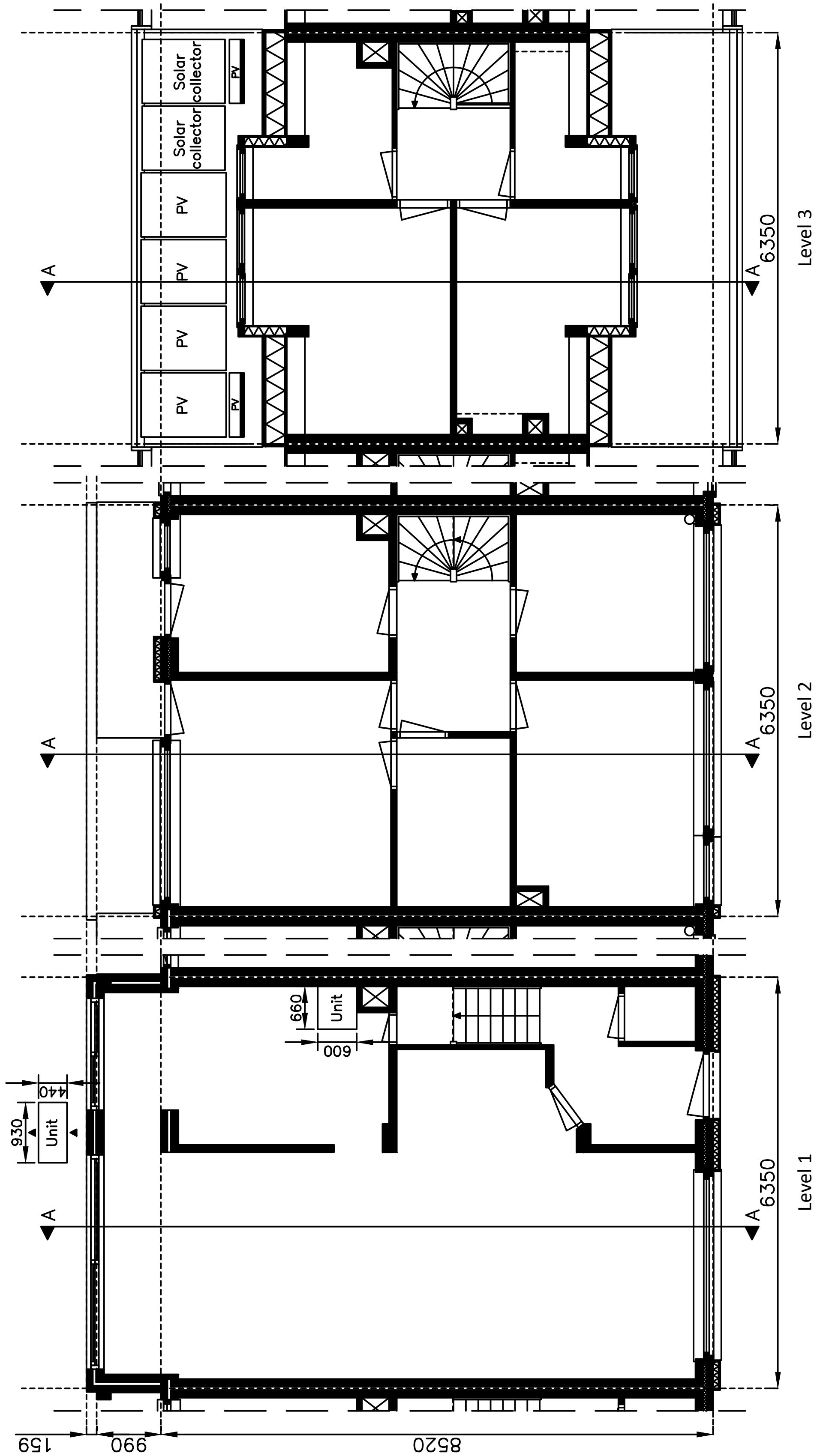


Figure 96: Floorplans strategy C
scale 1:100

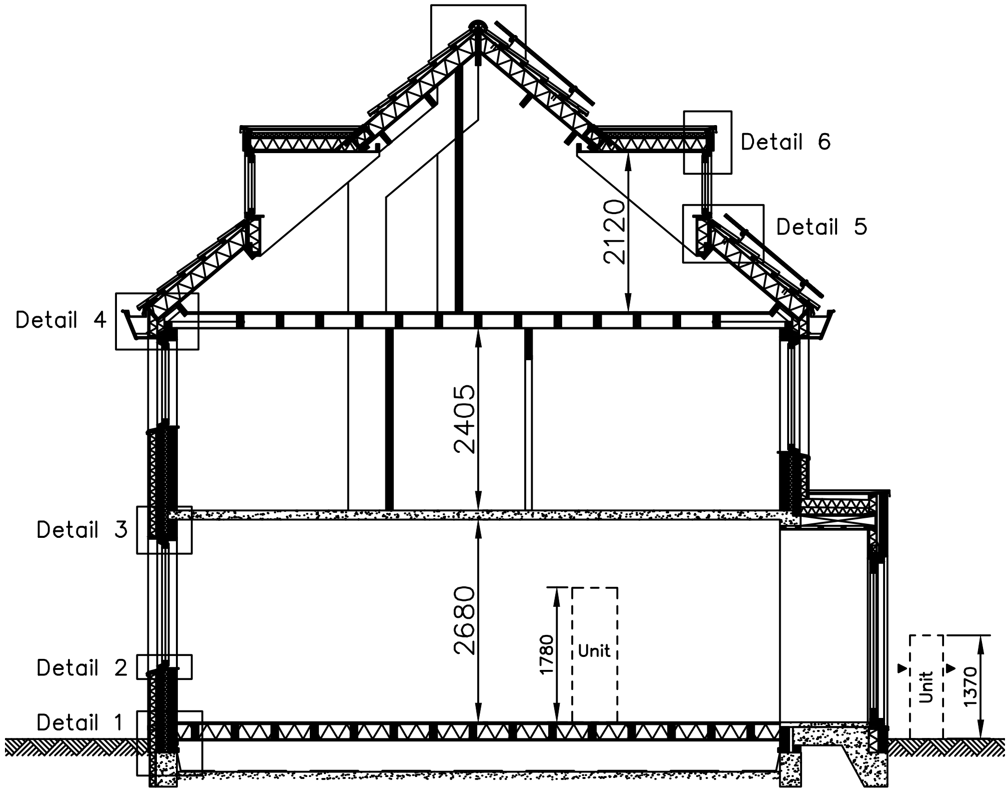


