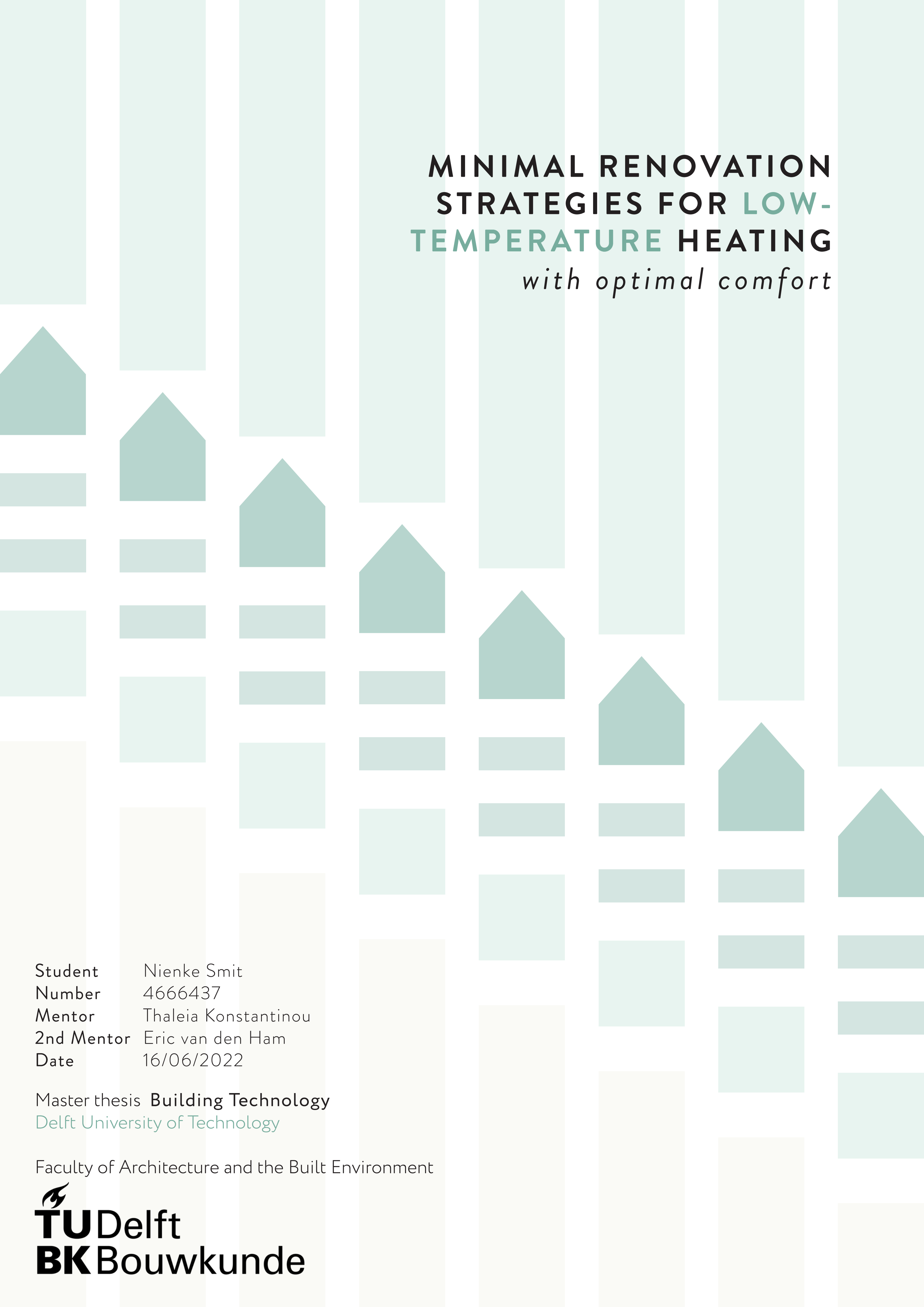

# MINIMAL RENOVATION STRATEGIES FOR LOW-TEMPERATURE HEATING

## *with optimal comfort*

| | |
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To prepare the housing stock for the transition to collective, low-temperature heating, minimal renovation strategies for the integration of low-temperature heating and optimal comfort are studied within this research for various single-family housing typologies. Renovation measures on the building and installation scale were considered for the different typologies, which vary in terms of the construction period and building type. The simulations are performed in the software DesignBuilder, on a case study dwelling located in the Netherlands. The low-temperature readiness is assessed based on heat balance and air temperature simulations. Computational Fluid Design within the software is used to determine the effect of the renovation measures on the draught rate and radiant temperature, as these aspects are critically affected by the lowering of the radiator's supply temperature. Additionally, the effect on radiant asymmetry is measured in the software program Stralingsverloop. The outcomes of the study regarding low-temperature readiness indicate the differences in effectiveness of the measures for the different typologies. The study on thermal comfort shows the posibilities for optimizing the thermal comfort through the integration of renovation measures, in particular through the installation of balance ventilation and high performance glazing. Based on the outcomes of both the studies, a individual recommendation is given for each typology.

# CONTENT

# CONTENT

1.1 Background

To limit global warming to an acceptable level of 1.5 degrees Celsius, countries have to reduce the usage of fossil fuels. In 2015, multiple countries, among which the Netherlands, signed the Paris Agreement to commit themselves to achieve this (United Nations, 2015). As a response to this, the Climate Agreement was introduced in the Netherlands, in which the Dutch government has set out measures and goals for different sectors to accomplish this reduction (Rijksoverheid, 2019). The goal for the built environment, which is responsible for 34% of the total energy use in the Netherlands (CBS & ECN, 2017), is to be almost CO2 neutral by 2050. To achieve CO$_2$ neutrality in the building sector, special consideration should be given to the energy demand of heating, as the average household in the Netherlands spends 62% of the total energy usage on space heating (Milieu Centraal, 2020).

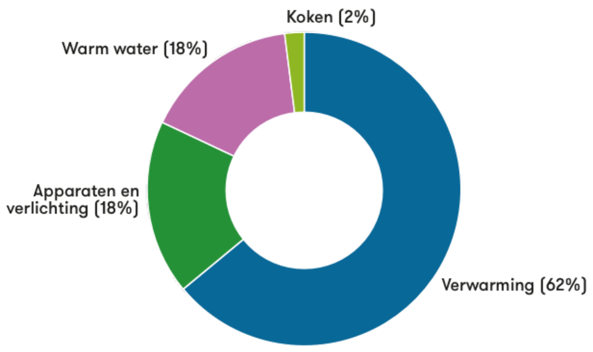


Figure 1.1: Share of applications in the energy consumption of an average household in the Netherlands in 2019 (Milieu Centraal, 2020)

Momentarily, 78% of the total heating requirement is covered by natural gas (CBS & ECN, 2017). However, the natural gas extraction in the province of Groningen will be stopped in 2022, as it has led to earthquakes in the region, as stated by Wiebes (2019). The reduction of natural gas extraction in the Netherlands, together with the climate ambitions stated in the Climate Agreement, have as a consequence that the housing stock of the Netherlands has to be disconnected from the gas grid. The goal for 2030 is to have 1.5 million houses disconnected from the gas grid (Rijksoverheid, 2019). For these residences, other sustainable solutions for space heating have to be implemented.

Ecofys and Greenvis (2016) suggest the following three options for space heating: All-electric, collective heating and sustainable gas. From these three options, collective heating is the most feasible one for the existing building stock. The all-electric option is only achievable in very well insulated houses, with an energy label higher than label A and with a low heating demand. It is therefore not a suitable alternative for a large segment of the existing housing stock as they could simply not be renovated to this level. Furthermore, the availability of sustainable gas in the future is still unsure, and it cannot be anticipated if this could be a viable solution for the existing stock. The availability of sustainable gas at this moment is minimal and it is expected that if the availability remains limited, it will only be utilized for high-value applications that have limited or no alternatives. Collective heating, on the contrary, could be a promising option. for the existing housing stock.

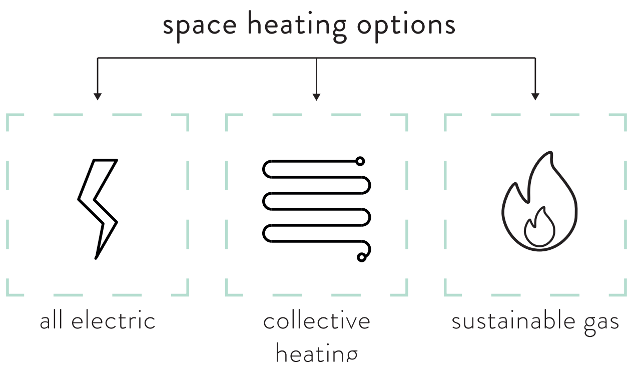


Figure 1.2: Alternative options for space heating (own image)

Momentarily, most collective heating grids in the Netherlands supply heat from high-temperature sources, with a temperature of around 90 degrees Celsius (CE Delft, 2019). It is expected that in the future, there will be a reduction in the availability of high-temperature heat due to several developments (Ecofys and Greenvis, 2016). First of all, conventional heat sources that supply high-temperature heat, such as coal- and gas-fired powerplants, will be phased out in the future as a result of the CO$_2$ emission targets. Secondly, the increasing efficiency of industrial processes will result in a decrease in waste heat, together with a decrease in the temperature of this heat. Last of all, due to the increased efficiency in waste processing and recycling, there is a reduction in waste streams available for waste incineration plants.
Next to this, sustainable heat sources, for example shallow geothermal heat and solar thermal energy, will supply heat at a lower temperature. Due to these developments, the attention is shifting to low-temperature heat in collective heating systems, and the next generation of district heating will be supplying low-temperature heat, of around 50 degrees Celsius (Interreg North-West Europe, 2018).

However, a large part of the existing Dutch housing stock is not ready for the transition to low-temperature heating. Most residences have been built in the first decades after the Second World War (CBS, 2021). Over the years the energy standards have been adapted in order to reduce energy costs, as can be seen in figure 1.3. The thermal performance of houses built before the introduction of the Bouwbesluit in 1992 is considered inadequate today. A switch to low-temperature heat without any intervention would mean that these houses cannot be heated to a comfortable temperature anymore, because the heating capacity of the heating system is lower when a lower supply temperature is used (Gustaffson, 2015). Therefore, these houses need to be renovated in order to prepare for the integration of low-temperature heating. Taking these renovation measures is the responsibility of homeowners, but the renovation rates are currently too low, due to several barriers and lack of motivation (TNO, 2019).

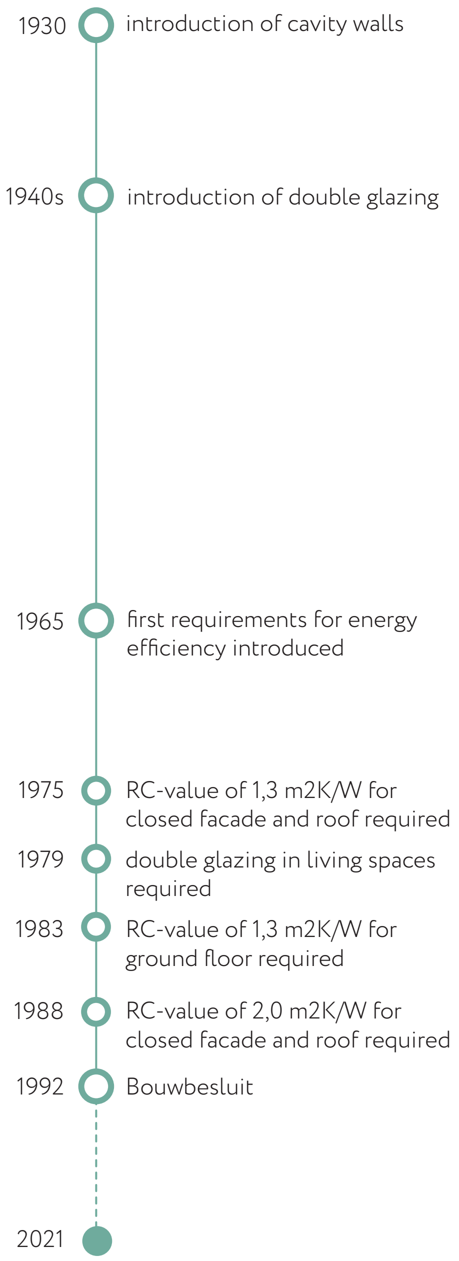


Figure 1.3: Timeline of the development of energy standards in the Netherlands, based on Agentschap NL (2011) and Regionaal Energieloket (n.d.)

### 1.2 Problem Statement

The foregoing background research has led to the following general problem statement, that will be tackled in this thesis.

*The renovation rates of preparing housing for the integration of low-temperature heating are too low, which restricts the progress of the energy transition.*

Multiple studies have focused on providing a solution for this problem. Each of these studies tackles a specific barrier for renovation, and investigate how this barrier can be lifted or how the motivation of homeowners can be increased regarding the specific topic. Three different fields of barriers are identified by Bjørneboe et al. (2018): Information, process and finance.
The research in the field of information barriers aims particularly at providing decision support for homeowners (Cetiner & Edis, 2014, Konstantinou & Knaack, 2011, Serrano-Jiménez et al., 2021) in order to tackle the knowledge barrier of homeowners. They provide frameworks that outline the effects of renovation concepts on certain factors, so a considered decision can be made. Factors that are analysed and compared, for example, are the environmental impact, economical aspects, social impacts et cetera.
Solutions for barriers related to the process tend to focus on shortening the process or minimalising the obstruction created by the renovation. For example in Zimmerman (2012), a prefabricated system is proposed for low energy renovation of buildings. Both the solutions for information and process barriers are valuable contributions, but these fields are not considered to be the main obstacle for homeowners (CBS, 2021, Milieudefensie, 2021, SCP, 2021).
In the category of finance, research tends to concentrate on methods of lowering the costs of renovation (barrier) or demonstrating the financial benefits (motivation). Research has been done, for example, on optimizing life cycle costs (Mejjaouli & Alzahrani, 2020), on the cost-effectiveness of renovation (Dodoo et al., 2017) or on outlining the role transaction costs play in the decision-making process (Ebrahimigharehbaghi et al., 2020). In multiple studies among Dutch homeowners (CBS, 2021, Milieudefensie, 2021, SCP, 2021), it emerges that indeed the costs are considered as one of the main barriers for homeowners to perform measures. However, research by the NIBUD (2020), the National Institute for Budget Information, shows that the vast majority of homeowners, 95%, have financial possibilities, either through a mortgage, consumptive credit or own savings/capital, to invest an amount of €20.000 in renovating their home. This indicates that the financial barrier is often psychological rather than substantial. Furthermore, it is demonstrated by Bjørneboe et al. (2018) that energy renovation often is presented as an economic investment that has a short payback time. In spite of the fact that this presentation is deceptive, this statement also shows that the general advertisement of energy renovation aims at financial gain. However, the value financial benefit holds for homeowners is often exaggerated, and solely financial profit is not a big enough motivation for most of them and thus does not lead to a significant increase in renovation rates. (Bjørneboe et al., 2018).
Additionally, Bjørneboe et al. demonstrate that an improvement of the thermal comfort and indoor climate is one of the top motivators of homeowners to perform renovation measures. An improvement of thermal comfort is seen as a personal gain and affects people in their daily lives. Switching the selling point of energy renovation to comfort enhancement instead of seeing it as an additional benefit could therefore be promising. This perspective of thermal comfort as a bonus is reflected in research as well. For example, in research where thermal comfort is mentioned (Kauko et al., 2014, Mejjaouli & Alzahrani, 2020, Wang et al., 2015), it is either used as a constraint or additional measuring value in optimisations. However, research is lacking on the use of energy renovation to optimise thermal comfort.

These findings have led to the following specific problem statement:

*Switching the selling point of energy renovation to the improvement of thermal comfort could potentially increase renovation rates, but research on optimising thermal comfort in this field is lacking.*

### 1.3 Research Objective

The following research objective is proposed to provide a solution for this problem:

*To investigate and develop renovation strategies for the integration of low-temperature heating for different single-family housing typologies, in which the thermal comfort is optimized.*

Due to the large differences in building characteristics between the different Dutch residential housing typologies, it is expected that the outcomes vary substantially for every typology. Therefore, the various typologies are considered separately.
In this research, the focus is on single-family housing, as these types of dwellings represent the vast majority of the housing stock and tend to have a higher energy usage due to their characteristics, which will be further elaborated in chapter 6.

Different phases are followed in order to achieve the research objective.

Phase 1 focuses on the exploration of the different topics within the research. The state of the art of collective heating in the Netherlands is studied, together with the developments regarding low-temperature heating in this field. Furthermore, the minimal requirements for the integration of low-temperature heating will be investigated. An inventory of applicable renovation measures will be created, in which the measures are split into three sections. An elaborate study will be performed on the different aspects of thermal comfort and how these aspects can be optimized. Additionally, the single-family housing typologies will be investigated and sensitive parameters for renovation will be identified.

In Phase 2 the renovation strategies are drafted based on cost-effectiveness of the measures. A case study is selected and investigated on which the renovation concepts are tested in terms of thermal comfort and heating requirements.

Phase 3 focuses on testing the renovation strategies on the case study with the use of the simulation software DesignBuilder. Within this program, a static heat balance for a winter design week is generated to determine the heat losses and gains. Air temperature simulations are performed as well to further test the strategies. Computational Fluid Design (CFD) is used to determine the effects of different strategies on thermal comfort aspects. The alterations of the different typologies are tested in the same manner.

Phase 4 focuses on the processing of the results. The results are ordered correctly and the first basis is laid out for the interpreting of the results.

Phase 5 is the concluding phase, in which the focus lies on interpreting the results and establishing recommendations based on the outcomes of the previous four phases. A framework is created which gives a helpful insight into the best suitable renovation strategies for different typologies.

Each phase will have a final product as a result, as depicted in the table in figure 1.4 below.

| Phase | Final product |
|---|---|
| Phase 1 | - Low-temperature ready requirements<br>- Descriptive inventory of renovation measures<br>- Thermal comfort benchmarks<br>- Descriptive analysis of typologies |
| Phase 2 | - Overview of preliminary renovation strategies<br>- Report on case study house |
| Phase 3 | - Test outcomes |
| Phase 4 | - Textual and visual representation of the test outcomes |
| Phase 5 | - Conclusion and recommendations<br>- Framework |

Figure 1.4: Table of final products of the different phases

The following boundary conditions take effect in this research:

- As previously mentioned, this research focuses solely on the Dutch single-family housing stock, see section 6.2.
- It is assumed that the houses will be connected to a collective heating grid and that the space heating demand is covered by this connection completely.
- For this research, it is presumed that the existing heat delivery system, the radiators, will not be replaced.
- In this research, the supply temperature used for low-temperature heating will be set at 55 °C, and the return temperatuer at 35 °C, as explained in section 3.2.
- The renovation measures considered in this research are only the measures applicable on the building and installation scale, for further explaination see section 4.1.
- The optimising of the thermal comfort will focus on minimising local discomfort due to draught and radiant asymmetry, as described in section 5.6.
- In this research, only the winter situation is considered, because this period is critically affected by a decrease in heating capacity.
- Minimal is regarded in the sense of cost-effectiveness, which is elaborated in chapter 8.

### 1.4 Research Question

From the research objective the following research question was derived:

*Which minimal renovation strategies are needed to prepare different single-family housing typologies for the integration of low-temperature heating and optimize the thermal comfort of the residence?*

To answer the research question, the following sub-questions will be answered:

*1. Which renovation measures can be applied to prepare a building for low-temperature heating?*

*2. Which sensitive parameters for renovation can be recognized in the single-family housing stock?*

*3. How can the thermal comfort of a house be optimized through the implementation of renovation measures?*

### 1.5 Approach and Methodology

The following chapters will be covered in this thesis:

1. Research Framework
This chapter will discuss the background, problem statement, objectives, research questions, methodology and relevance of the research.

2. Collective Heating & Low-Temperature
In this chapter, the developments of district heating and the characteristics of low-temperature heating will be discussed.

3. Low-Temperature Ready
In this chapter, the minimum criteria for the integration of low-temperature heating will be established and the term low-temperature ready will be defined. Changes regarding the existing heating system will be investigated.

4. Renovation Measures
This chapter will go into the different renovation measures, categorized into the following 3 sections: opaque envelope, window systems and supply systems.

5. Thermal Comfort
An eloborate study is performed on the general concept of thermal comfort. Local thermal discomfort will be discussed, and the specific research focus on thermal comfort will be explained.

6. Housing Typologies and Sensitive Parameters
In this chapter, the different housing typologies will be discussed, and the sensitive parameters for renovation linked to these typologies will be analysed.

7. Case Study Selection
This chapter will give a detailed descriptive and visual presentation of the selected case study and will explain on what basis this case study was selected.

8. Renovation Strategies
In this chapter, the method of composing the renovation strategies will be explained.

9. Simulations
This chapter will describe the methodology that is used for the simulations. Information on the used software is provided and the inputs, calibration, outputs and use of CFD are clarified.

10. Results
This chapter will present the results of the simulations, categorized by the type of analysis. In the end, a recommendation for each typology is given.

11. Conclusion
In chapter 12 the conclusions of the research will be presented.

12. Discussion
In this chapter, the shortcomings of the research and potential follow-up topics will be discussed.

On the following page, a flowchart of the methodology is displayed. Three key research methods can be identified within the methodology:

Literature review
At the start of the thesis, a literature review was performed to gain knowledge of the topic, identify what has been researched already, and find where the research gaps lie within this topic. The following sub-topics were explored: Renovation drives and barriers, collective heating and low-temperature heating, low-temperature ready requirements, applicable renovation measures, thermal comfort aspects, Dutch housing typologies and sensitive parameters

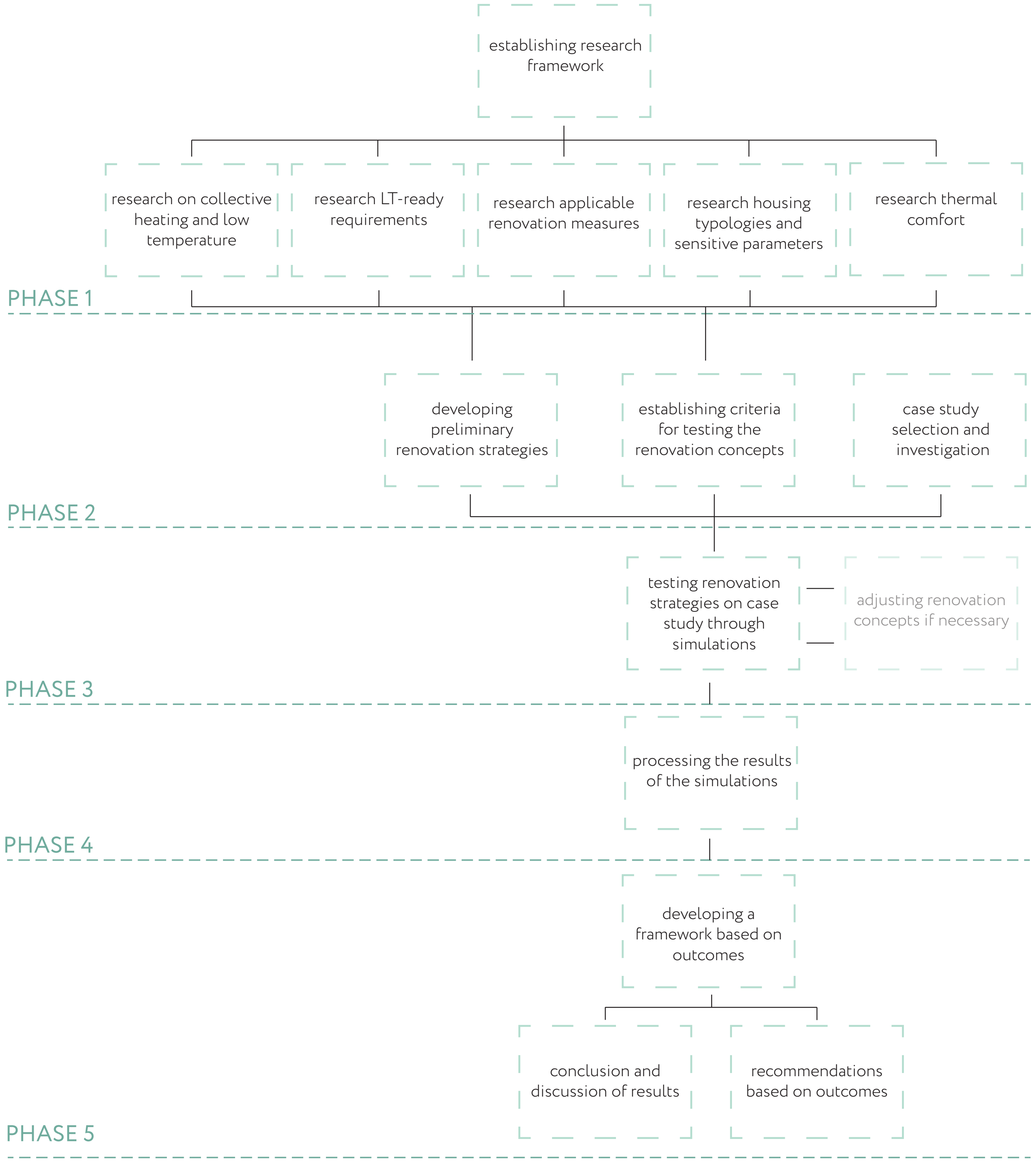


Figure 1.5: Flowchart of research process (own image)

for renovation. Based on the literature review, preliminary renovation strategies are proposed for the case study.

### Case study investigation

The second method consulted was the case study investigation. A representative case study for one of the typologies was selected, which was thoroughly investigated to create a representative 3D model.

### Simulations

Multiple renovation strategies were tested on the case study and the typology iterations through the use of the simulation software DesignBuilder. These simulations gave insight in the heating demand of the building and through the use of CFD the effects on the local thermal comfort were analysed.

## 1.6 Relevance

### Social Relevance

The energy transition required to achieve the climate ambitions to limit global warming effects every sector in the Netherlands, including the building sector. To be ready for this transition and the switch to low-temperature heating, the current housing stock has to be updated and thermally improved. Currently, the renovation rates are too low to achieve these ambitions. Homeowners and housing associations are the ones responsible for carrying out renovation measures, and thus solutions for this problem have to be sought in removing barriers and increasing the motivation among this group. This research focuses on increasing the appeal of renovation for home-owners, the private rental sector and social housing associations through a heightened focus on thermal comfort. In the case of home-owners (which live in the house in question), it is a valuable investment as it is a direct improvement of their own comfort. For the private and social housing sector it is interesting as well, as their property value increases.
This is of social relevance as the solution provided could help oppose a wider societal problem. Additionally, the solution presented leads to a more comfortable and valuable housing stock, which is favourable for both home-owners and housing associations.

### Scientific Relevance

There has been a great deal of research on the topic of thermal comfort in relation to energy renovation. However, what is lacking within this research is the focus on optimising thermal comfort. In research, thermal comfort is approached as a constraint (Mejjaouli & Alzahrani, 2020, Wang et al., 2015) or an additional measuring value (Kauko et al., 2014). Studies by Bjørneboe et al. (2018) have demonstrated that a focus on enhancing the thermal comfort could potentially be an interesting selling point to increase renovation rates. Next to this, the case studies presented in the studies mentioned above, lie within different climatic regions than the Netherlands, which could lead to different outcomes as thermal comfort heavily depends on outside weather conditions. A separate evaluation of the thermal comfort aspects in the Netherlands is therefore necessary. Furthermore, the specific focus on the differences between housing typologies is also underrepresented in research but can also be of value. =

## 2.1 Introduction

The operational principle of collective heating, according to Sayegh et al. (2017), is to produce heat centrally and later distribute it to consumers through pipes buried in the ground, in order to cover their heating and domestic hot water (DHW) demands. Collective heating holds potential for the decarbonisation of the built environment, because it enables the use of renewable energy sources for space heating (Lund et al., 2018).
District heating networks are well-established in the Netherlands. At the moment, the amount of housing connected to district heating in the Netherlands is estimated at 450.000 (CBS & TNO, 2020), meaning 5,9% of the total residential building stock is connected to district heating. This includes houses connected to large scale networks, delivering over 150 TJ/year, and small scale networks, delivering under 150 TJ/year. In 2019, 30% of the heat distributed by large scale networks was generated by renewable energy sources (CBS &TNO, 2020). However, it should be commented that most of this renewable energy was produced by biomass plants, which sparks controversy as research (Hoogervorst, 2017) demonstrates that using biomass for the space heating of residences has a low energetic efficiency. Furthermore, it states that the incineration of biomass locally increases the amount of particular matter in the air, which can lead to disturbance and damages the public health. The prospects of district heating in the Netherlands are optimistic, as it is expected that the number of households connected to district heating will be doubled in 2030 compared to 2020, according to Dutch New Energy Research (2020).

## 2.2 Developments of District Heating

As described by Tereshchenko & Nord (2018), the first district heating grid dates back to 1880, and since then four generations of district heating can be identified. Figure 2.1 gives an overview of the different generations and the techniques used. The first generation of district heating (1GDH) used steam as the transportation fluid of heat as can be seen in this figure, with a temperature of over 200 degrees Celsius. The steam was produced through the burning of coal. Throughout the generations, improvements were made in terms of efficiency, supply temperature, heat sources and prefabrication of materials (Lund et al., 2014). The third generation, shortened as 3GDH, has been in use since the 1980s and still takes a big share of the extensions, as specified by Lund et al. Hot water with a temperature of below 100 degrees Celsius is used as the heat carrier, provided by a mix of heat sources, ranging from renewables to fossil fuels. The fourth generation of district heating (4GDH), according to Lund et al. (2014), is set up to deliver low temperature heat of 30-70 degrees Celsius. Improvements of the 4GDH in comparison to the 3GDH are the lower supply temperature and the use of thermal storage, twin pipes and smart technology (Interreg North-West Europe, 2018).

## 2.3 Low-Temperature Heat

As explained in the previous section, the different generations of district heating have a different supply temperature. At present, 4 grades of temperature can be identified in collective heating: high temperature, medium temperature, low temperature and really low temperature (CE Delft, 2019). Figure 2.2 displays a table of the supply temperatures of the specific grades and their suitable heat sources. Low temperature water, as explained

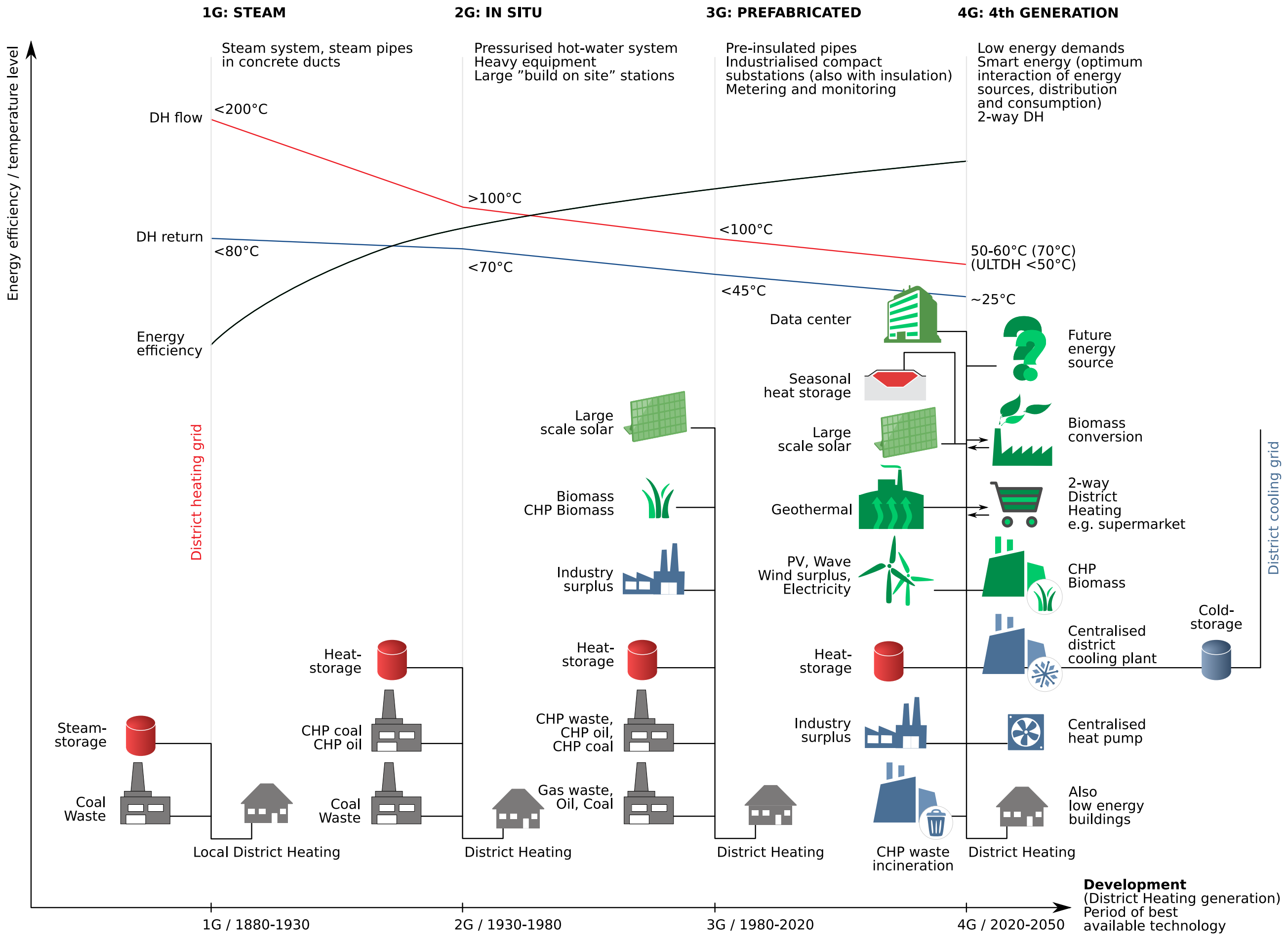


Figure 2.1: Illustration of the concept of 4th Generation District Heating in comparison to the previous three generations (Lund et al., 2014)

| Heat Gradiation | Supply Temperature | Suitable Heat Sources |
|---|---|---|
| High Temperature Heat | > 75 °C | geothermal energy, biomass boilers, waste heat (from industry, waste incineration and power plants) |
| Medium Temperature Heat | 55 - 75 °C | geothermal energy, biomass boilers, waste heat (from industry, waste incineration and power plants), solar thermal energy, heat pump |
| Low Temperature Heat | 30 - 55 °C | shallow geothermal energy, low temperature waste heat, solar thermal energy, heat pump |
| Really Low Temperature heat | 10 - 30 °C | aquathermal energy, really low temperature waste heat, solar thermal energy |

Figure 2.2: Table of supply temperatures and suitable heat sources of different heat gradiations, based on CE Delft, 2019

earlier, will be used as the heat carrier in the 4GDH. A lower supply temperature has several benefits compared to medium and high temperature. It facilitates the use of renewable heat sources, such as shallow geothermal heat, and waste streams from the industry (Ecofys & Greenvis, 2016).Waste heat of a high temperature has been used in earlier generations, but due to efficiency improvements and the increase of recycling, the availability of waste heat from certain sectors will decrease and the temperature of the heat provided by these sources will be lower (Ecofys & Greenvis, 2016). In addition to this, waste heat from new sectors can also be utilized when a lower temperature is used. Other advantages of the usage of low temperature are that the grid losses will be lower and the efficiency will be higher compared to high temperature heat (Lund et al., 2014). Low temperature heat also has benefits on the home scale. In general, the usage of a lower temperature leads to a higher thermal comfort and improved air quality, as will be explained in section 5.5. Next to this, the use of low temperature increases the suitability of a heat pump, as they work more efficiently at a lower condenser temperature (Gustafsson, 2015).

# 3. Low-Temperature Ready

## introduction

### 3.1 Introduction

Gustafsson (2015) states that the utilisation of a lower supply temperature reduces the heating capacity of the heating system. To provide the same amount of heat as high-temperature heating systems, low-temperature heating systems have to utilize larger areas or higher transfer coefficients. This can lead to problems in houses with a high heating demand, where the current heating device is not able to fulfil the total heating demand with a lower heating temperature. If that is the case, certain measures have to be taken to prepare the house for the implementation of low-temperature heat. These measures can include the renovation of building components, the implementation of energy efficiency measures, the replacement of critical radiators and the placement of higher efficiency panels (Lund et al., 2018). In this research, the focus will be on the renovation of building components and the implementation of energy efficiency measures.

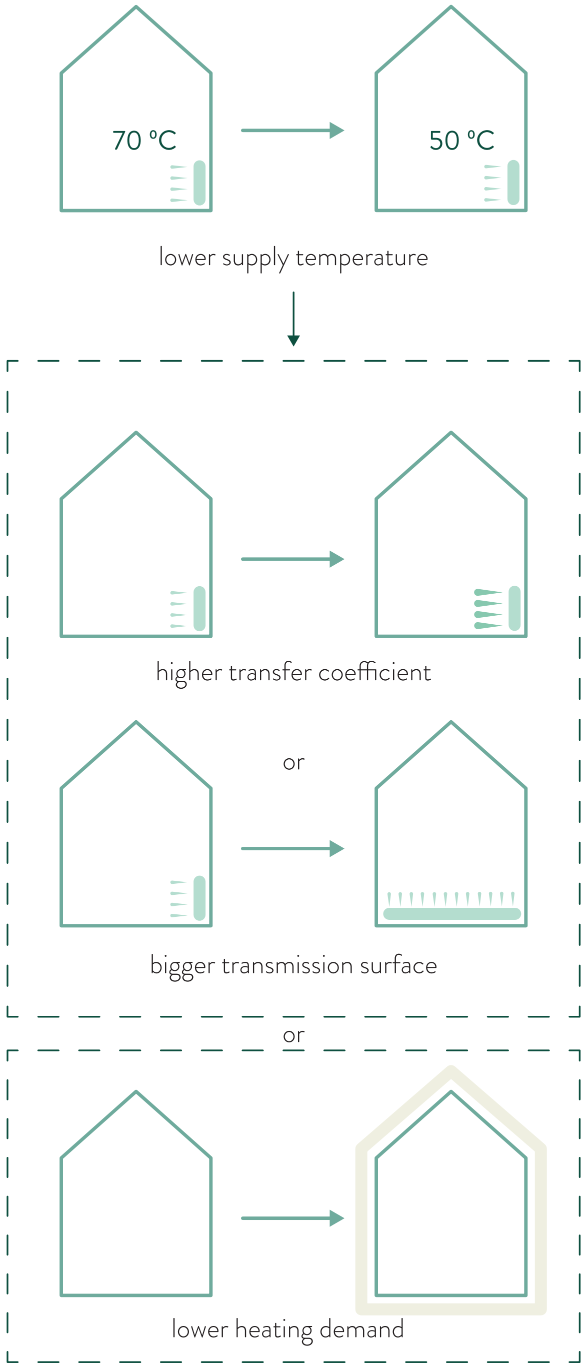


Figure 3.1: Schematic of the options for the integration of low temperature heat (own image)

### 3.2 Definition of Low-Temperature Ready

First of all, the definition of 'low-temperature ready' should be defined. In this research, the following definition is maintained:

*The full space-heating demand of the house, with an indoor temperature of 21 degrees Celsius assumed, can be supplied by the existing heating system with a supply temperature of 55 degrees Celsius, at all times when necessary.*

The existing heating system considered here consists of a central heating unit and panel radiator delivery units, which will be further elaborated in section 3.4. The heating demand assumed here is the one after the application of renovation measures.

The temperature of 21 °C is selected, because this is the winter setpoint temperature proposed by the ISSO (2014b). Research (Essent & MeMo$^2$, 2020) points out that this temperature is higher than the actual setpoint temperature in most houses, however a higher temperature ensures a safety margin for the sizing of the heating system.
Various ranges have been found in the literature for the supply temperature of low-temperature heat. In this research, the range 40 - 55 °C as proposed by the ISSO (2012) will be used. The calculations and simulations will operate with the upper limit, thus 55 °C. For this research there is chosen for the upper limit, because this temperature can be seen as the division between low-temperature ready and not low-temperature ready. if a dwelling can run comfortable with this supply temperature, it can be considered ready.
The return temperature is set at 35 °C, as the same temperature difference of 20 °C is required to be able to calculate the new radiator output based on the existing radiator output with equation 3.13, which is elaborated in section 3.3.2.

## 3.3 The Heat Balance

To be able to supply the heating demand at all times, the heating capacity of the heating system should be equal to or higher than the heating demand. This can be expressed by the following equation:

$$\dot{Q}_{demand} \leq \dot{Q}_{output}$$

(eq. 3.1)

### 3.3.1 Heating Demand

To determine the static heating demand, the heat losses and heat gains ought to be calculated. To do so, the following equation can be used:

$$\dot{Q}_{demand} = \dot{Q}_{trans} + \dot{Q}_{vent} + \dot{Q}_{inf} + \dot{Q}_{int} + \dot{Q}_{sun}$$

(eq. 3.2)

Where;

$Q_{trans}$ = heat loss through transmission in W
$Q_{vent}$ = heat loss through ventilation in W
$Q_{inf}$ = heat loss through infiltration in W
$Q_{int}$ = heat gain through internal gains in W
$Q_{sun}$ = heat gain through solar radiance in W

Together, the heat losses can be summed by:

$$\dot{Q}_{trans} + \dot{Q}_{vent} + \dot{Q}_{inf} = \dot{Q}_{loss} = H \times (T_i - T_e)$$

(eq. 3.3)

The total heat loss coefficient consists of:

$$H = H_{trans} + H_{vent} + H_{inf}$$

(eq. 3.4)

The heat loss coefficient of transmission can be calculated as followed:

$$H_{trans} = \Sigma U \times A$$

(eq. 3.5)

Where;

$U$ = thermal transmittance in W/m$^2$K
$A$ = surface area in m$^2$

The heat loss coefficient of ventilation can be calculated as followed:

$$H_{vent} = \frac{1}{3} \times n_{vent} \times V$$

(eq. 3.6)

Where;

$n_{vent}$ = ventilation rate in h$^{-1}$
$V$ = ventilation volume in m$^3$

The heat loss coefficient of infiltration can be calculated as followed:

$$H_{inf} = \frac{1}{3} \times n_{inf} \times V$$

(eq. 3.7)

Where;

$n_{vent}$ = infiltration rate in h$^{-1}$
$V$ = infiltration volume in m$^3$

The 1/3 here refers to the energy required to raise one cubic metre of air through one Kelvin, which is 0,33 Wh, meaning that the heat capacity per cubic metre is 0,33 Wh/m$^3$K (The Open University, n.d.).

