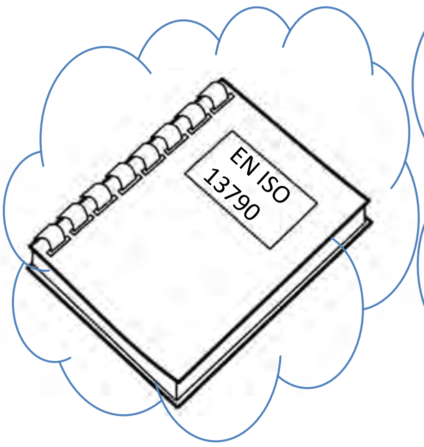
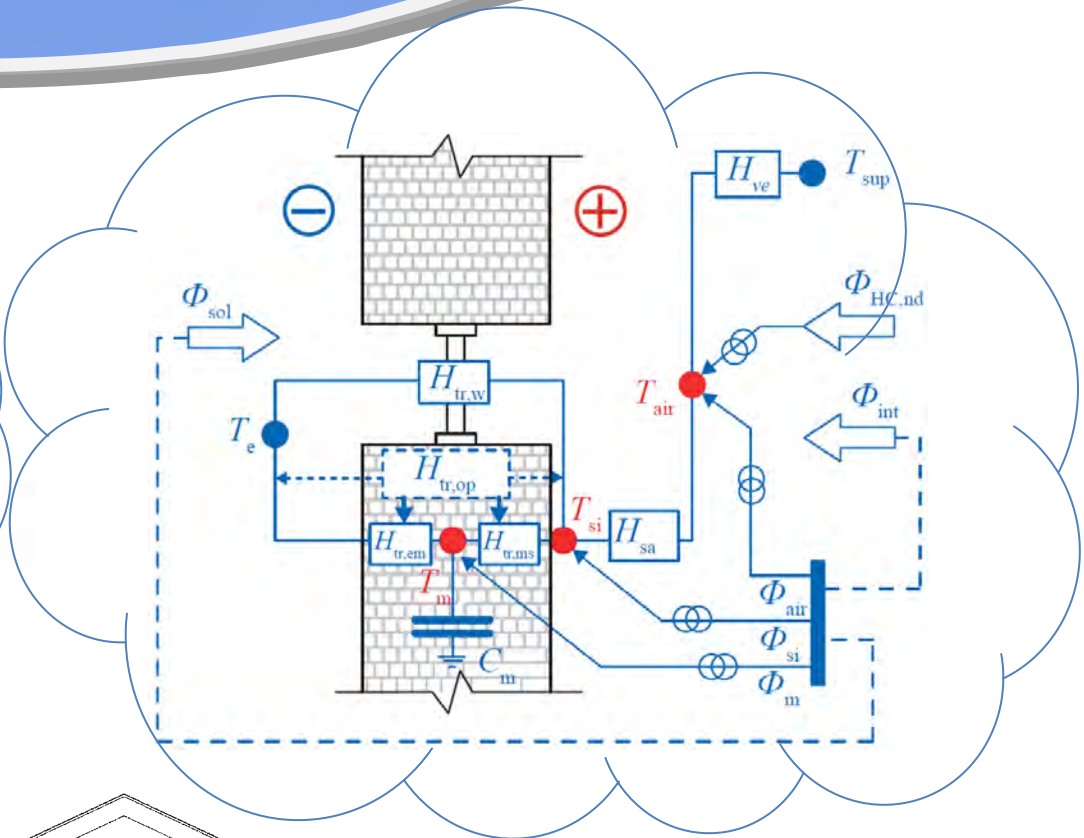
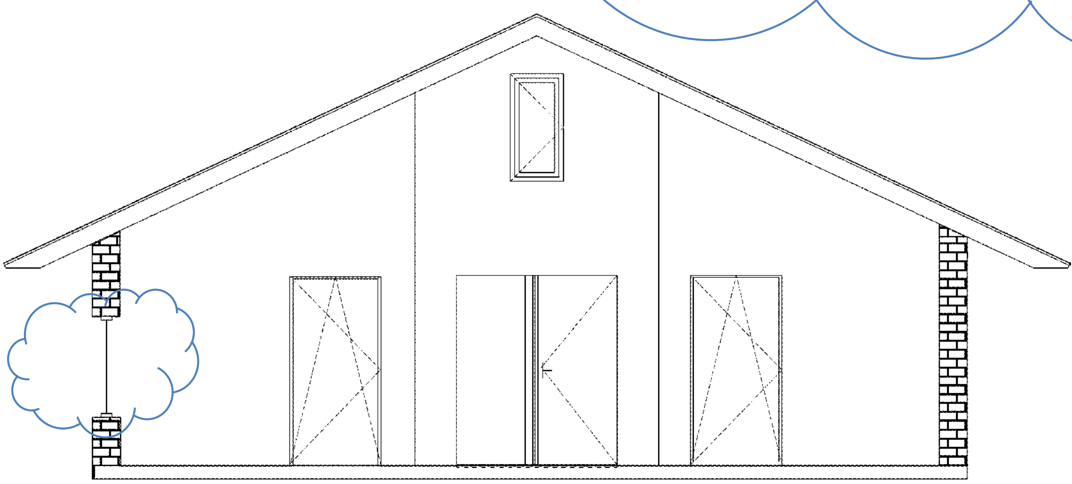
Jacqueline Valencienne Orlikowski