Figure 97: Section A-A strategy C scale 1:100

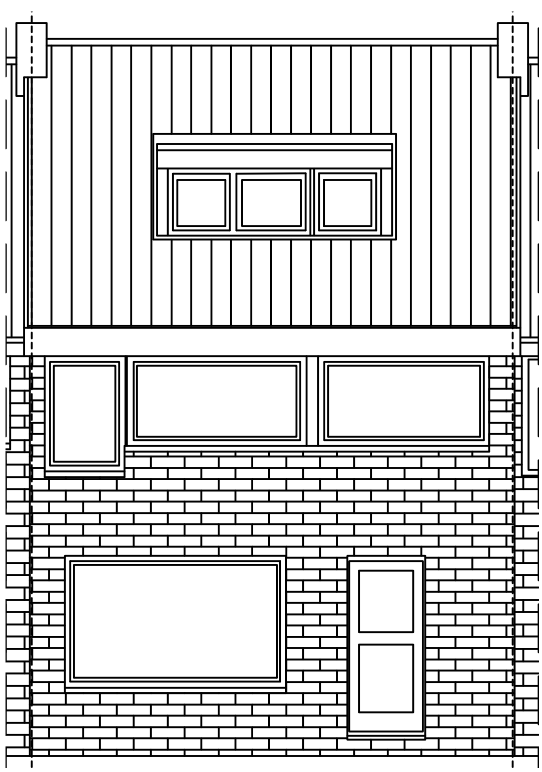