The heat gains consist of the internal gains and the solar gains.

The internal gains can be calculated by the following equation:

$$\dot{Q}_{int} = \dot{Q}_{persons} + \dot{Q}_{lighting} + \dot{Q}_{appliances}$$

(eq. 3.8)

Where;

$Q_{persons}$ = heat produced by persons in W
$Q_{lighting}$ = heat produced by lighting in W
$Q_{appliances}$ = heat produced by appliances in W

The solar gains can be calculated by the following equation;

$$\dot{Q}_{solar} = q_{solar} \times A_{window} \times g\text{-}factor$$

(eq. 3.9)

Where;

$q_{solar}$ = intensity of solar radiation on the glass in W/m$^2$
$A_{window}$ = window surface in m$^2$
$g$-factor = solar heat gain coefficient (no unit)

### 3.3.2 Heating Capacity

To cover the static heating demand, the heat supply of the heat emission system, in this case a radiator, has to be sufficient. To calculate the heating capacity of a radiator, the following equation can be used (Johansson & Wollerstrand, 2010):

$$\dot{Q}_{capacity} = A \times k \times \Delta T_{lmtd}$$

(eq. 3.10)

Where;

$Q_{capacity}$ = radiator output in W
$A$ = surface area of radiator in m$^2$

$k$ = total heat transfer coefficient in W/m$^2$K, calculated by the formula below.

$$\frac{1}{k} = \frac{1}{\alpha_{water-metal}} + \frac{\delta_{metal}}{\lambda_{metal}} + \frac{1}{\alpha_{conv} + \alpha_{rad}}$$

(eq. 3.11)

Where;

$\alpha_{water-metal}$ = heat transfer coefficient between internal water and radiator in W/m$^2$K
$\lambda_{metal}$ = conductivity in W/mK
$\delta_{metal}$ = radiator wall thickness in m
$\alpha_{conv}$ = heat transfer coefficient between air that contains convective parts and radiator in W/m$^2$K
$\alpha_{rad}$ = heat transfer coefficient between air that contains radiative parts and radiator in W/m$^2$K

$\Delta t_{lmtd}$ = logarithmic mean temperature difference between heated surface temperature and ambient air temperature in K

$$\Delta T = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in} - T_{air}}{T_{out} - T_{air}}\right)}$$

(eq. 3.12)

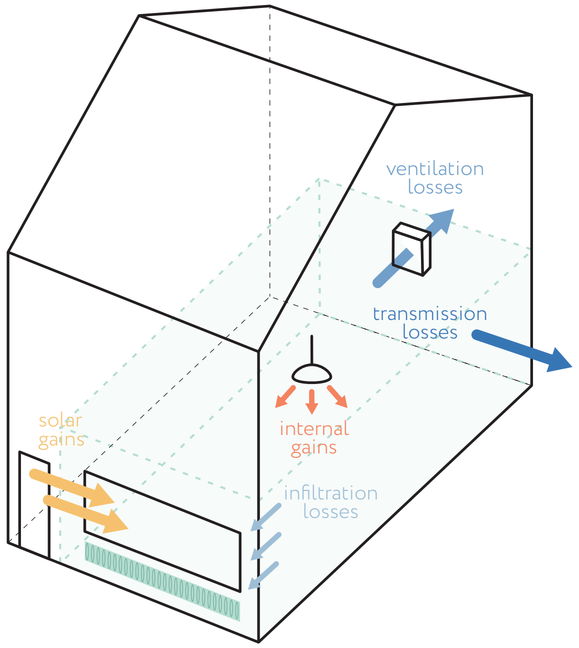


Figure 3.2: Schematic of the heat losses and gains in a dwelling (own image)

Where;

$T_{in}$ = supply temperature in °C
$T_{out}$ = return temperature in °C
$T_{air}$ = air temperature in °C

When the heating capacity of the radiator is already known, the heating capacity of the same system running on a lower supply and return temperature can be calculated by the following equation, presented by Østergaard & Svendsen (2016):

$$\varphi = \left(\frac{\Delta T}{\Delta T_0}\right)^n \times \varphi_0$$

(eq. 3.13)

Where;

$\varphi$ = the design heating power of the radiators in the house at the renewed temperature set
$\Delta t$ = logarithmic mean temperature at dimensioning temperatures, calculated with equation 3.12
$\Delta t_0$ = logarithmic mean temperature at original temperatures, calculated with equation 3.12
$n$ = radiator exponent
$\varphi_0$ = the design heating power of the radiators in the house at the original temperature set

### 3.4 Heating System

The heat delivery system considered in this research in the pre-renovation state is a central heating system with water-based plate radiators that discharge heat. See figure 3.3 for a visual representation. This system is most frequently used in the Netherlands to provide space heating (Milieu Centraal, n.d.). The water is heated by the central heating boiler, which in most cases still operates on natural gas. The water is then distributed to the vertical panel radiators, which emit the heat through radiation and/or convection. In most systems the radiators are placed in parallel, meaning that each radiator has its own supply and return flow and can be operated separately. The cooled down water exiting the radiators flows back to the central heating boiler, where it is reheated. The central heating system is also connected to an expansion vessel, which ensures that large pressure differences are prevented. This is essential, because the water in the pipes expands when heated, which creates pressure differences in the system. If this is not prevented, the system can burst open. When the house is connected to the collective heating grid, the central heating boiler is no longer necessary. A heat delivery set is placed instead, with a supply and return pipe connecting the house to the grid.

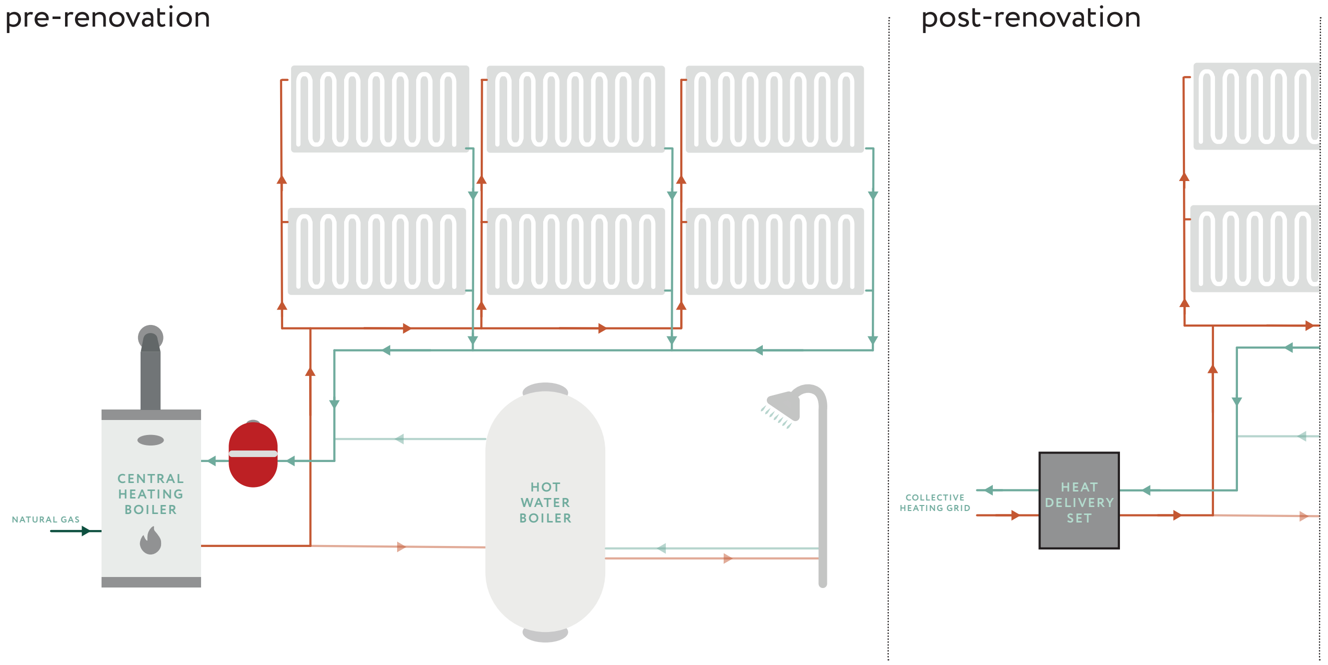

pre-renovation
post-renovation

Figure 3.3: Schematic of the heating systems (own image)

### 3.4.1 Domestic Hot Water

In both the pre-renovation and post-renovation heating systems, the domestic hot water is reheated by a hot water boiler. This is required by law for low-temperature heating systems, as legislation for legionella prevention states that water of a (temporary) temperature below 60 degrees Celcius has to be reheated for safety reasons when used for domestic purposes (Ecofys & Greenvis, 2016). Dwellings that will be disconnected from the gas grid and connected to a low-temperature collective heating grid, therefore need additional and alternative solutions to provide domestic hot water. This forms an additional barrier to the transition to low-temperature heating. Easing these regulations by allowing a lower temperature when additional safety measures are taken, could provide a solution to lift this obstacle.

### 3.4.2 Radiator Types

There are numerous types of panel radiators, which differ in the number of plates and convectors. The type is indicated by a code consisting of two numbers: the first one indicating the number of plates, the second one the number of convectors. Radiator types without a convector discharge direct radiant heat, which warms up the ambient air. A convector radiator diffuses predominantly convective heat. The radiator sucks in the cold air as a result of under-pressure. This air is then warmed up by an array of heated fins in between the plates, which are shaped to maximize the surface area in contact with the air. Convective radiators generally have a higher output than radiators that rely solely on radiant heat transfer (Gelis & Akyurek, 2021). In figure 3.4 the different top views of the types are portrayed. A higher type number corresponds with a higher capacity.

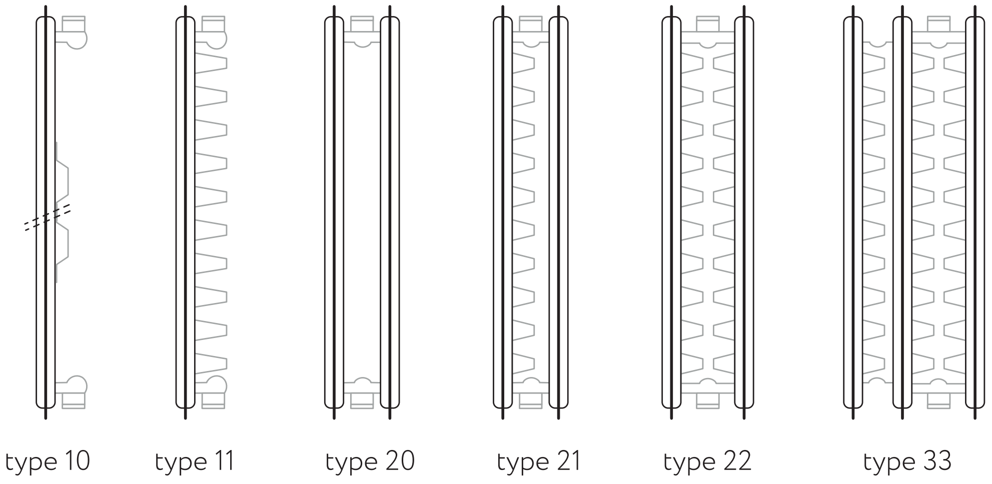


Figure 3.4: Schematic of radiator types, top view (own image)

### 4.1 Introduction

To reduce the heating demand of a dwelling, measures can be applied on various scales: The building scale, the installation scale and the room-scale. On the building scale, this concerns the altering of the thermal performance of the building envelope, the replacement of window systems and the improvement of the airtightness of the building. Measures taken on the installation scale regard the changing of the ventilation system or heating system. It should be noted that the altering of the heating system does in fact affect the heating system's capacity and/or efficiency and does not lead to a decrease in the heating demand, but leads to an increase in heating capability. Transformations on the room-scale include the placement of radiator ventilators, radiator foil, insulating curtains and thermostat control.

The renovation measures considered here are interventions on the building scale and installation scale, hence the measures that alter the building envelope or the ventilation system. There is specifically chosen not to investigate the altering of the heating system, as this research focuses on the possibilities within the existing heating system. Measures on the room-scale are disregarded within this research. For radiator ventilators, there are no valid sources available yet that report on the efficiency of the object, and the functionality, therefore, is questionable. The energy savings possible with radiator foil is limited to a maximum of 4% (Barguilla Jiménez, 2013), which is insignificant compared to the effect of the measures on the building and installation scale. Furthermore, the effect of room-scale actions is difficult to simulate correctly and thus to validate. Next to this, the operation of some room-scale measures, such as the thermostat control and insulating curtains, depends heavily on the user's operation for their effectiveness.

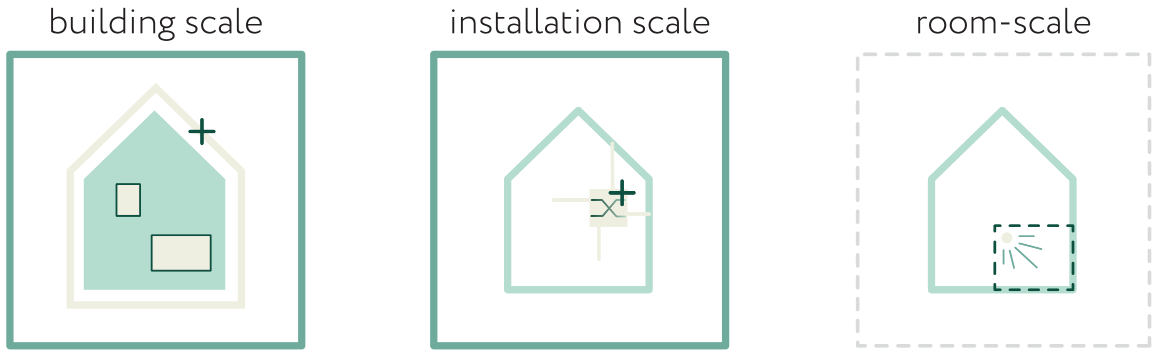

building scale
installation scale
room-scale

Figure 4.1: Schematic of different renovation scales (own image)

The following renovation measures are considered in this research:

| | |
|---|---|
| Window systems: | No change in glazing and window frame |
| | HR ++ glazing + new window frame (total U-value of 1,35) |
| | Triple glazing + new window frame (total U-value of 1,14) |
| Ventilation system: | No change in ventilation system |
| | Ventilation system C.1 |
| | Ventilation system C.2 |
| | Ventilation system D.2 |
| Wall insulation: | No extra insulation |
| | Cavity insulation (+ Rd of 1,0) |
| | Interior insulation, 5 cm (+ Rd of 1,4) |
| | Interior insulation, 10 cm (+ Rd of 2,8) |
| | Exterior insulation, 10 cm (+ Rd of 2,8) |
| Roof insulation: | No extra insulation |
| | Interior insulation, 10 cm (+ Rd of 2,8) |
| | Interior insulation, 15 cm (+ Rd of 4,5) |
| Ground floor insulation: | No extra insulation |
| | Crawlspace insulation (+ Rd of 4,0) |
| | Above ground floor insulation, 4 cm (+ Rd of 1,5) |
| | Below ground floor insulation, 10 cm (+ Rd of 3,3) |

Figure 4.2: Table overview of renovation measures

The insulation thicknesses considered for the different types is based on a cost-effective analysis, which will be further explained in chapter 8.

### 4.2 Window Systems

Windows are often considered the weakest part of the building envelope, as they have a relatively high thermal transmittance, and poorly fitted frames can significantly impact the airtightness of the house and thus the comfort and energy usage. They typically account for around 20% of the total heat loss of a residence (Palmer & Cooper, 2013).

Double glazing was commercially introduced in the Netherlands in the late 40s of the 20th century. The gap between the two glazing panes in this window system was filled with dehydrated air which was hermetically sealed around the edges. The thermal performance of double glazing was significantly improved compared to single glazing and due to the stepwise transition from cold to warm, surface condensation was avoided (Van Der Voorde et al., 2015). Another, additional advantage of double glazing was the improved acoustic insulation. During the century, multiple improvements have been made to enhance the thermal performance of double glazing even further. Standard double glazing was followed up by HR (high efficiency) glazing, which has a coating on the inner side of the glass pane to increase the thermal resistance. HR+ glazing was introduced after, and besides the coating on the glass pane, it also contained a noble gas, either krypton or argon, in the cavity instead of air.
HR+ glazing was succeeded by HR++ glazing, which has an argon filling and an enhanced coating. This is the predominantly used type in construction at the moment. The latest invention is HR+++ glazing, more commonly known as 'triple glazing'. As the name suggests, it consists of three panes, of which the outer two contain an improved coating. The two cavities are filled with a noble gas as well. As a result of the extra glass pane, triple glazing is considerably

thicker and thus heavier than double glazing types. Consequently, it often cannot be placed within the existing frames. Table 4.3 gives an overview of the different types and corresponding U-values.

All glazing types introduced before HR++ glazing are no longer applied in construction, due to their inferior thermal performance compared to newer glazing types. They are only used in special replacement cases where colour preservation is desired. These types are therefore not considered suitable renovation measures in this research.

| Glazing type | U-value [W/(m$^2$K) |
|---|---|
| Single glazing | 5,80 |
| Double glazing | 2,70 |
| HR-glazing | 2,00 |
| HR+-glazing | 1,60 |
| HR++-glazing | 1,20 |
| Triple glazing | 0,9 |

Figure 4.3: Table U-values of different glazing types (ISSO, 2014a)

Moreover, the material and the type of frame impact the thermal performance of the window. In table 4.4 the different types and their corresponding U-values are depicted.

| Frame type | U-value [W/(m$^2$K) |
|---|---|
| Wood laminated with insulation | 1,20 |
| Wood or plastic | 2,40 |
| Metal with thermal break | 3,80 |
| Metal without thermal break | 7,00 |

Figure 4.4: Table U-values of different frame types (ISSO, 2014a)

Explanatory note on considered measures:
- In the second intervention option, the U-value of the HR++ glazing is estimated at 1,2 W/m$^2$K and the U-value of the frame at 1,2 W/m$^2$K. The material of the frame is wood laminated with insulation and the frame has plastic spacers.
- In the third intervention option, the U-value of the HR+++ glazing is estimated at 0,9 W/m$^2$K and the U-value of the frame at 1,2 W/m$^2$K. The material of the frame is wood laminated with insulation and the frame has plastic spacers.

### 4.3 Ventilation Systems

The different ventilation systems are divided into four categories, based on the type of supply and exhaust. In table 4.5 the different ventilation systems are depicted.

|  | Natural supply | Mechanical supply |
|---|---|---|
| Natural exhaust | System A | System B |
| Mechanical exhaust | System C | System D |

Figure 4.5: Table overview of ventilation systems

#### 4.3.1 Ventilation System A

Ventilation system A is often referred to as 'natural ventilation'. It does not make use of mechanical components to supply or exhaust ventilation air. Ventilation can be provided by (self-regulating) air vents, cracks in the construction and by more advanced techniques like windcatchers. This system has not been used anymore in new construction since the 1980s due to the fact that it is often not able to provide the desired level of ventilation 24 hours per day. Sufficient ventilation is essential for a healthy indoor climate.

#### 4.3.2 Ventilation System B

The system using natural exhaust and mechanical supply is known as ventilation system B. It is not applied in buildings anymore as it can lead to an increased energy demand and has multiple practical issues. It is therefore not considered in this research.

#### 4.3.3 Ventilation System C

Mechanical ventilation, 'ventilation system C', is often used in dwellings. It mechanically removes the air in the room and naturally supplies the outdoor air. The air generally enters the home through ventilation vents above the windows. A central exhaust fan is connected to the exhaust points, which are preferably located in every room, or at least in the living room and the 'wet spaces', i.e. the kitchen, toilet, bathroom and laundry room. It is a relatively simple system that is not very susceptible to human error. A disadvantage of this system is that it can lead to a cold draft at the window and thus impact the local thermal comfort, which will be further explained in section 5.5.
Mechanical systems are further subdivided by the method of control of the airflow rate, which is indicated with a number behind the letter C. For this research, the C1 and C3 systems are considered. In the C1 system, the supply ventilation grill is manually operated. The C3(c) system regulates the supply airflow based on preset time schedules. This system can lead to a decrease in ventilation losses as the system is only running when ventilation is required. It has to be noted that, for this system to work properly, it is important that the actual occupancy schedule is in line with the preset schedule.
$CO_2$-controlled ventilation systems (C4 and C5) are not considered within this research, because these systems depend heavily on the resident’s behaviour and presence and therefore their general impact on the thermal comfort and heating demand is difficult to quantify. Furthermore, wind-pressure regulated ventilation systems (C2) are not regarded as well, due to the fact that there are better performing alternatives on the market, resulting in these systems not being used anymore in new construction. It is also not possible to simulate both these systems in the DesignBuilder software.

#### 4.3.4 Ventilation System D

Ventilation system D, balance ventilation, mechanically supplies and exhausts the ventilation air. Two central fans, one for the supply and one for the exhaust, are connected to various ventilation points in the dwelling. As the name suggests, the airflows within this system are balanced. This system was introduced due to the improved airtightness of housing construction, which could possibly lead to an insufficient amount of ventilation. A great benefit of this ventilation method is the potential to recover the heat from the exhaust air. Due to the supply and exhaust channels required, this system is quite space-intensive and it is therefore not always possible to implement this system in an existing dwelling.
As for ventilation system C, this system is likewise subdivided by the method of control of the airflow rate and zoning. For the scope of this research, only system D2 is considered: a mechanical system using heat recovery, with no further control or zoning.

### 4.4 Opaque Envelope: Wall Insulation

Wall insulation can be applied on different layers of the wall construction: the exterior, the interior, and when present, the cavity.

#### 4.4.1 Exterior Wall Insulation

Exterior wall insulation can be applied to the outer layer of the exterior wall. From a practical point of view, this type is superior to the other types, as the installation is not limited by space constraints. Furthermore, it gives the possibility for an aesthetic update of the facade. Drawbacks are the relatively high costs compared to other methods.

### 4.4.2 Interior Wall Insulation

Insulating the interior wall is done by installing an insulation layer on the inner side of the wall. This method is often seen as inferior to the other types, due to the decrease in usable room surface and the increased risk of moisture and humidity problems. It is, however, a more affordable option than exterior insulation, when no cavity is present or when the present cavity is considered too small.

### 4.4.3 Cavity Wall Insulation

Most residences built after 1930 are equipped with a cavity between the two wall layers. Before the introduction of energy efficiency regulations, these cavities were not insulated. It is possible to post-insulate these cavities. The width of the cavity, however, is a limiting factor of this method. On the other hand, it is the most affordable and least disruptive method.

## 4.5 Opaque Envelope: Roof Insulation

The exact method of insulating the roof is dependent on the type of roof: pitched or flat roof. For both types, insulation can be placed on the in- or outside of the construction.

### 4.5.1 Pitched Roof Insulation

The most common way to insulate a pitched roof is by insulating the interior side of the construction. In some cases, the exterior face of the construction is insulated. This type of construction is known as a sarking roof.

### 4.5.2 Flat Roof Insulation

For flat roof constructions, a distinction is made between a warm and cold roof construction. When the exterior side of a flat roof construction is insulated, it is called a warm roof construction. Insulating the bottom side of the construction, as is done in the case of a cold roof construction, is possible as well. However, this method is only favourably in special cases, for example when there are building height restrictions that have to be satisfied. This is because there is an increased risk of condensation problems when this construction method is used (Solvari BV, 2019).

If the attic of a residence is not in use as a living space, the attic floor can be insulated as well.

## 4.6 Opaque Envelope: Ground Floor Insulation

To limit the heat transmission to the ground, the ground floor can be insulated.
There are several ways to execute this: insulating the crawl space, below the ground floor and on top of the ground floor. Insulating the ground floor is beneficial for the thermal comfort as the floor surface temperature is higher, lowering the risk of cold feet.

### 4.6.1 Crawl Space Insulation

When a crawl space is present underneath the house, crawl space insulation, also known as 'ground insulation' can be considered. The insulation material, often in the form of a sprayable substance, is sprayed at the bottom of the crawl space. This method has several benefits. It is a feasible option, even when the height of the crawl space is limited. Next to this, moisture and vermin problems are avoided due to the improved humidity. It is also the most affordable option for the insulating of the ground floor. Drawbacks are the inaccessibility of the crawlspace after renovation and the lower yield compared to floor insulation.

### 4.6.2 Below Floor Insulation

In the case of below floor insulation, the insulation material is placed against the ceiling of the cellar or crawlspace. A

prerequisite is that the crawl space is of sufficient height, i.e. minimum of around 450 mm, because the installer has to be able to access the crawl space.

### 4.6.3 Above Floor Insulation

When a crawlspace or cellar is not present or inaccessible, above floor insulation can be considered. This option is less efficient as the top layer of the floor has to be removed or the insulation is placed on top of the existing finishing, meaning that in both cases a new finishing has to be provided. Next to this, the floor thickness increases, and thus the floor-to-ceiling height decreases. This has as a consequence that doors and plinths have to be altered. Furthermore, the load-bearing capacity of the construction has to be able to carry the extra load.

## 4.7 Renovation Strategies

In this research, sets of renovation measures that simultaneously can be applied to a building will be tested on their effect on the heating demand and thermal comfort. These sets of renovation measures are referred to as 'renovation strategies'. These renovation strategies will be composed based on cost-effectiveness. In chapter 8 more information regarding the specific renovation concepts will be provided.

## 5.1 Introduction

The most commonly used definition of thermal comfort is the one introduced by The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE): ''The condition of mind that expresses satisfaction with the thermal environment''. This definition suggests that thermal comfort is a subjective evaluation and emphasizes that the perception of thermal comfort goes beyond environmental and physiological factors, and is a cognitive process influenced by many other factors, as explained by Lin & Deng (2008).
Thermal comfort is a recurring theme within architecture. The architectural design aims to serve the users of the building and therefore it must provide a thermal environment that is comfortable for its occupants. A prerequisite of human well-being, regarding health and productivity, is achieving a balance between minimal physiological responses and maximal acclimatization, as described by Auliciems & Szokolay (2007). With the improvements of heating systems in the late 18th century and the introduction of cooling systems in the early 20th century, the focus on thermal comfort expanded (Auliciems & Szokolay, 2007). The development of these systems made it possible to over-cool or over-heat buildings and therefore the necessity to investigate standard design temperatures arose. The knowledge of thermal comfort expanded in the 20th century as a result of the lobby of the heating, ventilation and air-conditioning (HVAC) industry. 'Comfort' was a product sold by the HVAC industry, and therefore it needed to be redefined to a set of physical variables that could be controlled by their systems, to ensure a comfortable environment for the building occupants (Nicol & Roaf, 2017).
The increasing welfare in the western world, together with the enhancing technology in building construction and microclimate control, have as a consequence that the indoor climate humans are exposed to is becoming more homogeneous. This could potentially be hazardous as humans become adapted to a very narrow band of environmental conditions. In a world threatened by anthropogenic climate change and the deterioration of ecosystems, this development should be investigated in regard to the biological fitness of the human species and sustainability overall Auliciems & Szokolay (2007).

This chapter will first discuss the physiological aspect of thermal comfort and the different components influencing thermal comfort. The models used to measure thermal comfort will be discussed, as well as the phenomenon of local thermal discomfort. At the end, the chapter elaborates on the thermal comfort focus of this research.

## 5.2 Thermo Regulation

The heat produced by the human body must be released to the surrounding environment, to maintain a steady deep body temperature of 37 degrees Celsius. The heat is transported by the blood vessels to the skin surface where it is emitted to the surroundings through convection, net radiation and conduction. The following equation is used to express the heat balance of the human body (Auliciems & Szokolay, 2007):

$$M \pm R \pm C_v \pm C_d - E = \Delta S$$

(eq. 5.1)

where;

$M$ = metabolic rate in Watt
$C_v$ = convection in Watt
$R$ = net radiation in Watt
$C_d$ = conduction in Watt
$E$ = evaporation heat loss in Watt

$\Delta S$ = change in heat stored in Watt

A positive $\Delta S$ results in a higher body temperature, and a negative $\Delta S$ in a lower body temperature. Both these changes are undesirable and possibly dangerous, which is why the human body regulates the body temperature through thermoregulation. Thermoregulation is the mechanism used by a mammal to preserve its core body temperature within acceptable limits independent of external temperatures (Osilla et al., 2021). It is a form of homeostasis and is needed in order to survive.

To warm conditions or an increase in metabolic heat production the body reacts in the two following ways: vasodilation and sweat production. These are autonomous reactions of the body and thus not self-regulatable. The body reacts first by vasodilation, an expansion of the blood vessels in the skin, which increases the blood supply to the skin. This leads to an increase in skin temperature, which in turn increases the heat emission of the body to the surrounding environment. If this mechanism is insufficient to restore the heat balance of the body, the second mechanism is activated: sweating. The sweat is transported from the sweat glands to the skin surface. Here the sweat evaporates, and the energy needed to do so is extracted from the body, which in turn cools down the skin. If these two mechanisms cannot restore the thermal equilibrium, hyperthermia will occur.

To respond to cold conditions, the body also has several autonomous mechanisms to restore the heat balance. The first mechanism activated is vasoconstriction, the constriction of the blood vessels in the skin. This action lowers the blood flow to the skin and therefore less heat is dissipated to the environment. When it appears to be deficient to restore balance, the metabolic heat production is increased through muscular tension 'shivering'. Another autonomous reaction of the body is the emergence of 'goosebumps', the erection of the body hair which aims to increase the thermal insulating value of the skin. This response of the body, however, is considered quite ineffective in comparison to the other mechanisms. If all these mechanisms fail to achieve a thermal balance, hypothermia will occur (ISSO, 2014b).

It has to be noted that a thermal equilibrium does not necessarily have to lead to a sensation of thermal comfort. Other factors, mostly psychological, affect the experience of comfort, such as expectations, past experiences, socio-cultural factors and habits. However, it can be assumed that a thermal neutral state on a physiological basis is a precondition of thermal comfort (Auliciems & Szokolay, 2007).

## 5.3 Factors Influencing Thermal Comfort

Several variables affect the heat balance of the body and thus the thermal comfort. They can be classified into three categories: environmental, personal and contributing factors, as described by Auliciems & Szokolay (2007).

| Environment | Personal | Contributing factors |
|---|---|---|
| Air temperature | Metabolic rate | Food and drink |
| Air movement | Clothing | Acclimatization |
| Humidity | | Body shape |
| Radiation | | Subcutaneous fat |
| | | Age and gender |
| | | State of health |

Figure 5.1: Table overview of variables affecting thermal comfort

### 5.3.1 Environmental Factors

The air temperature, also known as the dry-bulb temperature, is measured by a dry-bulb thermometer that is freely displayed to the air, but covered from moisture and radiation. The variable is a spatial average which considers the ankle, waist and head levels. The convective heat emission is partially determined by this variable.

The air movement is defined as the rate of air movement at a point, without consideration of its direction. It is assessed by its velocity in m/s. As well as the air temperature, it is a spatial average considering three heights. The air movement affects the convective heat dissipation, the surface resistance of the body and clothing and the evaporation of moisture from the skin.

The amount of water vapour in the air is called humidity and it affects the ability to evaporate moisture from the skin (sweating). If the air is almost saturated, it restricts moisture to evaporate and thus the cooling down of the body. It can be specified in several ways: The relative humidity in %, absolute humidity/moisture content in g/kg or vapour pressure in kPa.

The radiance exchange is determined by the temperatures and emissivity of the surrounding surfaces, such as the walls and the ceilings, but also larger radiant bodies like the sun. In calculations the mean radiant temperature is used, which is a fictive homogenous temperature of the environment, where the radiance exchange between a human and its environment is the same as in the actual situation. The effect of the different surfaces on the human body is corrected by the view factor, a geometrical factor which takes into account the relative size of the surface in regard to the position of the person (Kennisbank Bouwfysica, n.d.).

### 5.3.2 Personal Factors

As described above, the personal factors influencing the thermal comfort are the metabolic rate and clothing. The metabolic rate is influenced by two body mechanisms that produce heat: the basal metabolism, which is a result of the various biological processes and is continuous and uncontrollable, and the muscular metabolism, which is dependent on the body activity and thus controllable, except in the case of shivering. In table 5.2 an overview is shown of some typical metabolic rates of different activities. The unit used for the metabolic rates is power density per body surface in $W/m^2$. In thermal comfort studies the unit met is also used, where 1 met corresponds with 58.2 $W/m^2$. For an average size male, this value relates to approximately 100 W.

| Activity | Met | $W/m^2$ |
|---|---|---|
| Sleeping | 0,7 | 40 |
| Reclining, lying in bed | 0,8 | 46 |
| Seated, and rest | 1,0 | 58 |
| Standing, sedentary work | 1,2 | 70 |
| Very light work (shopping, cooking, light industry) | 1,6 | 93 |
| Medium light work (housework, machine tool work) | 2,0 | 116 |
| Steady medium work (jackhammer, social dancing) | 3,0 | 175 |
| Heavy work (sawing, planing by hand, tennis) | 6,0 | 350 |
| Very heavy work (squash, furnace work) | 7,0 | 410 |

Figure 5.2: Table overview of typical metabolic rates of different activities, based on Auliciems & Szokolay (2007)

Clothing affects the insulating value of the body. To rate the clothing insulation level in thermal comfort studies, the unit clo has been introduced. 1 clo corresponds to an insulating cover over the entire body of a transmittance of 6.45 $W/m^2K$. In figure 5.3 an overview is given of some standard clothing attires and their corresponding clo-values.

### 5.3.3 Contributing Factors

Food and drink contribute to the thermal comfort as they can influence the metabolic rate of the body. Acclimatization also plays a big role in thermal comfort, and can happen as quickly as 20 to 30 minutes after changed conditions in the case of short-term acclimatization, or can take up more than 6 months in the case of long-term physiological adaption. Long-term acclimatization is a complex process of the body where physiological and psychological readjustments are made when the person is exposed to thermal stress (ISSO, 2014b). These adaptions can include the increase of blood volume for a more efficient vasodilation, an improved sweat production and the adaption of temperature preferences closer to the exposed thermal stress level (Auliciems & Szokolay, 2007). Behaviour thermoregulation also plays a part in the perception of thermal comfort. Conscious actions, such as the change of clothing and adjustment of activity level, are linked with the recognition of thermal (dis)comfort sensation (Djongyang et al., 2010).
The subcutaneous fat and body shape of a

| Man | | Clo | Women | | Clo |
|---|---|---|---|---|---|
| Underwear | Singlets | 0,06 | Underwear | Bra + panties | 0,05 |
| | T-shirt | 0,09 | | Half slip | 0,13 |
| | Briefs | 0,05 | | Full slip | 0,19 |
| | Long, upper | 0,35 | | Long, upper | 0,35 |
| | Long, lower | 0,35 | | Long, lower | 0,35 |
| Shirt | Light, short | 0,14 | Blouse | Light | 0,20 |
| | Light, long sleeve | 0,22 | | Heavy | 0,29 |
| | Heavy, short sleeve | 0,25 | Dress | Light | 0,22 |
| | Heavy, long sleeve | 0,29 | | Heavy | 0,70 |
| Vest | Light | 0,15 | Skirt | Light | 0,10 |
| | Heavy | 0,29 | | Heavy | 0,22 |
| Trousers | Light | 0,26 | Slacks | Light | 0,26 |
| | Heavy | 0,32 | | Heavy | 0,44 |
| Pullover | Light | 0,20 | Pullover | Light | 0,17 |
| | Heavy | 0,37 | | Heavy | 0,37 |
| Jacket | Light | 0,22 | Jacket | Light | 0,17 |
| | Heavy | 0,49 | | Heavy | 0,37 |
| Socks | Ankle length | 0,04 | Stockings | Any length | 0,01 |
| | Knee length | 0,10 | | Panty-hose | 0,01 |
| Footwear | Sandals | 0,02 | Footwear | Sandals | 0,02 |
| | Shoes | 0,04 | | Shoes | 0,04 |
| | Boots | 008 | | Boots | 0,08 |

Figure 5.3: Table overview of clothing insulation levels (clo) of different type of garment, based on AHSRAE 1985

human are critical aspects as well. The body mass, influenced partially by the level of fat, determines the heat production, but the amount of heat transfer is depended on the measure of the body surface (Auliciems & Szokolay, 2007). Someone with a high body mass to surface ratio, i.e. a more rounded person, would therefore prefer a colder environment.

It is believed that the age and gender of a person can influence the perceived thermal comfort of a person. Especially the range of thermal conditions that are viewed as comfortable varies. Females and elderly people have a higher sensitivity to deviations from the optimal state than males and the young (Z. Wang et al., 2018). Most studies have confirmed that elderly people do not have a different perspective on thermal comfort than younger people (Van Hoof, 2008). The differences between groups and individuals are therefore most likely to be explained by the differences in physiological responses, activity level and clothing insulation. Elderly and females may therefore have a preference for a higher temperature.

### 5.3 Predicting Thermal Comfort & Standards

There are multiple models to assess the quality of the thermal environment. Fanger's PMV-PPD model and the adaptive model are the ones most commonly used and will be discussed in this paragraph.

#### 5.3.1 Fanger's PMV-PPD model

The most recognized model to predict thermal comfort sensation is the model of P.O. Fanger proposed in the 1970s. As stated by Carlucci et al. (2018) this model is a 'steady-state model or rational model of thermal comfort that predicts the average general thermal sensation and dissatisfaction of a large group of human occupants exposed to moderate thermal environments'. Fanger based the model on principles regarding the heat balance of the body and experimental data collected in a steady-state climate chamber. Participants in the experiment had to rate their general, whole-body thermal sensation on a 7-point scale, ranging from cold (-3) to too hot (+3) (Van Hoof, 2008). It is often referred to as the PMV-PPD model, named after the two measuring indices of the model. The PMV stands for the Predicted Mean Vote and provides an index to predict the average thermal sensation on the 7-point scale based on six factors: air temperature, mean radiant temperature, relative humidity, insulation level, metabolic rate and airspeed (ISSO, 2014b). As it is more useful to predict the percentage of dissatisfied persons as a result of a specific thermal state instead of the PMV, the PPD was introduced. The PPD, Predicted Percentage of Dissatisfied relates the PMV to the relative amount of people who would be dissatisfied with the thermal environment. For this conversion to PPD, it is assumed that people rating their thermal environment 'neutral', 'slightly warm' or 'slightly cold' are satisfied with their environment, and others are dissatisfied (Van Hoof, 2008). Due to individual differences, there is no thermal environment that would satisfy all occupants. The model accounts for this, as the PPD is still at 5% when the PMV is at 0, which is highlighted in figure 5.4.

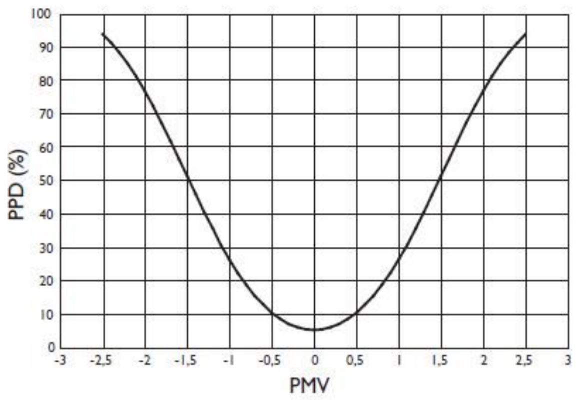


Figure 5.4: Table of the PMV index and corresponding PPD index, according to Fanger (1972)

The model was first incorporated in the EN ISO 3770 in 1984, and the ANSI/ASHRAE followed in 1992. Subsequently, in 2000 it was incorporated by the Chinese GB/T standard 18049 (Carlucci et al., 2018).

Over the years, there has been a lot of critique on the PMV-PPD model and multiple studies have demonstrated various errors within the model. Criticism regarding the model is often focused on the application in various types of buildings, its geographical application range, the input parameters and the model as a whole. The main critique point is that the model is based on experiments executed in a laboratory steady-state environment, which is not representative of the actual environment (Djongyang et al., 2010). This affects the model's ability to correctly predict the thermal sensation in especially natural ventilated buildings, where people are able to control their environment.

Next to this, the model considers the occupants as passive receptors of thermal impulses. What it did not take into account is the positive attitude people have regarding the ability to adapt to their thermal environment, through their behaviour, physiological adaption and psychological expectations (Carlucci et al., 2018).
As a reaction to this, there is a growing acceptance of the more adaptive approach to comfort, which is based on field studies in existing buildings. This model assumes that occupants take conscious actions in combination with the physiological adaption of the body to achieve a level of thermal comfort. They are therefore more accepting of a wider range of thermal conditions (Nicol & Roaf, 2017). Further on in this paragraph, more detail on this model will be provided.

Furthermore, the model assumes that thermal neutrality corresponds with the satisfaction of the thermal environment. As mentioned earlier in paragraph 5.2, thermoneutrality does not necessarily have to lead to the acceptability of the thermal environment. The model illustrates how the thermal environment is perceived and directly links this perception to a level of satisfaction. However, satisfaction is quite subjective and cannot be assumed solely based on the rating of the thermal environment.