Prognosis of heat consumption of smart grid buildings on basis of the weather forecast

Investigation of buildings‘ heat capacity and design of a calculation tool on basis of EN ISO 13790







AALBORG UNIVERSITY
STUDENT REPORT

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STUDENT REPORT

Title:
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Subtitle:
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Project period:
February 2014 - June 2014

Project group:
B-223c

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In cooperation with:
WATERKOTTE GmbH

Editions: 5

Number of pages: 71

Number of appendix pages: 14

Appendix CD

Completed: 6th of June 2014

Drawing on frontpage [Homics and Kirkedal, 2013]

Synopsis:

This master thesis contains an investigation of buildings' capacity of heat storage and the design of a calculation tool making it possible to give a prognosis of the heat demand for smart grid buildings.
The ability of different buildings covering comfort temperature is tested, when they, as in case of smart grid buildings, have only a limited period of heating energy availability. Four different building heavinesses are taken into consideration, each of them once within a passive house and once in a building after actual standards. Further, are floor heat and radiators, as well as two different locations with varying weather conditions implemented within the investigation. The goal is to make a statement regarding which building types are recommendable for an implementation of smart grids.
The design of a calculation tool shall allow to give a prognosis of the heat demand with a reasonably sized computation process. Input parameters regarding weather conditions are delimited in a short sensitivity analysis. The calculation tool is verified with real life measurements of a chosen building of the comfort house project.

Preface

The project is made by Jacqueline Valencienne Orlikowski on the 4^{th} semester of the Master of Science in Indoor Environmental and Energy Engineering at Aalborg University in spring 2014. The overall theme of the project is *Heat capacity and heat consumption.* The aim of the project is to obtain knowledge and perform theoretical and research oriented investigations regarding the overall theme.

The author wants to pronounce special thanks to supervisors Rasmus Lund Jensen and Michal Pomianowski for time spent during the master thesis and the informative meetings and helpful guidance. The author is further thankful for the cooperation with WATERKOTTE GmbH and the useful guidance from Andreas Jung, who gave the initial idea about the project.

Reading guide

The master thesis appears as a main report with a final conclusion in the end. After the final conclusion, the appendices are placed. The report includes methods, assumptions and results. References to the appendices are made, as the appendices work as references to the report. The appendices contain tables, figures, further descriptions and theory. In addition to the written report an appendix CD is attached on the back of the report. The table of content for the appendix CD is located in appendix A. The appendix CD contains calculation spread sheets, simulation files, drawings and further documentation that are not included in the report.

The chapters in the report are numbered chronologically and their figures, tables, and equations are numbered according to the number of the chapter in which they appear. This means that the first table of the second chapter will be named table 2.1, the second table will be named 2.2 and so on. Descriptions of tables and figures are given below the relevant table or figure and a reference is stated, when an object is not produced by the author.

The reference will be referred to in the report after Harvard method for books as [Last name, Year], norms and instructions are referred to as [Title, Year] and websites are referred to as [Website name, Year]. The sources are completely listed in the literature section, where books are completed with the name of the author, title, edition, publication date and publisher. Web pages are completed with author, title and year. If the content is exclusively made by the author, there will be no reference.

Abstract

The present master thesis contains an investigation about buildings' capacity of heat storage and a calculation tool able to prognosticate the heat demand after simple hourly method of EN ISO 13790 [2008].

Smart grid building are one of the newest technologies complying stricter becoming energy requirements of building regulations. To bring energy supply and energy consumption by means of a photovoltaic and heat pump heating system closer together, buildings need a relatively good capacity of storing heat due to the limited period of photovoltaic availability. To investigate which buildings are recommendable for implementing a smart grid system, eight different building variations are created and analysed regarding their ability to store a specific comfort temperature for a selected period of the day. Their heaviness is classified due to a varying heat capacity, ranging from extra light to extra heavy. Moreover, are mentioned heaviness categories further divided into today common standards regarding heat losses and passive house standard. Investigations are implemented in BSim, simulating a constant high heating phase in eight hours of day, to analyse the temperature drop in the remaining 16 hours without heating. An implementation of smart grids seems rational in buildings of actual standard that in majority include heavy materials. All versions of passive houses from light to heavy building heaviness are recommendatory for a smart grid implementation.