Figure 98: Front view strategy C scale 1:100

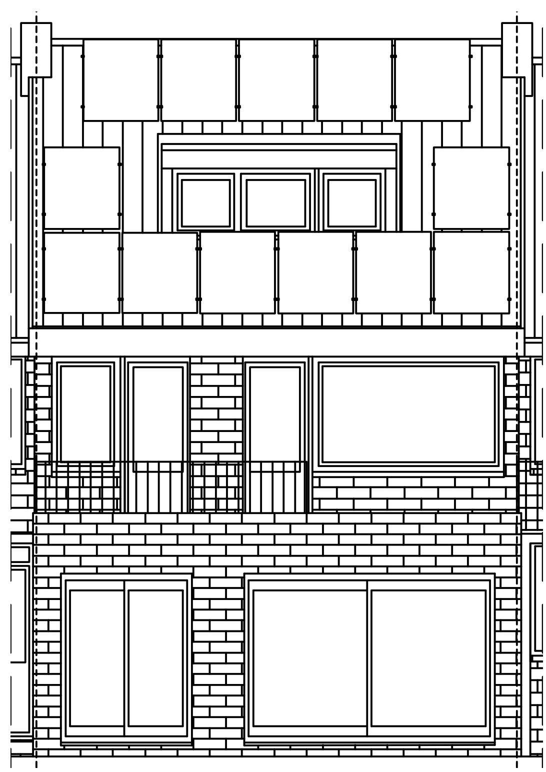


Figure 99: Back view