#### 5.3.2 The Adaptive Model

As previously mentioned, the adaptive model was developed as a reaction to misconceptions in the existing PMV-PPD model. In the 1970s, Nicol and Humphreys speculated that the feedback mechanism between the occupant's thermal comfort perception and its behaviour could be the reason why people are accepting a wider range of temperatures in existing buildings than Fanger's model predicts. After the introduction of this theory, plentiful field studies were performed on this matter, which reinforced the theory that occupants of naturally ventilated buildings indeed have better thermal adaptability than occupants of mechanically ventilated buildings. The adaptive theory assumes that the optimal indoor temperature is directly related to the outdoor temperature (Carlucci et al., 2018). Allowing a wider range of temperatures also decreases the energy demand needed to cool and heat the building, which is a great advantage in an energy-constrained world. In 2004, the adaptive model was incorporated in the ASHRAE 55, and later on also in European and Chinese guidelines (Carlucci et al., 2018).
In the Dutch guidelines, the ISSO 74, the adaptive thermal comfort theory is clearly present, as in these norms, a distinction is

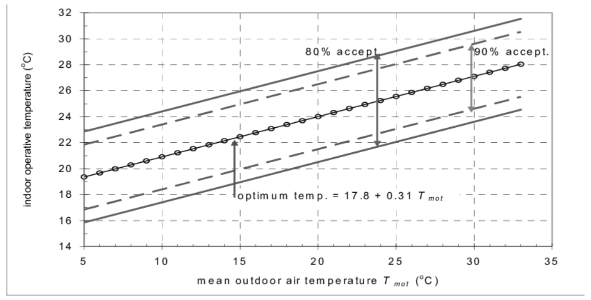


Figure 5.5: Graph of ASHRAE 55 thermal comfort norm, based on adaptive thermal comfort model

made between alpha and beta buildings. An alpha building is a building where occupants are able to alter their thermal environment by opening a window and/or by the adjustment of active cooling. Furthermore, occupants in alpha buildings have the possibility to adjust their clothing based on outside weather conditions (ISSO, 2014b). Buildings that do not comply with these two conditions are marked as beta buildings. Figure 5.6 shows the difference between these building types. In summer, the maximum allowed temperature is higher for alpha buildings than beta buildings.

It has to be noted that the models are validated for office-like environments and do not necessarily reflect the comfort in residential spaces, where there are zones with more variable requirements and less predictable activities (Peeters et al., 2009). However, research in the field of residential thermal comfort is limited and there are not yet validated methods to assess the specific comfort in dwellings.

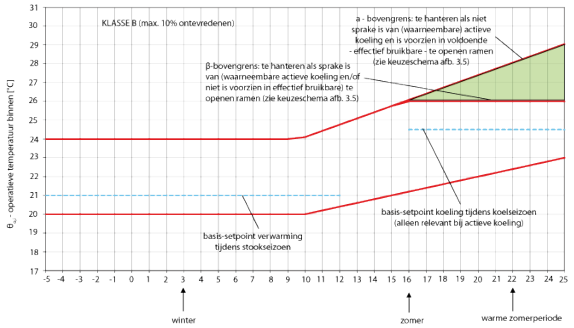
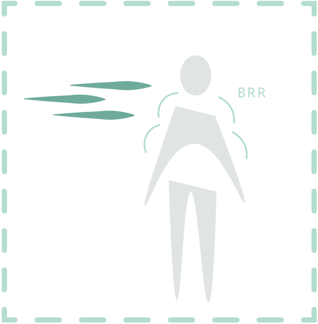


Figure 5.6: Graph of ISSO 74 thermal comfort for class B norm, based on ISSO (2014b)

## 5.4 Local Thermal Discomfort

The phenomenon of local thermal discomfort can be described as the thermal dissatisfaction experienced due to the unwanted heating or cooling of a particular part of the body (Khodakarami & Knight, 2008). Hence, the thermal discomfort of the body is not measured for the body as a whole. Local thermal discomfort can occur due to various factors. The aspects that are most frequently mentioned in literature and thermal comfort standards will be discussed in this paragraph. These aspects are (cold) draught, vertical temperature gradient, radiant asymmetry and floor surface temperature.

### 5.4.1 Draught



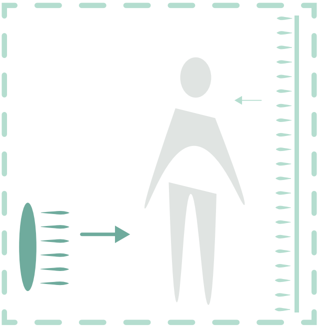
The most frequently mentioned cause of local thermal discomfort is draught. It is defined as the undesired local cooling of the human body due to air movement (Pinto et al., 2019). According to Olesen & Parsons (2002), people performing light sedentary activities are more sensitive to thermal discomfort as a result of draught than people engaged in activities of higher movement levels. Uncovered parts of the body are also more sensitive to draught (Detelin, 2002). The PPD by cause of draught, the draught rate, as proposed by the EN ISO 7730 and ASHRAE Standard 55, is determined by multiple parameters: The air velocity, the turbulence intensity and the local air temperature. Turbulence intensity is defined by Kimura (2016) as 'the ratio of standard deviation of fluctuating wind velocity to the mean wind speed, and it represents the intensity of wind velocity fluctuation'. As stated by Melikou (1988), a high turbulent airflow leads to more feelings of dissatisfaction than a low turbulent airflow with the same air velocity and temperature. In more simplistic norms only the maximum level of air velocity is defined, with an assumed temperature and turbulence intensity level. In table 5.7, the maximum air velocities are stated for the different requirement categories as proposed by the ISO 7730.

When higher temperatures occur, often the temperature limit of 25 °C is mentioned, the local cooling of the body due to airflow can become desired, and draught turns into a pleasant breeze. The precondition here is that the occupants have direct control over the airflow supply (ISO, 2005).

### 5.4.2 Vertical Temperature Gradient

Local discomfort can occur as well when the vertical temperature gradient is considerably large. Current standards by the EN ISO 7730 advise a maximum of 3 Kelvin/m in air temperature difference for requirement category I, measured between head and feet. (Möhlenkamp et al., 2018). As stated by Olesen & Parsons (2002), people are more sensitive to a temperature increase upwards. The standards, therefore, do not apply for the opposite case as the downwards temperature increase is not as critical. It has to be noted that the standards are derived from research performed on occupants in seating conditions, and therefore the standards are not able to correctly predict the PPD of occupants performing other, more intensive activities (Detelin, 2002).

### 5.4.3 Radiant Asymmetry



Radiant asymmetry is the difference between the plane radiant temperature on one side of a plane and the plane radiant temperature on the opposite side of that same plane (Fanger et al., 1985). The cause of radiant asymmetry can be a warm or cold surface, but also solar irradiation can influence this aspect. Fanger explains that a difference in radiant temperature does not necessarily have a negative effect on thermal comfort and in some cases it is even desired, for example when warming up in front of a fireplace. However, when undesired it can cause discomfort to some parts of the body. As research by Fanger et al. (1985) pointed out, there is a difference in sensitivity for different types of radiant surfaces and the main temperature sensation experienced from those surfaces. People tend to be more sensitive to warm ceilings and cool walls (windows). Therefore, different norms are composed based on the type of surface, and the main temperature sensation (warm or cold). As well as the vertical temperature gradient, the norms for radiant asymmetry are derived from research studying occupants in sedentary activities (Olesen & Parson, 2002). Research by Langkilde et al. (1985) suggests

that occupants with a higher metabolic rate are less sensitive to radiant asymmetry.
In table an overview is given of the maximum radiant asymmetry of different surfaces for different requirement categories, as proposed by the ISO 7730.

### 5.4.4 Floor Surface Temperature

A too cold or too warm floor surface can also be of influence on the local thermal discomfort. Measured often by floor surface temperature, it is in fact the heat loss to the floor that causes the discomfort, which is also affected by several other factors, such as the conductivity and heating capacity of the floor material and the type of shoewear the occupant is wearing (Detelin, 2002). The norms by the ISO 7730 as depicted in figure 5.7. For sedentary activities, a temperature range of 19 to 26 °C is advised. For spaces equipped with floor heating systems, the upper limit is stretched to 29 °C (Olesen & Parsons, 2002).
These standards are proposed for situations where only the feet touch the floor surface and do not apply for situations in which people sit or kneel on the ground, which is more common in other cultures (Olesen & Parsons, 2002).

| Aspect | Unit | Requirement Category I | Requirement Category II | Requirement Category III |
|---|---|---|---|---|
| Draught Rate | Percentage % | 10 | 20 | 30 |
| Maximum Air Velocity | m / s | Winter: 0,10<br>Summer: 0,12 | Winter: 0,16<br>Summer: 0,19 | Winter: 0,21<br>Summer: 0,24 |
| PPD: Vertical Air Temperature Difference | Percentage % | 3 | 5 | 10 |
| Vertical Air Temperature Difference | Kelvin | 2 | 3 | 4 |
| PPD: Range of Floor Temperature | Percentage % | 10 | 10 | 15 |
| Range of Floor Surface Temperature | Degrees Celsius | 19 - 29 | 19 - 29 | 17 -31 |
| PPD: Radiant Temperature Asymmetry | Percentage % | 5 | 5 | 10 |
| RTA: Warm Ceiling | Kelvin | < 5 | <5 | < 7 |
| RTA: Cool Wall | Kelvin | < 10 | < 10 | < 13 |
| RTA: Cool Ceiling | Kelvin | < 14 | < 14 | < 18 |
| RTA: Warm Wall | Kelvin | < 23 | < 23 | < 35 |

Figure 5.7: Table of local thermal comfort requirements per requirement category, based on ISSO (2014b)

### 5.5 Research Focus Thermal Comfort

This paragraph will discuss the specific research focus regarding thermal comfort.
It is assumed that general thermal comfort will be achieved when the heating demand of the house is met by the heating system, as the operative temperature will in that case remain in the acceptable range. However, low-temperature heating can affect the comfort on a local level. The next paragraph will elaborate on this.

### 5.5.1 Low-temperature Heating

Lowering the supply temperature of the heating system will affect the thermal comfort within a dwelling. Due to the lower temperature of the heating system, the system is less capable to compensate for the downdraught of the window (DWA, 2016). This downdraught occurs when the surface temperature of the inner pane of the window is significantly lower than the air temperature, thus when the glazing has a high U-value. When the warm air comes in contact with the cold surface, it, therefore, cools down, resulting in a downwards, cold draught. To compensate for this effect, radiators are often placed underneath the windows. The heat emitted rises up, and counter effects the downdraught from the windows. However, when the supply temperature is lowered, this counter-effect becomes less prominent and more downdraught can be experienced.
The same effect can be expected when natural ventilation grills are positioned above the windows, which also cause a cold downdraught.

Thermal discomfort caused by radiant asymmetry is also avoided by the placement of a hot, radiant surface beneath the cold window surface. This effect also becomes smaller when the supply temperature is lowered, as the radiant temperature of the radiator's surface is lower.

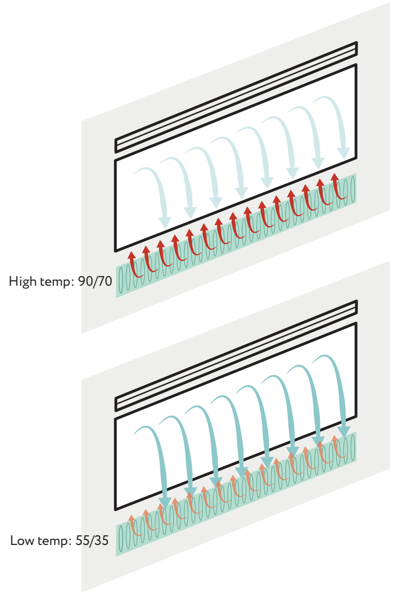


Figure 5.8: Effect of radiator temperature on downdraught (own image)

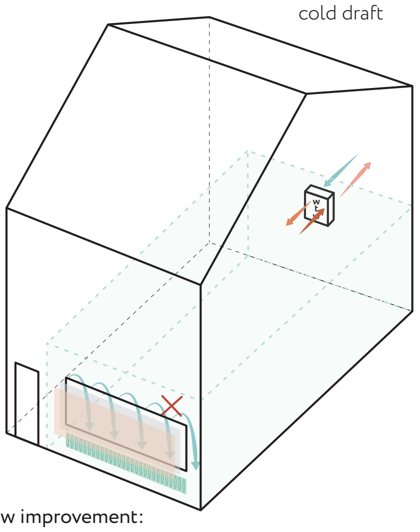
Furthermore, the heating-up period of a house, i.e. the time required to heat up the house after cooling down for a couple of hours, is shorter with a conventional heating system running on high-temperature than that of low-temperature systems (Eijdems et al., 1999). However, when a dwelling has been properly insulated the drop in temperature after a setback will be smaller as a result of the limited cooling down of the thermal mass within the insulated envelope. Furthermore, longer heating-up periods can be anticipated by advanced technology which enables occupants to adjust their thermostat remotely.

Low-temperature heating positively affects thermal comfort as well, as the radiant heat transmission component of low-temperature systems is higher than that of high-temperature systems, as explained by Eijdems et al. (1999). The heat transfer by convection is reduced, and to provide the same comfort levels, the air temperature can thus be lower. Studies (Karmann et al., 2017) have pointed out that occupants do prefer heating systems that work predominantly on radiant heat. It is presumed that this preference for radiant heat can be ascribed to the more natural feel it provides, as it feels similar to the radiant heat of the sun.

For low-temperature floor heating systems, the local thermal discomfort can be affected, as a result of the floor surface and vertical temperature gradient (Eijdems et al., 1999). As this research assumes the preservation of the existing heating system, the panel radiator, no significant effect on the floor surface temperature and vertical temperature gradient is expected.
As highlighted earlier, critical aspects regarding local thermal discomfort of wall panel radiators operating on a lower temperature are the draught and radiant asymmetry. The following paragraphs will elaborate on these matters.

### 5.5.2 Draught

Thermal discomfort as a result of draught can be reduced by the implementation of renovation measures. As discussed earlier in the paragraph, the surface temperature of the window affects the level of downdraught. When the glazing of a residence is improved, i.e. the glass is replaced by a type with a lower U-value, the surface temperature of the glass becomes higher when a winter situation with no or low solar irradiation is considered. A higher window surface temperature results in a smaller temperature difference between the air and the surface, leading to a reduction of downdraught that can be felt.
A higher level of insulation is not expected to have a great influence on the draught rate. It could possibly lead to a higher air temperature, which can affect the draught rate in a positive sense. However, the air temperature remains mainly affected by the heating device.



Ventilation type D.2:
**positive** effect
air entering is pre-heated, leading to less cold draft

Window improvement:
**positive** effect
improved U-value leads to less downdraught

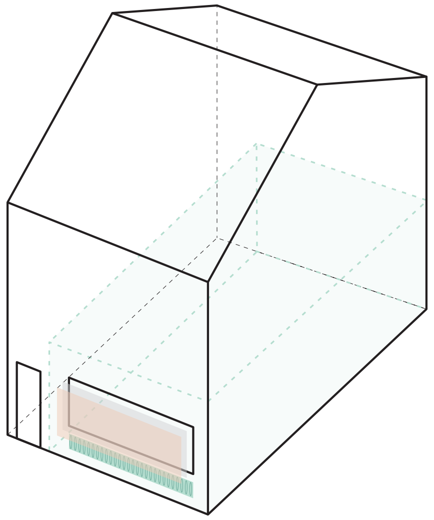
Figure 5.9: Effect of window improvement on draught (own image)

When balance ventilation with heat recovery is installed, it can be expected that the thermal comfort close to the supply point is improved, compared to a ventilation system where the supply air is not preheated. Due to the increase in the air temperature of the incoming air, the draught rate reduces.

Point of consideration that should not be overlooked is the effect of the measures on the overall heating demand. When the heating demand is reduced to a level where the radiator in a room is not often required to be on during occupancy hours in winter, the compensating effect of the radiator on the downdraught of the window is fully disregarded. A thermally improved house could therefore be more uncomfortable in winter than anticipated (DWA, 2016).

### 5.5.3 Radiant Asymmetry

The radiant asymmetry is affected by the surfaces in a room and their radiant temperature. A high radiant asymmetry is assumed to occur in the proximity of a window, especially when the surface temperature of that window is relatively low due to a poor U-value.
For this research, the mean radiant temperature, shortened to MRT, is measured as well, as it can be a good indication of whether unpleasant radiant asymmetry is experienced in a room. The mean radiant temperature is the average of the surface temperatures in the room, corrected for the view factor (Kennisbank Bouwfysica, n.d). As explained earlier in this chapter, people are notably sensitive to radiant asymmetry caused by a cold, vertical surface. In the vicinity of a cold surface, in this case the window, the MRT drops, which indicates that the radiant asymmetry is higher at that point. For winter conditions, it is assumed that radiant asymmetry caused by the presence of warm vertical surfaces, is experienced as pleasant, if the radiant asymmetry caused by the surface is within the acceptable limits prescribed by the ISSO (2014b). An increase in MRT, thus is associated with increased comfort.
The only surface temperature which can be noticeably affected by the implementation of renovation measures is the window surface. Through the application of a glazing type with a lower U-value, the inner surface temperature can be increased, which influences the radiant temperature and radiant asymmetry a person experiences. Nonetheless, this effect is not able to countereffect the reduction in radiant temperature caused by the lower temperature setting of the radiator.
Furthermore, no significant effect on the radiant temperature and the radiant asymmetry is expected by an increase in insulation value or change in ventilation system.



Window improvement:
**positive** effect
improved U-value leads to less 'cold' radiation from the window

Figure 5.10: Effect of window improvement on radiant temperature (own image)

## 6.1 Introduction

This chapter will discuss the different housing typologies considered within this research. The differences between the typologies will be analyzed and specific factors, the sensitive parameters for renovation, will be investigated further.

## 6.2 Housing Typologies

The categorisation of typologies of the Voorbeeldwoningen (Agentschap NL, 2011) is followed within this research, because it gives a thorough overview of the different typologies in the Dutch building stock. This classification is based on two variating factors: the building type and the construction period. The building type in this organisation is determined by two matters: the number of surfaces exposed to the outdoor environment, and, for the multi-family housing typologies, the way of access. Next to the determining factors, there are building characteristics that seem correlated to the type, such as the average surface area, amount of floors and amount of rooms. The other factor, the construction period, correlates with the level of insulation, window glazing type, ventilation system and level of airtightness.

In appendix A, an overview of the typologies and their building characteristics can be found, which is based on the document of Agentschap NL (2011), as well as the numbers mentioned in the upcoming paragraph.

As previously stated, this research specifically focuses on single-family housing types. In this study, the term single-family housing is used for all housing that does not have another dwelling on top and/or underneath them. Hence, within this scope, the housing types detached housing, semi-detached housing and terraced housing are considered. This definition is slightly broader than the general English definition, which only considers fully detached housing as single-family housing. However, the Dutch equivalent 'eengezinswoningen' does include the other types as well and is the best term to cover the content.

This specific scope of housing types is selected for three reasons. First of all, the Dutch residential housing stock consists for a majority, in fact 64%, of single-family housing (CBS, 2021a). Secondly, the natural gas consumption of apartments is significantly lower than that of apartments (CBS, 2021b) and thus the most environmental benefit can be achieved here. Lastly, due to the large differences in building characteristics between multi-family and single-family housing, it is not possible to make valid assumptions for multi-family housing based on a single-family case study.

### 6.2.1 Housing Types

*Terraced Housing*

Figure 6.1: Terraced housing (Funda, 2022d)

Terraced housing is the most common building type in the Netherlands, with 41,8% of the total housing stock falling within this category Characterized by the (semi)-identical blocks of housing, these dwellings often consist of 2 to 3 floors and 3 to 5 rooms, on a living area of around 100 square meters. As they are located in between other residences, the heat transmission through the walls is less compared to other single-family housing types.

*Semi-detached Housing*

Figure 6.2: Semi-detached housing (Funda, 2022g)

12,2% of the housing stock consists of semi-detached housing. With only one side of the house connected to another dwelling, these houses are often more spacious compared to terraced housing, with 3 to 4 floors and 4 to 5 bedrooms on an average of 110+ square meters. However, the transmission losses through the walls are higher with this type of dwelling.

*Free-standing Housing*

Figure 6.3: Free-standing housing (Funda, 2022b)

A quite diverse category is the free-standing housing type. After terraced housing, it is the most commonly found type within the Dutch residential housing stock, with a 14,2% share. There are large differences between the dwellings in this category, but on average these houses consist of 4 to 7 bedrooms, spread out over 2 to 4 floors and 130+ square meters.

### 6.2.2 Construction Period

*Up to 1964*

Figure 6.4: Housing pre 1964 (Funda, 2022f)

The first category marks all these houses built up to 1964. This category thus spans a large range, however, as there were no regulations regarding energy efficiency before 1965, the thermal performance of these houses can be expected to be similar to each other. The expected Rc-values of houses up to 1964 can be found in figure 6.9. Within this period, cavity walls were introduced in the 1930s, and later in the late 1940s, double glazing came up in the Netherlands. The majority of the housing in this period, therefore, has regular double glazing installed, either as the original window type or as a replacement for single glazing. Almost all housing, around 90%, still has natural ventilation.

*1965-1974*

Figure 6.5: Housing between 1965-1974 (Funda, 2022c)

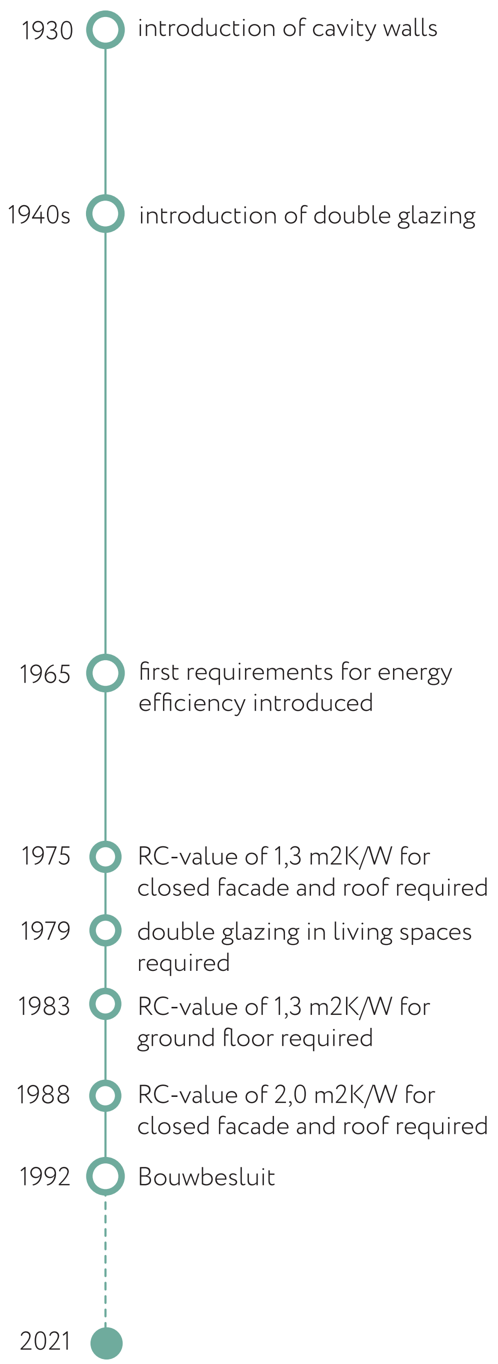


Figure 6.6: Timeline of the development of energy standards in the Netherlands, based on Agentschap NL (2011) and Regionaal Energieloket (n.d.)

In 1965, the first energy efficiency requirements were introduced. It has to be noted that these requirements were still very reserved and are insignificant compared to the standards of new housing construction today. Most housing built in this period still has double glazing, but the percentage with single glazing decreases compared to the previous period. The share of houses with natural ventilation remains approximately the same.

*1975-1991*

Figure 6.7: Housing between 1975-1991 (Funda, 2022a)

Triggered by the oil crisis in 1973, the standards for housing construction improved in 1975. For the facade and roof, a minimum value of 1,3 $m^2K/W$ was required. In 1984, the same value was also prescribed for the ground floor. Regular double glazing is still the most commonly found type of glazing, but the number of houses with single glazing has decreased. Interesting to see is that the share of houses with HR glazing is lower as well, compared to the previous periods. This can be explained by the fact that housing from earlier periods is more likely to have undergone a renovation already. Mechanical ventilation is coming up as well in this timeframe, and almost half of the single-family housing types, 46%, have mechanical ventilation installed.

*1992-2006*

Figure 6.8: Housing between 1992-2006 (Funda, 2022e)

1992 was the year of the introduction of the Bouwbesluit. The requirements for the roof and facade were improved to 2,0 $m^2K/W$. The majority of housing built in this period has HR glazing or better installed, and single glazing is nearly absent. Mechanical ventilation is most commonly found in dwellings, and around 10% of the housing already has balance ventilation installed.

| Construction Year | Facade | Roof | Floor |
|---|---|---|---|
| till 1964 | 0,35 | 0,15 | 0,22 |
| 1965 - 1974 | 0,43 | 0,86 | 0,17 |
| 1975 - 1983 | 1,3 | 1,3 | 0,52 |
| 1984 - 1987 | 1,3 | 1,3 | 1,3 |
| 1988 - 1991 | 2 | 2 | 1,3 |

Figure 6.9: Table with expected Rc-values in $m^2K/W$ based on construction period, based on ISSO (2022)

### 6.3 Sensitive Parameters

A sensitive parameter for renovation is defined in this research as follows:

*A building characteristic, determined by the housing typology, that can possibly influence the heating demand and/or thermal comfort of a dwelling in a negative or positive sense, and thus the best suitable renovation strategy.*

For the purpose of this research, the characteristics of the typologies are simplified. A simplification of the typologies has the benefit that the individual effect of certain sensitive parameters can be recognized. For that reason, loosely correlated factors to the type of housing, such as the surface area and amount of floors, are not regarded within this research. The sensitive parameter of the different building types that is considered, is the number of surfaces exposed to the environment. As previously stated, the number of surfaces can highly impact the heat loss through the building envelope, because the heat flow through a wall connected to the exterior is greater than the heat flow through a separation wall. For the construction period, the parameters level of insulation, glazing type and ventilation system are considered. These factors influence the amount of heat that is lost through transmission and ventilation.
The construction years 1975 - 1983 and 1984-1987 are merged for this research, because they individually have a small timespan, and the Rc-values for facade and roof are identical. The highest Rc-value for the floor 1,3 $m^2K/W$, is assumed. The fifth period, 1988-1992 is not separately considered within this research, as it shares great similarities with the case study regarding the Rc-values.

There are, indeed, many other building characteristics that influence the heating demand and/or thermal comfort. However, as these do not directly link to the housing typology, the influence of these factors is disregarded and the factors are assumed stable within this research.

### 7.1 Introduction

This chapter discusses the selected case study house, which is modelled within the simulation software to test the different renovation strategies. First, a visual and descriptive analysis of the house is executed, based on the information and data available. Secondly, the motivation behind the selection of the case study is clarified.

### 7.2 Case Study Description

The information of the house that is present and used within this research is provided by the LTReady project of the TU Delft and partners. This case study has been documented and used within this project. Documentation on the project can be found in appendix C.

The dwelling used as a case study for this research is located in Utrecht, the Netherlands. The house, a mid-terraced 3 storey dwelling, was built in 1979 and is owned by housing corporation Mitros. Figure 7.1 shows the front facade of the dwelling.

Figure 7.1: Front facade case study dwelling, provided by the LTReady project

The front facade is orientated to the south.

In figure 7.2 the floor plans of the house are depicted, with the measurements. On the ground floor the hall, toilet, kitchen and living room are located. The second floor consists of three bedrooms, a hallway and a bathroom. On the third floor, the storage attic and one large bedroom are positioned. The total floor area of the house rounds up to 132,5 square meters.

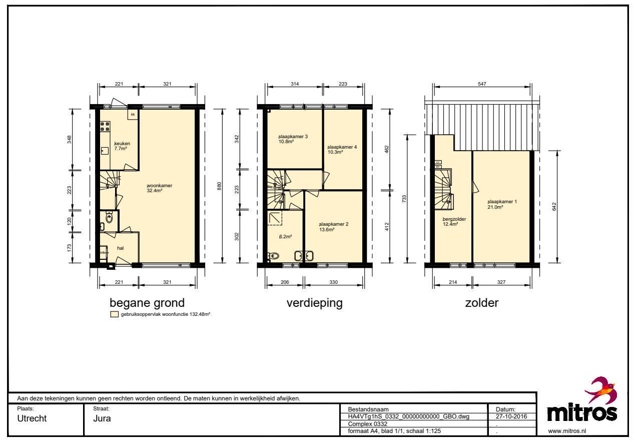


Figure 7.2: Floorplans of case study building, provided by housing company Mitros

On the following page, more photos of the in- and outside of the house are shown. As visible in these pictures, the house was unoccupied for the duration of the measurements. It is expected that this has no significant impact on the results, as the heating system was set up for the measurements as if the space was occupied.

The Rc-values of the different opaque components are known and depicted in the table in figure 7.3. The exact composition of the construction has not been made available. For this reason, simplified constructions were composed to represent the building, based on the Rc-values and well-educated guesses on materialisation. The glazing type was known, as HR+-glazing was used in the windows. Compared to the insulation standards of the time the house was built, the external roof and ground floor are very well insulated. The standards in 1979 advise a minimum insulation value of 1,3 m$^2$K/w, while both components have a Rc-value exceeding this in great measure.

| Component | Rc-value [m$^2$K/w] |
|---|---|
| External wall | 1,94 |
| External roof | 3,75 |
| Ground floor | 3,33 |
| Seperation wall | 0,55 |
| Interior wall | 0,45 |
| Internal floor | 0,55 |
| Crawl space floor | 0,41 |

Figure 7.3: Table of Rc-values of different components, based on numbers provided by the LTReady project

In the house a central heating system with radiator distribution units is present. The heating capacity of the radiators per room is known and used to calculate the full capacity of the system.

Informed by someone of the project, balance ventilation with heat recovery is present in the dwelling. However, for the measurements the heat recovery was turned off, so in the model, a non-pre-heated airflow supply is assumed.

Chapter 9 will further discuss the conversion of the information and data to inputs for the simulation model.

Figure 7.4-7.6: From top till bottom: North facade, Living Room and Bedroom 4, photos provided by the LTReady project

# 7. Case Study Selection

## motivation

### 7.3 Motivation

The number one criteria for the case study selection was that the house is still in the same state as when built regarding the thermal performance, thus that the house has not been renovated yet to update its thermal performance. This is to ensure that the dwelling is representative of the construction period it was built in. This is the case for the dwelling described. A point of critique is that the insulation values of the ground floor and roof are substantially higher than the minimal requirements at that time, which is why the case study is modelled as well with Rc-values of the construction period 1975-1987.

Furthermore, the shape of the dwelling is rather simplistic and thus it is expected that a larger segment of the terraced housing stock identifies with this type of dwelling. There are also no other elements in this dwelling that could lead to substantial differences in heat losses and gains compared to other typical dwellings of this period, such as an extension or large glazing areas. Additionally, the indoor layout of the house is typical for a Dutch terraced house, considering the room distribution per floor and the presence of a living room which spans the full length of the house.

# 8. Renovation Strategies

## introduction

### 8.1 Introduction

In this chapter, the method of composing the renovation strategies is discussed. For a complete overview of the composed strategies, Appendix D can be consulted.

### 8.2 Cost-Effectiveness Analysis

The proposed renovation measures, as presented in chapter 4, were categorised based on cost-effectiveness. In this research, cost-effectiveness is explained in terms of return of investment, i.e. the average amount of time in years it takes for a measure to pay itself back. Figure 8.1 displays the measures, categorised by return of investment. These numbers were derived from research performed by Rutten (2021). This research made a preselection to rule out measures that were deemed not cost-effective. The energy savings of a thicker amount of insulation, for example, stagnate at a certain point. After the tipping point, a higher level of insulation has a relatively low energetic benefit and is thus not economically viable anymore. Figure 8.2 depicts this phenomenon.

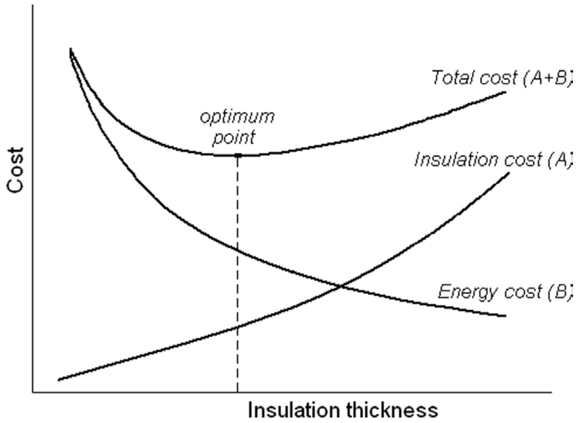


Figure 8.2: Graph presenting the optimal insulation thickness (Kaynakli, 2014)

### 8.3 Composing the Strategies

As can be seen from figure 8.1, ventilation systems have a relatively long return of investment period. However, a properly working ventilation system is a prerequisite for a healthy environment. A minimum change of ventilation system to system C1,

| Component | Measure | Total costs | Return of investment |
|---|---|---|---|
| Wall | Cavity insulation, extra Rd = 1,00 | € 1.843,68 | 2,4 years |
| Wall | Interior insulation 5 cm, extra Rd = 1,4 | € 2.631,92 | 3,3 years |
| Wall | Interior insulation 10 cm, extra Rd = 2,8 | € 3.540,40 | 3,8 years |
| Floor | Below ground floor 10 cm, extra Rd =3,5 | € 1.888,92 | 4,2 years |
| Roof | Roof inside 10 cm, extra Rd = 2,8 | € 4.270,40 | 5,2 years |
| Roof | Roof inside 15 cm, extra Rd = 4,5 | € 6.052,00 | 6,8 years |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 | € 7.815,60 | 8,3 years |
| Glazing | HR++ glazing | € 3.320,88 | 8,7 years |
| Floor | Above ground floor 4 cm, extra Rd = 1,8 | € 3.553,65 | 9,4 years |
| Floor | Crawl space, extra Rd = 4,0 | € 1.626,57 | 13,9 years |
| Glazing | Triple glazing | € 4.411,66 | 14 years |
| Ventilation | C1 | € 2.512,00 | 16,7 years |
| Ventilation | D1 | € 6.123,00 | 20,7 years |
| Ventilation | C3 | € 4.304,00 | 28,5 years |

Figure 8.1: Table presenting the measures categorised based on return of investment

therefore, is assumed for all typologies, when no mechanical ventilation is present yet. Because the ventilation systems deviate immensely from the other measures in terms of return of investment, the three systems are individually considered as the starting point for a series of renovation strategies. A change of ventilation system is thus taken as the baseline, from which the other measures are added in order or cost-effectiveness. The first strategy, therefore, starts with the application of cavity wall insulation and below ground floor insulation. From there on, the strategies are built up in the same manner as the table. When a succeeding measure concerns a component on which a measure is already applied, it replaces this preceding measure. Figure 8.3 presents a flowchart example of the method for visual representation.
In this research, a minimal strategy is described as the minimum number of the most cost-effective measures, that are required for a dwelling for the transition to low-temperature heating.

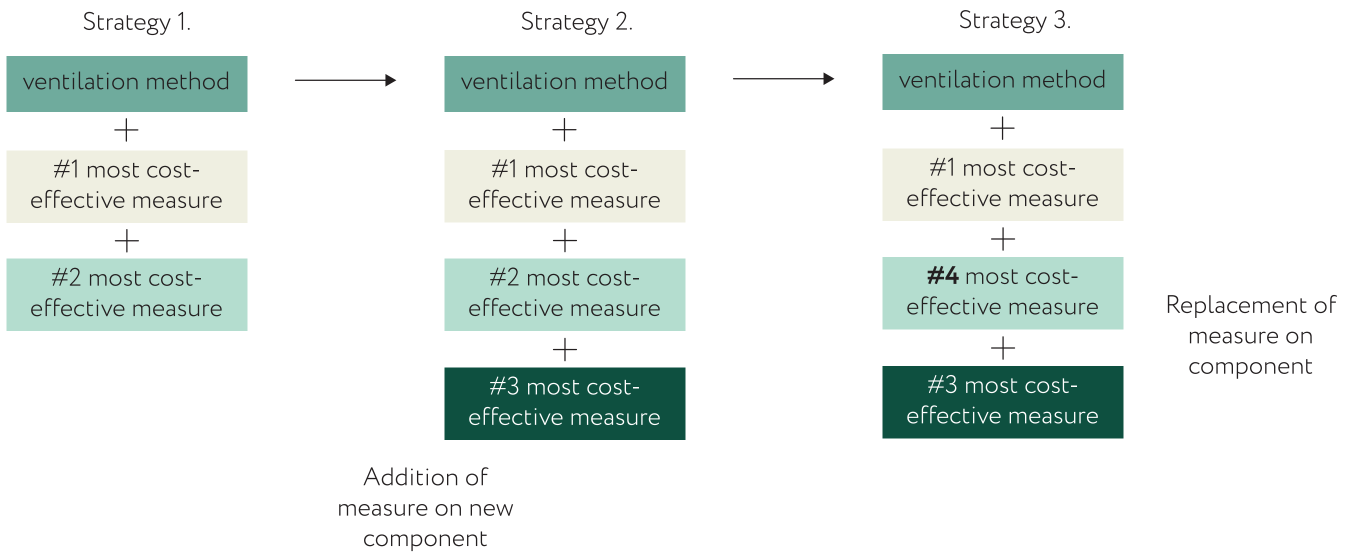


Figure 8.3: Flowchart depicting the method used for the composing renovation strategies, based on an example (own image)

# 9. Simulations

introduction

## 9.1 Introduction

The case study house, presented in chapter 7, is modelled in the simulation software Designbuilder. This chapter will first discuss the software, and will further explain the inputs. Furthermore, the calibration method and the simulation method are explained. Lastly, the process of working in CFD is discussed.

## 9.2 DesignBuilder

DesignBuilder is a simulation software that can be used to quickly assess the performance of a building, regarding energy, $CO_2$, lighting and comfort. DesignBuilder Software Developer Ltd., established in 1999, is the company behind the software, which was released in 2005 (DesignBuilder, n.d.). Its focus on minimalizing modelling and simulation time makes it a suitable option for this research, as the adjusting of building components can be done in a fast manner. It also provides the option to import models from BIM or to build your own model within the software. Within the program, there is a hierarchical order of levels, starting on the site level and working down to the component level. The activity, construction, openings, lighting and/or HVAC can be set for each level. The program enables the user to work with pre-set templates and has an elaborate component library, which speeds up the modelling time.
For the simulation code of calculation, it makes use of the software EnergyPlus, a building simulation program that enables you to model the heating, cooling, ventilation and energy flows. It is validated by the ANSI/ASHRAE 140 2004 standard (Florida Solar Energy Center & Lixing, 2007). EnergyPlus can also be used as a stand-alone program, but it does not contain a user-friendly graphical interface.
Designbuilder also contains a Computational Fluid Design modelling tool, which will be further elaborated on in section 9.6.

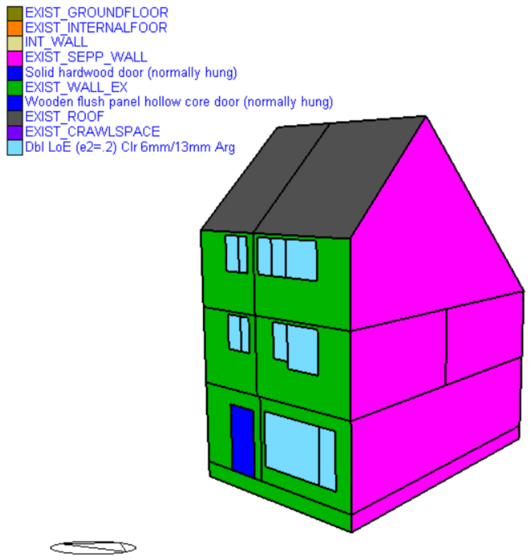


Figure 9.1: 3D visualisation of the basis model of the case study building in DesignBuilder, own image

## 9.3 Inputs

Multiple data inputs are required to be able to build a representative model of the building and its performance. In this paragraph, each input parameter category will be discussed individually.

### 9.3.1 Site Data & Hourly Weather Data

To be able to simulate the actual weather conditions of the site, the site data, such as the location and the hourly weather data have to be inputted. In this instance, the location template set for the case study is the template of De Bilt, located in the Netherlands. This template contains specific data on the site's geographical location and details. For the weather data file, the location of De Bilt was selected as well. The weather data file defines the weather conditions used for simulations. The location of De Bilt is an adequate option for this case study, because it is the location of the general weather station in the Netherlands and it is located relatively close to the actual site (8,0 km distance). The only data that was edited within these templates is the ground monthly temperature of the month of February, in which the winter design week falls. This was done, because the ground temperature has a standard temperature which is the same for each month, which is incorrect and gives a false representation of the heat exchange between the crawl space and the ground. The temperature is set at 7 °C, which is the average ground temperature at a depth of 50 cm in the winter design week, according to numbers by the KNMI (2022).

### 9.3.2 Geometry

The geometry of the house is constructed with the use of floorplans of the case study, depicted in figure 9.2, and data on the surface area of the different facade components. There were no documents available of the facade views, with the exact dimensions and the specific location of the facade components, such as the windows and doors. These elements, therefore, were estimated based on pictures, standardized sizing and known surface areas of the components.