strategy C scale 1:100

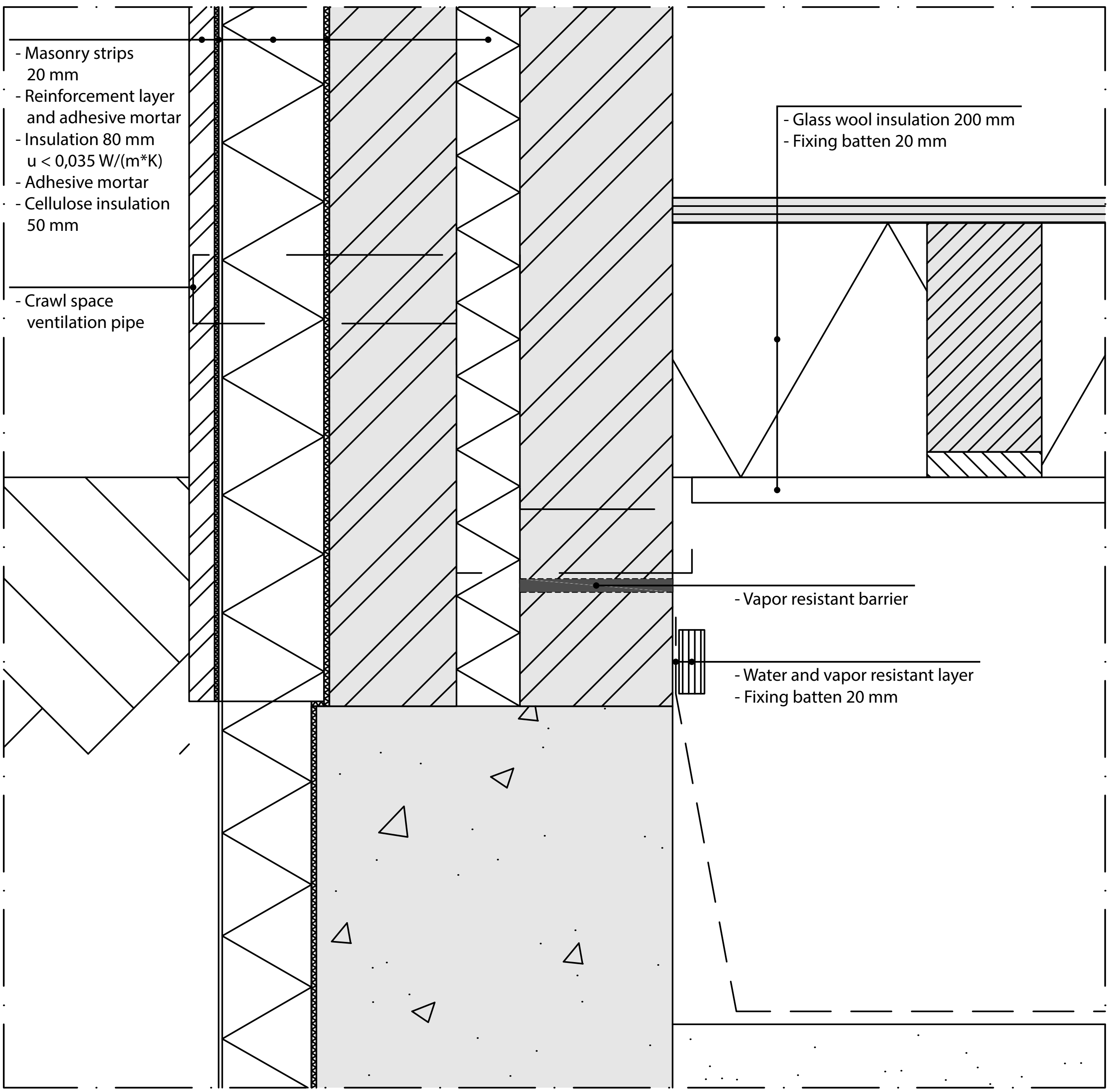
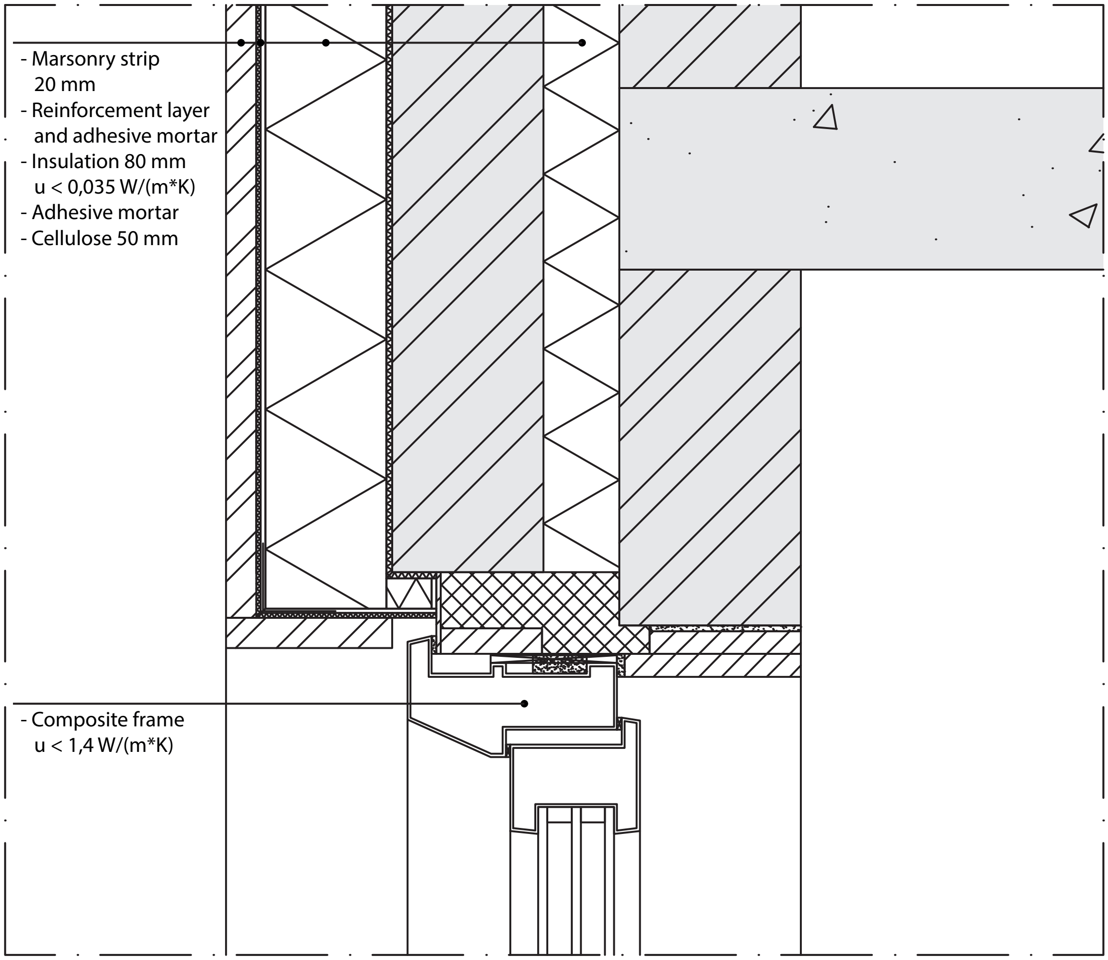


Figure 100: Detail 1 strategy A, in light gray the original construction
scale 1:5

Figure 101: Detail 3 strategy C, in light gray the original construction
scale 1:5



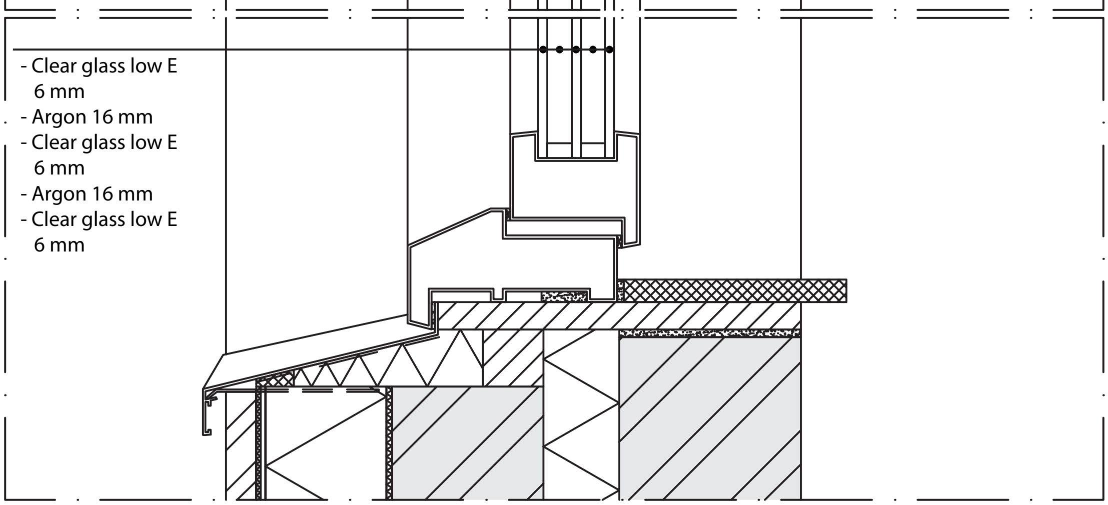


Figure 102: Detail 2 strategy C, in light gray the original construction
scale 1:5