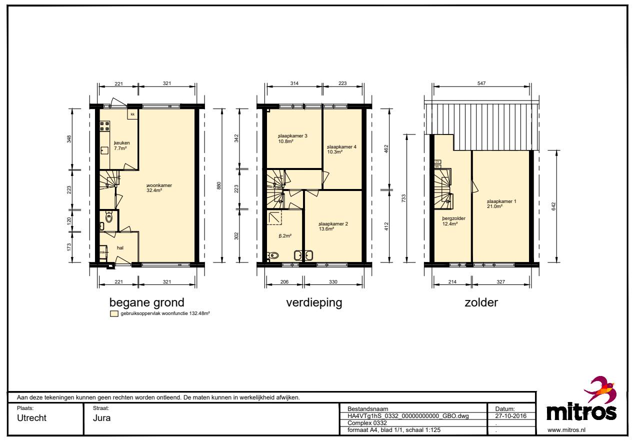


Figure 9.2: Floorplans of case study building, provided by housing company Mitros (2016)

A hole is simulated in the first floor and the second floor to represent the stairwell. This is to ensure that air- and heat flows between the different floors are simulated properly.

The case study in question is a terraced house located between two other houses. To be able to model the transmission losses and gains correctly, the walls on the west and east side of the building are modelled as adiabatic, meaning that there is no heat transferred across the external surfaces. This option can be used for surfaces between zones that are of similar conditions, in this case, the living zones of the adjacent buildings.

The model is orientated correctly, with the front facade facing southwards.

### 9.3.3 Activity

In the activity tab, the occupancy, environmental control and equipment can be loaded in. During measurements, no occupants were present in the case study, however, occupancy is set in the model to ensure the ventilation is modelled accordingly. The occupancy for the whole house, except the crawlspace, is set at the standard level for a residential lounge, 0,0118 people/m$^2$, scheduled for 24/7. No changes have been made on room-scale as the differences between rooms are negligible. The crawlspace is set as unoccupied.

For the environmental control, the heating setpoint temperatures and minimum fresh air are inputted. The setpoint temperature is set at 20 °C, and the heating setback temperature is at 16°C.
The minimum fresh air per person is set at 10,0 l/(s*person), the standard for residential zones. No ventilation setpoint temperatures are set for the indoor temperature control, to provide a sufficient amount of ventilation regardless of the indoor temperature. No equipment is set as well, as there was no data available on this.

### 9.3.4 Construction & Openings

Of the construction, only the Rc-values were known. Simplified constructions which match these Rc-values have therefore been modelled to represent the actual construction. Assumptions on materialisation have been made based on standard construction in the Netherlands. In appendix E, an overview of the construction assemblies of the different components and their Rc-values can be found. The glazing type of the dwelling was known: HR glazing, with a U-value of 1,24 W/m$^2$K. For the window, a wooden frame with a U-value of 0,12 W/m$^2$K was assumed. The airtightness of the whole dwelling is set to 0,5 air change per hour, accordingly to the data that was provided.

### 9.3.5 HVAC

In the HVAC tab, the heating and cooling, ventilation and domestic hot water are set. Due to the variations per zone, a specific HVAC template was constructed for each of the zones. Data were available on the availability and sizing of the heating equipment per room and were input accordingly. The heating schedule was based on real-time monitoring of the air temperature, which will be further explained in section 9.4. Cooling was turned off in each of the zones as this is assumed irrelevant for the winter situation. The domestic hot water is switched off as well, as only the energy usage of zone heating is investigated in this research.
The type of ventilation in the basis model is set to natural ventilation, with an air change rate of outside air per hour specific to that zone, conforming to the data available. The ventilation schedule is set to 24/7, as no time control is present in the original situation. There is an outdoor minimum temperature constraint set at 0 °C, as it is expected that when the outdoor temperature drops below a certain temperature occupants will close the vents as a response to draught. This value of 0 °C is based on studies on occupant behaviour regarding opening windows at different outdoor temperatures (Jeong et al., 2016), because no data was available on occupant behaviour regarding the control of ventilation vents. The assumption here is made that when the outdoor temperature exceeds a certain level where people will fully close a window, ventilation grills will be closed as well.

To model ventilation system C.3, the ventilation schedule was adjusted to the occupancy schedule instead of a 24/7 ventilation schedule. For balance ventilation with heat recovery, with an efficiency of 70%, the ventilation rate was lowered by 70%. The outdoor minimum temperature constraint for this option is removed, as the air is preheated.

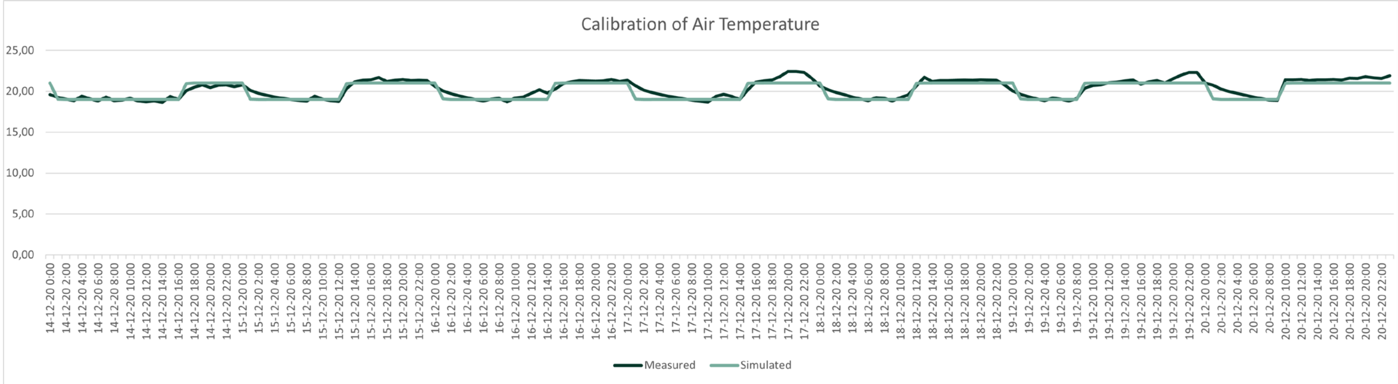


Figure 9.3: Graph outlining the measured and simulated air temperature (own image)

### 9.4 Calibration

A calibration was performed on the model to guarantee that the simulation model is a good replication of the case study in the existing situation. Executing a calibration is an important method to validate the model. To be able to calibrate a model, either hourly data on the air temperature or energy usage is required. For the case study in question, data were available on the air temperature per hour in the living room, measured for the span of two weeks. Unfortunately, the first week consists of the setting up of the test set-up and incomplete data, hence only the data from 14-12-2020 till 20-12-2020 was used. To calibrate the model accordingly, the inputs for the environmental set points and heating schedules were adjusted. The environmental setpoints were set to 21/19 degrees Celcius, instead of 20/16 degrees Celsius, which was indicated in the info sheet of the case study. The heating timetable was adjusted per day to match the real-life heating schedule.
Figure 9.3 displays a graph of the measured and simulated air temperature, after calibration.

### 9.5 Outputs

Two types of simulations were performed, to research the minimal requirements for each of the typologies to be low-temperature ready. First, the heating demand in kWh per winter design week was calculated for the different strategies. For a selection of strategies, the hourly air temperature data was simulated to ensure that the desired heating can be provided at all times.

### 9.5.1. Heating Demand

A winter design week, in this case 10-02-2020 till 16-02-2020, was simulated. The outputs required in this study were the heat losses and gains of the whole building block, during the run period. With the use of EnergyPlus, the heat flows through the separate components in kWh per run period could be calculated.
In total, the heat gains and losses through the following components were computed:

- Glazing
- Walls
- Ceilings (internal)
- Floors (internal)
- Partitions (internal)
- External infiltration
- External ventilation
- Solar Gains exterior windows

With these numbers, the total heating demand in kWh for the whole run period could be calculated. This heating demand was multiplied by 1.25, which is commonly used as a safety margin in the building service industry (Hudson, 2001) & (Darren & Eckert, 2017).

The heating capacity of the system was calculated manually, with the use of equations 3.12 and 3.13, which were introduced in chapter 3.

$$\Delta T = \frac{T_{in} - T_{out}}{\ln\left(\frac{T_{in} - T_{air}}{T_{out} - T_{air}}\right)}$$

(eq. 3.12)

Where;
$T_{in}$ = supply temperature in °C
$T_{out}$ = return temperature in °C
$T_{air}$ = air temperature in °C
$\Delta t_{lmtd}$ = logarithmic mean temperature difference between heated surface temperature and ambient air temperature in K

Inputs:
$T_{in0}$ = 90 °C
$T_{out0}$ = 70 °C
$T_{air0}$ = 20 °C*

$T_{in}$ = 55 °C
$T_{out}$ = 35 °C
$T_{air}$ = 20 °C*

*According to NEN 442-2 (NEN, 2014) the indoor air temperature should be set to 20 °C to calculate the logarithmic mean temperature.

$$\varphi = \left(\frac{\Delta T}{\Delta T_0}\right)^n \times \varphi_0$$

(eq. 3.13)

Where;
$\varphi$ = the design heating power of the radiators in the house at the renewed temperature set
$\Delta t$ = logarithmic mean temperature at dimensioning temperatures, calculated with equation 3.12
$\Delta t_0$ = logarithmic mean temperature at original temperatures, calculated with equation 3.12
$n$ = radiator exponent
$\varphi_0$ = the design heating power of the radiators in the house at the original temperature set

Inputs;
$\varphi$ = 8575 W
$\Delta t$ = 23,60 °C
$\Delta t_0$ = 59,44 °C
$n$ = 1,3 [-]
Resulting in a new capacity for the radiator of:

$\varphi_0$ = 2581 W

As can be seen, the radiator's capacity reduces by approximately 70% when the supply and return temperature is lowered.

For a winter design week consisting of 168 hours, this rounds up to 433,61 kWh.
In the following equation, the simulated heating demand and the calculated heating output are filled in.

$$\dot{Q}_{difference} = \dot{Q}_{output} - (\dot{Q}_{demand} \times 1{,}25)$$

(eq. 9.1)

When the outcome is negative, the strategy is considered not low-temperature ready.
When the outcome is positive, the strategy is considered low-temperature ready.

When the basis model was established, first the existing situation was tested. Then, for the different renovation strategies, the process was repeated on the case study.
For each strategy, a different construction template was composed. The assumption is made that the level of infiltration decreases when changes are made to the building envelope. A new infiltration rate of 0,3 ac/h is assumed for all strategies, based on the air change rate for a well-insulated dwelling (constructed between 2000-2010), calculated according to NTA 8800;2022 (NEN, 2022).
More information on this calculation method is provided in appendix B.
Subsequently, the different strategies were tested on the various housing typologies' sensitive parameters.
The housing types 'freestanding' and 'semi-detached' were modelled by changing the adiabatic walls to exterior walls. For the semi-detached option, one separation wall was adjusted. For the freestanding option, both of the separation walls were changed to exterior walls.
For the construction periods, the existing basis model was altered on the grounds of construction and glazing type, accordingly to the suited values for that period. This was done based on the assumed Rc-values, construction and glazing, of which an overview can be found in appendix E.
New construction templates were made of the existing situation and the renovation strategies based on these numbers.

### 9.5.2. Air Temperature Simulations

For a selection of strategies that were considered (almost) low-temperature ready based on the heating demand simulation, the hourly air temperature in the living room was simulated during the winter design week. As

the effect on the heating demand of some strategies was very similar to the preceding strategy, not all strategies were simulated in this manner. For these simulations, the heating output of the heating system in DesignBuilder is set accordingly to the heating output of the low-temperature system.
The air temperature per hour was compared to the simulated air temperature in the living room, in the existing situation.
For each strategy, the number of hours of underreporting was calculated and represented as a percentage of the total number of hours. Additionally, the number of hours exceeding a temperature difference of -0,5, -1,0, -1,5, -2,0 and -2,5 degrees Celcius is noted, and converted to a percentage of the total number of hours.

### 9.6 CFD

Computational Fluid Design, often shortened to CFD, is a tool that uses data structures and numerical analysis to analyse the fluid flows. Over the past decades, there have been plentiful technical improvements in the performance and the analytical method is widely used in a legion of industries (Norton & Sun, 2006). Through the use of visualisation techniques, the various flows can be depicted in an easily understandable fashion. For the preparation of a CFD simulation, boundary conditions for the surfaces and flow are required. In DesignBuilder, a user-friendly CFD tool with a graphical interface is available.

For this project, CFD simulations were executed to study which measures lead to the most optimal environment regarding local thermal comfort. The draught rate and the mean radiant temperature in the living room were measured in this instance. At first, variations of the sensitive parameters were simulated with the use of CFD, to gain insight into the effects of the parameters on the comfort level in the room. Additionally, different renovation strategies were simulated with the use of CFD on the case study.

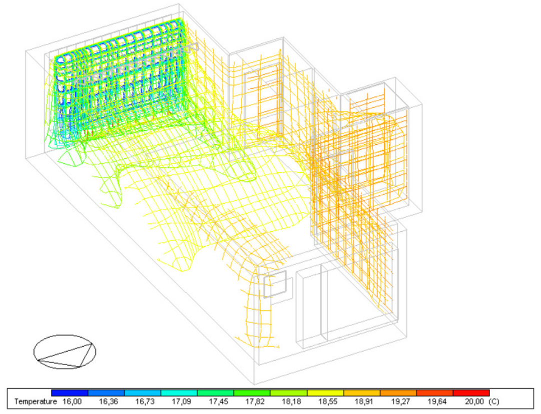


Figure 9.4: Example of a CFD simulation, extracted from DesignBuilder (own image)

The radiator is positioned below the window, and the inlet point for the ventilation is assumed to be at the top of the window for all strategies. The points of measurement are in the middle of the window, at 0,50 meters distance from the inner window pane, at 0,10, 1,10 and 1,70 meters height, as seen from the top of the floor. In general, a distance of 1,0 m from the window is considered as the living zone. However, in practice, people place their furniture relatively close to the window in residential settings. A measurement at 0,50 m, therefore, gives a more realistic view of the comfort sensation (DWA, 2016). The points of height represent the feet, lower back and head level of a regular person.
The following boundary conditions were adjusted, to test the effect of the parameters on the environment:

- The window surface temperature, which is affected by the glazing type that is installed.
- Surface temperatures of the indoor opaque surfaces and the indoor air temperature, which is influenced by the level of insulation.
- The temperature of the incoming air, representing the differences between ventilation types with and without heat recovery.
- the temperature of the radiator, influenced by the installed supply temperature.

Different sets of boundary conditions are simulated to test the effect of the parameters on the environment and the related comfort. In figure 9.5, the different options per sensitive parameter are depicted.

| Sensitive parameter | Type of boundary condition | Options |
|---|---|---|
| Glazing type | Window surface temperature | -Double glazing<br>- HR glazing<br>- HR++ glazing<br>- Triple glazing |
| Insulation level | Wall surface temperature, air temperature | - Existing level<br>- Medium level (strategy 2)<br>- High level (strategy 6) |
| Ventilation type | Air temperature supply air | - Ventilation type C1 and C3<br>- Ventilation type D2 |
| Radiator supply temperature | Radiator surface temperature | - 90 °C<br>- 55 °C<br>- 35 °C<br>- 20 °C |

Figure 9.5: Table of the tested sensitive parameter's options and the corresponding boundary conditions

The mean radiant temperature can be directly measured.
For the draught rate the air temperature, velocity and turbulence intensity are required. The first two can be derived from the CFD analysis, however, for the turbulence intensity, an estimation had to be made.
An average turbulence intensity of 2,5% is assumed for all strategies, based on the average value of a medium-turbulence case (Turbulence Intensity - CFD, 2022).

When the air temperature, velocity and turbulence intensity are known, the following equation can be used to calculate the Draught Rate (TSI Incorporated, 2013):

$$DR = ([34 - t_a] \times [v - 0{,}05]^{0{,}62}) \times (0{,}37 \times v \times t_u + 3{,}14)$$

(eq. 9.2)

Where;

DR = predicted percentage of people dissatisfied due to draught in %
$t_a$ = local air temperature in °C
v = local average airspeed in m/s
$T_u$ = local turbulence intensity in %

For each set of boundary conditions, the mean radiant temperature and draught rate are measured at 0,10, 1,10 and 1,70 m. Afterwards, the same is done for a selection of strategies on the case study model, with different insulation levels, glazing types and ventilation systems. For this set of simulations, the heating output of the system is set accordingly to the heating output of the system at the lowered supply temperature.

### 9.7 Radiant Asymmetry Program

Due to limitations within DesignBuilder, it is not possible to measure radiant asymmetry within the program. Therefore, the program 'Stralingsverloop', which translates to 'radiance course', developed in 2002, is used in addition to research the effect on the radiant asymmetry of a selection of measures. This program has a simplistic interface in which a rectangular room can be modelled. First, the program requests the dimensions of the room. In this case, the living room is simplified to a rectangular space, and the excess space between the kitchen and the hall is disregarded, as depicted in figure 9.6.

# 9. Simulations

## radiant asymmetry program

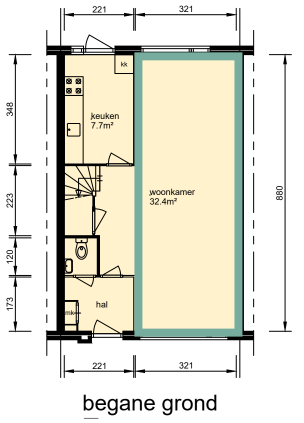


Figure 9.6: Plan of the ground floor, with the modelled rectangular surface area indicated in green

For each of the surfaces, the following inputs are required:

- The temperature on the exterior side in °C
- The Rc-value of the surface in k*m2/W

A window or a radiator can be added to the surface. The inputs required for the window surface are:

- Dimensions: height and length in meter
- Positioning: distance from the left corner in x- and y-direction, in meter
- Temperature on the exterior side in °C
- The U-value of the glazing in W/(k*m2)

The inputs required for the radiator surface are:

- Dimensions: height and length in meter
- Positioning: distance from the left corner in x- and y-direction, in meter
- The surface temperature in °C

With these data inputs, the program calculates the mean radiant temperature and the radiant asymmetry in x-, y- and z-direction in degrees Celcius. This is depicted in four different colour-coded graphs, as illustrated in figure 9.7. It has to be noted that the x- and y-axes depicted here are not up to scale. Furthermore, it self-generates the legend for each case individually and this cannot be adjusted, thus the colors per image cannot be interpreted in the same manner.

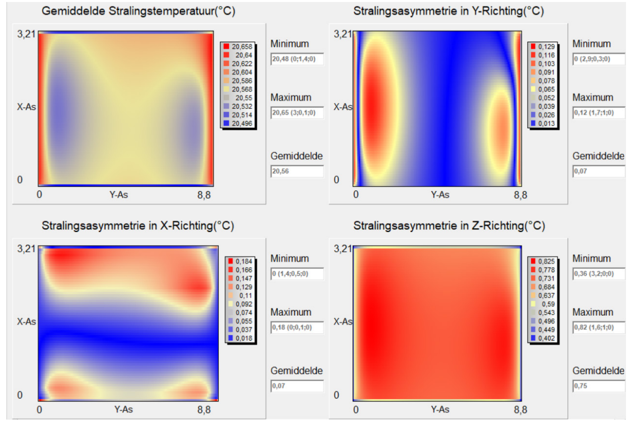


Figure 9.7: Example of the outputs generated by the program 'stralingsverloop' (own image)

For the analysis different renovation cases have been tested, where a low-temperature radiator is assumed:

| | |
|---|---|
| Insulation: wall | - cavity wall insulation<br>- 5 cm wall insulation<br>- 10 cm wall insulation |
| Insulation: floor | - 4 cm above ground floor insulation<br>- 10 cm below ground floor insulation |
| Glazing | - double glazing<br>- HR++ glazing<br>- triple glazing |
| Combinations: | - 10 cm wall insulation and 10 cm below ground floor insulation |

Figure 9.8: Table with tested variables in radiant asymmetry program

Additionally, different renovation measures and combinations have been tested as well where no radiator is assumed. The radiator is of great influence on the radiant asymmetry, and the differences between measures could, therefore, be more noticable in a situation where no radiator is running.

# 10. Results

## introduction

### 10.1 Introduction

In this chapter, the results of the simulations in the software DesignBuilder and Stralingsverloop, as explained in the previous chapter, will be presented.
Four types of studies have been performed during the simulations, which will be discussed. The first two focus on analysing the low-temperature readiness of the strategies. The final two focus on finding the optimal conditions on a local thermal comfort level.

1. Heating demand simulations: The heating demand is calculated for a winter design week in kWh, and the sufficiency of the low-temperature heating system to cover this particular heating demand is analysed per strategy and typology.

2. Air temperature simulations: For a selection of the strategies, the air temperature per hour during the winter design week is analysed as well. This is done to ensure that the strategies provide a comfortable environment at all times and are, thus, low-temperature ready.

3) The CFD analysis: The effect on the mean radiant temperature and the draught rate is measured for a selection of sensitive parameters and strategies with the use of CFD.

4) Radiant asymmetry analysis: For a selection of measures, the radiant asymmetry is calculated with the program Stralingsverloop. This is to gain insight into the actual link between radiant temperature and radiant asymmetry.

### 10.2 Heating Demand

The results derived from the steady heating demand calculation give preliminary insight into which strategies are low-temperature ready and which are not. Figures 10.1 to 10.6 contain the tables that depict which strategies are low-temperature ready per housing typology, according to the heating demand during a winter design week. In green, the strategies that are considered low-temperature ready are indicated. The full version of the table, including the specific heat loss or gain per component, can be found in Appendix F. The numbers in the graph indicate the difference between the heating demand and heating capacity, as explained in section 9.5.1. Furthermore, the effectiveness of the measures is indicated in the tables in the Appendix. Here, the reduction in heat loss through the particular component is indicated as a percentage. This percentage is calculated by dividing the reduction in heat loss compared to the existing situation, by the heat loss in the existing situation:

$$E_{reduction} = -\frac{Q_{exist} - Q_{new}}{Q_{exist}} \times 100\%$$

(eq. 10.1)

Where;

$E_{reduction}$ = Effectiveness of measure indicated by the reduction of heat loss through the component in %
$Q_{exist}$ = Heat loss in kWh through specific component in the existing situation
$Q_{new}$ = Heat loss in kWh through specific component in the new situation, where a measure is applied to that specific component

### 10.2.1 Case Study

The case study dwelling in question can reach a coverable heating demand with all three types of ventilation systems. Per ventilation system, it differs which additional measures are required for the opaque and transparent parts of the building envelope.

# 10. Results

## heating demand

With more advanced ventilation systems, the necessary level of additional measures can be lower. With no change of ventilation system, a minimum of 10 cm below ground floor insulation, 10 cm exterior wall insulation and 15 cm interior roof insulation is required. When ventilation system C3 is installed, a minimum of 10 cm below ground floor insulation, 10 cm interior wall insulation and 10 cm interior roof insulation is sufficient. With ventilation system D2, only 10 cm below ground floor insulation and 10 cm interior wall ventilation are required at a minimum.

### 10.2.2 Construction Periods

For the first three construction periods, the results do not seem to differ a lot. Approximately the same level of renovation is required for each construction period that is analysed. With a change to ventilation system C.3. , a high level of insulation, with 10 cm below ground floor insulation, 10 cm interior wall insulation and 15 cm interior roof insulation, and HR++ glazing is required at a minimum for all the periods. For the third period the minimum requirements are similar, with the same level of insulation for floor and wall, but a lower level of roof insulation and no change of glazing.
For the first two periods, the change to balance ventilation does not affect the amount and level of the additional measures. For the third period, the minimum requirements are similar, with the same level of required insulation for floor and wall, but with a lower level of required roof insulation and no change of glazing.

Interesting here is that the effectiveness of certain measures, here indicated by the percentage of reduction of heat loss through the component, differs substantially between the different periods. The measures applied to the opaque envelope of the pre-1964 dwelling are in absolute and relative numbers more effective than the same measures applied to the opaque envelope of the case study dwelling. This can be explained by the phenomenon mentioned earlier in chapter 8, regarding the cost-effectiveness of insulation and its thickness. The relation between the insulation thickness and the reduction of heat loss is not linear, and after a certain point, the optimum, the addition of insulation has a minimal impact on the heat loss in an absolute and relative sense.

### 10.2.3 Building Types

The differences between the various housing types regarding the minimum requirements are more substantial than the differences between the construction periods. For a semi-detached dwelling, a change of ventilation system is required. When ventilation system C.3. is selected, a minimum of 10 cm below ground floor insulation, 10 cm interior wall insulation and 10 cm interior roof insulation is required. For balance ventilation, the same measures to the building envelope are required at a minimum. The only strategy that is deemed sufficient for the freestanding dwelling is strategy 27, with balance ventilation, 10 cm below ground floor insulation, 10 cm exterior wall insulation, 15 cm interior roof insulation and the implementation of HR++ glazing.

What is striking is that the total heating demand of the freestanding dwelling is not outstanding, especially compared to the heating demand of the early construction periods. However, a high level of intervention is still required due to the characteristics of the dwelling, because the effectiveness of the measures is lower, as a result of the relatively high insulation level already implemented.

# 10. Results

## air temperature simulations

### 10.2.4 General Conclusions

Generally, what can be derived from the results, is that the typology of a building greatly affects the level of renovation that is required to reach low-temperature readiness and therefore should be considered when evaluating a suitable renovation strategy. Particularly interesting to see is that the effectiveness of measures in absolute and relative numbers depends mostly on the construction year and the related Rc-values, and is, as a matter of fact, not greatly influenced by the building type. This effect is partially reflected in the differences in low-temperature readiness between typologies. A typology where the measures have a relatively high impact can be made low-temperature ready in fewer steps compared to a typology where the measures are of lower effectiveness. This, however, is only the case when the heating demand is relatively high.
Furthermore, when looking at the measures individually, it stands out that the reduction of heat loss caused by triple glazing, compared to the reduction caused by HR++ glazing, is not as prominent as expected. Next to this, certain measures, the insulating of the ground floor, for example, have relatively high effectiveness, but as the heat loss through that component is relatively low compared to the heat loss through the other components, the overall effect of these measures is quite minimal. The same can be said in reverse. The switch of the ventilation system, for example, has a high impact in an absolute sense because the heat losses through ventilation are relatively high, even though the stand-alone effectiveness of a change in the ventilation system is low in a relative sense. This indicates that the absolute effectiveness of measures heavily depends on the relative heat loss through the component compared to the total heat loss.

### 10.3 Air Temperature Simulations

Hourly air temperature simulations in the living room for the winter design week were performed for strategies that were assumed low-temperature ready based on the heating demand calculation. In Appendix F, the tables with the outcomes per strategy can be found. These tables indicate the amount of underreporting hours per strategy, thus the hours that the air temperature in the room with a low-temperature heating supply is lower compared to the temperature in the existing situation with a high-temperature heating supply. Additionally, the maximum temperature difference between the two is indicated.
For this part of the research, a boundary condition is introduced, where the new simulated air temperature may not exceed the air temperature in the existing situation by -1 degrees Celcius, more than 10% of the time. This boundary condition differs from the previously stated definition of low-temperature ready. Through new insights gained by the air temperature simulations, it was found that it is unrealistic to expect that the existing heating system with a lower supply temperature is able to cover the full heating demand at all times with an indoor temperature of 21 degrees Celcius assumed, even when a high level of renovation is renovation is implemented. For this reason, this boundary condition was altered. The temperature difference of -1 degrees is selected, as research points out that the majority of the households, i.e. 77%, sets their thermostat to 20 degrees Celcius or lower (Essent & MeMo2, 2020). It can therefore be assumed that a -1 degrees Celcius difference is approved by most households.

# 10. Results

*air temperature simulations*

### Pre 1964

| Strategy | Low Temperature Ready [Remaining capacity in kWh] |
|---|---|
| | |
| BASIS | N.A. |
| BASIS LOW TEMP | -1229 |
| | |
| STRATEGY 1 | -663 |
| STRATEGY 2 | -636 |
| STRATEGY 3 | -602 |
| STRATEGY 4 | -134 |
| STRATEGY 5 | -93 |
| STRATEGY 6 | - 91 |
| STRATEGY 7 | -45 |
| STRATEGY 8 | -67 |
| STRATEGY 9 | -58 |
| STRATEGY 10 | -62 |
| | |
| STRATEGY 11 | -625 |
| STRATEGY 12 | -598 |
| STRATEGY 13 | -564 |
| STRATEGY 14 | -83 |
| STRATEGY 15 | -43 |
| STRATEGY 16 | -41 |
| STRATEGY 17 | 5 |
| STRATEGY 18 | -18 |
| STRATEGY 19 | -7 |
| STRATEGY 20 | -11 |
| | |
| STRATEGY 21 | -611 |
| STRATEGY 22 | -584 |
| STRATEGY 23 | -550 |
| STRATEGY 24 | -62 |
| STRATEGY 25 | -22 |
| STRATEGY 26 | -21 |
| STRATEGY 27 | 25 |
| STRATEGY 28 | 2 |
| STRATEGY 29 | 15 |
| STRATEGY 30 | 10 |

### 1965 - 1974

| Strategy | Low Temperature Ready [Remaining capacity in kWh] |
|---|---|
| | |
| BASIS | N.A.- |
| BASIS LOW TEMP | -1009 |
| | |
| STRATEGY 1 | -382 |
| STRATEGY 2 | -363 |
| STRATEGY 3 | -325 |
| STRATEGY 4 | -116 |
| STRATEGY 5 | -84 |
| STRATEGY 6 | -81 |
| STRATEGY 7 | -35 |
| STRATEGY 8 | -33 |
| STRATEGY 9 | -48 |
| STRATEGY 10 | -53 |
| | |
| STRATEGY 11 | -331 |
| STRATEGY 12 | -312 |
| STRATEGY 13 | -274 |
| STRATEGY 14 | -65 |
| STRATEGY 15 | -34 |
| STRATEGY 16 | -32 |
| STRATEGY 17 | 14 |
| STRATEGY 18 | 17 |
| STRATEGY 19 | 2 |
| STRATEGY 20 | -2 |
| | |
| STRATEGY 21 | -315 |
| STRATEGY 22 | -296 |
| STRATEGY 23 | -258 |
| STRATEGY 24 | -44 |
| STRATEGY 25 | -13 |
| STRATEGY 26 | -12 |
| STRATEGY 27 | 34 |
| STRATEGY 28 | 36 |
| STRATEGY 29 | 24 |
| STRATEGY 30 | 19 |

Figure 10.1 & 10.2: Tables presenting the strategies leading to a low-temperature ready dwelling per typology

GREEN: Low-temperature ready according to steady heating demand calculation
**BOLD**: Low-temperature ready according to air temperature simulations

# 10. Results

*air temperature simulations*

### 1975 - 1987

| Strategy | Low Temperature Ready [Remaining capacity in kWh] |
|---|---|
| | |
| BASIS | N.A. |
| BASIS LOW TEMP | -575 |
| | |
| STRATEGY 1 | -270 |
| STRATEGY 2 | -255 |
| STRATEGY 3 | -230 |
| STRATEGY 4 | -81 |
| STRATEGY 5 | -54 |
| STRATEGY 6 | -50 |
| STRATEGY 7 | -4 |
| STRATEGY 8 | -25 |
| STRATEGY 9 | -9 |
| STRATEGY 10 | -13 |
| | |
| STRATEGY 11 | -220 |
| STRATEGY 12 | -206 |
| STRATEGY 13 | -180 |
| STRATEGY 14 | -32 |
| STRATEGY 15 | -5 |
| STRATEGY 16 | -2 |
| STRATEGY 17 | 44 |
| STRATEGY 18 | 23 |
| STRATEGY 19 | 40 |
| STRATEGY 20 | 36 |
| | |
| STRATEGY 21 | -201 |
| STRATEGY 22 | -187 |
| STRATEGY 23 | -161 |
| STRATEGY 24 | -12 |
| STRATEGY 25 | 15 |
| STRATEGY 26 | 17 |
| STRATEGY 27 | 64 |
| STRATEGY 28 | 42 |
| STRATEGY 29 | 59 |
| STRATEGY 30 | 54 |

### Reference: Case study, 1979

| Strategy | Low Temperature Ready [Remaining capacity in kWh] |
|---|---|
| | |
| BASIS | N.A. |
| BASIS LOW TEMP | -274 |
| | |
| STRATEGY 1 | -91 |
| STRATEGY 2 | -81 |
| STRATEGY 3 | -61 |
| STRATEGY 4 | -19 |
| STRATEGY 5 | -4 |
| STRATEGY 6 | 0 |
| STRATEGY 7 | 12 |
| STRATEGY 8 | 2 |
| STRATEGY 9 | 5 |
| STRATEGY 10 | -1 |
| | |
| STRATEGY 11 | -42 |
| STRATEGY 12 | -32 |
| STRATEGY 13 | -13 |
| STRATEGY 14 | 29 |
| STRATEGY 15 | 43 |
| STRATEGY 16 | 46 |
| STRATEGY 17 | 59 |
| STRATEGY 18 | 49 |
| STRATEGY 19 | 52 |
| STRATEGY 20 | 47 |
| | |
| STRATEGY 21 | -23 |
| STRATEGY 22 | -13 |
| STRATEGY 23 | **6** |
| STRATEGY 24 | **48** |
| STRATEGY 25 | **62** |
| STRATEGY 26 | **64** |
| STRATEGY 27 | **76** |
| STRATEGY 28 | **66** |
| STRATEGY 29 | **70** |
| STRATEGY 30 | **65** |

Figure 10.3 & 10.4: Tables presenting the strategies leading to a low-temperature ready dwelling per typology

GREEN: Low-temperature ready according to steady heating demand calculation
**BOLD**: Low-temperature ready according to air temperature simulations

# 10. Results

## air temperature simulations

Semi-detached

| Strategy | Low Temperature Ready [Remaining capacity in kWh] |
|---|---|
| | |
| BASIS | N.A. |
| BASIS LOW TEMP | -366 |
| | |
| STRATEGY 1 | -149 |
| STRATEGY 2 | -127 |
| STRATEGY 3 | -80 |
| STRATEGY 4 | -40 |
| STRATEGY 5 | -26 |
| STRATEGY 6 | -18 |
| STRATEGY 7 | -7 |
| STRATEGY 8 | -17 |
| STRATEGY 9 | -14 |
| STRATEGY 10 | -18 |
| | |
| STRATEGY 11 | -101 |
| STRATEGY 12 | -79 |
| STRATEGY 13 | -33 |
| STRATEGY 14 | 7 |
| STRATEGY 15 | 20 |
| STRATEGY 16 | 27 |
| STRATEGY 17 | 38 |
| STRATEGY 18 | 28 |
| STRATEGY 19 | 32 |
| STRATEGY 20 | 27 |
| | |
| STRATEGY 21 | -80 |
| STRATEGY 22 | -58 |
| STRATEGY 23 | -12 |
| STRATEGY 24 | 28 |
| STRATEGY 25 | 41 |
| STRATEGY 26 | 45 |
| STRATEGY 27 | 56 |
| STRATEGY 28 | 47 |
| STRATEGY 29 | 51 |
| STRATEGY 30 | 46 |

Freestanding

| Strategy | Low Temperature Ready [Remaining capacity in kWh] |
|---|---|
| | |
| BASIS | N.A. |
| BASIS LOW TEMP | -494 |
| | |
| STRATEGY 1 | -236 |
| STRATEGY 2 | -200 |
| STRATEGY 3 | -124 |
| STRATEGY 4 | -84 |
| STRATEGY 5 | -71 |
| STRATEGY 6 | -61 |
| STRATEGY 7 | -51 |
| STRATEGY 8 | -60 |
| STRATEGY 9 | -58 |
| STRATEGY 10 | -62 |
| | |
| STRATEGY 11 | -191 |
| STRATEGY 12 | -155 |
| STRATEGY 13 | -80 |
| STRATEGY 14 | -42 |
| STRATEGY 15 | -29 |
| STRATEGY 16 | -20 |
| STRATEGY 17 | -10 |
| STRATEGY 18 | -19 |
| STRATEGY 19 | -16 |
| STRATEGY 20 | -20 |
| | |
| STRATEGY 21 | -174 |
| STRATEGY 22 | -138 |
| STRATEGY 23 | -63 |
| STRATEGY 24 | -24 |
| STRATEGY 25 | -12 |
| STRATEGY 26 | -5 |
| STRATEGY 27 | 4 |
| STRATEGY 28 | -4 |
| STRATEGY 29 | -1 |
| STRATEGY 30 | -5 |

Figure 10.5 & 10.5: Tables presenting the strategies leading to a low-temperature ready dwelling per typology

GREEN: Low-temperature ready according to steady heating demand calculation
**BOLD**: Low-temperature ready according to air temperature simulations

# 10. Results

## CFD analysis

### 10.3.1 Case Study

For the case study, all the renovation strategies were tested to gain insight into the effects of the different strategies on the air temperature. What is striking is that a section of the renovation strategies that were deemed sufficient by the heating demand method discussed earlier, do, in fact, not lead to a comfortable air temperature a significant portion of the time. A steady decline can be seen within the strategies in the number of underreporting hours and the degree of underreporting. However, only strategies 23 to 30 are, considering the boundary conditions regarding air temperature, low-temperature ready. This can possibly be explained by the fact that the heat losses due to ventilation are relatively high, especially during the peak demand. A change in the ventilation system, therefore, is a prerequisite for the implementation of a lower supply temperature. The building already has adequate insulation and thus the heat losses through the opaque parts are relatively low, resulting in a low effectiveness of insulation measures. Additional insulation, therefore, is not able to solely cover-up for the decrease in heating capacity of 70%.

### 10.3.2 Construction Periods

A selection of strategies for the construction periods was tested on the air temperature. For all the different construction periods, there are no strategies that lead to a comfortable indoor temperature most of the time. This can be ascribed to the fact that the same sizing of the heating system is used for each period, and the relative oversizing of the heating system is, therefore, much lower compared to the situation of the case study, because the heating demand of these periods, in their existing situation, is higher. What is noticeable in the outcomes, however, is that the number of underreporting hours and the level of underreporting differs between the construction periods. Apparent is that when balance ventilation is installed, the number of underreporting hours increases, but the level of underreporting decreases. This can be explained by the fact that for the ventilation types C1 and C3 a constraint was set in place, where the ventilation is switched off when the outdoor temperature reaches below 0 °C. This is not the case for ventilation type D2, thus explaining the higher number of underreporting hours.

### 10.3.3 Building Types

For the building types, the same matters apply as for the different construction periods. None of the strategies is sufficient for the implementation of low-temperature heating, and it is expected that this is due to the same reasons as for the construction periods.

### 10.4 CFD Analysis

The CFD analysis was performed to gain insight into the effects of different sensitive parameters on the local thermal comfort, in this research specifically the draught and mean radiant temperature. For the analysis, boundary conditions were altered as a result of different glazing types, ventilation supply air temperatures, radiator temperatures and insulation levels. The effect on air velocity, air temperature and the mean radiant temperature was measured in front of the window at 0,5 m distance, at feet, lower back and head level. The complete table with outcomes can be found in appendix F. As a reference level, the existing situation is assumed. It has to be noted that it is assumed here that the radiator in all cases can provide the required amount of heat, to be able to see the effects of the different measures on the local thermal comfort in a situation where general comfort is achieved already. Additionally, to see which strategy reaches the most optimal level of local thermal comfort, a selection of renovation strategies is tested on the case study in the same manner. The other typologies are disregarded here as these cannot achieve a state of general comfort, as explained in the previous section. Furthermore, it is expected that the results of the case study regarding the most optimal comfort apply to the other typologies as well.

### 10.4.1 Glazing Type

The glazing types double, HR, HR++ and triple glazing have been tested. Due to the compensating effect of the radiator, the differences that are measured in mean radiant temperature between the various types are relatively small, even though the window surface temperature between the glazing type differs substantially. This is likewise the case for a low-temperature radiator, as is depicted in figure 10.6. The replacement of double glazing with triple glazing, in this case, affects the mean radiant temperature at head level by +1 °C. As a matter of fact, when no radiator is running, as can be seen on the right in figure 10.6, the glazing type is of great influence on the mean radiant temperature. It has to be noted here that, however, the radiator is expected to be running during occupancy hours, as will be further explained in section 10.4.3.

The velocity at feet and head level decreases slightly when improved glazing is installed and the air temperature increases, however, these effects are small and only noticeable in cases where balance ventilation is not installed.

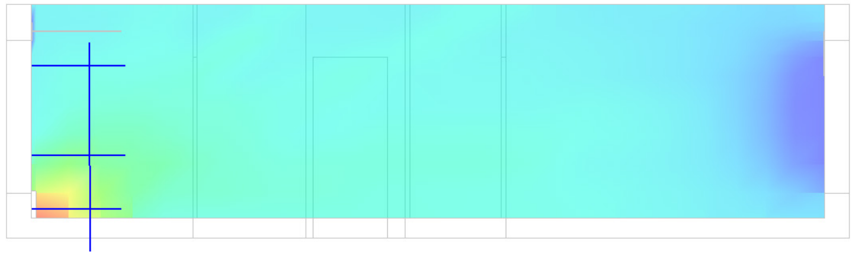
### 10.4.2 Air Supply Temperature

The temperature of the incoming air has a considerable effect on the draught rate. Compared to the original situation, the increase in supply air temperature caused by balance ventilation leads to a decrease of 42% to 50% of the draught rate in a dwelling with a low-temperature radiator. To achieve optimal comfort, balance ventilation should, therefore, be considered in cases where it is applicable. The mean radiant temperature is not significantly affected by a change in air supply temperature.