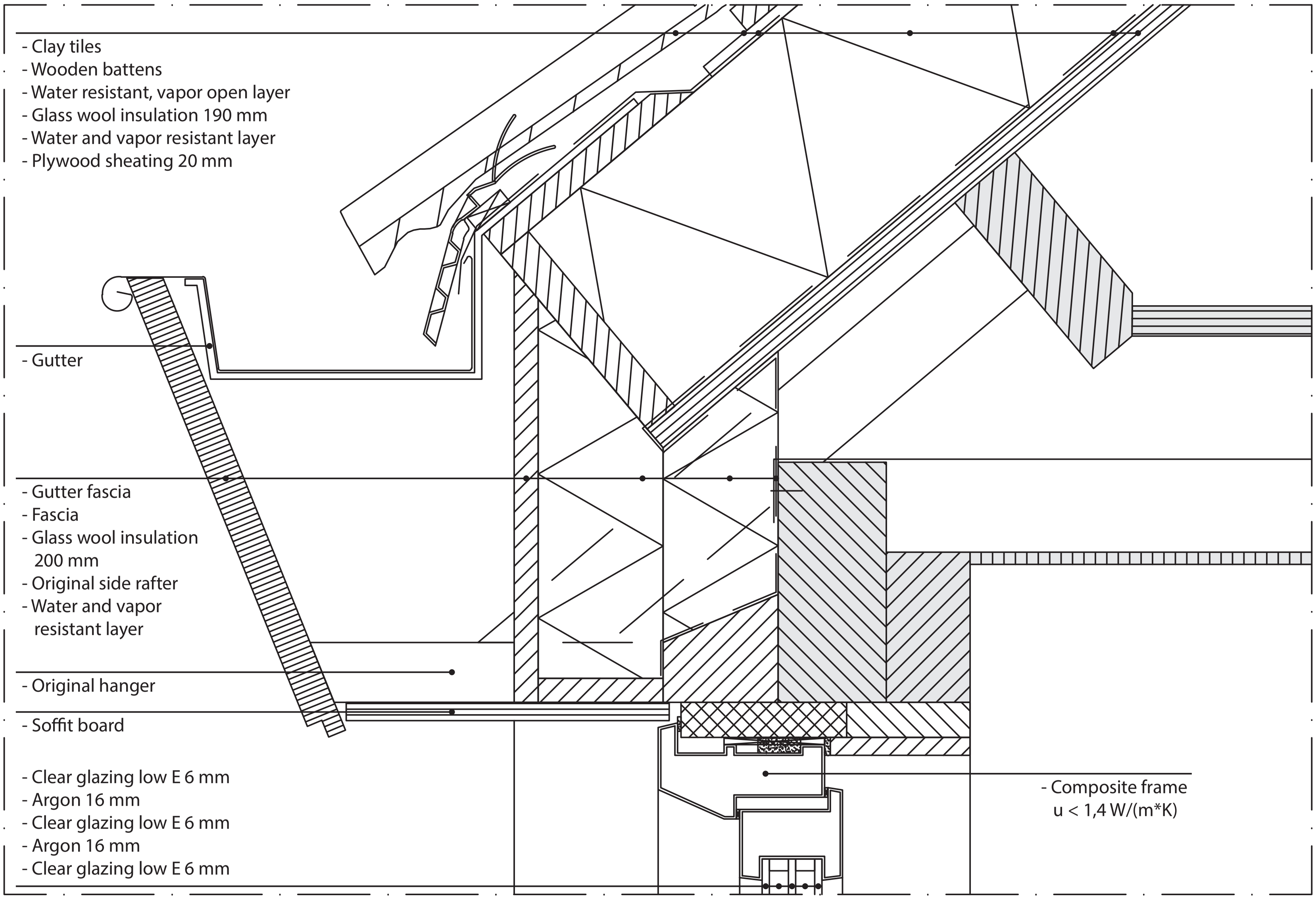


Figure 103: Detail 4 strategy C, in light gray the original construction
scale 1:5