### 10.4.3 Radiator Temperature

The effect of the radiator temperature was analysed as well, as it was expected that in a well-insulated dwelling, the radiator output would be off or running at a lower output for the majority of the time. To test this hypothesis, the radiator output in the living room of the case study simulation model was monitored for two strategies that were both low-temperature ready, but differed greatly in the level of intervention. The minimal strategy has balance ventilation and cavity wall insulation installed. The maximal strategy, on the contrary, has balance ventilation, 10 cm of exterior wall insulation, 15 cm of interior roof insulation and HR++ glazing installed. In contrast to what was expected, the radiator output during occupancy hours does not vary as much as expected, and with these differences not a significant change in radiator temperature can be expected. Figure 10.7 displays a graph with the differences in radiator output in kW between the different strategies.

double glazing



triple glazing

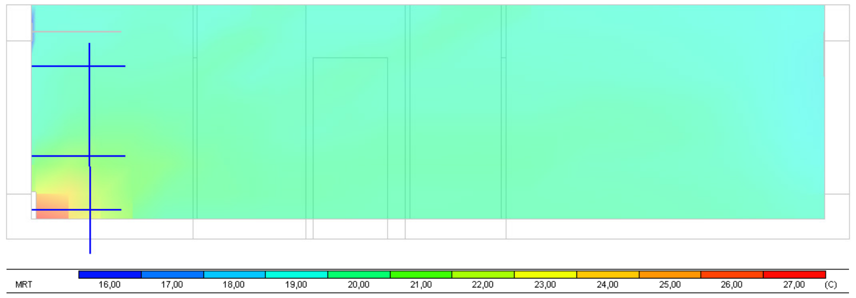


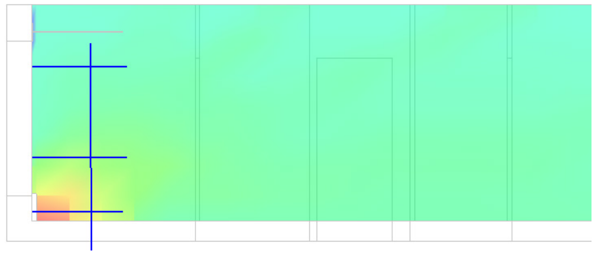
Figure 10.6: CFD Analysis of different glazing types, extracted from DesignBuilder (other parameters are constant) (own image)

When comparing the existing situation to the same situation with a low-temperature radiator, it is seen that the mean radiant temperature cannot reach the same level as a high-temperature radiator, as displayed in figure 10.8. The difference in MRT is at least 2 °C at 0,10 and 1,10 m. When the radiator is running on an even lower temperature, i.e. 35 or 20 °C, the radiant temperature drops even more at these height levels. At head level, no large differences are noticeable between the options. The draught rate is not significantly affected by a change in radiator temperature.

### 10.4.4 Insulation Level

Different levels of insulation have been tested, to see if this could potentially influence the thermal comfort on a local level. The insulation levels tested were the existing situation, strategy 2 and strategy 6. For the highest insulation level, an increase in mean radiant temperature can be detected at 1,10 meters compared to the medium level of insulation. At other heights, the mean radiant temperature is not affected. Compared to the existing level of insulation,

radiator temperature at 55 °C



radiator temperature at 90 °C

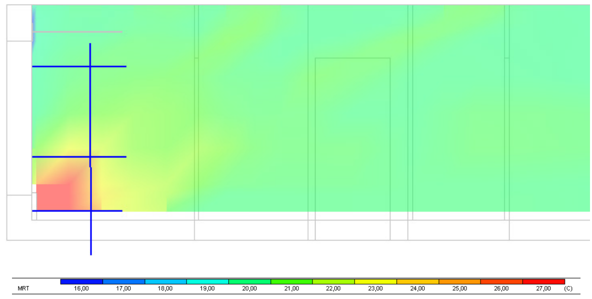


Figure 10.8: CFD Analysis of different radiator temperatures (other parameters are constant), extracted from DesignBuilder (own image)

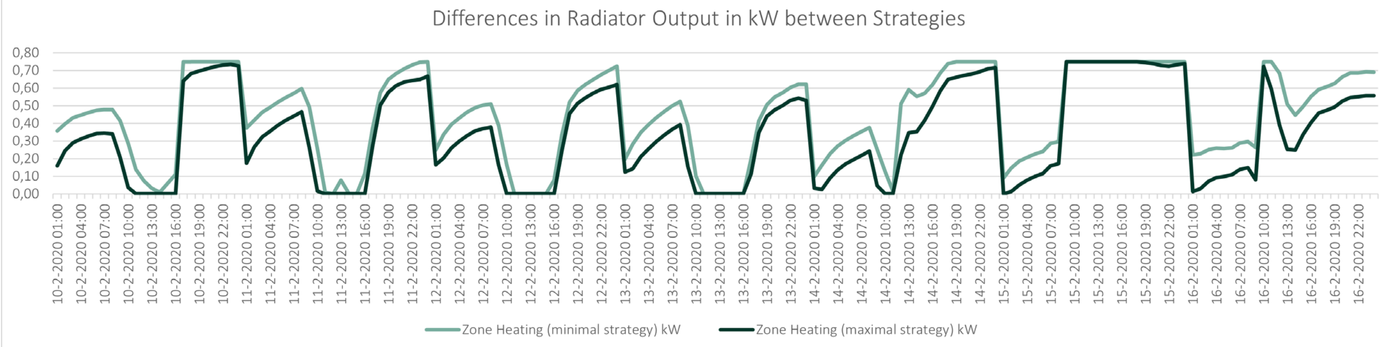


Figure 10.7: Graph outlining the measured radiator outputs in the living room of different strategies (own image)

# 10. Results

## CFD analysis

there is a slight increase of around +1 degrees Celcius seen in mean radiant temperature. However, the affected height level and temperature difference vary depending on the other sensitive parameters.
The draught rate remains mainly unaffected by a change in insulation level.

### 10.4.5 Different Strategies

For the case study, multiple strategies were tested with the use of CFD. First, the existing situation was simulated as a reference. Then, the existing situation with a low-temperature heating system was tested. In contrast to the previously tested parameters, general comfort is not assumed here and the inputs for the air and surface temperatures here are dependent on the situation where the heating system is running on a lower supply temperature. The local thermal comfort, therefore, is in these cases affected as well by the sufficiency of the heating system.
The strategies tested were 4, 6, 7 and 6 + triple glazing, as well as the equivalents of these strategies with different ventilation methods. There is chosen to test strategy 6 + triple glazing instead of strategy 10. These strategies differ in the type of ground floor insulation. As below ground floor insulation performed better in the heating demand simulations than crawl space insulation, it made more sense to test this option with triple glazing than the general strategy 10.

When investigating the local thermal comfort aspects between the existing situation and the existing situation with the low-temperature radiator, it can be seen that the mean radiant temperature is significantly lower when a lower supply temperature is used. This is due to two reasons. First of all, there is a reduction in the radiant temperature of the radiator's own surface. Furthermore, there is a reduction in the surface temperature of the various surfaces, because the indoor temperature is lower due to the inability of the heating system to heat the room to an appropriate temperature. Interesting is that the draught rate is, in fact, lower in the case of low-temperature heating. However, this can be ascribed to the lower, insufficient indoor temperature. This leads to a smaller temperature difference between the window surface and indoor air, which results in a reduction in downdraught at the window area.

The general pattern that can be detected when analysing the outcomes of the CFD analysis of the different strategies, is that the local comfort increases when the level of intervention increases. This is the case for both the mean radiant temperature and the draught rate. This can partly be ascribed to the fact that for the first strategies tested, the heating system is insufficient which affects comfort on a general and local level.
The mean radiant temperature, especially at waist- and head-level, steadily increases when the strategies rise. However, for the strategies that are considered low-temperature ready, this steady increase stops and the mean radiant temperature remains the same at all heights.
Almost the same phenomenon can be detected for the draught rate. Where for the first two strategies the draught rate is relatively high, the draught rate drops at strategy 7 at all height levels, and the draught rate remains approximately the same for all strategies above, with a couple of deviations. At waist-level, at 1,1 meter, an additional drop can be seen for the last strategy. At head level, the strategies with balance ventilation have a significantly lower draught rate as well than the preceding strategies. This effect was expected as the previous analysis already indicated that balance ventilation was of great influence on the draught rate. No difference in the draught rate, however, was again detected between the strategies that are low-temperature ready.

# 10. Results

## radiant asymmetry

### 10.5 Radiant Asymmetry Program

Different measures and their effect on mean radiant temperature and radiant asymmetry have been tested as well in the software program Stralingsverloop to investigate if the assumptions regarding radiant asymmetry based on mean radiant temperature are indeed correct. Images of the outcomes categorised by measure can be found in Appendix F.

When comparing the existing situation with a high-temperature radiator, to the same situation with a low-temperature radiator, a drop in mean radiant temperature can be seen. The difference in MRT ranges from 3,5 °C in close proximity to the radiator, to 0,3 °C in the middle of the room. In all three directions, the radiant asymmetry decreases by approximately 50% when a low-temperature radiator is assumed. However, as discussed in chapter 5, radiant asymmetry caused by a hot radiant surface can actually be considered pleasant, depending on the circumstances. The radiant asymmetry caused by the high-temperature radiator is still well within the acceptable limits and it is therefore assumed that, for the winter situation, the high-temperature radiator does in fact deliver a higher local thermal comfort sensation compared to the low-temperature radiator.

Different variations of wall and ground floor insulation have been tested in addition. What stands out, when you compare the existing situation to the new types, is that the MRT and the degree of radiant asymmetry remain unaffected by the application of insulation, regardless of the thickness.
The various glazing types tested seem to have a small effect on the radiant asymmetry. The replacement of double glazing with HR++ glazing leads to a decrease of approximately 0,3 °C in radiant asymmetry. A change to triple glazing leads to an additional decrease of 0,1 °C. However, due to the relatively small decrease, it is questionable if this decline in radiant asymmetry is noticeable for humans.

Due to the large impact the radiator has on the radiant asymmetry, some parameters were tested again in a situation where no radiator is assumed. The difference between double glazing and triple glazing becomes more prominent here. The distribution of the mean radiant temperature is more even in the case of triple glazing. In all the directions, the maximum radiant asymmetry is approximately twice as high in the case of double glazing, and the area which is highly affected is larger. However, in both cases, the radiant asymmetry is still fairly within the acceptable limits.
Even in the case of no radiator, the addition of ground floor or wall insulation has no noticeable influence on the radiant asymmetry.

### 10.6 Final Results

The results of the heating demand simulations and air temperature simulations indicate which renovation strategies are a suitable option for the transition to low-temperature heating for the different typologies. Next to this, the results give insight into the effect of measures on different typologies and why the requirements differ per typology.
What can be seen for the different construction periods is that, regardless of the relatively large differences in Rc-value, almost the same level of intervention is required for the first three categories. This can be explained by the high effectiveness of the initial insulating measures when little to no insulation is in place yet. For the building types, however, the opposite case is valid. The insulation level of the dwellings here is

# 10. Results

## final results

already quite up to standard, which has as a result that additional insulation or a different glazing type is less effective and there are thus less options to significantly lower the heating demand, leading to a higher level of intervention being required.

Only for the case study building suitable renovation strategies could be found. This does not mean that the other typologies are not appropiate for low-temperature heating. The relative oversizing of the heating capacity in the existing situation has a large effect on the outcomes. All typologies have been simulated with the same capacity, however, if corrected for the relative oversizing, it could well be possible that the other typologies would be able to switch to low-temperature heating as well. It could even be the case that dwellings from earlier construction periods, if they have the same relative level of oversizing of the heating system as the case study dwelling, would be easier to prepare for low-temperature heating. This sounds controversial, but a reduction of 70% of the heating demand is expected to be easier to achieve in a situation where little to no insulation is in place, because additional insulation here functions as 'low hanging fruit' and has a high impact already.

It is thus important, when looking at the renovation options for a dwelling, to consider the effectiveness of the measures in regard to the building typology, and the oversizing of the heating capacity. Next to this it is important, as the air temperature simulations indicate, to identify the components with the largest share in heat losses, especially during the peak demand, and address these components first. For the early construction periods these critical components are the walls and the roofs. For (semi) well-insulated dwellings, the ventilation system is a more crucial part.

The CFD analysis and the program Stralingsverloop helped to gain insight into the thermal comfort effects on a local level of certain measures. What became evident here is that it is crucial that general comfort is achieved in the first place. When this is the case, the actual impact of the measures can be evaluated.  What was found was that it is possible to optimize, and in some cases increase, the local thermal comfort through the use of renovation measures.

The implementation of a low-temperature heating system in the first case increases the draught rate. However, this negative effect can be balanced by a change on the accounts of ventilation or glazing. Ventilation type D2, where the supply air is preheated, is the most effective in reducing the amount of draught experienced. The glazing type has a small effect as well on the draught rate, especially in cases where the supply air is not preheated. An improvement of the glazing could therefor be an alternative if the installation of balance ventilation is not possible due to spatial constraints. However, the level of draught reduction is lower with this alternative.

The mean radiant temperature in front of the window reduces when the radiator is set to a lower temperature, leading to a decrease of comfort. This consequence of low-temperature heating can partially be compromised by the implementation of renovation measures. Local discomfort caused by radiant asymmetry can be adressed by implementing glazing with a lower U-value. The addition of insulation or the changing of the ventilation system has little to no impact on this matter, as was expected.

# 11. Conclusion

This research aims to find an answer to the research question proposed earlier in this thesis:

*Which minimal renovation strategies are needed to prepare different single-family housing typologies for the integration of low-temperature heating and optimize the thermal comfort of the residence?*

To be able to formulate a well-educated answer to this question, extensive research is performed in the first place on the topics of collective and low-temperature heating, low-temperature ready requirements, applicable renovation measures, thermal comfort, single-family housing typologies and minimal cost-effective renovation strategies. From this literature study, the basis for the practical research is established. A selection of renovation measures on the building and installation scale is studied and assembled to form renovation strategies, which are laid out based on a cost-effectiveness analysis. Through an examination of the Dutch single-family housing stock, sensitive parameters related to the construction period and building type are recognized within the building stock.

An elaborate study on the thermal comfort within a residence demonstrates that the local thermal comfort regarding draught and the mean radiant temperature was partially negatively affected by the implementation of low-temperature heating. The application of renovation measures could possibly counter these unfavourable effects to optimize the comfort in a low-temperature dwelling.

The composed renovation strategies are tested within the simulation software DesignBuilder. The first part of the analysis investigates which minimal strategies are required for the transition to low-temperature heating for the different typologies. The indicators tested here were the heating demand during a winter design week, which gave preliminary insight into the strategies which were low-temperature ready, and hourly air temperature simulations during that same winter design week, which indicate whether the peak demand could be satisfied. The results show that only for the case study building there are suitable renovation strategies that comply with the conditions for both the indicators. The strategies that meet the requirements have at a minimum additional ground floor and wall insulation installed, in combination with the implementation of balance ventilation. The insufficiency of the strategies to meet the requirements for the other typologies is associated with the use of the same heating capacity in all cases, leading to a relatively smaller portion of oversizing of the heating capacity for the other typologies.

The simulations indicate, besides the level of renovation required, the differences between the various typologies. These differences are best noticeable in the effectiveness of measures. The measures implemented, especially the more minimal measures, show great effectiveness in the early construction periods. Due to the poor Rc-value of the opaque parts of these dwellings, the addition of insulation is highly effective here. The building types on the other hand, which have the same thermal properties as the case study but a higher number of exposed external surfaces, require a higher level of intervention, because the application of insulation has less impact in an absolute and relative sense. Additionally, effectiveness is determined by the relative share in heat losses of a component, which can differ between the typologies. For early construction periods, the wall and roof components are more critical, while for newer buildings the ventilation type plays a crucial role.

The second part of the analysis focuses on finding the optimal local thermal comfort conditions possible with renovation

# 11. Conclusion

measures. There is chosen to specifically focus on minimizing the local thermal discomfort by radiant asymmetry and draught, as these aspects are negatively affected by the implementation of low-temperature heating. The CFD tool within DesignBuilder and the software Stralingsverloop are used to test the effects on the following indicators: mean radiant temperature, air temperature, air velocity and radiant asymmetry, all tested on various height levels in the close proximity of the window. The outcomes show that a reduction in draught rate can be accomplished by the implementation of balance ventilation. Furthermore, in cases where no balance ventilation is applied, glazing with an improved U-value can have a positive effect on this matter. Counterbalancing the negative effect of low-temperature heating on the radiant temperature is more difficult and can not fully be achieved. However, the installation of glazing with a lower U-value can help oppose the thermal discomfort experienced as a result of radiant asymmetry. Increasing the insulation value of the different opaque parts has no significant effect on both thermal comfort aspects, and functions only as a measure to lower the heating demand. In all cases, it is of uttermost importance that the heating system is sufficient and thus general comfort is achieved.

This research cannot specifically indicate which renovation strategies are needed per typology to be low-temperature ready and optimize thermal comfort, as this is dependent on several individual factors as well. However, based on the outcomes, recommendations can be made on which type of measures are best to consider per typology to reach low-temperature readiness and to optimize local thermal comfort.
To determine which minimal renovation strategies are required for a dwelling for the transition to low-temperature heating, the relative oversizing of the heating system, the effectiveness of measures and the relative share in heat losses of a component should all be taken into consideration. The last two are strongly related to the building typology, especially to the construction year.
For earlier construction periods, pre-1975, the roof and wall are the most critical parts and should therefore be tackled first in order to reach low-temperature readiness. From a thermal comfort perspective, it is advisable to implement balance ventilation as well to reduce the level of draught. This is, however, due to the large sizing of the system, not always possible, especially in older dwellings. Replacement of the double glazing by HR++ glazing is also effective in reducing the draught and helps to counter radiant asymmetry experienced near the window surface, leading to a more optimal thermal comfort. Dwellings built post-1975 often have a better-insulated building envelope and the ventilation system here becomes more critical and should thus be undertaken first. The best option, if possible, is to switch to balance ventilation because of the positive effect on the local thermal comfort. HR++ glazing can be implemented additionally to reduce radiant asymmetry and optimize the thermal comfort, however, the gain in comfort is lower as in most cases HR glazing is already installed in the existing situation. The outcomes of the analysis do give no reason to adjust the advice considerably based on the building type. The only thing that should be considered is that the wall component is more critical as it has a higher relative heat loss when a larger part of the wall is exposed to the exterior.

# 12. Discussion

The research performed in this thesis has a couple of limitations. First of all, the case study in question has in the actual situation balance ventilation installed, which was turned off during the air temperature measurements. In this research, therefore, it was assumed that in the original situation there was no preheating of the incoming air supply. However, this gives a slightly distorted view of the results, as the installed capacity of the heating system is sized to a heating demand where balance ventilation is considered. In reality, the same dwelling where in fact ventilation system A or C is installed, would be assumed to have a higher heating capacity.
The same case rests for the other typologies, as they have a higher heating demand than the case study and it is expected that in reality their heating capacity is adjusted to that heating demand. However, it is hard to quantify the actual heating capacities of the other typologies and for the simplicity of comparison, it is more suitable in this case to presume the same heating capacity. Follow-up research could potentially zoom in more on the effects of measures and the differences within these effects between typologies, in a case where a heating capacity is assumed for each typology that is more in line with the actual situation.
Furthermore, due to limited detailed information available on the case study, the construction assembly of the different components is simplified. The transmission losses through the opaque envelope are assumed to not be affected, as the Rc-values were known. However, the thermal mass is dependent on the type of material and a wrong assumption here could thus affect the heat storage ability of the dwelling.
Moreover, for this research ventilation rates are assumed based on prescribed numbers for adequate ventilation. In reality, especially in households where ventilation is manually controlled, the actual ventilation is assumed to be lower as a result of human behaviour. This research tries to take human behaviour into account by introducing a minimum outdoor temperature limit for manually operated ventilation systems. However, it remains difficult to simulate ventilation in a sense that it gives a proper representation of the actual situation. The reduction in heating demand generated by the installation of balance ventilation can therefore be overestimated as well.
In addition, in this research, it is assumed that the dwellings have not been renovated yet. It is likely, especially for older dwellings, that in most cases some level of renovation has already been implemented. However, the differences in renovation level have a strong individual character and are therefore disregarded.
Lastly, in this research small differences in mean radiant temperature and radiant asymmetry are detected between HR++ glazing and triple glazing. It is however questionable if these differences are noticeable for humans, as they are relatively small. Further research on this topic could provide more insight if the two are substantially distinctive.

In the background research, it is stated that solely financial gain is not a big enough motivator for energy renovation for most people. In the period between the background research and the finalisation of this research, the gas prices have immensely increased due to scarcity and geopolitical developments, and the financial impulse to perform measures with it as well. Thus, this statement, as of today, might not be credible anymore. For the same reasons, the return of investment rates presented in chapter 8 is not valid anymore as well. However, the ranking of the measures is not expected to change due to these price developments, and the proposed strategy composition method, therefore, is still valid.

# 12. Discussion

The performed study provoked ideas for interesting topics for follow-up research. First of all, a more elaborate study on the differences between renovation strategies in radiator output and the related surface temperature and comfort could be interesting. This is particularly intriguing if a longer measuring period is considered, where intermediate seasons are included as well. It could be that with milder weather conditions a considerable difference in the functioning of the radiator during occupancy hours could be identified.
Furthermore, the differences between internal and external insulation remain underappreciated within this research. Further research could zoom in more on the effect the location of the insulation with respect to the wall could have on the local thermal comfort.
Within the framework of energy renovation, it could also be of interest to research the willingness of people to compromise on certain aspects of their comfort for the integration of a more sustainable heating solution. As this research indicates, it is difficult to reach the same level of comfort with a lower temperature supply, and it is valuable to investigate if households are also accepting of this.

# 13. References

- ABF Research. (2019, September). *Nieuw onderzoek naar de energiezuinigheid van woningen en huishoudens.* https://abfresearch.nl/publicaties/nieuw-onderzoek-naar-de-energiezuinigheid-van-woningen-en-huishoudens/

- Agentschap NL. (2011, January). *Voorbeeldwoningen 2011 Bestaande bouw.* NL Energie en Klimaat. https://www.agentschapnl.nl/woningbouw

- Auliciems, A., & Szokolay, S. V. (2007). *Thermal Comfort* (Second Revised ed.). Passive and Low Energy Architecture International.

- Barguilla Jiménez, N. (2013, February). *The effect of a thin foil on the heat losses behind a radiator* (Master Thesis). University of Gävle, Faculty of Engineering and Sustainable Development, Department of Building, Energy and Environmental Engineering. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A608648&dswid=979

- Bjørneboe, M. G., Svendsen, S., & Heller, A. (2018). Initiatives for the energy renovation of single-family houses in Denmark evaluated on the basis of barriers and motivators. *Energy and Buildings*, 167, 347–358. https://doi.org/10.1016/j.enbuild.2017.11.065

- Carlucci, S., Bai, L., de Dear, R., & Yang, L. (2018). Review of adaptive thermal comfort models in built environmental regulatory documents. *Building and Environment*, 137, 73–89. https://doi.org/10.1016/j.buildenv.2018.03.053

- CBS. (2021a, June). *Klimaatverandering en energietransitie: opvattingen en gedrag van Nederlanders in 2020.* https://www.cbs.nl/nl-nl/longread/rapportages/2021/klimaatverandering-en-energietransitie-opvattingen-en-gedrag-van-nederlanders-in-2020

- CBS. (2021b, October 27). *Voorraad woningen; gemiddeld oppervlak; woningtype, bouwjaarklasse, regio.* opendata.cbs.nl. https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82550NED/table?fromstatweb

- CBS. (2021c, November 21). *Energieverbruik particuliere woningen; woningtype en regio's.* opendata.cbs.nl. https://opendata.cbs.nl/#/CBS/nl/dataset/81528NED/table

- CBS & ECN. (2017, April). *Monitoring warmte 2015* (ECN-E--17-018). Retrieved from https://www.cbs.nl/nl-nl/publicatie/2017/15/monitoring-warmte-2015

- CBS & TNO. (2020, August). *Warmtemonitor 2019.* CBS. https://www.cbs.nl/nl-nl/achtergrond/2020/35/warmtemonitor-2019

- CE Delft. (2019, March). *Functioneel ontwerp LT warmtenetten gebouwde omgeving.* https://www.rvo.nl/sites/default/files/2019/04/functioneel%20ontwerp%20LT-warmtenetten.pdf

- Cetiner, I., & Edis, E. (2014). An environmental and economic sustainability assessment method for the retrofitting of residential buildings. *Energy and Buildings*, 74, 132–140. https://doi.org/10.1016/j.enbuild.2014.01.020

- Darren, J., & Eckert, C. (2017). Overdesign in building services: the hidden energy use. *21st International Conference on Engineering Design.*

- DesignBuilder. (n.d.). *About DesignBuilder.* Designbuilder.Co.Uk. Retrieved April 22, 2022, from https://designbuilder.co.uk/about-us

# 13. References

- Detelin, M. (2002). Practical evaluation of the thermal comfort parameters. *Annual International Course: Ventilation and Indoor Climate*, 158–170.
- Djongyang, N., Tchinda, R., & Njomo, D. (2010). Thermal comfort: A review paper. *Renewable and Sustainable Energy Reviews*, 14(9), 2626–2640. https://doi.org/10.1016/j.rser.2010.07.040

- Dodoo, A., Gustavsson, L., & Tettey, U. Y. (2017). Final energy savings and cost-effectiveness of deep energy renovation of a multi-storey residential building. *Energy*, 135, 563–576. https://doi.org/10.1016/j.energy.2017.06.123

- Dutch New Energy Research. (2020, November). *Nationaal Warmtenet Trendrapport* 2021. https://www.warmtenettrendrapprt.nl/trendrapport/

- DWA. (2016). *Comfortbeleving in goed geïsoleerde woningen met ventilatiesysteem C en lage temperatuurverwarming*. UNETO-VNI.

- Ebrahimigharehbaghi, S., Qian, Q. K., Meijer, F. M., & Visscher, H. J. (2020). Transaction costs as a barrier in the renovation decision-making process: A study of homeowners in the Netherlands. *Energy and Buildings*, 215, 109849. https://doi.org/10.1016/j.enbuild.2020.109849

- Ecofys & Greenvis. (2016, September). *Collectieve warmte naar lage temperatuur: Een verkenning van mogelijkheden en routes*. Retrieved from https://www.topsectorenergie.nl/sites/default/files/uploads/urban%20energy/publicaties/collectieve%20warmte%20naar%20lage%20temperatuur%20-%20definitief.pdf

- Eijdems, H. H. E. W., Boerstra, A. C., & op 't Veld, P. J. M. (1999). *Low temperature heating systems: Impact on IAQ, thermal comfort and energy consumption*. Cauberg Huygen, BBA, Novem. https://www.aivc.org/resource/low-temperature-heating-systems-impact-iaq-thermal-comfort-and-energy-consumption

- Essent & MeMo$^2$. (2020, February 7). *Thermostaat thuis staat gemiddeld op 20 graden*. www.essent.nl. Retrieved February 25, 2022, from https://www.essent.nl/content/overessent/actueel/index.html/thermostaat-thuis-staat-gemiddeld-op-20-graden/

- Fanger, P. O. (1972). *Thermal comfort: analysis and applications in environmental engineering*, . McGraw-Hill.

- Fanger, P., Ipsen, B., Langkilde, G., Olessen, B., Christensen, N., & Tanabe, S. (1985). Comfort limits for asymmetric thermal radiation. *Energy and Buildings*, 8(3), 225–236. https://doi.org/10.1016/0378-7788(85)90006-4

- Florida Solar Energy Center, & Lixing, G. (2007). *ASHRAE Standard 140–2004 Standard Method Of Test For The Evaluation Of Building Energy Analysis Computer Programs: Test Results For The DOE-2.1E (V120) That Is Incorporated In EnergyGauge Summit 3.14*. FSEC Energy Research Center. https://stars.library.ucf.edu/fsec/435

- Gelis, K., & Akyurek, E. F. (2021). Entropy generation of different panel radiator types: Design of experiments using response surface methodology (RSM). *Journal of Building Engineering*, 41, 102369. https://doi.org/10.1016/j.jobe.2021.102369

- Gustafsson, M. (2015, May). *Energy efficient and economic renovation of residential buildings with low-temperature heating and air heat recovery* [Licentiate Thesis, KTH Royal Institute of Technology] Digitala Vetenskapliga Arkivet.

# 13. References

- Hoogervorst, N. (2017). *Toekomstbeeld Klimaatneutrale warmtenetten in Nederland*. PBL. https://www.pbl.nl/publicaties/toekomstbeeld-klimaatneutrale-warmtenetten-in-nederland

- Hudson, G. (2001). The use of the pre-heat margin in heating system design: a review based upon published literature. *Building Services Engineering Research and Technology*, 22(4), 255–260. https://doi.org/10.1177/014362440102200404

- Interreg North-West Europe. (2018, October). *Guide to Integrating 4DHC with Energy Efficiency Retrofitting*. https://www.nweurope.eu

- ISO. (2005). *Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria* (No. 3). https://www.iso.org/standard/39155.html

- ISSO. (2010, December). *ISSO-publicatie 32: Uitgangspunten temperatuursimulatieberekeningen*. Stichting ISSO. https://open.isso.nl/publicatie/isso-publicatie-32-uitgangspunten-temperatuursimulatieberekeningen/2010

- ISSO. (2012, July). *Handboek HBi Installatietechniek* (No. 2). Stichting ISSO. https://open.isso.nl/publicatie/handboek-hbi-installatietechniek/2012

- ISSO. (2014a, March). *Kleintje U- en Rc-waarden* (No. 2). Stichting ISSO. https://open.isso.nl/publicatie/kleintje-u-en-rc-waarden/2014

- ISSO. (2014b, December). *ISSO-publicatie 74 Thermische behaaglijkheid* (No. 2). Stichting ISSO. https://open.isso.nl/publicatie/isso-publicatie-74-thermische-behaaglijkheid/2014

- ISSO. (2022, January). ISSO-publicatie 82.1 E*nergieprestatie woningen en woongebouwen* (No. 4). Stichting ISSO. https://open.isso.nl/publicatie/isso-publicatie-82-1-energieprestatie-woningen-en-woongebouwen/2022/1

- Jeong, B., Jeong, J. W., & Park, J. (2016). Occupant behavior regarding the manual control of windows in residential buildings. *Energy and Buildings*, 127, 206–216. https://doi.org/10.1016/j.enbuild.2016.05.097

- Johansson, P.-O., & Wollerstrand, J. (2010). *Heat Output from Space Heating Radiator with Add-on-fan Blowers*. Nordic Energy Research. https://www.comsol.com/paper/heat-output-from-space-heating-radiator-with-add-on-fan-blowers-8377

- Karmann, C., Schiavon, S., & Bauman, F. (2017). Thermal comfort in buildings using radiant vs. all-air systems: A critical literature review. *Building and Environment*, 111, 123–131. https://doi.org/10.1016/j.buildenv.2016.10.020

- Kauko, H., Alonso, M. J., Stavset, O., & Claussen, I. C. (2014). Case Study on Residential Building Renovation and its Impact on the Energy Use and Thermal Comfort. *Energy Procedia*, 58, 160–165. https://doi.org/10.1016/j.egypro.2014.10.423

- Kennisbank Bouwfyica. (n.d.). *Stralingstemperatuur*. Klimapedia.nl. Retrieved April 12, 2022, from https://klimapedia.nl/module/stralingstemperatuur

- Khodakarami, J., & Knight, I. (2008). Required and Current Thermal Conditions for Occupants in Iranian Hospitals. *HVAC&R Research*, 14(2), 175–193. https://doi.org/10.1080/10789669.2008.10391002

# 13. References

- Kimura, K. (2016). Wind loads. *Innovative Bridge Design Handbook,* 37–48. https://doi.org/10.1016/b978-0-12-800058-8.00003-7

- KNMI. (2022). *KNMI - Bodemtemperaturen.* www.knmi.nl. Retrieved May 24, 2022, from https://www.knmi.nl/nederland-nu/klimatologie/bodemtemperaturen

- Konstantinou, T., & Knaack, U. (2011). Refurbishment of Residential Buildings: A Design Approach to Energy-Efficiency Upgrades. *Procedia Engineering*, 21, 666–675. https://doi.org/10.1016/j.proeng.2011.11.2063

- Langkilde, G., L. Gunnarsen, and N. Mortensen (1985). *Comfort limits during infrared radiant heating of industrial spaces.* CLIMA 2000, Copenhagen.

- Lin, Z., & Deng, S. (2008). *A study on the thermal comfort in sleeping environments in the subtropics—Developing a thermal comfort model for sleeping environments.* Building and Environment, 43(1), 70–81. https://doi.org/10.1016/j.buildenv.2006.11.026

- Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th Generation District Heating (4GDH). *Energy*, 68, 1–11. https://doi.org/10.1016/j.energy.2014.02.089

- Lund, H., ØStergaard, P. A., Chang, M., Werner, S., Svendsen, S., Sorknæs, P., Thorsen, J. E., Hvelplund, F., Mortensen, B. O. G., Mathiesen, B. V., Bojesen, C., Duic, N., Zhang, X., & Möller, B. (2018). The status of 4th generation district heating: Research and results. *Energy*, 164, 147–159. https://doi.org/10.1016/j.energy.2018.08.206

- Mejjaouli, S., & Alzahrani, M. (2020). Decision-making model for optimum energy retrofitting strategies in residential buildings. *Sustainable Production and Consumption*, 24, 211–218. https://doi.org/10.1016/j.spc.2020.07.008

- Melikou, A. K. (1988). *Technical Review: Quantifying Draught Risk* (No. 2). Brüel & Kjaer.

- Milieu Centraal (2020). *Aandeel van toepassingen in het energiegebruik in huis van een gemiddeld huishouden in Nederland in 2019.* Retrieved from https://www.energieinnederland.nl/feiten-en-cijfers/energiecijfers/

- Milieu Centraal. (n.d.). *Lage temperatuur verwarming (ltv).* Retrieved April 3, 2022, from https://www.milieucentraal.nl/energie-besparen/duurzaam-verwarmen-en-koelen/lage-temperatuur-verwarming-ltv/

- Milieudefensie. (2021, April). *Wonen en energie.* I&O Research. https://milieudefensie.nl/actueel/milieudefensie-wonen-en-energie.pdf

- Möhlenkamp, M., Schmidt, M., Wesseling, M., Wick, A., Gores, I., & Müller, D. (2018). Thermal comfort in environments with different vertical air temperature gradients. *Indoor Air*, 29(1), 101–111. https://doi.org/10.1111/ina.12512

- NEN. (2014). NEN-EN 442–2: *Radiators and convectors - Part 2: Test methods and rating.* https://www.nen.nl/en/nen-en-442-2-2014-en-202612

- NIBUD. (2020, September). *Kunnen woningeigenaren energie-investeringen betalen?* NIBUD. https://www.nibud.nl/beroepsmatig/rapport-kunnen-woningeigenaren-energie-investeringen-betalen/

- Nicol, J. F., & Roaf, S. (2017). Rethinking thermal comfort. *Building Research & Information,* 45(7), 711–716. https://doi.org/10.1080/09613218.2017.1301698

- Norton, T., & Sun, D. W. (2006). Computational fluid dynamics (CFD) – an effective and efficient design and analysis tool for the food industry: A review. *Trends in Food Science & Technology*, 17(11), 600–620. https://doi.org/10.1016/j.tifs.2006.05.004

- Olesen, B., & Parsons, K. (2002). Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730. *Energy and Buildings*, 34(6), 537–548. https://doi.org/10.1016/s0378-7788(02)00004-x

- Osilla, E. V., Marsidi, J. L., & Sharma, S. (2021, May 21). *Physiology, Temperature Regulation.* NCBI. Retrieved February 15, 2022, from https://www.ncbi.nlm.nih.gov/books/NBK507838/

- Østergaard, D. S., & Svendsen, S. (2016). Theoretical overview of heating power and necessary heating supply temperatures in typical Danish single-family houses from the 1900s. *Energy and Buildings*, 126, 375–383. https://doi.org/10.1016/j.enbuild.2016.05.034

- Regionaal Energieloket. (n.d.). *Energie Besparen.* https://regionaalenergieloket.nl/energiebesparen

- Palmer, J., & Cooper, I. (2013). United Kingdom housing energy fact file 2013. *A report prepared under contract to DECC by Cambridge Architectural Research, Eclipse Research Consultants and Cambridge Energy. London, UK, Department of Energy & Climate Change.*

- Peeters, L., Dear, R. D., Hensen, J., & D'haeseleer, W. (2009). Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy*, 86(5), 772–780. https://doi.org/10.1016/j.apenergy.2008.07.011

- Pinto, D., Rocha, A., Simões, M. L., Almeida, R. M., Barreira, E., Pereira, P. F., Ramos, N. M., & Poças Martins, J. (2019). An innovative approach to evaluate local thermal discomfort due to draught in semi-outdoor spaces. *Energy and Buildings*, 203, 109416. https://doi.org/10.1016/j.enbuild.2019.109416

- Regionaal Energieloket. (n.d.). *Energie Besparen.* https://regionaalenergieloket.nl/energiebesparen

- Rijksoverheid. (2019). *Klimaatakkoord.* Retrieved from https://www.rijksoverheid.nl/documenten/rapporten/2019/06/28/klimaatakkoord

- Rutten, S. (2021). *LT-READY: Affordable renovation concepts that enable low-temperature heating and provide thermal comfort.* https://repository.tudelft.nl/islandora/object/uuid%3A8b8dedf6-de44-4438-ae6d-2a471656e243?collection=education

- Sayegh, M., Danielewicz, J., Nannou, T., Miniewicz, M., Jadwiszczak, P., Piekarska, K., & Jouhara, H. (2017). Trends of European research and development in district heating technologies. *Renewable and Sustainable Energy Reviews*, 68, 1183–1192. https://doi.org/10.1016/j.rser.2016.02.023

- Serrano-Jiménez, A., Femenías, P., Thuvander, L., & Barrios-Padura, N. (2021). A multi-criteria decision support method towards selecting feasible and sustainable housing renovation strategies. *Journal of Cleaner Production*, 278, 123588. https://doi.org/10.1016/j.jclepro.2020.123588

- Sociaal en Cultureel Planbureau. (2021, April 29). *Drijfveren en ervaren*

# 13. References

*barrières bij woningeigenaren*. www.SCP.nl. Retrieved November 18, 2021, from https://www.scp.nl/actueel/nieuws/2021/04/29/woningverduurzaming

- Solvari BV. (2019, February 5). *Koud dak: opbouw en nadelen*. Dakisolatie-advies.nl. Retrieved March 10, 2022, from https://www.dakisolatie-advies.nl/koud-dak

- Tereshchenko, T., & Nord, N. (2018). Future Trends in District Heating Development. Current Sustainable/*Renewable Energy Reports*, 5(2), 172–180. https://doi.org/10.1007/s40518-018-0111-y

- The Open University. (n.d.). *Energy in Buildings*. Open.Edu. Retrieved March 12, 2022, from https://www.open.edu/openlearn/nature-environment/energy-buildings/

- TSI Incorporated. (2013). *Draft Rate: A Determining Factor in the Quantification Of Human Comfort*. https://tsi.com

- *Turbulence intensity* - CFD. (2022, March 15). Https://Www.Cfd-Online.Com. Retrieved April 29, 2022, from https://www.cfd-online.com/wiki/turbulence_intensity

- United Nations. (2015, December). *Paris Agreement*. https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en#EndDec

- Van Der Voorde, S., Bertels, I., & Wouters, I. (2015). Glas en beglazing. naoorlogsebouwmaterialen.be. Retrieved April 8, 2022, from http://naoorlogsebouwmaterialen.be/materiaal/glas-en-beglazing/#:%7E:text=Dubbel%20glas%20was%20%C3%A9%C3%A9n%20van,1950%20was%20het%20courant%20verkrijgbaar.

- Van Hoof, J. (2008). Forty years of Fanger's model of thermal comfort: comfort for all? *Indoor Air*, 18(3), 182–201. https://doi.org/10.1111/j.1600-0668.2007.00516.x
- Wang, Z., de Dear, R., Luo, M., Lin, B., He, Y., Ghahramani, A., & Zhu, Y. (2018). Individual difference in thermal comfort: A literature review. *Building and Environment*, 138, 181–193. https://doi.org/10.1016/j.buildenv.2018.04.040

- Wang, Q., Ploskić, A., & Holmberg, S. (2015). Retrofitting with low-temperature heating to achieve energy-demand savings and thermal comfort. *Energy and Buildings*, 109, 217–229. https://doi.org/10.1016/j.enbuild.2015.09.047

- Wiebes, E.D. (2019, September 10). *Gaswinningsniveau Groningen in 2019-2020* [letter to parliament]. Retrieved from https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail?id=2019Z16814&did=2019D34862

- Zimmerman, M. (2012). P*refabricated Systems for Low Energy Renovation of Residential Buildings*. AECOM Ltd. http://www.iea-ebc.org/Data/publications/EBC_PSR_Annex50.pdf

# 13. References

## list of figures

- Funda. (2022a). *Achillesburg 44* [Photograph]. Funda. https://www.funda.nl/koop/nieuwegein/huis-42793141-achillesburg-44/

- Funda. (2022b). *De Hoop 2* [Photograph]. Funda. https://www.funda.nl/koop/zeewolde/huis-42794803-de-hoop-2/

- Funda. (2022c). *Hondsdrafstraat 7* [Photograph]. Funda. https://www.funda.nl/koop/arnhem/huis-42705450-hondsdrafstraat-7/

- Funda. (2022d). *Kayersdijk 79 C* [Photograph]. Funda. https://www.funda.nl/koop/apeldoorn/huis-42794628-kayersdijk-79-c/

- Funda. (2022e). *Krekelbos 28* [Photograph]. Funda. https://www.funda.nl/koop/eersel/huis-42794178-krekelbos-28/

- Funda. (2022f). *Laurens Costerplein 20* [Photograph]. Funda. https://www.funda.nl/koop/amersfoort/huis-42798274-laurens-costerplein-20/

- Funda. (2022g). *Sterreschans 2* [Photograph]. Funda. https://www.funda.nl/koop/assendelft/huis-42790454-sterreschans-2/

- Kaynakli, O. (2014). Economic thermal insulation thickness for pipes and ducts: A review study. Renewable and Sustainable Energy Reviews, 30, 184–194. https://doi.org/10.1016/j.rser.2013.09.026

- Milieu Centraal (2020). *Aandeel van toepassingen in het energiegebruik in huis van een gemiddeld huishouden in Nederland in 2019*. Retrieved from https://www.energieinnederland.nl/feiten-en-cijfers/energiecijfers

# Appendix A

*building characteristics typologies*

| Housing Typology | Average Surface [m$^2$] | Average amount of Floors | Average amount of Rooms | Single Glazing [%] | Double Glazing [%] | HR Glazing [%] | Insulation* | Natural Ventilation [%] | Mechanical Ventilation [%] | Balance Ventilation [%] | Airtight Sealing [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | |
| Free-standing Housing | | | | | | | | | | | |
| 1000 -1964 | 130+ | 2 to 4 | 4 to 6 | 29 | 58 | 13 | Low | 89 | 11 | 0 | 18 |
| 1965 - 1974 | 130+ | 2 to 4 | 4 to 6 | 17 | 69 | 14 | Low | 91 | 9 | 0 | 52 |
| 1975 - 1991 | 130+ | 2 to 4 | 4 to 7 | 15 | 76 | 9 | Medium Low | 78 | 20 | 1 | 100 |
| 1991 - 2005 | 130+ | 2 to 4 | 4 to 7 | 1 | 45 | 54 | Sufficient | 35 | 48 | 16 | 100 |
| | | | | | | | | | | | |
| Semi-detached Housing | | | | | | | | | | | |
| 1000 - 1964 | 110+ | 3 to 4 | 4 to 5 | 28 | 57 | 15 | Low | 90 | 7 | 2 | 26 |
| 1965 - 1974 | 110+ | 3 | 4 to 5 | 25 | 57 | 18 | Low | 87 | 11 | 0 | 44 |
| 1975 - 1991 | 110+ | 3 | 4 to 6 | 20 | 72 | 8 | Medium Low | 55 | 44 | 1 | 100 |
| 1991 - 2005 | 110+ | 3 | 4 to 6 | 3 | 53 | 44 | Sufficient | 21 | 62 | 16 | 100 |
| | | | | | | | | | | | |
| Row-Housing | | | | | | | | | | | |
| 1000 - 1945 | 100 | 3 | 3 to 5 | 38 | 52 | 10 | Low | 89 | 9 | 0 | 26 |
| 1946 - 1964 | 100 | 3 | 4 to 5 | 28 | 69 | 12 | Low | 91 | 9 | 0 | 27 |
| 1965 - 1974 | 100 | 3 | 4 to 5 | 22 | 60 | 18 | Low | 82 | 18 | 0 | 35 |
| 1975 - 1991 | 100 | 3 | 4 to 5 | 21 | 69 | 10 | Medium Low | 44 | 53 | 2 | 100 |
| 1991 - 2005 | 100 | 2 to 3 | 4 to 5 | 2 | 43 | 55 | Sufficient | 12 | 73 | 12 | 100 |
| | | | | | | | | | | | |

# Appendix B

## *calculation of renewed heating capacity low temperature*

**Theoretical overview of heating power and necessary heating supply temperatures in typical Danish single-family houses from the 1900s**

**Østergaard, Dorte Skaarup; Svendsen, Svend**

$$\phi = \left(\frac{\Delta T}{\Delta T_0}\right)^n \cdot \phi_0 \qquad \Delta T = \frac{T_s - T_r}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)}$$

| | | | | |
|---|---|---|---|---|
| High Temperature | Ts 0 | Supply Temperature | 90 | [°C] |
| | Tr 0 | Return Temperature | 70 | [°C] |
| | Ti 0 | Indoor Air Temperature | 20 | [°C] |
| | Delta T 0 | Logarithmic Mean Temperature | 59,44 | [°C] |
| | | | | |
| Low Temperature | Ts | Supply Temperature | 55 | [°C] |
| | Tr | Return Temperature | 35 | [°C] |
| | Ti | Indoor Air Temperature | 20 | [°C] |
| | Delta T | Logarithmic Mean Temperature | 23,60 | [°C] |
| | | | | |
| Heating Power LT | n | Radiator Exponent | 1,3 | [-] |
| | Phi 0 | Design Heating power of the Radiators HT | 8575 | [W] |
| | Phi | Design Heating power of the Radiators LT | 2581 | [W] |

High temperature 90/70/20

| Room | Output | |
|---|---|---|
| Living Room | 2584 | [W] |
| Kitchen | 1326 | [W] |
| Hallway | 509 | [W] |
| Toilet | - | [W] |
| Hallway 2 | - | [W] |
| Bedroom 1 | 1768 | [W] |
| Bedroom 2 | 796 | [W] |
| Bedroom 3 | 945 | [W] |
| Bathroom | - | [W] |
| Attic | - | [W] |
| Bedroom 4 | 647 | [W] |
| TOTAL | 8575 | [W] |

Low temperature 55/35/20

| Room | Output | |
|---|---|---|
| Living Room | 778 | [W] |
| Kitchen | 399 | [W] |
| Hallway | 153 | [W] |
| Toilet | - | [W] |
| Hallway 2 | - | [W] |
| Bedroom 1 | 532 | [W] |
| Bedroom 2 | 240 | [W] |
| Bedroom 3 | 284 | [W] |
| Bathroom | - | [W] |
| Attic | - | [W] |
| Bedroom 4 | 195 | [W] |
| TOTAL | 2581 | [W] |

░ Fill in
▒ Interim answer
▓ Answer

---

# Appendix B

## *calculation ofinfiltration rate based on type and year*

| | | |
|---|---|---|
| $F_{type}$ | 1 | [-] |
| | | |
| $F_{year}$ | 2 | [-] |
| | | |
| $q_{v10;spec;reken}$ | 1 | [dm³/(s*m²)] |
| | | |
| $q_{v10;lea;ref}$ | 2 | [dm³/(s*m²)] |
| | | |
| $N_{lea}$ | 0,67 | [-] |
| | | |
| A (usage area) | 147,40 | [m²] |
| | | |
| Qv1;lea;ref | 226,90 | [m³/h] |
| | | |
| V (usage volume) | 387,50 | [m³] |
| | | |
| Airchange per hour | 0,59 | [h-1] |

$$q_{v10;lea;ref} = f_{type} \times f_y \times q_{v10;spec;reken}$$

(eq. A.1)

$q_{v10;lea;ref}$ = the specific air permeability of a dwelling, considering a uniform pressure difference of 10 Pa, in dm³/(s*m²)
$f_{type}$ = the building type dependent correction factor for the calculation value for air permeability
$f_y$ = the construction year dependent correction factor for the calculation value for air permeability
$q_{v10;spec;reken}$ = the calculation value for the specific air permeability , considering a uniform presuure difference of 10 Pa, in dm³/(s*m²) = 1 dm³/(s*m²) for single-family housing with a pitched roof

$$q_{v1;lea;ref} = q_{v10;lea;ref} \times \frac{1}{10^{n_{lea}}} \times A_g \times 3{,}6$$

(eq. A.2)

$q_{v1;lea;ref}$ = the air permeability of a dwelling, considering a uniform pressure difference of 1 Pa, in m³/h
$n_{lea}$ = the flow exponent (no unit) = 0,67 for leakage losses
$A_g$ = the usage area for the calculation zone in m²

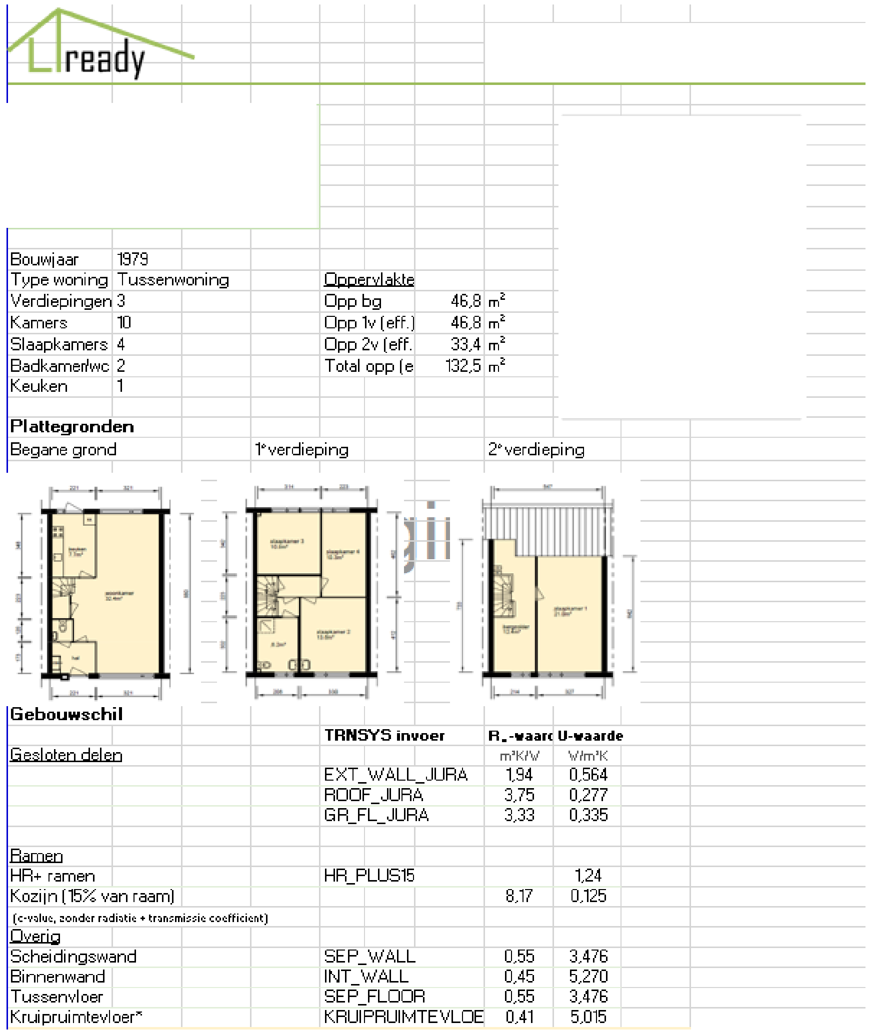
| | | | | | |
|---|---|---|---|---|---|
| $F_{type}$ | freestanding | semi-detached | terraced | | |
| | 1,4 | 1,2 | 1 | | |
| $F_{year}$ | < 1970 | 1970 ≤ 1980 | 1980 ≤ 1990 | 1990 ≤ 2000 | 2000 ≤ 2010 |
| | 3 | 2,5 | 2 | 1,5 | 1 |

░ Fill in
▒ Interim answer
▓ Answer

Calculation method of the NEN. (2022). NTA 8800:2022 *Energieprestatie van gebouwen - bepalingsmethode.* https://www.nen.nl/nta-8800-2022-nl-290717

# Appendix C

## *resultsheet info case study dwelling, from LTReady project*



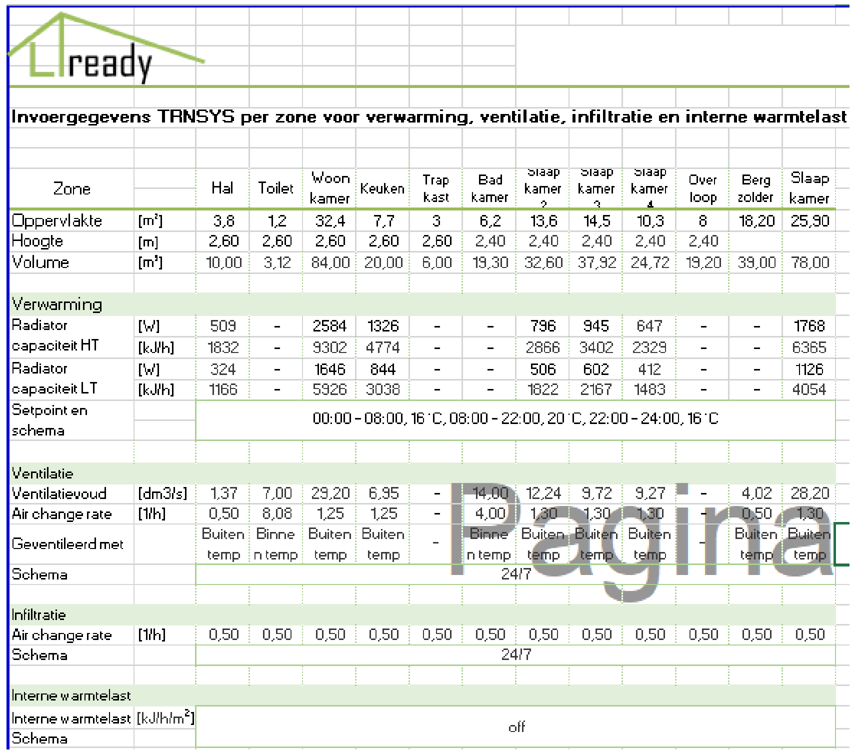
| | | | | |
|---|---|---|---|---|
| Bouwjaar | 1979 | | | |
| Type woning | Tussenwoning | Oppervlakte | | |
| Verdiepingen | 3 | Opp bg | 46,8 | m² |
| Kamers | 10 | Opp 1v (eff.) | 46,8 | m² |
| Slaapkamers | 4 | Opp 2v (eff. | 33,4 | m² |
| Badkamer/wc | 2 | Total opp (e | 132,5 | m² |
| Keuken | 1 | | | |

**Plattegronden**

| Begane grond | 1°verdieping | 2°verdieping |
|---|---|---|

**Gebouwschil**

| | TRNSYS invoer | R-waard | U-waarde |
|---|---|---|---|
| Gesloten delen | | m²K/W | W/m²K |
| | EXT_WALL_JURA | 1,94 | 0,564 |
| | ROOF_JURA | 3,75 | 0,277 |
| | GR_FL_JURA | 3,33 | 0,335 |
| Ramen | | | |
| HR+ ramen | HR_PLUS15 | | 1,24 |
| Kozijn (15% van raam) | | 8,17 | 0,125 |
| (c-value, zonder radiatie + transmissie coefficient) | | | |
| Overig | | | |
| Scheidingswand | SEP_WALL | 0,55 | 3,476 |
| Binnenwand | INT_WALL | 0,45 | 5,270 |
| Tussenvloer | SEP_FLOOR | 0,55 | 3,476 |
| Kruipruimtevloer* | KRUIPRUIMTEVLOE | 0,41 | 5,015 |



**Invoergegevens TRNSYS per zone voor verwarming, ventilatie, infiltratie en interne warmtelast**

| Zone | | Hal | Toilet | Woon kamer | Keuken | Trap kast | Bad kamer | Slaap kamer 2 | Slaap kamer 3 | Slaap kamer 4 | Over loop | Berg zolder | Slaap kamer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oppervlakte | [m²] | 3,8 | 1,2 | 32,4 | 7,7 | 3 | 6,2 | 13,6 | 14,5 | 10,3 | 8 | 18,20 | 25,90 |
| Hoogte | [m] | 2,60 | 2,60 | 2,60 | 2,60 | 2,60 | 2,40 | 2,40 | 2,40 | 2,40 | 2,40 | | |
| Volume | [m³] | 10,00 | 3,12 | 84,00 | 20,00 | 6,00 | 19,30 | 32,60 | 37,92 | 24,72 | 19,20 | 39,00 | 78,00 |
| Verwarming | | | | | | | | | | | | | |
| Radiator | [W] | 509 | - | 2584 | 1326 | - | - | 796 | 945 | 647 | - | - | 1768 |
| capaciteit HT | [kJ/h] | 1832 | - | 9302 | 4774 | - | - | 2866 | 3402 | 2329 | - | - | 6365 |
| Radiator | [W] | 324 | - | 1646 | 844 | - | - | 506 | 602 | 412 | - | - | 1126 |
| capaciteit LT | [kJ/h] | 1166 | - | 5926 | 3038 | - | - | 1822 | 2167 | 1483 | - | - | 4054 |
| Setpoint en schema | | 00:00 - 08:00, 16 °C, 08:00 - 22:00, 20 °C, 22:00 - 24:00, 16 °C | | | | | | | | | | | |
| Ventilatie | | | | | | | | | | | | | |
| Ventilatievoud | [dm3/s] | 1,37 | 7,00 | 29,20 | 6,95 | - | 14,00 | 12,24 | 9,72 | 9,27 | - | 4,02 | 28,20 |
| Air change rate | [1/h] | 0,50 | 8,08 | 1,25 | 1,25 | - | 4,00 | 1,30 | 1,30 | 1,30 | - | 0,50 | 1,30 |
| Geventileerd met | | Buiten temp | Binnen temp | Buiten temp | Buiten temp | - | Binnen temp | Buiten temp | Buiten temp | Buiten temp | - | Buiten temp | Buiten temp |
| Schema | | 24/7 | | | | | | | | | | | |
| Infiltratie | | | | | | | | | | | | | |
| Air change rate | [1/h] | 0,50 | 0,50 | 0,50 | 0,50 | 0,50 | 0,50 | 0,50 | 0,50 | 0,50 | 0,50 | 0,50 | 0,50 |
| Schema | | 24/7 | | | | | | | | | | | |
| Interne warmtelast | | | | | | | | | | | | | |
| Interne warmtelast | [kJ/h/m²] | off | | | | | | | | | | | |
| Schema | | | | | | | | | | | | | |

# Appendix D

## *overview of strategies*

| Strategy 1 | Measures |
|---|---|
| Glazing | - |
| Wall | Cavity insulation, extra Rd = 1,00 |
| Roof | - |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C1 |

| Strategy 2 | Measures |
|---|---|
| Glazing | - |
| Wall- | Interior insulation 5 cm, extra Rd = 1,4 |
| Roof | - |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C1 |

| Strategy 3 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 10 cm, extra Rd = 2,8 |
| Roof | - |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C1 |

| Strategy 4 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 10 cm, extra Rd = 2,8 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C1 |

| Strategy 5 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C1 |

| Strategy 11 | Measures |
|---|---|
| Glazing | - |
| Wall= | Cavity insulation, extra Rd = 1,00 |
| Roof | - |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C3 |

| Strategy 12 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 5 cm, extra Rd = 1,4 |
| Roof | - |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C3 |

| Strategy 13 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 10 cm, extra Rd = 2,8 |
| Roof | - |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C3 |

| Strategy 14 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 10 cm, extra Rd = 2,8 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C3 |

| Strategy 15 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C3 |

| Strategy 21 | Measures |
|---|---|
| Glazing | - |
| Wall | Cavity insulation, extra Rd = 1,00 |
| Roof | - |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | D2 |

| Strategy 22 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 5 cm, extra Rd = 1,4 |
| Roof | - |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | D2 |

| Strategy 23 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 10 cm, extra Rd = 2,8 |
| Roof | - |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | D2 |

| Strategy 24 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 10 cm, extra Rd = 2,8 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | D2 |

| Strategy 25 | Measures |
|---|---|
| Glazing | - |
| Wall | Interior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | D2 |

# Appendix D

## overview of strategies

| Strategy 6 | Measures |
|---|---|
| Glazing | - |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C1 |

| Strategy 7 | Measures |
|---|---|
| Glazing | HR++ glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C1 |

| Strategy 8 | Measures |
|---|---|
| Glazing | HR++ glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Above ground floor 4 cm, extra Rd = 1,8 |
| Ventilation | C1 |

| Strategy 9 | Measures |
|---|---|
| Glazing | HR++ glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Crawl space, extra Rd = 4,0 |
| Ventilation | C1 |

| Strategy 10 | Measures |
|---|---|
| Glazing | Triple glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Crawl space, extra Rd = 4,0 |
| Ventilation | C1 |

| Strategy 16 | Measures |
|---|---|
| Glazing | - |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C3 |

| Strategy 17 | Measures |
|---|---|
| Glazing | HR++ glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | C3 |

| Strategy 18 | Measures |
|---|---|
| Glazing | HR++ glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Above ground floor 4 cm, extra Rd = 1,8 |
| Ventilation | C3 |

| Strategy 19 | Measures |
|---|---|
| Glazing | HR++ glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Crawl space, extra Rd = 4,0 |
| Ventilation | C3 |

| Strategy 20 | Measures |
|---|---|
| Glazing | Triple glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Crawl space, extra Rd = 4,0 |
| Ventilation | C3 |

| Strategy 26 | Measures |
|---|---|
| Glazing | - |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | D2 |

| Strategy 27 | Measures |
|---|---|
| Glazing | HR++ glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Below ground floor 10 cm, extra Rd =3,5 |
| Ventilation | D2 |

| Strategy 28 | Measures |
|---|---|
| Glazing | HR++ glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Above ground floor 4 cm, extra Rd = 1,8 |
| Ventilation | D2 |

| Strategy 29 | Measures |
|---|---|
| Glazing | HR++ glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Crawl space, extra Rd = 4,0 |
| Ventilation | D2 |

| Strategy 30 | Measures |
|---|---|
| Glazing | Triple glazing, new window frame |
| Wall | Exterior insulation 10 cm, extra Rd = 2,8 |
| Roof | Roof inside 15 cm, extra Rd = 4,5 |
| Floor | Crawl space, extra Rd = 4,0 |
| Ventilation | D2 |

# Appendix E

## overview of constructions - case study

### Wall Constructions Case Study and Renovation Measures

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Wall case study | Rsi | - | - | 0,13 |
| | Gypsum Plaster | 2 | 0,4 | 0,01 |
| | Brick | 100 | 0,62 | 0,16 |
| | Mineral Fibre/Wool | 50 | 0,038 | 1,32 |
| | Air | 50 | 0,24 | 0,21 |
| | Brick | 80 | 0,84 | 0,10 |
| | Rse | - | - | 0,04 |
| | Rc | | | 1,96 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Cavity insulation (+ Rd of 1,0) | Rsi | - | - | 0,13 |
| | Gypsum Plaster | 2 | 0,4 | 0,01 |
| | Brick | 100 | 0,62 | 0,16 |
| | Mineral Fibre/Wool | 90 | 0,038 | 2,37 |
| | Air | 10 | 0,066 | 0,15 |
| | Brick | 80 | 0,84 | 0,10 |
| | Rse | - | - | 0,04 |
| | Rc | | | 2,95 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Interior insulation, 5 cm (+ Rd of 1,4) | Rsi | - | - | 0,13 |
| | Gypsum Plaster | 2 | 0,4 | 0,01 |
| | MW Glass Wool (Standard Board) | 50 | 0,036 | 1,39 |
| | Brick | 100 | 0,62 | 0,16 |
| | Mineral Fibre/Wool | 50 | 0,038 | 1,32 |
| | Air | 50 | 0,24 | 0,21 |
| | Brick | 80 | 0,84 | 0,10 |
| | Rse | - | - | 0,04 |
| | Rc | | | 3,34 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Interior insulation, 10 cm (+ Rd of 2,8) | Rsi | - | - | 0,13 |
| | Gypsum Plaster | 2 | 0,4 | 0,01 |
| | MW Glass Wool (Standard Board) | 100 | 0,036 | 2,78 |
| | Brick | 100 | 0,62 | 0,16 |
| | Mineral Fibre/Wool | 50 | 0,038 | 1,32 |
| | Air | 50 | 0,24 | 0,21 |
| | Brick | 80 | 0,84 | 0,10 |
| | Rse | - | - | 0,04 |
| | Rc | | | 4,73 |

▢ Fill in
🟩 Answer

# Appendix E

## overview of strategies - case study

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Exterior insulation, 10 cm (+ Rd of 2,8) | Rsi | - | - | 0,13 |
| | Gypsum Plaster | 2 | 0,4 | 0,01 |
| | Brick | 100 | 0,62 | 0,16 |
| | Mineral Fibre/Wool | 50 | 0,038 | 1,32 |
| | Air | 50 | 0,24 | 0,21 |
| | Brick | 80 | 0,84 | 0,10 |
| | MW Glass Wool (Standard Board) | 100 | 0,036 | 2,78 |
| | Brick | 50 | 0,84 | 0,06 |
| | Rse | - | - | 0,04 |
| | Rc | | | 4,79 |

### Roof Constructions Case Study and Renovation Measures

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Roof case study | Rsi | - | - | 0,10 |
| | Wood Multiplex | 20 | 0,12 | 0,17 |
| | Mineral Fibre/Wool | 130 | 0,038 | 3,42 |
| | Roofing Felt | 5 | 0,19 | 0,03 |
| | Clay Tile | 30 | 1 | 0,03 |
| | Rse | - | - | 0,04 |
| | Rc | | | 3,78 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Interior insulation, 10 cm (+ Rd of 2,8) | Rsi | - | - | 0,10 |
| | Wood Multiplex | 20 | 0,12 | 0,17 |
| | MW Glass Wool (standard board) | 100 | 0,036 | 2,78 |
| | Mineral Fibre/Wool | 130 | 0,038 | 3,42 |
| | Roofing Felt | 5 | 0,19 | 0,03 |
| | Clay Tile | 30 | 1 | 0,03 |
| | Rse | - | - | 0,04 |
| | Rc | | | 6,56 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Interior insulation, 15 cm (+ Rd of 2,8) | Rsi | - | - | 0,10 |
| | Wood Multiplex | 20 | 0,12 | 0,17 |
| | MW Glass Wool (High Performance Panels) | 150 | 0,032 | 4,69 |
| | Mineral Fibre/Wool | 130 | 0,038 | 3,42 |
| | Roofing Felt | 5 | 0,19 | 0,03 |
| | Clay Tile | 30 | 1 | 0,03 |
| | Rse | - | - | 0,04 |
| | Rc | | | 8,47 |

▨ Fill in
🟩 Answer

# Appendix E

## overview ofconstructions - case study

### Floor Constructions Case Study and Renovation Measures

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Floor case study | Rsi | - | - | 0,10 |
| | Timber Flooring | 20 | 0,14 | 0,14 |
| | XPS Extruded Polystyrene - CO2 Blowing | 95 | 0,034 | 2,79 |
| | Cast Concrete | 100 | 1,13 | 0,09 |
| | Rse | - | - | 0,17 |
| | Rc | | | 3,30 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Crawlspace insulation (+ Rd of 4,0) | Rsi | - | - | 0,10 |
| | Cast Concrete | 150 | 1,13 | 0,13 |
| | Spray-On R12 Insulation PU Foam | 170 | 0,042 | 4,05 |
| | Rse | - | - | 0,17 |
| | Rc | | | 4,45 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Above ground floor insulation, 4 cm (+ Rd of 1,5) | Rsi | - | - | 0,10 |
| | Timber Flooring | 20 | 0,14 | 0,14 |
| | XPS Extruded Polystyrene - HFC Blowing | 40 | 0,03 | 1,33 |
| | Timber Flooring | 20 | 0,14 | 0,14 |
| | Cast Concrete | 100 | 1,13 | 0,09 |
| | XPS Extruded Polystyrene - CO2 Blowing | 100 | 0,034 | 2,94 |
| | Rse | - | - | 0,17 |
| | Rc | | | 4,92 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Below ground floor insulation, 10 cm (+ Rd of 3,3) | Rsi | - | - | 0,10 |
| | Timber Flooring | 20 | 0,14 | 0,14 |
| | XPS Extruded Polystyrene - CO2 Blowing | 95 | 0,034 | 2,79 |
| | Cast Concrete | 100 | 1,13 | 0,09 |
| | XPS Extruded Polystyrene - HFC Blowing | 100 | 0,03 | 3,33 |
| | Rse | - | - | 0,17 |
| | Rc | | | 6,63 |

▨ Fill in
🟩 Answer

# Appendix E

## overview ofconstructions - construction periods

### Assumed Rc-values per component for different Construction Periods*

| Construction Year | Facade | Roof | Floor | Notes |
|---|---|---|---|---|
| till 1964 | 0,35 | 0,15 | 0,22 | Very low: Assumed that Rse and Rsi are not included |
| 1965 - 1974 | 0,43 | 0,86 | 0,17 | Very low: Assumed that Rse and Rsi are not included |
| 1975 - 1983 | 1,3 | 1,3 | 0,52 | Not included because similar to next group |
| 1984 - 1987 | 1,3 | 1,3 | 1,3 | |
| 1988 - 1992 | 2 | 2 | 1,3 | |

*based on ISSO. (2022, January). ISSO-publicatie 82.1 E*nergieprestatie woningen en woongebouwen* (No. 4). Stichting ISSO. https://open.isso.nl/publicatie/isso-publicatie-82-1-energieprestatie-woningen-en-woongebouwen/2022/1

### Wall Constructions per Construction Period

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Wall pre 1964 | Rsi | - | - | 0,13 |
| | Brick | 100 | 0,84 | 0,12 |
| | Air | 10 | 0,066 | 0,15 |
| | Brick | 80 | 0,84 | 0,10 |
| | Rse | - | - | 0,04 |
| | Rc | | | 0,54 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Wall 1965 - 1974 | Rsi | - | - | 0,13 |
| | Brick | 100 | 0,84 | 0,12 |
| | Air | 15 | 0,066 | 0,23 |
| | Brick | 80 | 0,84 | 0,10 |
| | Rse | - | - | 0,04 |
| | Rc | | | 0,61 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Wall 1976-1987 | Rsi | - | - | 0,13 |
| | Gypsum Plaster | 2 | 0,4 | 0,01 |
| | Brick | 100 | 0,62 | 0,16 |
| | Mineral Fibre/Wool | 25 | 0,038 | 0,66 |
| | Air | 50 | 0,24 | 0,21 |
| | Brick | 80 | 0,84 | 0,10 |
| | Rse | - | - | 0,04 |
| | Rc | | | 1,30 |

### Floor Constructions per Construction Period

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Floor pre 1964 | Rsi | - | - | 0,10 |
| | Timber Flooring | 20 | 0,14 | 0,14 |
| | Rse | - | - | 0,17 |
| | Rc | | | 0,41 |

⬜ Fill in
🟩 Answer

# Appendix E

## overview ofconstructions - construction periods

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Floor 1965 - 1974 | Rsi | - | - | 0,10 |
| | Timber Flooring | 20 | 0,14 | 0,14 |
| | Rse | - | - | 0,17 |
| | Rc | | | 0,41 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Floor 1975 - 1987 | Rsi | - | - | 0,10 |
| | Timber Flooring | 20 | 0,14 | 0,14 |
| | XPS Extruded Polysterene - CO2 Blowing | 25 | 0,034 | 0,74 |
| | Cast Concrete | 100 | 1,13 | 0,09 |
| | Rse | - | - | 0,17 |
| | Rc | | | 1,24 |

### Roof Constructions per Construction Period

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Roof pre 1964 | Rsi | - | - | 0,10 |
| | Wood Multiplex | 20 | 0,12 | 0,17 |
| | Roofing Felt | 5 | 0,19 | 0,03 |
| | Clay Tile | 30 | 1 | 0,03 |
| | Rse | - | - | 0,04 |
| | Rc | | | 0,36 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Roof 1965 - 1974 | Rsi | - | - | 0,10 |
| | Wood Multiplex | 20 | 0,12 | 0,17 |
| | MW Stone Wool (rolls) | 25 | 0,04 | 0,63 |
| | Roofing Felt | 5 | 0,19 | 0,03 |
| | Clay Tile | 30 | 1 | 0,03 |
| | Rse | - | - | 0,04 |
| | Rc | | | 0,99 |

| Component | Material | Thickness [mm] | Lambda [W/mK] | R-value [m2K/W] |
|---|---|---|---|---|
| Roof 1975 - 1987 | Rsi | - | - | 0,10 |
| | Wood Multiplex | 20 | 0,12 | 0,17 |
| | MW Stone Wool (rolls) | 40 | 0,04 | 1,00 |
| | Roofing Felt | 5 | 0,19 | 0,03 |
| | Clay Tile | 30 | 1 | 0,03 |
| | Rse | - | - | 0,04 |
| | Rc | | | 1,36 |

For the renovation measures for the different construction periods, the same methodology of applying insulation is applied as for the case study dwelling.

⬜ Fill in
🟩 Answer

# Appendix F

## Strategy outcomes

### Pre 1964

| Strategy | Sufficient Heating Capacity | Capacity [W] | Difference (Heating capacity and Demand) [kW] | Heating Capacity [kWh] | Heating Demand x1,25 | Heating Demand [kWh] | Glazing [kWh] | Walls [kWh] | Ceiling (int) [kWh] | Floors (int) [kWh] | Ground Floor [kWh] | Partitions (int) [kWh] | Roofs [kWh] | External infiltration [kWh] | External Ventilation [kWh] | Solar gains Windows (ext) [kWh] | Effectiveness [reduction in percentage] | Effectiveness [reduction in percentage] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | |
| BASIS | N.A. | 8575 | -222 | 1441 | -1663 | -1330 | -124 | -233 | 6 | -15 | -135 | -16 | -421 | -424 | -136 | 167 | | |
| BASIS LOW TEMP | 🟫 | 2581 | -1229 | 434 | -1663 | -1330 | -124 | -233 | 6 | -15 | -135 | -16 | -421 | -424 | -136 | 167 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 1 | 🟫 | 2581 | -663 | 434 | -1096 | -877 | -133 | -96 | -117 | 111 | -24 | -12 | -481 | -150 | -142 | 167 | -59% (wall) | -82% (ground floor) |
| STRATEGY 2 | 🟫 | 2581 | -636 | 434 | -1070 | -856 | -133 | -72 | -117 | 110 | -24 | -12 | -484 | -150 | -142 | 167 | -69% (wall) | |
| STRATEGY 3 | 🟫 | 2581 | -602 | 434 | -1036 | -828 | -134 | -43 | -116 | 110 | -25 | -11 | -487 | -149 | -141 | 167 | -82% (wall) | |
| STRATEGY 4 | 🟫 | 2581 | -134 | 434 | -568 | -454 | -144 | -48 | 16 | -18 | -25 | -3 | -86 | -160 | -153 | 167 | -84% (roof) | |
| STRATEGY 5 | 🟫 | 2581 | -93 | 434 | -527 | -422 | -145 | -48 | 25 | -26 | -25 | -2 | -55 | -159 | -153 | 167 | -87% (roof) | |
| STRATEGY 6 | 🟫 | 2581 | -91 | 434 | -524 | -419 | -145 | -48 | 25 | -26 | -25 | -2 | -55 | -158 | -152 | 167 | -79% (wall) | |
| STRATEGY 7 | 🟫 | 2581 | -45 | 434 | -478 | -383 | -29 | -49 | 17 | -18 | -25 | -1 | -55 | -158 | -152 | 87 | -77% (glazing) | |
| STRATEGY 8 | 🟫 | 2581 | -67 | 434 | -501 | -401 | -29 | -48 | 40 | -41 | -44 | -1 | -55 | -158 | -152 | 87 | -67% (ground floor) | |
| STRATEGY 9 | 🟫 | 2581 | -58 | 434 | -491 | -393 | -29 | -51 | 25 | -26 | -24 | -1 | -55 | -165 | -154 | 87 | -82% (ground floor) | |
| STRATEGY 10 | 🟫 | 2581 | -62 | 434 | -496 | -396 | -25 | -51 | 26 | -27 | -24 | -1 | -55 | -165 | -154 | 79 | -80% (glazing) | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 11 | 🟫 | 2581 | -625 | 434 | -1058 | -847 | -133 | -97 | -115 | 107 | -24 | -13 | -486 | -151 | -102 | 167 | | -25% (ventilation C3) |
| STRATEGY 12 | 🟫 | 2581 | -598 | 434 | -1032 | -825 | -134 | -73 | -114 | 107 | -24 | -13 | -489 | -150 | -102 | 167 | | |
| STRATEGY 13 | 🟫 | 2581 | -564 | 434 | -997 | -798 | -134 | -43 | -114 | 107 | -25 | -13 | -492 | -149 | -101 | 167 | | |
| STRATEGY 14 | 🟫 | 2581 | -83 | 434 | -517 | -413 | -145 | -48 | 16 | -19 | -25 | -4 | -86 | -160 | -110 | 167 | | |
| STRATEGY 15 | 🟫 | 2581 | -43 | 434 | -476 | -381 | -145 | -48 | 25 | -27 | -25 | -3 | -55 | -160 | -110 | 167 | | |
| STRATEGY 16 | 🟫 | 2581 | -41 | 434 | -474 | -379 | -145 | -49 | 25 | -27 | -25 | -3 | -55 | -158 | -109 | 167 | | |
| STRATEGY 17 | 🟩 | 2581 | 5 | 434 | -428 | -343 | -29 | -49 | 17 | -19 | -25 | -2 | -55 | -159 | -109 | 87 | | |
| STRATEGY 18 | 🟫 | 2581 | -18 | 434 | -451 | -361 | -29 | -49 | 40 | -42 | -44 | -2 | -55 | -159 | -109 | 87 | | |
| STRATEGY 19 | 🟫 | 2581 | -7 | 434 | -441 | -352 | -29 | -52 | 26 | -27 | -24 | -2 | -55 | -165 | -110 | 87 | | |
| STRATEGY 20 | 🟫 | 2581 | -11 | 434 | -445 | -356 | -25 | -51 | 26 | -28 | -24 | -3 | -55 | -165 | -110 | 79 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 21 | 🟫 | 2581 | -611 | 434 | -1045 | -836 | -133 | -97 | -117 | 107 | -24 | -19 | -485 | -151 | -84 | 167 | | -38% (ventilation D2) |
| STRATEGY 22 | 🟫 | 2581 | -584 | 434 | -1018 | -814 | -134 | -72 | -117 | 106 | -24 | -19 | -488 | -150 | -84 | 167 | | |
| STRATEGY 23 | 🟫 | 2581 | -550 | 434 | -983 | -787 | -134 | -43 | -116 | 106 | -24 | -19 | -491 | -149 | -83 | 167 | | |
| STRATEGY 24 | 🟫 | 2581 | -62 | 434 | -496 | -397 | -144 | -48 | 16 | -20 | -25 | -7 | -86 | -160 | -89 | 167 | | |
| STRATEGY 25 | 🟫 | 2581 | -22 | 434 | -456 | -365 | -145 | -48 | 24 | -28 | -25 | -7 | -55 | -159 | -88 | 167 | | |
| STRATEGY 26 | 🟫 | 2581 | -21 | 434 | -454 | -364 | -145 | -50 | 24 | -28 | -25 | -6 | -55 | -158 | -87 | 167 | | |
| STRATEGY 27 | 🟩 | 2581 | 25 | 434 | -409 | -327 | -29 | -50 | 16 | -20 | -25 | -6 | -55 | -158 | -87 | 87 | | |
| STRATEGY 28 | 🟩 | 2581 | 2 | 434 | -432 | -345 | -29 | -50 | 39 | -43 | -43 | -6 | -55 | -159 | -87 | 87 | | |
| STRATEGY 29 | 🟩 | 2581 | 15 | 434 | -419 | -335 | -29 | -52 | 24 | -27 | -24 | -6 | -55 | -165 | -89 | 87 | | |
| STRATEGY 30 | 🟩 | 2581 | 10 | 434 | -423 | -339 | -25 | -52 | 25 | -28 | -23 | -6 | -55 | -165 | -89 | 79 | | |