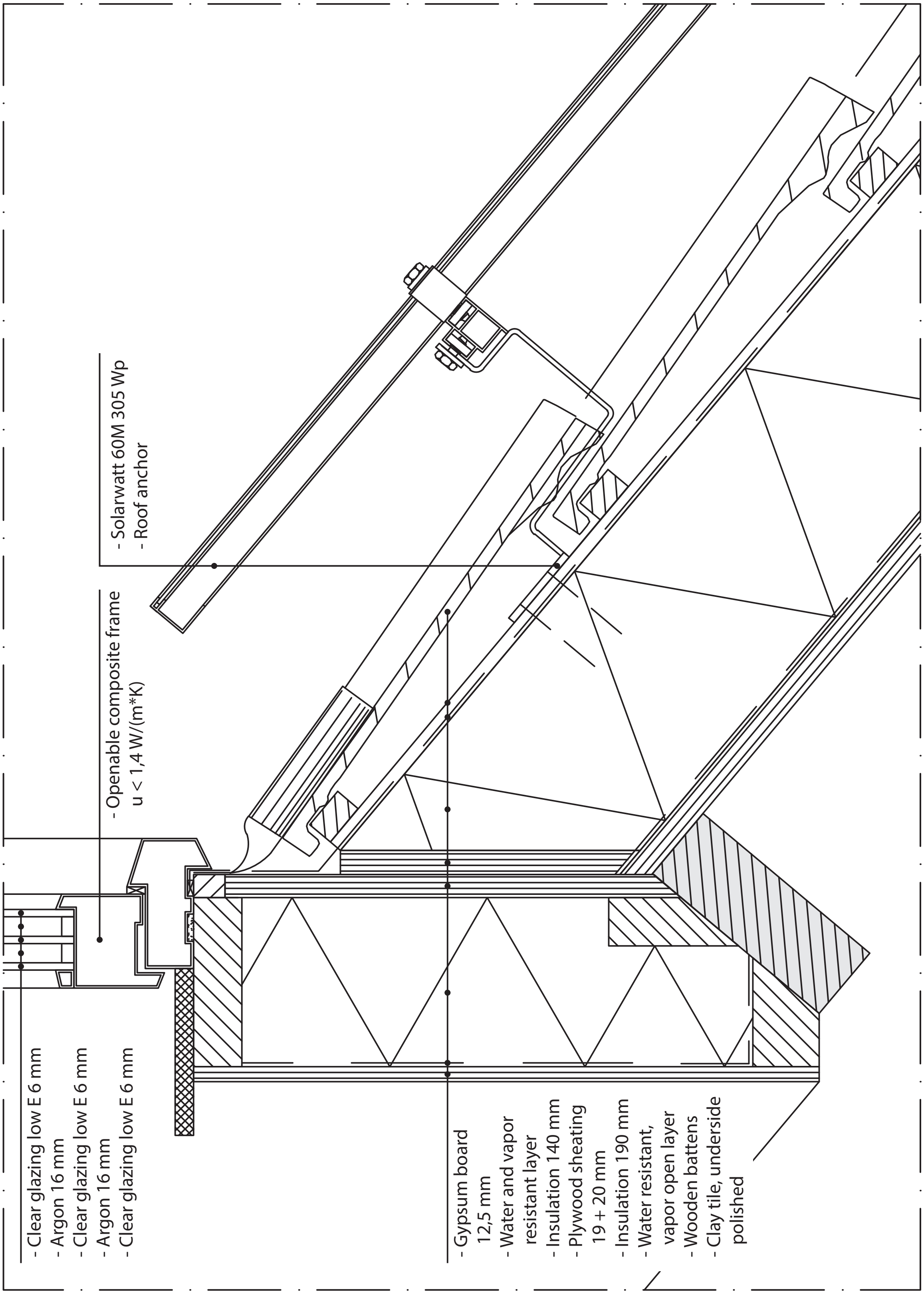


Figure 104: Detail 5 strategy C, in light gray the original construction
scale 1:5