GREEN: Low-temperature ready
TAUPE: Not low-temperature ready

# Appendix F

## Strategy outcomes

1965 - 1974

| Strategy | Sufficient Heating Capacity | Capacity [W] | Difference (Heating capacity and Demand) [kW] | Heating Capacity [kWh] | Heating Demand x1,25 | Heating Demand [kWh] | Glazing [kWh] | Walls [kWh] | Ceiling (int) [kWh] | Floors (int) [kWh] | Ground Floor [kWh] | Partitions (int) [kWh] | Roofs [kWh] | External infiltration [kWh] | External Ventilation [kWh] | Solar gains Windows (ext) [kWh] | Effectiveness [reduction in percentage] | Effectiveness [reduction in percentage] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | |
| BASIS | N.A. | 8575 | -2 | 1441 | -1443 | -1154 | -130 | -226 | 101 | -106 | -137 | -8 | -218 | -455 | -143 | 167 | | |
| BASIS LOW TEMP | | 2581 | -1009 | 434 | -1443 | -1154 | -130 | -226 | 101 | -106 | -137 | -8 | -218 | -455 | -143 | 167 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 1 | 🟫 | 2581 | -382 | 434 | -815 | -652 | -140 | -92 | -23 | 20 | -24 | -5 | -242 | -160 | -153 | 167 | -59% (wall) | -82% (ground floor) |
| STRATEGY 2 | 🟫 | 2581 | -363 | 434 | -797 | -637 | -141 | -76 | -23 | 20 | -25 | -5 | -242 | -160 | -153 | 167 | -66% (wall) | |
| STRATEGY 3 | 🟫 | 2581 | -325 | 434 | -758 | -607 | -141 | -45 | -23 | 20 | -25 | -5 | -243 | -159 | -152 | 167 | -80% (wall) | |
| STRATEGY 4 | 🟫 | 2581 | -116 | 434 | -549 | -439 | -145 | -47 | 20 | -21 | -25 | -2 | -73 | -160 | -153 | 167 | -67% (roof) | |
| STRATEGY 5 | 🟫 | 2581 | -84 | 434 | -518 | -414 | -145 | -47 | 26 | -28 | -25 | -2 | -50 | -159 | -152 | 167 | -77% (roof) | |
| STRATEGY 6 | 🟫 | 2581 | -81 | 434 | -515 | -412 | -145 | -48 | 27 | -28 | -25 | -1 | -50 | -158 | -151 | 167 | -79% (wall) | |
| STRATEGY 7 | 🟫 | 2581 | -35 | 434 | -469 | -375 | -29 | -48 | 18 | -19 | -25 | -1 | -50 | -158 | -151 | 87 | -78% (glazing) | |
| STRATEGY 8 | 🟫 | 2581 | -33 | 434 | -467 | -373 | -29 | -48 | 17 | -18 | -24 | -1 | -50 | -157 | -151 | 87 | -82% (ground floor) | |
| STRATEGY 9 | 🟫 | 2581 | -48 | 434 | -482 | -385 | -29 | -51 | 27 | -27 | -24 | -1 | -50 | -164 | -154 | 87 | -82% (ground floor) | |
| STRATEGY 10 | 🟫 | 2581 | -53 | 434 | -486 | -389 | -25 | -50 | 27 | -28 | -24 | -1 | -49 | -164 | -153 | 79 | -81% (glazing) | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 11 | 🟫 | 2581 | -331 | 434 | -764 | -611 | -141 | -92 | -23 | 19 | -24 | -6 | -242 | -161 | -109 | 167 | | -24% (ventilation C3) |
| STRATEGY 12 | 🟫 | 2581 | -312 | 434 | -746 | -596 | -141 | -76 | -23 | 19 | -25 | -6 | -243 | -160 | -109 | 167 | | |
| STRATEGY 13 | 🟫 | 2581 | -274 | 434 | -708 | -566 | -142 | -46 | -23 | 19 | -25 | -6 | -244 | -159 | -108 | 167 | | |
| STRATEGY 14 | 🟫 | 2581 | -65 | 434 | -498 | -399 | -145 | -47 | 20 | -22 | -25 | -3 | -73 | -160 | -110 | 167 | | |
| STRATEGY 15 | 🟫 | 2581 | -34 | 434 | -467 | -374 | -145 | -48 | 27 | -29 | -26 | -3 | -50 | -159 | -109 | 167 | | |
| STRATEGY 16 | 🟫 | 2581 | -32 | 434 | -465 | -372 | -145 | -48 | 27 | -29 | -26 | -3 | -50 | -158 | -108 | 167 | | |
| STRATEGY 17 | 🟩 | 2581 | 14 | 434 | -419 | -335 | -29 | -48 | 19 | -20 | -25 | -2 | -50 | -158 | -109 | 87 | | |
| STRATEGY 18 | 🟩 | 2581 | 17 | 434 | -417 | -334 | -29 | -48 | 17 | -19 | -24 | -2 | -50 | -158 | -108 | 87 | | |
| STRATEGY 19 | 🟩 | 2581 | 2 | 434 | -431 | -345 | -29 | -51 | 27 | -29 | -24 | -2 | -50 | -165 | -110 | 87 | | |
| STRATEGY 20 | 🟫 | 2581 | -2 | 434 | -436 | -349 | -25 | -51 | 28 | -30 | -24 | -3 | -49 | -164 | -110 | 79 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 21 | 🟫 | 2581 | -315 | 434 | -749 | -599 | -141 | -92 | -23 | 17 | -24 | -11 | -243 | -161 | -89 | 167 | | -38% (ventilation D2) |
| STRATEGY 22 | 🟫 | 2581 | -296 | 434 | -730 | -584 | -141 | -76 | -23 | 17 | -25 | -11 | -243 | -161 | -89 | 167 | | |
| STRATEGY 23 | 🟫 | 2581 | -258 | 434 | -691 | -553 | -142 | -45 | -23 | 17 | -25 | -10 | -244 | -159 | -88 | 167 | | |
| STRATEGY 24 | 🟫 | 2581 | -44 | 434 | -478 | -382 | -145 | -47 | 19 | -23 | -25 | -7 | -73 | -160 | -88 | 167 | | |
| STRATEGY 25 | 🟫 | 2581 | -13 | 434 | -447 | -357 | -145 | -47 | 26 | -30 | -25 | -7 | -50 | -159 | -88 | 167 | | |
| STRATEGY 26 | 🟫 | 2581 | -12 | 434 | -445 | -356 | -145 | -49 | 26 | -30 | -25 | -6 | -50 | -158 | -87 | 167 | | |
| STRATEGY 27 | 🟩 | 2581 | 34 | 434 | -400 | -320 | -29 | -49 | 18 | -21 | -25 | -6 | -50 | -158 | -87 | 87 | | |
| STRATEGY 28 | 🟩 | 2581 | 36 | 434 | -398 | -318 | -29 | -49 | 17 | -20 | -24 | -6 | -50 | -157 | -87 | 87 | | |
| STRATEGY 29 | 🟩 | 2581 | 24 | 434 | -410 | -328 | -29 | -51 | 26 | -29 | -24 | -5 | -50 | -165 | -88 | 87 | | |
| STRATEGY 30 | 🟩 | 2581 | 19 | 434 | -414 | -331 | -25 | -51 | 26 | -30 | -23 | -6 | -49 | -164 | -88 | 79 | | |

GREEN: Low-temperature ready
TAUPE: Not low-temperature ready

# Appendix F

## Strategy outcomes

### 1975 - 1987

| Strategy | Sufficient Heating Capacity | Capacity [W] | Difference (Heating capacity and Demand) [kW] | Heating Capacity [kWh] | Heating Demand x1,25 | Heating Demand [kWh] | Glazing [kWh] | Walls [kWh] | Ceiling (int) [kWh] | Floors (int) [kWh] | Ground Floor [kWh] | Partitions (int) [kWh] | Roofs [kWh] | External infiltration [kWh] | External Ventilation [kWh] | Solar gains Windows (ext) [kWh] | Effectiveness [reduction in percentage] | Effectiveness [reduction in percentage] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | |
| BASIS | N.A. | 8575 | 432 | 1441 | -1009 | -807 | -139 | -118 | 40 | -44 | -65 | -6 | -179 | -314 | -151 | 167 | | |
| BASIS LOW TEMP | 🟫 | 2581 | -575 | 434 | -1009 | -807 | -139 | -118 | 40 | -44 | -65 | -6 | -179 | -314 | -151 | 167 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 1 | 🟫 | 2581 | -270 | 434 | -703 | -563 | -142 | -69 | -15 | 13 | -20 | -4 | -184 | -158 | -151 | 167 | -42% (wall) | -69% (ground floor) |
| STRATEGY 2 | 🟫 | 2581 | -255 | 434 | -689 | -551 | -142 | -59 | -15 | 13 | -20 | -4 | -184 | -157 | -150 | 167 | -50% (wall) | |
| STRATEGY 3 | 🟫 | 2581 | -230 | 434 | -663 | -531 | -143 | -39 | -15 | 13 | -21 | -4 | -185 | -156 | -149 | 167 | -67% (wall) | |
| STRATEGY 4 | 🟫 | 2581 | -81 | 434 | -515 | -412 | -145 | -40 | 15 | -16 | -21 | -2 | -67 | -155 | -149 | 167 | -63% (roof) | |
| STRATEGY 5 | 🟫 | 2581 | -54 | 434 | -487 | -390 | -146 | -41 | 21 | -21 | -21 | -1 | -47 | -154 | -148 | 167 | -74% (roof) | |
| STRATEGY 6 | 🟫 | 2581 | -50 | 434 | -483 | -387 | -146 | -40 | 21 | -21 | -21 | -1 | -47 | -153 | -147 | 167 | -66% (wall) | |
| STRATEGY 7 | 🟫 | 2581 | -4 | 434 | -438 | -350 | -29 | -41 | 13 | -13 | -21 | -1 | -47 | -153 | -147 | 87 | -79% (glazing) | |
| STRATEGY 8 | 🟫 | 2581 | -25 | 434 | -459 | -367 | -29 | -40 | 32 | -33 | -36 | -1 | -47 | -154 | -147 | 87 | -45% (ground floor) | |
| STRATEGY 9 | 🟫 | 2581 | -9 | 434 | -442 | -354 | -29 | -42 | 15 | -13 | -17 | 0 | -47 | -159 | -149 | 87 | -70% (ground floor) | |
| STRATEGY 10 | 🟫 | 2581 | -13 | 434 | -447 | -358 | -25 | -42 | 16 | -14 | -16 | -1 | -46 | -159 | -149 | 79 | 82% (glazing) | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 11 | 🟫 | 2581 | -220 | 434 | -653 | -523 | -142 | -69 | -14 | 12 | -20 | -5 | -184 | -158 | -108 | 167 | | -28% (ventilation C3) |
| STRATEGY 12 | 🟫 | 2581 | -206 | 434 | -639 | -511 | -143 | -59 | -14 | 12 | -20 | -5 | -184 | -157 | -108 | 167 | | |
| STRATEGY 13 | 🟫 | 2581 | -180 | 434 | -614 | -491 | -143 | -39 | -14 | 12 | -21 | -5 | -185 | -156 | -107 | 167 | | |
| STRATEGY 14 | 🟫 | 2581 | -32 | 434 | -466 | -372 | -145 | -40 | 16 | -17 | -21 | -3 | -67 | -155 | -107 | 167 | | |
| STRATEGY 15 | 🟫 | 2581 | -5 | 434 | -439 | -351 | -146 | -41 | 21 | -22 | -21 | -2 | -47 | -155 | -106 | 167 | | |
| STRATEGY 16 | 🟫 | 2581 | -2 | 434 | -435 | -348 | -146 | -41 | 22 | -22 | -21 | -2 | -47 | -153 | -105 | 167 | | |
| STRATEGY 17 | 🟩 | 2581 | 44 | 434 | -390 | -312 | -29 | -41 | 13 | -14 | -21 | -2 | -47 | -153 | -105 | 87 | | |
| STRATEGY 18 | 🟩 | 2581 | 23 | 434 | -410 | -328 | -29 | -41 | 32 | -34 | -36 | -2 | -47 | -154 | -106 | 87 | | |
| STRATEGY 19 | 🟩 | 2581 | 40 | 434 | -393 | -315 | -29 | -43 | 15 | -14 | -17 | -1 | -47 | -160 | -107 | 87 | | |
| STRATEGY 20 | 🟩 | 2581 | 36 | 434 | -398 | -318 | -25 | -42 | 16 | -15 | -16 | -2 | -46 | -159 | -107 | 79 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 21 | 🟫 | 2581 | -201 | 434 | -635 | -508 | -142 | -69 | -14 | 10 | -20 | -9 | -184 | -158 | -88 | 167 | | -42% (ventilation D2) |
| STRATEGY 22 | 🟫 | 2581 | -187 | 434 | -620 | -496 | -143 | -59 | -14 | 10 | -20 | -9 | -185 | -157 | -87 | 167 | | |
| STRATEGY 23 | 🟫 | 2581 | -161 | 434 | -595 | -476 | -143 | -39 | -15 | 10 | -21 | -9 | -185 | -156 | -86 | 167 | | |
| STRATEGY 24 | 🟫 | 2581 | -12 | 434 | -446 | -357 | -145 | -40 | 15 | -18 | -21 | -7 | -67 | -155 | -86 | 167 | | |
| STRATEGY 25 | 🟩 | 2581 | 15 | 434 | -419 | -335 | -146 | -41 | 21 | -24 | -21 | -6 | -47 | -154 | -85 | 167 | | |
| STRATEGY 26 | 🟩 | 2581 | 17 | 434 | -416 | -333 | -146 | -41 | 21 | -24 | -21 | -6 | -47 | -153 | -84 | 167 | | |
| STRATEGY 27 | 🟩 | 2581 | 64 | 434 | -370 | -296 | -29 | -41 | 12 | -15 | -21 | -5 | -47 | -153 | -84 | 87 | | |
| STRATEGY 28 | 🟩 | 2581 | 42 | 434 | -391 | -313 | -29 | -41 | 31 | -35 | -35 | -6 | -47 | -154 | -85 | 87 | | |
| STRATEGY 29 | 🟩 | 2581 | 59 | 434 | -374 | -300 | -29 | -43 | 14 | -15 | -17 | -5 | -47 | -159 | -86 | 87 | | |
| STRATEGY 30 | 🟩 | 2581 | 54 | 434 | -379 | -303 | -25 | -43 | 15 | -16 | -16 | -6 | -47 | -159 | -86 | 79 | | |

GREEN: Low-temperature ready
TAUPE: Not low-temperature ready

# Appendix F

## Strategy outcomes

### Case Study

| Strategy | Sufficient Heating Capacity | Capacity [W] | Difference (Heating capacity and Demand) [kW] | Heating Capacity [kWh] | Heating Demand x1,25 | Heating Demand [kWh] | Glazing [kWh] | Walls [kWh] | Ceiling (int) [kWh] | Floors (int) [kWh] | Ground Floor [kWh] | Partitions (int) [kWh] | Roofs [kWh] | External infiltration [kWh] | External Ventilation [kWh] | Solar gains Windows (ext) [kWh] | Effectiveness [reduction in percentage] | Effectiveness [reduction in percentage] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | |
| BASIS | N.A. | 8575 | 733 | 1441 | -707 | -566 | -73 | -105 | 14 | -17 | -24 | -3 | -72 | -261 | -150 | 125 | | |
| BASIS LOW TEMP | 🟫 | 2581 | -274 | 434 | -707 | -566 | -73 | -105 | 14 | -17 | -24 | -3 | -72 | -261 | -150 | 125 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 1 | 🟫 | 2581 | -91 | 434 | -525 | -420 | -74 | -79 | 2 | 2 | -16 | -2 | -73 | -156 | -149 | 125 | -25% (wall) | -33% (ground floor) |
| STRATEGY 2 | 🟫 | 2581 | -81 | 434 | -515 | -412 | -74 | -74 | 2 | 2 | -16 | -1 | -73 | -155 | -148 | 125 | -30% (wall) | |
| STRATEGY 3 | 🟫 | 2581 | -61 | 434 | -495 | -396 | -75 | -60 | 2 | 2 | -16 | -1 | -73 | -153 | -147 | 125 | -43% (wall) | |
| STRATEGY 4 | 🟫 | 2581 | -19 | 434 | -452 | -362 | -75 | -60 | 11 | -6 | -16 | 0 | -44 | -151 | -145 | 125 | -39% (roof) | |
| STRATEGY 5 | 🟫 | 2581 | -4 | 434 | -438 | -350 | -75 | -60 | 14 | -9 | -16 | 0 | -34 | -150 | -144 | 125 | -53% (roof) | |
| STRATEGY 6 | 🟩 | 2581 | 0 | 434 | -434 | -347 | -75 | -60 | 14 | -9 | -16 | 0 | -34 | -149 | -143 | 125 | -43% (wall) | |
| STRATEGY 7 | 🟩 | 2581 | 12 | 434 | -422 | -337 | -28 | -60 | 10 | -4 | -16 | 1 | -34 | -149 | -143 | 87 | -62% (glazing) | |
| STRATEGY 8 | 🟩 | 2581 | 2 | 434 | -432 | -346 | -28 | -60 | 16 | -12 | -21 | 1 | -34 | -150 | -144 | 87 | -13% (ground floor) | |
| STRATEGY 9 | 🟩 | 2581 | 5 | 434 | -429 | -343 | -28 | -63 | 7 | -3 | -10 | 1 | -34 | -154 | -145 | 87 | -58% (ground floor) | |
| STRATEGY 10 | 🟫 | 2581 | -1 | 434 | -434 | -347 | -25 | -62 | 9 | -5 | -10 | 0 | -34 | -154 | -145 | 79 | -66% (wall) | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 11 | 🟫 | 2581 | -42 | 434 | -475 | -380 | -75 | -79 | 3 | 1 | -16 | -3 | -73 | -156 | -107 | 125 | | -29% (ventilation C3) |
| STRATEGY 12 | 🟫 | 2581 | -32 | 434 | -466 | -373 | -75 | -74 | 3 | 1 | -16 | -3 | -73 | -155 | -106 | 125 | | |
| STRATEGY 13 | 🟫 | 2581 | -13 | 434 | -446 | -357 | -75 | -60 | 2 | 1 | -16 | -3 | -73 | -154 | -105 | 125 | | |
| STRATEGY 14 | 🟩 | 2581 | 29 | 434 | -405 | -324 | -75 | -60 | 11 | -7 | -16 | -2 | -44 | -152 | -104 | 125 | | |
| STRATEGY 15 | 🟩 | 2581 | 43 | 434 | -391 | -312 | -75 | -60 | 14 | -10 | -16 | -2 | -34 | -151 | -103 | 125 | | |
| STRATEGY 16 | 🟩 | 2581 | 46 | 434 | -387 | -310 | -75 | -60 | 14 | -10 | -16 | -1 | -34 | -149 | -103 | 125 | | |
| STRATEGY 17 | 🟩 | 2581 | 59 | 434 | -375 | -300 | -28 | -60 | 10 | -5 | -16 | -1 | -34 | -150 | -103 | 87 | | |
| STRATEGY 18 | 🟩 | 2581 | 49 | 434 | -385 | -308 | -28 | -61 | 16 | -13 | -21 | -1 | -34 | -150 | -103 | 87 | | |
| STRATEGY 19 | 🟩 | 2581 | 52 | 434 | -382 | -305 | -28 | -63 | 8 | -4 | -10 | -1 | -34 | -155 | -104 | 87 | | |
| STRATEGY 20 | 🟩 | 2581 | 47 | 434 | -387 | -309 | -25 | -63 | 9 | -6 | -10 | -2 | -34 | -154 | -104 | 79 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 21 | 🟫 | 2581 | -23 | 434 | -456 | -365 | -74 | -80 | 2 | 0 | -16 | -7 | -73 | -156 | -86 | 125 | | -43% (ventilation D2) |
| STRATEGY 22 | 🟫 | 2581 | -13 | 434 | -447 | -357 | -74 | -74 | 2 | 0 | -16 | -7 | -73 | -155 | -85 | 125 | | |
| STRATEGY 23 | 🟩 | 2581 | 6 | 434 | -427 | -342 | -75 | -60 | 2 | 0 | -16 | -6 | -73 | -154 | -85 | 125 | | |
| STRATEGY 24 | 🟩 | 2581 | 48 | 434 | -386 | -309 | -75 | -60 | 10 | -8 | -16 | -6 | -44 | -151 | -84 | 125 | | |
| STRATEGY 25 | 🟩 | 2581 | 62 | 434 | -372 | -298 | -75 | -60 | 13 | -11 | -16 | -6 | -34 | -150 | -83 | 125 | | |
| STRATEGY 26 | 🟩 | 2581 | 64 | 434 | -369 | -296 | -75 | -61 | 13 | -11 | -16 | -5 | -34 | -149 | -82 | 125 | | |
| STRATEGY 27 | 🟩 | 2581 | 76 | 434 | -357 | -286 | -28 | -61 | 9 | -6 | -16 | -5 | -34 | -149 | -82 | 87 | | |
| STRATEGY 28 | 🟩 | 2581 | 66 | 434 | -367 | -294 | -28 | -61 | 15 | -15 | -20 | -5 | -34 | -150 | -83 | 87 | | |
| STRATEGY 29 | 🟩 | 2581 | 70 | 434 | -363 | -291 | -28 | -63 | 7 | -6 | -10 | -5 | -34 | -154 | -84 | 87 | | |
| STRATEGY 30 | 🟩 | 2581 | 65 | 434 | -369 | -295 | -25 | -63 | 8 | -7 | -10 | -5 | -34 | -154 | -83 | 79 | | |

GREEN: Low-temperature ready
TAUPE: Not low-temperature ready

# Appendix F

## Strategy outcomes

### Semi-detached

| Strategy | Sufficient Heating Capacity | Capacity [W] | Difference (Heating capacity and Demand) [kW] | Heating Capacity [kWh] | Heating Demand x1,25 | Heating Demand [kWh] | Glazing [kWh] | Walls [kWh] | Ceiling (int) [kWh] | Floors (int) [kWh] | Ground Floor [kWh] | Partitions (int) [kWh] | Roofs [kWh] | External infiltration [kWh] | External Ventilation [kWh] | Solar gains Windows (ext) [kWh] | Effectiveness [reduction in percentage] | Effectiveness [reduction in percentage] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | |
| BASIS | N.A. | 8575 | 641 | 1441 | -800 | -640 | -72 | -199 | 3 | -7 | -23 | -4 | -69 | -250 | -144 | 125 | | |
| BASIS LOW TEMP | 🟫 | 2581 | -366 | 434 | -800 | -640 | -72 | -199 | 3 | -7 | -23 | -4 | -69 | -250 | -144 | 125 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 1 | 🟫 | 2581 | -149 | 434 | -582 | -466 | -73 | -138 | -5 | 8 | -15 | -3 | -71 | -150 | -144 | 125 | -31% (wall) | -35% (ground floor) |
| STRATEGY 2 | 🟫 | 2581 | -127 | 434 | -560 | -448 | -73 | -125 | -4 | 8 | -15 | -3 | -71 | -148 | -142 | 125 | -37% (wall) | |
| STRATEGY 3 | 🟫 | 2581 | -80 | 434 | -514 | -411 | -74 | -90 | -3 | 7 | -16 | -2 | -72 | -146 | -140 | 125 | -55% (wall) | |
| STRATEGY 4 | 🟫 | 2581 | -40 | 434 | -473 | -379 | -74 | -91 | 5 | -1 | -16 | -2 | -43 | -144 | -138 | 125 | -38% (roof) | |
| STRATEGY 5 | 🟫 | 2581 | -26 | 434 | -460 | -368 | -74 | -91 | 8 | -4 | -16 | -2 | -34 | -142 | -137 | 125 | -51% (roof) | |
| STRATEGY 6 | 🟫 | 2581 | -18 | 434 | -452 | -362 | -74 | -90 | 8 | -3 | -16 | -1 | -33 | -140 | -135 | 125 | -54% (wall) | |
| STRATEGY 7 | 🟫 | 2581 | -7 | 434 | -441 | -353 | -28 | -91 | 4 | 1 | -16 | -1 | -33 | -140 | -135 | 87 | -61% (glazing) | |
| STRATEGY 8 | 🟫 | 2581 | -17 | 434 | -450 | -360 | -28 | -90 | 10 | -7 | -20 | -1 | -33 | -141 | -136 | 87 | -13% (ground floor) | |
| STRATEGY 9 | 🟫 | 2581 | -14 | 434 | -447 | -358 | -28 | -93 | 2 | 2 | -10 | -1 | -33 | -145 | -137 | 87 | -57% (ground floor) | |
| STRATEGY 10 | 🟫 | 2581 | -18 | 434 | -452 | -361 | -24 | -93 | 3 | 0 | -10 | -2 | -33 | -145 | -137 | 79 | -67% (glazing) | |
| | | | | 434 | | | | | | | | | | | | | | |
| STRATEGY 11 | 🟫 | 2581 | -101 | 434 | -535 | -428 | -73 | -139 | -5 | 7 | -15 | -3 | -71 | -150 | -103 | 125 | | -28% (ventilation C3) |
| STRATEGY 12 | 🟫 | 2581 | -79 | 434 | -513 | -410 | -73 | -125 | -4 | 7 | -15 | -3 | -71 | -148 | -102 | 125 | | |
| STRATEGY 13 | 🟫 | 2581 | -33 | 434 | -467 | -373 | -74 | -90 | -3 | 6 | -16 | -3 | -72 | -146 | -100 | 125 | | |
| STRATEGY 14 | 🟩 | 2581 | 7 | 434 | -427 | -341 | -74 | -91 | 5 | -2 | -16 | -2 | -43 | -144 | -99 | 125 | | |
| STRATEGY 15 | 🟩 | 2581 | 20 | 434 | -413 | -331 | -75 | -92 | 8 | -5 | -16 | -2 | -34 | -143 | -98 | 125 | | |
| STRATEGY 16 | 🟩 | 2581 | 27 | 434 | -407 | -326 | -75 | -91 | 8 | -4 | -16 | -2 | -34 | -140 | -97 | 125 | | |
| STRATEGY 17 | 🟩 | 2581 | 38 | 434 | -396 | -317 | -28 | -92 | 4 | 1 | -16 | -2 | -34 | -140 | -97 | 87 | | |
| STRATEGY 18 | 🟩 | 2581 | 28 | 434 | -405 | -324 | -28 | -91 | 10 | -8 | -20 | -2 | -34 | -141 | -98 | 87 | | |
| STRATEGY 19 | 🟩 | 2581 | 32 | 434 | -402 | -321 | -28 | -95 | 2 | 1 | -10 | -2 | -34 | -145 | -98 | 87 | | |
| STRATEGY 20 | 🟩 | 2581 | 27 | 434 | -406 | -325 | -24 | -94 | 3 | -1 | -10 | -2 | -33 | -145 | -98 | 79 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 21 | 🟫 | 2581 | -80 | 434 | -514 | -411 | -73 | -140 | -6 | 7 | -15 | -5 | -71 | -150 | -83 | 125 | | -42% (ventilation D2) |
| STRATEGY 22 | 🟫 | 2581 | -58 | 434 | -491 | -393 | -73 | -125 | -5 | 6 | -15 | -5 | -71 | -148 | -81 | 125 | | |
| STRATEGY 23 | 🟫 | 2581 | -12 | 434 | -445 | -356 | -74 | -91 | -3 | 5 | -16 | -4 | -72 | -146 | -80 | 125 | | |
| STRATEGY 24 | 🟩 | 2581 | 28 | 434 | -406 | -325 | -74 | -91 | 5 | -3 | -16 | -4 | -43 | -144 | -79 | 125 | | |
| STRATEGY 25 | 🟩 | 2581 | 41 | 434 | -393 | -314 | -74 | -92 | 7 | -6 | -16 | -4 | -34 | -143 | -79 | 125 | | |
| STRATEGY 26 | 🟩 | 2581 | 45 | 434 | -388 | -311 | -74 | -93 | 7 | -5 | -16 | -3 | -34 | -140 | -77 | 125 | | |
| STRATEGY 27 | 🟩 | 2581 | 56 | 434 | -377 | -302 | -28 | -93 | 3 | 0 | -16 | -3 | -34 | -140 | -77 | 87 | | |
| STRATEGY 28 | 🟩 | 2581 | 47 | 434 | -386 | -309 | -28 | -93 | 9 | -8 | -20 | -3 | -34 | -141 | -78 | 87 | | |
| STRATEGY 29 | 🟩 | 2581 | 51 | 434 | -383 | -306 | -28 | -96 | 1 | 0 | -10 | -3 | -34 | -145 | -78 | 87 | | |
| STRATEGY 30 | 🟩 | 2581 | 46 | 434 | -387 | -310 | -24 | -96 | 2 | -1 | -9 | -4 | -34 | -145 | -78 | 79 | | |

GREEN: Low-temperature ready
TAUPE: Not low-temperature ready

# Appendix F

## Strategy outcomes

### Freestanding

| Strategy | Sufficient Heating Capacity | Capacity [W] | Difference (Heating capacity and Demand) [kW] | Heating Capacity [kWh] | Heating Demand x1,25 | Heating Demand [kWh] | Glazing [kWh] | Walls [kWh] | Ceiling (int) [kWh] | Floors (int) [kWh] | Ground Floor [kWh] | Partitions (int) [kWh] | Roofs [kWh] | External infiltration [kWh] | External Ventilation [kWh] | Solar gains Windows (ext) [kWh] | Effectiveness [reduction in percentage] | Effectiveness [reduction in percentage] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | |
| BASIS | N.A. | 8575 | 513 | 1441 | -928 | -742 | -70 | -324 | -3 | -2 | -22 | -2 | -67 | -241 | -135 | 125 | | |
| BASIS LOW TEMP | 🟫 | 2581 | -494 | 434 | -928 | -742 | -70 | -324 | -3 | -2 | -22 | -2 | -67 | -241 | -135 | 125 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 1 | 🟫 | 2581 | -236 | 434 | -669 | -535 | -72 | -225 | -7 | 10 | -15 | -2 | -70 | -145 | -136 | 125 | -31% (wall) | -32% (ground floor) |
| STRATEGY 2 | 🟫 | 2581 | -200 | 434 | -633 | -507 | -72 | -202 | -7 | 10 | -15 | -1 | -70 | -141 | -132 | 125 | -38% (wall) | |
| STRATEGY 3 | 🟫 | 2581 | -124 | 434 | -557 | -446 | -73 | -146 | -5 | 8 | -15 | -1 | -71 | -138 | -129 | 125 | -55% (wall) | |
| STRATEGY 4 | 🟫 | 2581 | -84 | 434 | -518 | -414 | -73 | -147 | 3 | 0 | -16 | -1 | -42 | -136 | -127 | 125 | -37% (roof) | |
| STRATEGY 5 | 🟫 | 2581 | -71 | 434 | -505 | -404 | -74 | -148 | 6 | -2 | -16 | -1 | -33 | -135 | -127 | 125 | -51% (roof) | |
| STRATEGY 6 | 🟫 | 2581 | -61 | 434 | -494 | -396 | -73 | -148 | 6 | -2 | -16 | -1 | -33 | -131 | -123 | 125 | -54% (wall) | |
| STRATEGY 7 | 🟫 | 2581 | -51 | 434 | -485 | -388 | -28 | -148 | 2 | 3 | -16 | 0 | -33 | -131 | -123 | 87 | -60% (glazing) | |
| STRATEGY 8 | 🟫 | 2581 | -60 | 434 | -494 | -395 | -28 | -147 | 8 | -5 | -20 | 0 | -33 | -132 | -124 | 87 | -9% (ground floor) | |
| STRATEGY 9 | 🟫 | 2581 | -58 | 434 | -491 | -393 | -28 | -152 | 0 | 3 | -9 | -1 | -33 | -136 | -125 | 87 | -59% (ground floor) | |
| STRATEGY 10 | 🟫 | 2581 | -62 | 434 | -495 | -396 | -24 | -151 | 1 | 2 | -9 | -1 | -33 | -135 | -125 | 79 | -66% (glazing) | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 11 | 🟫 | 2581 | -191 | 434 | -624 | -499 | -72 | -226 | -7 | 9 | -15 | -2 | -70 | -145 | -97 | 125 | | -28% (ventilation C3) |
| STRATEGY 12 | 🟫 | 2581 | -155 | 434 | -589 | -471 | -72 | -203 | -6 | 9 | -15 | -2 | -70 | -141 | -95 | 125 | | |
| STRATEGY 13 | 🟫 | 2581 | -80 | 434 | -514 | -411 | -73 | -147 | -4 | 7 | -15 | -1 | -71 | -138 | -93 | 125 | | |
| STRATEGY 14 | 🟫 | 2581 | -42 | 434 | -475 | -380 | -74 | -148 | 3 | 0 | -16 | -1 | -42 | -136 | -91 | 125 | | |
| STRATEGY 15 | 🟫 | 2581 | -29 | 434 | -462 | -370 | -74 | -148 | 6 | -3 | -16 | -1 | -33 | -135 | -91 | 125 | | |
| STRATEGY 16 | 🟫 | 2581 | -20 | 434 | -454 | -363 | -74 | -149 | 6 | -3 | -16 | -1 | -33 | -131 | -88 | 125 | | |
| STRATEGY 17 | 🟫 | 2581 | -10 | 434 | -444 | -355 | -28 | -149 | 2 | 2 | -16 | -1 | -33 | -131 | -88 | 87 | | |
| STRATEGY 18 | 🟫 | 2581 | -19 | 434 | -453 | -362 | -28 | -148 | 8 | -6 | -20 | -1 | -33 | -132 | -89 | 87 | | |
| STRATEGY 19 | 🟫 | 2581 | -16 | 434 | -450 | -360 | -28 | -153 | 1 | 2 | -9 | -1 | -33 | -136 | -90 | 87 | | |
| STRATEGY 20 | 🟫 | 2581 | -20 | 434 | -454 | -363 | -24 | -152 | 1 | 1 | -9 | -1 | -33 | -135 | -90 | 79 | | |
| | | | | | | | | | | | | | | | | | | |
| STRATEGY 21 | 🟫 | 2581 | -174 | 434 | -607 | -486 | -72 | -227 | -8 | 9 | -15 | -3 | -70 | -145 | -80 | 125 | | -41% (ventilation D2) |
| STRATEGY 22 | 🟫 | 2581 | -138 | 434 | -571 | -457 | -72 | -203 | -7 | 8 | -15 | -3 | -70 | -141 | -78 | 125 | | |
| STRATEGY 23 | 🟫 | 2581 | -63 | 434 | -496 | -397 | -73 | -147 | -5 | 6 | -15 | -3 | -71 | -138 | -76 | 125 | | |
| STRATEGY 24 | 🟫 | 2581 | -24 | 434 | -458 | -366 | -73 | -148 | 3 | -2 | -15 | -3 | -42 | -136 | -75 | 125 | | |
| STRATEGY 25 | 🟫 | 2581 | -12 | 434 | -445 | -356 | -74 | -148 | 5 | -4 | -15 | -2 | -33 | -135 | -74 | 125 | | |
| STRATEGY 26 | 🟫 | 2581 | -5 | 434 | -439 | -351 | -74 | -151 | 6 | -3 | -16 | -2 | -33 | -131 | -72 | 125 | | |
| STRATEGY 27 | 🟩 | 2581 | 4 | 434 | -429 | -343 | -28 | -151 | 1 | 1 | -16 | -2 | -33 | -131 | -72 | 87 | | |
| STRATEGY 28 | 🟫 | 2581 | -4 | 434 | -438 | -350 | -28 | -150 | 7 | -7 | -20 | -2 | -33 | -132 | -73 | 87 | | |
| STRATEGY 29 | 🟫 | 2581 | -1 | 434 | -435 | -348 | -28 | -155 | 0 | 1 | -9 | -2 | -33 | -136 | -73 | 87 | | |
| STRATEGY 30 | 🟫 | 2581 | -5 | 434 | -439 | -351 | -24 | -154 | 1 | 0 | -9 | -2 | -33 | -135 | -73 | 79 | | |

GREEN: Low-temperature ready
TAUPE: Not low-temperature ready

# Appendix F

## *Air temperature simulations*

### Case study

| Strategy number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |  | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |  | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Under reporting hours (hours) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| <0 | 69 | 69 | 68 | 63 | 62 | 62 | 61 | 63 | 63 | 63 |  | 54 | 54 | 51 | 47 | 47 | 47 | 45 | 46 | 47 | 47 |  | 88 | 66 | 62 | 57 | 53 | 53 | 46 | 49 | 57 | 53 |
| <-0,5 | 60 | 60 | 60 | 57 | 55 | 54 | 43 | 44 | 54 | 56 |  | 43 | 43 | 41 | 39 | 38 | 39 | 34 | 35 | 37 | 41 |  | 60 | 43 | 34 | 25 | 22 | 19 | 23 | 25 | 25 | 21 |
| <-1,0 | 53 | 52 | 49 | 35 | 33 | 32 | 31 | 32 | 33 | 37 |  | 36 | 34 | 32 | 30 | 30 | 29 | 27 | 28 | 30 | 32 |  | 52 | 20 | 15 | 12 | 10 | 8 | 12 | 13 | 14 | 8 |
| <-1,5 | 34 | 33 | 30 | 28 | 26 | 22 | 22 | 23 | 26 | 28 |  | 28 | 28 | 24 | 23 | 23 | 22 | 21 | 22 | 24 | 24 |  | 37 | 8 | 5 | 1 | 0 | 0 | 0 | 1 | 3 | 0 |
| <-2,0 | 27 | 26 | 21 | 19 | 19 | 18 | 17 | 17 | 18 | 19 |  | 22 | 22 | 20 | 17 | 17 | 16 | 16 | 16 | 17 | 17 |  | 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| <-2,5 | 18 | 18 | 18 | 17 | 17 | 7 | 0 | 1 | 14 | 9 |  | 16 | 16 | 16 | 6 | 3 | 0 | 0 | 0 | 0 | 0 |  | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Percentage of total hours (%) |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| <0 | 41 | 41 | 40 | 38 | 37 | 37 | 36 | 38 | 38 | 38 |  | 32 | 32 | 30 | 28 | 28 | 28 | 27 | 27 | 28 | 28 |  | 52 | 39 | 37 | 34 | 32 | 32 | 27 | 29 | 34 | 32 |
| <-0,5 | 36 | 36 | 36 | 34 | 33 | 32 | 26 | 26 | 32 | 33 |  | 26 | 26 | 24 | 23 | 23 | 23 | 20 | 21 | 22 | 24 |  | 36 | 26 | 20 | 15 | 13 | 11 | 14 | 15 | 15 | 13 |
| <-1,0 | 32 | 31 | 29 | 21 | 20 | 19 | 18 | 19 | 20 | 22 |  | 21 | 20 | 19 | 18 | 18 | 17 | 16 | 17 | 18 | 19 |  | 31 | 12 | **9** | **7** | **6** | **5** | **7** | **8** | **8** | **5** |
| <-1,5 | 20 | 20 | 18 | 17 | 15 | 13 | 13 | 14 | 15 | 17 |  | 17 | 17 | 14 | 14 | 14 | 13 | 13 | 13 | 14 | 14 |  | 22 | 5 | 3 | 1 | 0 | 0 | 0 | 1 | 2 | 0 |
| <-2,0 | 16 | 15 | 13 | 11 | 11 | 11 | 10 | 10 | 11 | 11 |  | 13 | 13 | 12 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |  | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| <-2,5 | 11 | 11 | 11 | 10 | 10 | 4 | 0 | 1 | 8 | 5 |  | 10 | 10 | 10 | 4 | 2 | 0 | 0 | 0 | 0 | 0 |  | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Maximum of under reporting (°C) | -3,27 | -3,28 | -3,11 | -2,86 | -2,78 | -2,64 | -2,49 | -2,51 | -2,68 | -2,69 |  | -3,00 | -2,99 | -2,85 | -2,63 | -2,56 | -2,44 | -2,29 | -2,31 | -2,45 | -2,48 |  | -3,06 | -1,87 | -1,71 | -1,51 | -1,44 | -1,33 | -1,47 | -1,52 | -1,62 | -1,27 |

GREEN: Low-temperature ready
TAUPE: Not low-temperature ready

# Appendix F

## Air temperature simulations

### Pre 1964

| Strategy number | 16 | 17 | 26 | 27 |
|---|---|---|---|---|
| Under reporting hours (hours) | | | | |
| <0 | 79 | 67 | 118 | 84 |
| <-0,5 | 53 | 48 | 57 | 54 |
| <-1,0 | 46 | 41 | 48 | 38 |
| <-1,5 | 37 | 34 | 39 | 22 |
| <-2,0 | 31 | 27 | 14 | 13 |
| <-2,5 | 23 | 21 | 6 | 1 |
| | | | | |
| Percentage of total hours (%) | | | | |
| <0 | 47 | 40 | 70 | 50 |
| <-0,5 | 32 | 29 | 34 | 32 |
| <-1,0 | 27 | 24 | 29 | 23 |
| <-1,5 | 22 | 20 | 23 | 13 |
| <-2,0 | 18 | 16 | 8 | 8 |
| <-2,5 | 14 | 13 | 4 | 1 |
| | | | | |
| Maximum of under reporting (°C) | -3,92 | -3,34 | -2,81 | -2,60 |

### 1965 - 1974

| Strategy number | 16 | 17 | 26 | 27 |
|---|---|---|---|---|
| Under reporting hours (hours) | | | | |
| <0 | 66 | 60 | 99 | 70 |
| <-0,5 | 50 | 43 | 53 | 49 |
| <-1,0 | 43 | 38 | 42 | 28 |
| <-1,5 | 34 | 31 | 24 | 19 |
| <-2,0 | 29 | 25 | 11 | 8 |
| <-2,5 | 22 | 19 | 3 | 0 |
| | | | | |
| Percentage of total hours (%) | | | | |
| <0 | 39 | 36 | 59 | 42 |
| <-0,5 | 30 | 26 | 32 | 29 |
| <-1,0 | 26 | 23 | 25 | 17 |
| <-1,5 | 20 | 18 | 14 | 11 |
| <-2,0 | 17 | 15 | 7 | 5 |
| <-2,5 | 13 | 11 | 2 | 0 |
| | | | | |
| Maximum of under reporting (°C) | -3,72 | -3,14 | -2,62 | -2,38 |

### 1975 - 1987

| Strategy number | 16 | 17 | 24 | 25 | 27 |
|---|---|---|---|---|---|
| Under reporting hours (hours) | | | | | |
| <0 | 65 | 57 | 105 | 87 | 69 |
| <-0,5 | 48 | 43 | 53 | 52 | 45 |
| <-1,0 | 41 | 36 | 45 | 41 | 25 |
| <-1,5 | 32 | 29 | 27 | 19 | 16 |
| <-2,0 | 25 | 23 | 12 | 9 | 3 |
| <-2,5 | 19 | 17 | 3 | 0 | 0 |
| | | | | | |
| Percentage of total hours (%) | | | | | |
| <0 | 39 | 34 | 63 | 52 | 41 |
| <-0,5 | 29 | 26 | 32 | 31 | 27 |
| <-1,0 | 24 | 21 | 27 | 24 | 15 |
| <-1,5 | 19 | 17 | 16 | 11 | 10 |
| <-2,0 | 15 | 14 | 7 | 5 | 2 |
| <-2,5 | 11 | 10 | 2 | 0 | 0 |
| | | | | | |
| Maximum of under reporting (°C) | -3,38 | -2,84 | -2,63 | -2,44 | -2,21 |

GREEN: Low-temperature ready
TAUPE: Not low-temperature ready

# Appendix F

## Air temperature simulations

### Semi-detached

| Strategy number | 13 | 14 | 17 | 23 | 24 | 27 |
|---|---|---|---|---|---|---|
| Under reporting hours (hours) | | | | | | |
| <0 | 64 | 58 | 58 | 84 | 71 | 67 |
| <-0,5 | 48 | 45 | 43 | 53 | 46 | 46 |
| <-1,0 | 42 | 39 | 35 | 41 | 33 | 24 |
| <-1,5 | 33 | 32 | 28 | 15 | 11 | 13 |
| <-2,0 | 27 | 24 | 22 | 6 | 2 | 1 |
| <-2,5 | 21 | 18 | 17 | 0 | 0 | 0 |
| | | | | | | |
| Percentage of total hours (%) | | | | | | |
| <0 | 38 | 35 | 35 | 50 | 42 | 40 |
| <-0,5 | 29 | 27 | 26 | 32 | 27 | 27 |
| <-1,0 | 25 | 23 | 21 | 24 | 20 | 14 |
| <-1,5 | 20 | 19 | 17 | 9 | 7 | 8 |
| <-2,0 | 16 | 14 | 13 | 4 | 1 | 1 |
| <-2,5 | 13 | 11 | 10 | 0 | 0 | 0 |
| | | | | | | |
| Maximum of under reporting (°C) | -3,59 | -3,39 | -2,78 | -2,30 | -2,07 | -2,06 |

### Freestanding

| Strategy number | 25 | 27 |
|---|---|---|
| Under reporting hours (hours) | | |
| <0 | 99 | 83 |
| <-0,5 | 52 | 54 |
| <-1,0 | 43 | 45 |
| <-1,5 | 34 | 21 |
| <-2,0 | 8 | 7 |
| <-2,5 | 1 | 0 |
| | | |
| Percentage of total hours (%) | | |
| <0 | 59 | 49 |
| <-0,5 | 31 | 32 |
| <-1,0 | 26 | 27 |
| <-1,5- | 20 | 13 |
| <-2,0 | 5 | 4 |
| <-2,5 | 1 | 0 |
| | | |
| Maximum of under reporting (°C) | -2,51 | -2,30 |

GREEN: Low-temperature ready
TAUPE: Not low-temperature ready

# Appendix F

## *CFD analysis outcomes*

| Number | Strategies | MRT 0,1 [°C] | MRT 1,1 [°C] | MRT 1,7 [°C] | AT 0,1 [°C] | V 0,1 [m/s] | DR 0,1 [%] | Tu [%] | AT 1,1 [°C] | V 1,1 [m/s] | DR 1,1 [%] | Tu [%] | AT 1,7 [°C] | V 1,7 [m/s] | DR 1,7 [%] | Tu [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | Original Situation | 26,00 | 24,00 | 20,00 | 19,27 | 0,12 | 9,21 | 2,50 | 18,18 | 0,12 | 9,89 | 2,50 | 18,91 | 0,08 | 5,52 | 2,5 |
| 1 | G2, V1, T1, I1 | 24,00 | 22,00 | 19,00 | 18,18 | 0,13 | 10,77 | 2,50 | 17,45 | 0,10 | 8,35 | 2,50 | 18,55 | 0,10 | 7,80 | 2,50 |
| 2 | G3, V1, T1, I1 | 24,00 | 21,00 | 19,00 | 17,82 | 0,14 | 11,89 | 2,50 | 17,45 | 0,12 | 10,35 | 2,50 | 18,18 | 0,10 | 7,98 | 2,50 |
| 3 | G4, V1, T1, I1 | 24,00 | 21,00 | 20,00 | 18,18 | 0,14 | 11,62 | 2,50 | 17,82 | 0,12 | 10,11 | 2,50 | 18,55 | 0,08 | 5,65 | 2,50 |
| 4 | G1, V1, T1, I1 | 24,00 | 21,00 | 19,00 | 17,45 | 0,14 | 12,16 | 2,50 | 17,09 | 0,12 | 10,57 | 2,50 | 18,18 | 0,10 | 7,98 | 2,50 |
| 5 | G1, V2, T1, I1 | 24,00 | 21,00 | 19,00 | 18,91 | 0,08 | 5,52 | 2,50 | 18,55 | 0,08 | 5,65 | 2,50 | 18,91 | 0,06 | 2,77 | 2,50 |
| 6 | G2, V2, T1, I1 | 24,00 | 21,00 | 20,00 | 19,27 | 0,08 | 5,38 | 2,50 | 18,91 | 0,08 | 5,52 | 2,50 | 18,91 | 0,06 | 2,77 | 2,50 |
| 7 | G2, V1, T2, I1 | 21,00 | 20,00 | 19,00 | 17,45 | 0,12 | 10,35 | 2,50 | 17,45 | 0,08 | 6,05 | 2,50 | 17,82 | 0,10 | 8,16 | 2,50 |
| 8 | G2, V2, T2, I1 | 21,00 | 20,00 | 19,00 | 18,91 | 0,08 | 5,52 | 2,50 | 18,55 | 0,08 | 5,65 | 2,50 | 18,91 | 0,06 | 2,77 | 2,50 |
| 9 | G2, V1, T3, I1 | 19,00 | 19,00 | 19,00 | 17,09 | 0,14 | 12,42 | 2,50 | 17,45 | 0,10 | 8,35 | 2,50 | 17,82 | 0,10 | 8,16 | 2,50 |
| 10 | G2, V2, T3, I1 | 19,00 | 19,00 | 19,00 | 18,55 | 0,08 | 5,65 | 2,50 | 18,55 | 0,06 | 2,84 | 2,50 | 18,91 | 0,06 | 2,77 | 2,50 |
| 11 | G4, V1, T3, I1 | 20,00 | 19,00 | 19,00 | 17,09 | 0,12 | 10,57 | 2,50 | 17,45 | 0,10 | 8,35 | 2,50 | 17,82 | 0,08 | 5,91 | 2,50 |
| 12 | G4, V2, T3, I1 | 20,00 | 19,00 | 19,00 | 18,55 | 0,08 | 5,65 | 2,50 | 18,55 | 0,06 | 2,84 | 2,50 | 18,91 | 0,06 | 2,77 | 2,50 |
| 13 | G4, V1, T2, I1 | 22,00 | 20,00 | 19,00 | 17,45 | 0,12 | 10,35 | 2,50 | 17,45 | 0,10 | 8,35 | 2,50 | 17,82 | 0,10 | 8,16 | 2,50 |
| 14 | G4, V2, T2, I1 | 21,00 | 20,00 | 19,00 | 18,91 | 0,08 | 5,52 | 2,50 | 18,91 | 0,06 | 2,77 | 2,50 | 18,91 | 0,06 | 2,77 | 2,50 |
| 15 | G2, V1, T1, I2 | 23,00 | 22,00 | 20,00 | 18,55 | 0,14 | 11,35 | 2,50 | 18,18 | 0,08 | 5,78 | 2,50 | 18,91 | 0,08 | 5,52 | 2,50 |
| 16 | G2, V1, T1, I3 | 24,00 | 22,00 | 20,00 | 18,55 | 0,12 | 9,66 | 2,50 | 18,18 | 0,12 | 9,89 | 2,50 | 18,91 | 0,10 | 7,61 | 2,50 |
| 17 | G2, V2, T1, I3 | 24,00 | 23,00 | 20,00 | 20,00 | 0,08 | 5,12 | 2,50 | 19,64 | 0,06 | 2,64 | 2,50 | 20,00 | 0,06 | 2,57 | 2,50 |
| 18 | G2, V1, T2, I3 | 23,00 | 22,00 | 20,00 | 18,18 | 0,14 | 11,62 | 2,50 | 17,82 | 0,08 | 5,91 | 2,50 | 18,55 | 0,08 | 5,65 | 2,50 |
| 19 | G2, V1, T3, I3 | 20,00 | 20,00 | 20,00 | 17,45 | 0,12 | 10,35 | 2,50 | 17,82 | 0,08 | 5,91 | 2,50 | 18,55 | 0,08 | 5,65 | 2,50 |
| 20 | G4, V1, T1, I3 | 24,00 | 22,00 | 20,00 | 18,55 | 0,12 | 9,66 | 2,50 | 17,82 | 0,08 | 5,91 | 2,50 | 18,55 | 0,08 | 5,65 | 2,50 |
| 21 | G4, V2, T1, I3 | 24,00 | 23,00 | 20,00 | 19,64 | 0,08 | 5,25 | 2,50 | 19,27 | 0,06 | 2,71 | 2,50 | 19,64 | 0,06 | 2,64 | 2,50 |
| 22 | G4, V2, T3, I3 | 20,00 | 20,00 | 20,00 | 18,91 | 0,08 | 5,52 | 2,50 | 18,91 | 0,06 | 2,77 | 2,50 | 19,27 | 0,06 | 2,71 | 2,50 |
| 23 | G2, V2, T1, I2 | 24,00 | 21,00 | 20,00 | 20,00 | 0,10 | 7,06 | 2,50 | 19,27 | 0,06 | 2,71 | 2,50 | 19,64 | 0,06 | 2,64 | 2,50 |

|  | Code | Additional Note |
|---|---|---|
| Window Types |  |  |
| Double Glazing | G1 |  |
| HR Glazing | G2 |  |
| HR++ Glazing | G3 |  |
| Triple Glazing | G4 |  |
|  |  |  |
| Ventilation |  |  |
| C1 and C3 | V1 | T = 0, Supply = 1,4 l/s |
| D2 | V2 | T = 14, Supply = 1,4 l/s |

|  | Code | Additional Note |
|---|---|---|
| Radiator Temp [°C] |  |  |
| 55 | T1 |  |
| 35 | T2 |  |
| 20 | T3 |  |
|  |  |  |
| Insulation Level |  |  |
| Existing | I1 | - |
| Medium | I2 | Strategy 2 |
| High | I3 | Strategy 6 |

# Appendix F

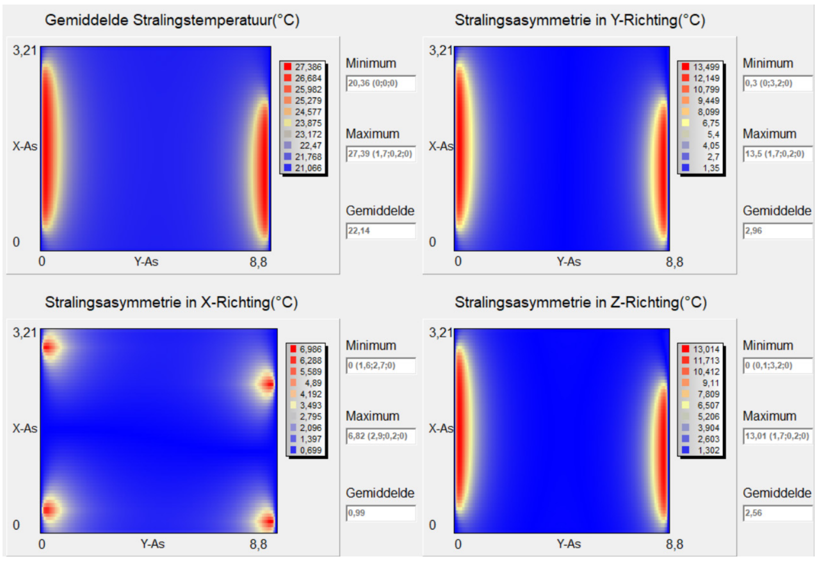
## CFD analysis outcomes

| Strategies (on case study) | MRT 0,1 [°C] | MRT 1,1 [°C] | MRT 1,7 [°C] | AT 0,1 [°C] | V 0,1 [m/s] | DR 0,1 [%] | Tu [%] | AT 1,1 [°C] | V 1,1 [m/s] | DR 1,1 [%] | Tu [%] | AT 1,7 [°C] | V 1,7 (m/s] | DR 1,7 [%] | Tu [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Existing | 26,00 | 21,00 | 20,00 | 18,09 | 0,14 | 11,69 | 2,50 | 18,09 | 0,10 | 8,03 | 2,50 | 18,09 | 0,10 | 8,03 | 2,5 |
| Existing LT | 21,00 | 17,00 | 16,00 | 15,55 | 0,10 | 9,31 | 2,50 | 14,91 | 0,07 | 5,41 | 2,50 | 15,55 | 0,07 | 5,23 | 2,50 |
| Strategy 4 | 22,00 | 19,00 | 18,00 | 17,45 | 0,14 | 12,16 | 2,50 | 16,82 | 0,10 | 8,67 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 |
| Strategy 6 | 23,00 | 19,00 | 19,00 | 17,45 | 0,14 | 12,16 | 2,50 | 17,45 | 0,10 | 8,35 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 |
| Strategy 7 | 23,00 | 20,00 | 19,00 | 17,45 | 0,10 | 8,35 | 2,50 | 16,82 | 0,07 | 4,87 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 |
| Strategy 6 (+triple glazing) | 23,00 | 20,00 | 19,00 | 17,45 | 0,10 | 8,35 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 |
| Strategy 14 | 23,00 | 20,00 | 19,00 | 18,09 | 0,10 | 8,03 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 | 18,09 | 0,07 | 4,51 | 2,50 |
| Strategy 16 | 23,00 | 20,00 | 19,00 | 17,45 | 0,10 | 8,35 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 |
| Strategy 17 | 23,00 | 20,00 | 19,00 | 17,45 | 0,10 | 8,35 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 |
| Strategy 16 (+triple glazing) | 23,00 | 20,00 | 19,00 | 17,45 | 0,10 | 8,35 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 | 17,45 | 0,07 | 4,69 | 2,50 |
| Strategy 24 | 23,00 | 21,00 | 20,00 | 18,73 | 0,10 | 7,70 | 2,50 | 18,09 | 0,07 | 4,51 | 2,50 | 18,73 | 0,05 | 0,00 | 2,50 |
| Strategy 26 | 23,00 | 21,00 | 20,00 | 18,73 | 0,10 | 7,70 | 2,50 | 18,73 | 0,07 | 4,33 | 2,50 | 18,73 | 0,05 | 0,00 | 2,50 |
| Strategy 27 | 23,00 | 21,00 | 20,00 | 18,73 | 0,10 | 7,70 | 2,50 | 18,73 | 0,07 | 4,33 | 2,50 | 18,73 | 0,05 | 0,00 | 2,50 |
| Strategy 26 (+triple glazing) | 23,00 | 21,00 | 20,00 | 19,36 | 0,10 | 7,39 | 2,50 | 18,73 | 0,05 | 0,00 | 2,50 | 19,36 | 0,05 | 0,00 | 2,50 |

# Appendix F

## Radiant asymmetry

Existing situation:
high-temperature



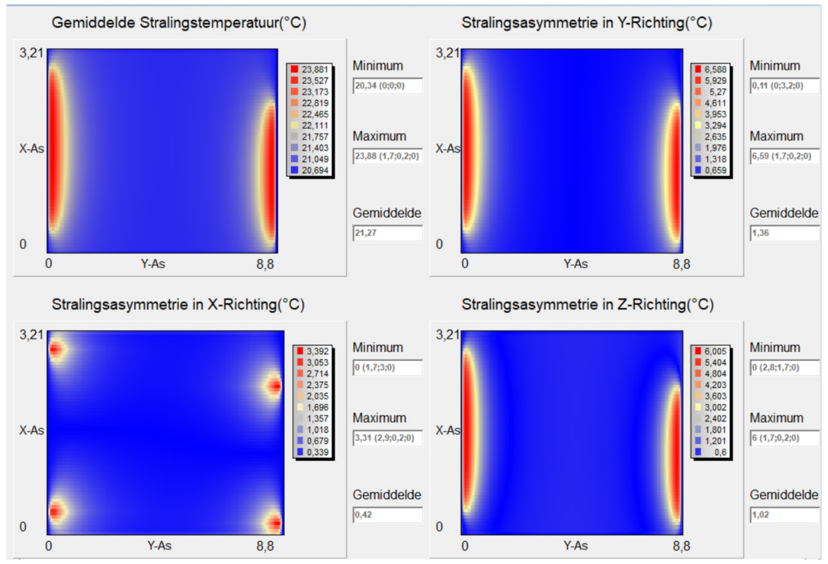
Gemiddelde Stralingstemperatuur(°C)
Minimum 20,36 (0;0;0)
Maximum 27,39 (1,7;0,2;0)
Gemiddelde 22,14

Stralingsasymmetrie in Y-Richting(°C)
Minimum 0,3 (0;3,2;0)
Maximum 13,5 (1,7;0,2;0)
Gemiddelde 2,96

Stralingsasymmetrie in X-Richting(°C)
Minimum 0 (1,6;2,7;0)
Maximum 6,82 (2,9;0,2;0)
Gemiddelde 0,99

Stralingsasymmetrie in Z-Richting(°C)
Minimum 0 (0,1;3,2;0)
Maximum 13,01 (1,7;0,2;0)
Gemiddelde 2,56

Existing situation:
low-temperature



Gemiddelde Stralingstemperatuur(°C)
Minimum 20,34 (0;0;0)
Maximum 23,88 (1,7;0,2;0)
Gemiddelde 21,27

Stralingsasymmetrie in Y-Richting(°C)
Minimum 0,11 (0;3,2;0)
Maximum 6,59 (1,7;0,2;0)
Gemiddelde 1,36

Stralingsasymmetrie in X-Richting(°C)
Minimum 0 (1,7;3;0)
Maximum 3,31 (2,9;0,2;0)
Gemiddelde 0,42

Stralingsasymmetrie in Z-Richting(°C)
Minimum 0 (2,8;1,7;0)
Maximum 6 (1,7;0,2;0)
Gemiddelde 1,02

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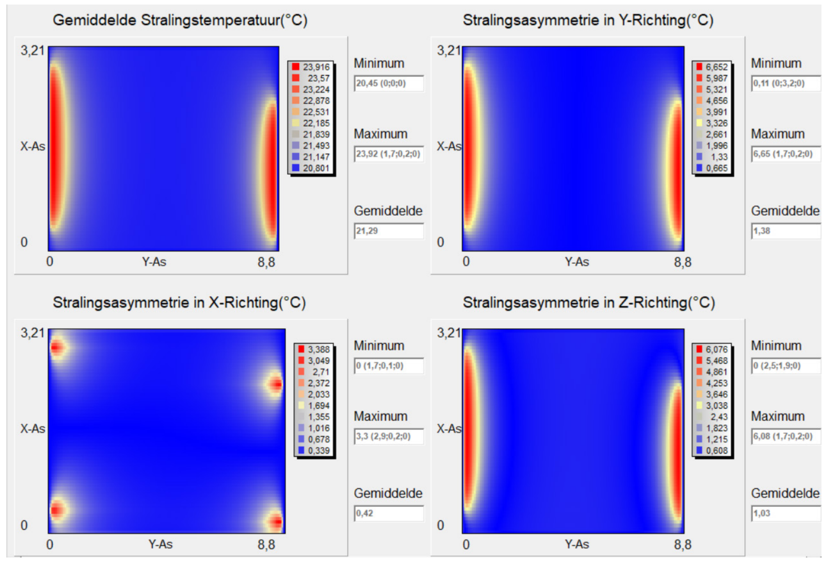
# Appendix F

## Radiant asymmetry

Cavity wall insulation



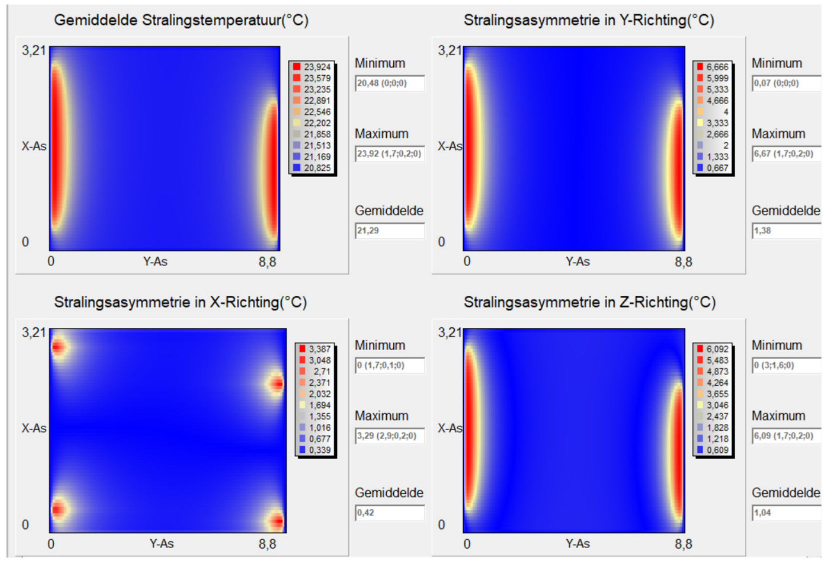
Gemiddelde Stralingstemperatuur(°C)
Minimum 20,45 (0;0;0)
Maximum 23,92 (1,7;0,2;0)
Gemiddelde 21,29

Stralingsasymmetrie in Y-Richting(°C)
Minimum 0,11 (0;3,2;0)
Maximum 6,65 (1,7;0,2;0)
Gemiddelde 1,38

Stralingsasymmetrie in X-Richting(°C)
Minimum 0 (1,7;0,1;0)
Maximum 3,3 (2,9;0,2;0)
Gemiddelde 0,42

Stralingsasymmetrie in Z-Richting(°C)
Minimum 0 (2,5;1,9;0)
Maximum 6,08 (1,7;0,2;0)
Gemiddelde 1,03

+5 cm interior wall insulation



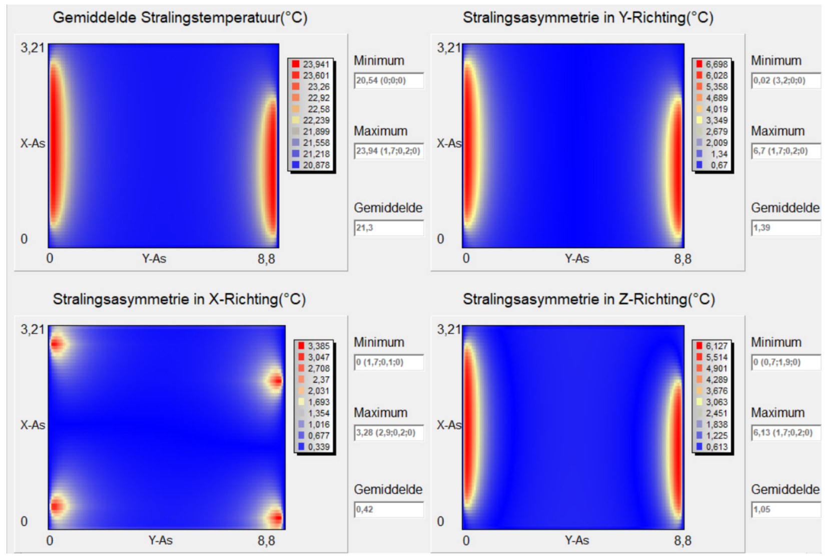
Gemiddelde Stralingstemperatuur(°C)
Minimum 20,48 (0;0;0)
Maximum 23,92 (1,7;0,2;0)
Gemiddelde 21,29

Stralingsasymmetrie in Y-Richting(°C)
Minimum 0,07 (0;0;0)
Maximum 6,67 (1,7;0,2;0)
Gemiddelde 1,38

Stralingsasymmetrie in X-Richting(°C)
Minimum 0 (1,7;0,1;0)
Maximum 3,29 (2,9;0,2;0)
Gemiddelde 0,42

Stralingsasymmetrie in Z-Richting(°C)
Minimum 0 (3;1,6;0)
Maximum 6,09 (1,7;0,2;0)
Gemiddelde 1,04

+10 cm exterior wall insulation



Gemiddelde Stralingstemperatuur(°C)
Minimum 20,54 (0;0;0)
Maximum 23,94 (1,7;0,2;0)
Gemiddelde 21,3

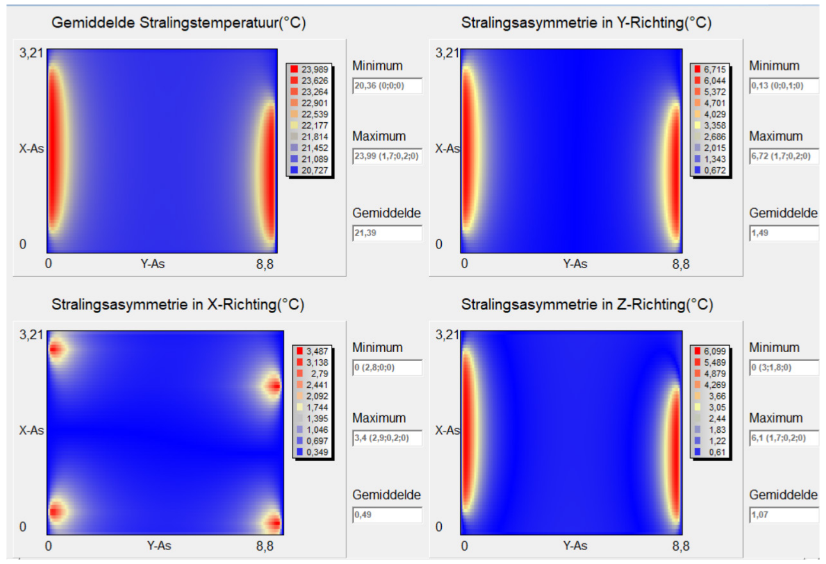
Stralingsasymmetrie in Y-Richting(°C)
Minimum 0,02 (3,2;0;0)
Maximum 6,7 (1,7;0,2;0)
Gemiddelde 1,39

Stralingsasymmetrie in X-Richting(°C)
Minimum 0 (1,7;0,1;0)
Maximum 3,28 (2,9;0,2;0)
Gemiddelde 0,42

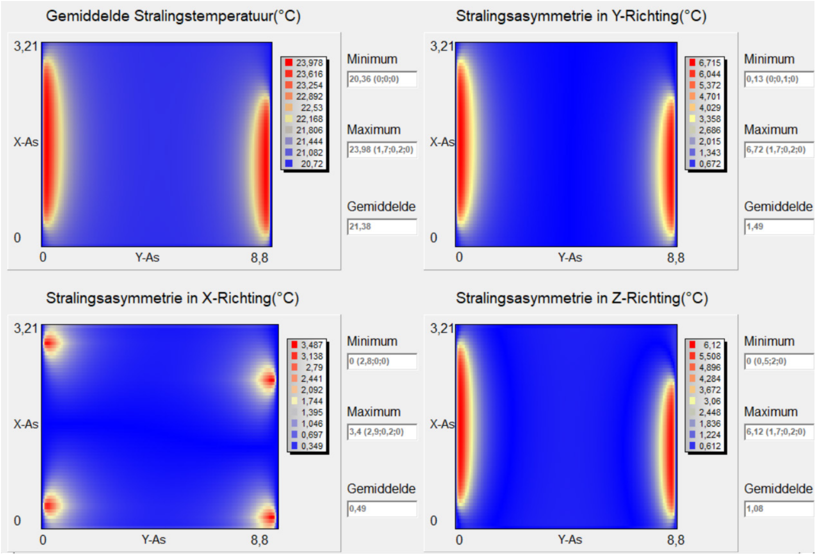
Stralingsasymmetrie in Z-Richting(°C)
Minimum 0 (0,7;1,9;0)
Maximum 6,13 (1,7;0,2;0)
Gemiddelde 1,05

# Appendix F

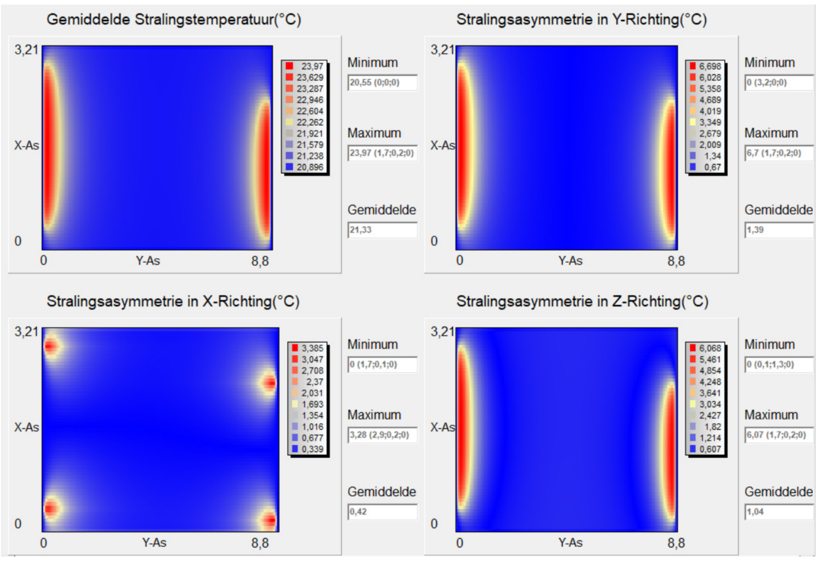
## Radiant asymmetry



+ 4 cm above ground floor insulation



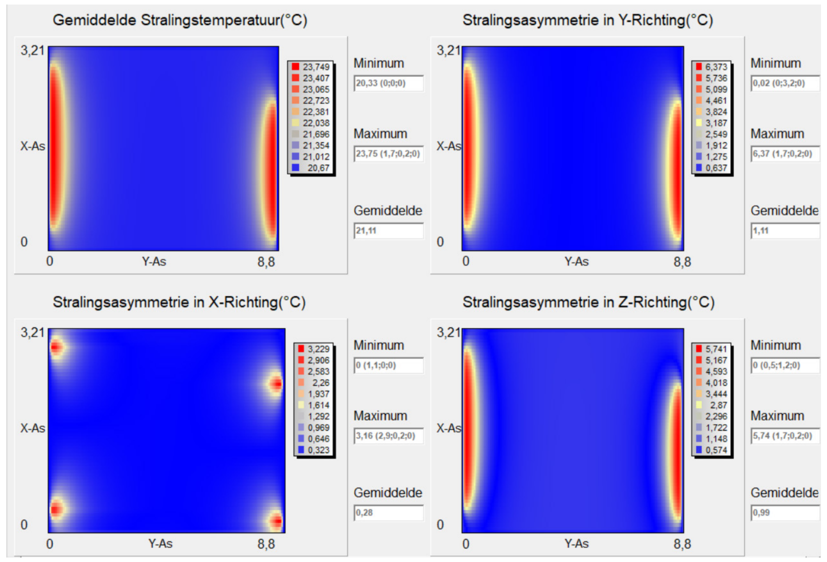
+10 cm below ground floor insulation



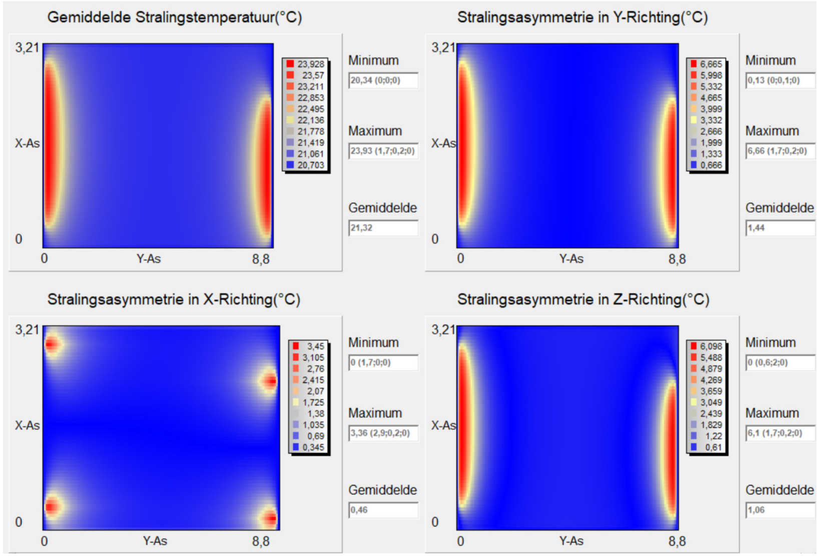
+10 cm exterior wall insulation AND +10 cm below ground floor insulation

# Appendix F

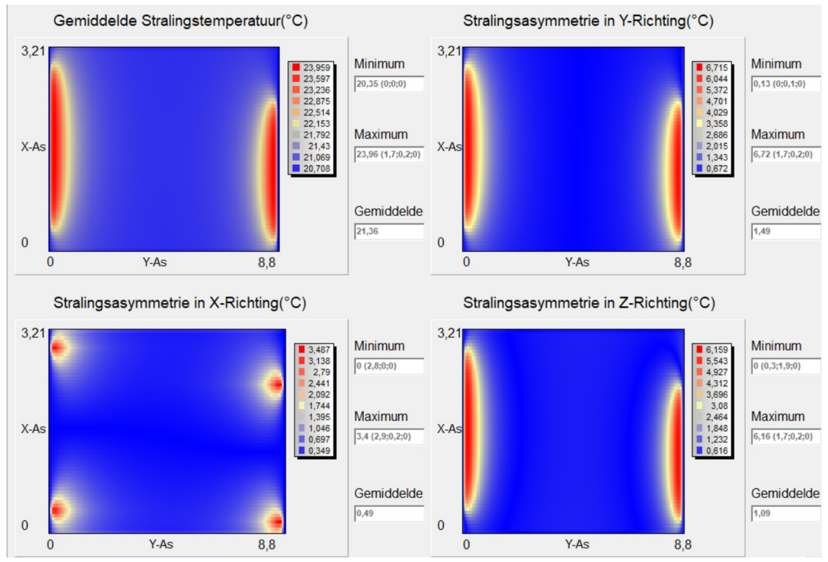
## Radiant asymmetry



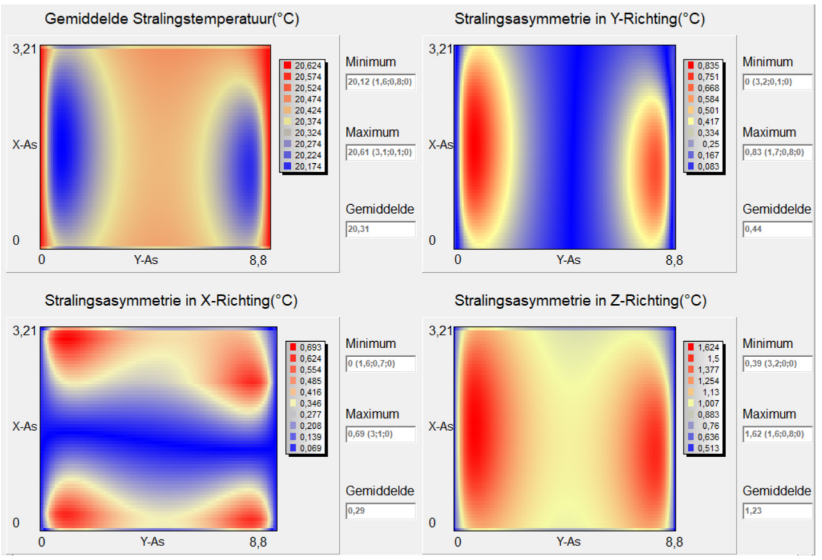
Double glazing



HR++ glazing



Triple glazing



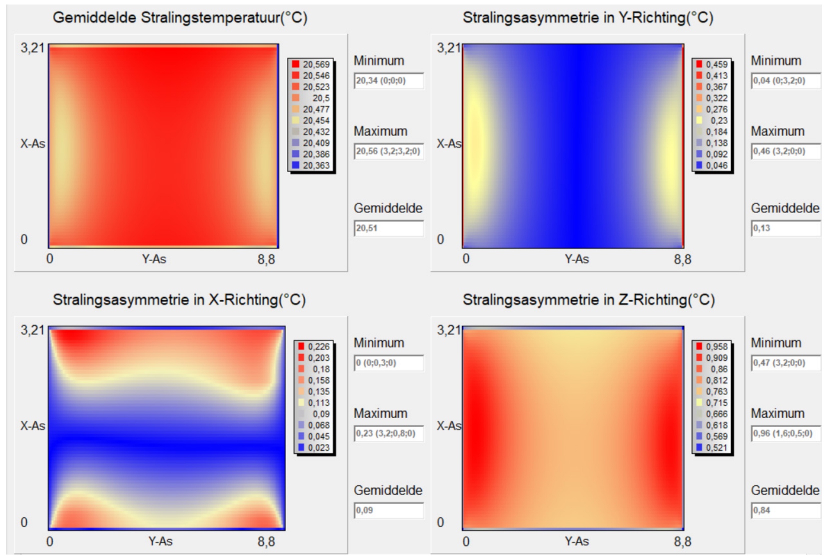
Gemiddelde Stralingstemperatuur(°C): Minimum 20,12 (1,6;0,8;0) · Maximum 20,61 (3,1;0,1;0) · Gemiddelde 20,31

Stralingsasymmetrie in Y-Richting(°C): Minimum 0 (3,2;0,1;0) · Maximum 0,83 (1,7;0,8;0) · Gemiddelde 0,44

Stralingsasymmetrie in X-Richting(°C): Minimum 0 (1,6;0,7;0) · Maximum 0,69 (3;1;0) · Gemiddelde 0,29

Stralingsasymmetrie in Z-Richting(°C): Minimum 0,39 (3,2;0;0) · Maximum 1,62 (1,6;0,8;0) · Gemiddelde 1,23

Double glazing (NO RADIATOR)



Gemiddelde Stralingstemperatuur(°C): Minimum 20,34 (0;0;0) · Maximum 20,56 (3,2;3,2;0) · Gemiddelde 20,51

Stralingsasymmetrie in Y-Richting(°C): Minimum 0,04 (0;3,2;0) · Maximum 0,46 (3,2;0;0) · Gemiddelde 0,13

Stralingsasymmetrie in X-Richting(°C): Minimum 0 (0;0,3;0) · Maximum 0,23 (3,2;0,8;0) · Gemiddelde 0,09

Stralingsasymmetrie in Z-Richting(°C): Minimum 0,47 (3,2;0;0) · Maximum 0,96 (1,6;0,5;0) · Gemiddelde 0,84

Triple glazing (NO RADIATOR)

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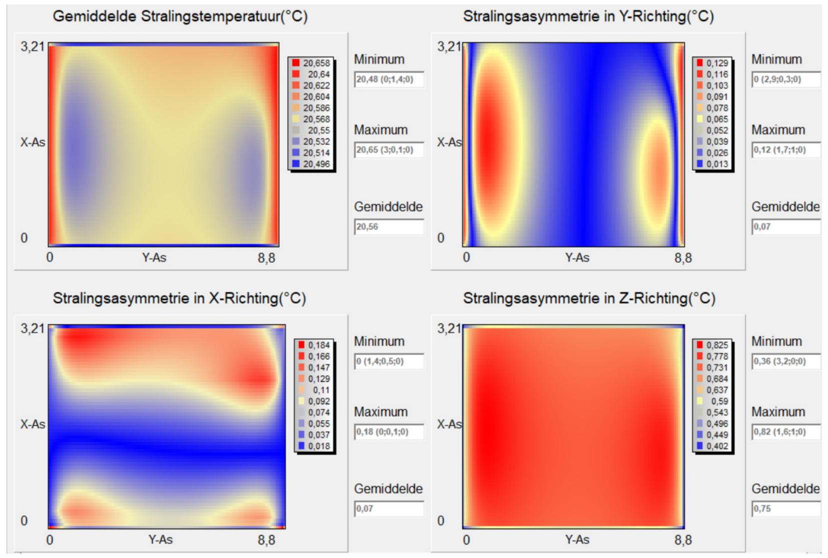


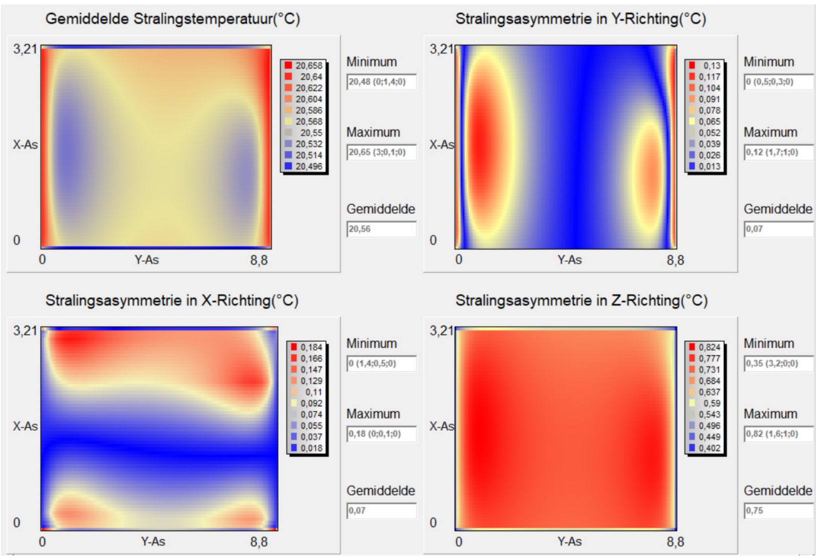
Gemiddelde Stralingstemperatuur(°C): Minimum 20,48 (0;1,4;0) · Maximum 20,65 (3;0,1;0) · Gemiddelde 20,56

Stralingsasymmetrie in Y-Richting(°C): Minimum 0 (2,9;0,3;0) · Maximum 0,12 (1,7;1;0) · Gemiddelde 0,07

Stralingsasymmetrie in X-Richting(°C): Minimum 0 (1,4;0,5;0) · Maximum 0,18 (0;0,1;0) · Gemiddelde 0,07

Stralingsasymmetrie in Z-Richting(°C): Minimum 0,36 (3,2;0;0) · Maximum 0,82 (1,6;1;0) · Gemiddelde 0,75

Triple glazing and +10 cm wall exterior wall insulation
(NO RADIATOR)



Gemiddelde Stralingstemperatuur(°C): Minimum 20,48 (0;1,4;0) · Maximum 20,65 (3;0,1;0) · Gemiddelde 20,56

Stralingsasymmetrie in Y-Richting(°C): Minimum 0 (0,5;0,3;0) · Maximum 0,12 (1,7;1;0) · Gemiddelde 0,07

Stralingsasymmetrie in X-Richting(°C): Minimum 0 (1,4;0,5;0) · Maximum 0,18 (0;0,1;0) · Gemiddelde 0,07

Stralingsasymmetrie in Z-Richting(°C): Minimum 0,35 (3,2;0;0) · Maximum 0,82 (1,6;1;0) · Gemiddelde 0,75

Triple glazing and +10 cm below ground floor insulation
(NO RADIATOR)