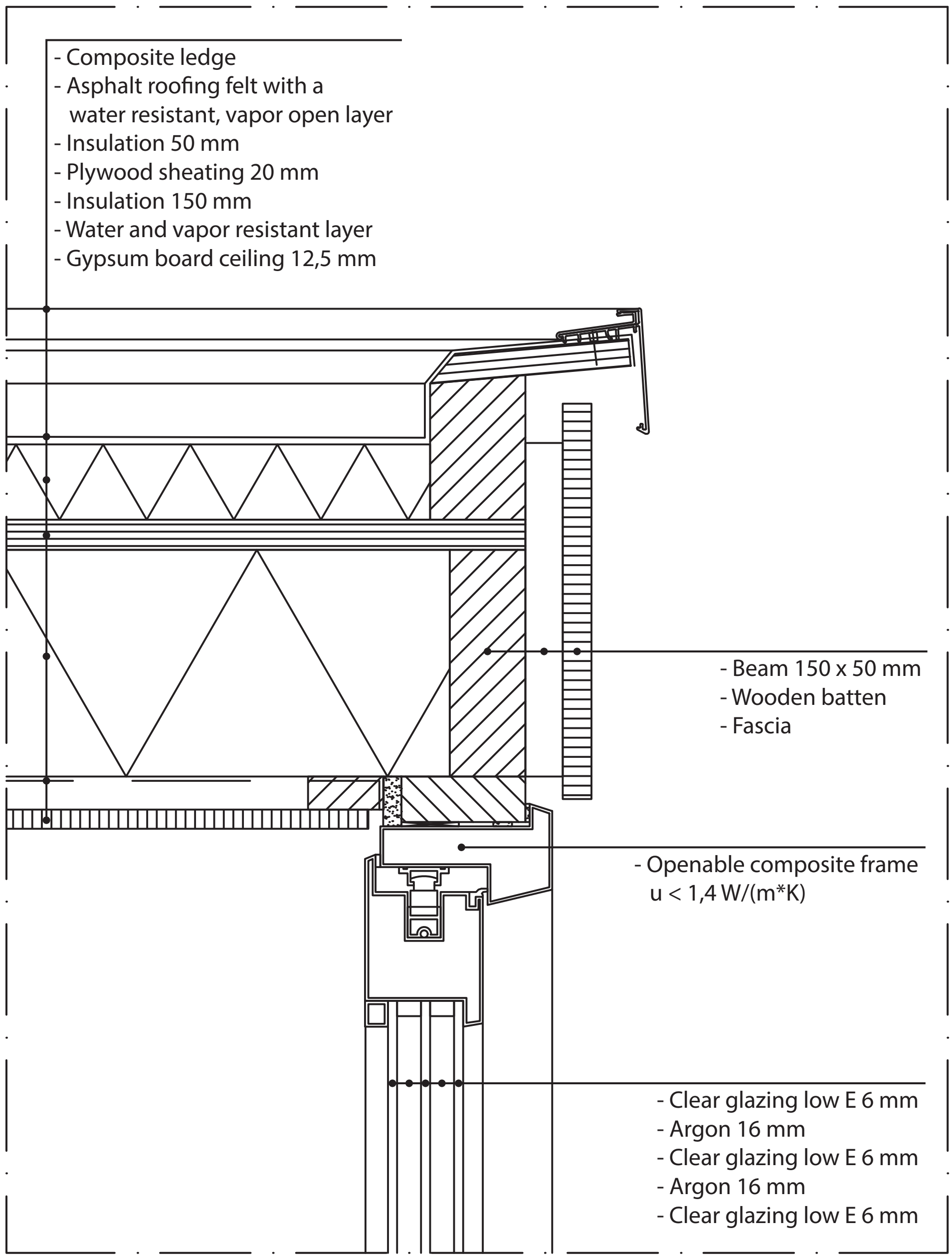


Figure 105: Detail 6 strategy C, in light gray the original construction
scale 1:5

Global warming and earthquakes are major threats for the Netherlands. Within this master thesis you will find three refurbishment strategies which reduce the energy consumption of post-war era houses and help make a better tomorrow.