Further, is a main content of present master thesis the design of a calculation tool to make a prognosis regarding the heat demand, which can be implemented into heat pump controller. Chosen method is the simple hourly method after EN ISO 13790 [2008] due to the possible input of hourly data from conducted measurements of the smart grid building and its simplicity accompanied with a limited amount of input data. After a short presentation of the theory, a simplified sensitivity analysis is carried out, as the EN ISO 13790 [2008] leaves it to a certain degree to the user which weather parameters are to be implemented. External air temperature, solar radiation, wind and relative humidity are taken into consideration, as these can be achieved from weather services.

After the amount of input data is delimited, the necessary input information regarding building characteristics and ventilation system are explained. Further is a closer look given to solar and internal heat gains. The output of the calculation tool gives an overview of expected heating demand and expected internal air temperature, when the heating device only delivers in a limited period of the day.

To verify the calculation tool, simulated parameters are compared to measured heating supply and operative temperature of a building of the comfort house project.

First, simulated operative temperatures with given heat demand are compared to measured operative temperatures. Second, the simulated heating demand with a given heating set temperature is juxtaposed to measured heating supply. Deviations lay in an acceptable range, which verifies the possible use of the calculation tool in heat pump controller.

Symbols and units

Symbol	Description	Unit
A	Area of exposed surface	[m^2]
A_{floor}	Area of the floor	[m^2]
A_j	Area of the element j	[m^2]
A_w	Area of window	[m^2]
b_c	Temperature factor for constructions	[-]
b_l	Temperature factor for thermal linear loss	[-]
c_i	Specific heat capacity	[J/kgK]
C_m	Internal heat capacity of the building	[Wh/m^2K]
$C_{1,2,3}$	Calculation constants	[$-$]
d_i	Thickness of layer i	[m]
E	East	[°]
f_c	Shading factor	[-]
f_c	Shading set point	[°C] or [W/m^2]
f_{fin}	Partial shadow correction factor for side fins	[-]
f_g	Glazing area fraction	[-]
f_{hor}	Partial shadow correction factor for the horizon	[-]
f_{ov}	Partial shadow correction factor for overhangs	[-]
f_{sh}	Shading factor	[-]
f_{wc}	Partial shadow correction factor for wall cavity	[-]
g	Solar heat gain coefficient	[-]
g_{gl}	Solar energy transmittance of transparent	[-]
H	Overall heat loss	[W]
h	Height	[m]
H_i	Heat loss caused by infiltration	[W]
H_t	Heat loss caused by transmission	[W]
$H_{tr,em}$	Specific heat flow external air and thermal mass	[W/K]
$H_{tr,ms}$	Specific heat flow thermal mass and internal surfaces	[W/K]
$H_{tr,opa}$	Specific heat transfer through opaque construction	[W/K]
$H_{tr,w}$	Specific heat transfer through windows	[W/K]
H_v	Heat loss caused by ventilation	[W]
I_{dif}	Diffuse solar radiation	[W/m^2]
I_{dir}	Direct solar radiation	[W/m^2]
I_{ref}	Reflected solar radiation	[W/m^2]
I_{sol}	Total solar incidence	[W/m^2]
l	Linear thermal length	[m]
N	Day number of the year	[-]
N	North	[°]

Symbol	Description	Unit
n	Amount	[-]
NE	Northeast	[°]
NW	Northwest	[°]
n_0	Basic air change rate	[h^{-1}]
$q_{ve,b}$	Basic ventilation	[l/sm^2]
$q_{ve,day}$	Daytime ventilation	[l/sm^2]
$q_{ve,evening}$	Evening ventilation	[l/sm^2]
$q_{ve,night}$	Night ventilation	[l/sm^2]
q_{50}	Air change at 50 Pa pressure difference	[h^{-1}]
R	Thermal resistance of the construction	[m^2K/W]
R_{se}	External thermal resistance	[m^2K/W]
R_{si}	Internal thermal resistance	[m^2K/W]
S	South	[°]
SE	Southeast	[°]
SW	Southwest	[°]
t	time step	[-]
t_i	Internal air temperature	[°C]
t_o	External air temperature	[°C]
T_{prop}	Proportional band	[°C]
t-1	previous time step	[-]
U	Overall heat transmission coefficient	[W/m^2K]
U_j	Heat transmission coefficient of the building element	[W/m^2K]
W	West	[°]
w	Width	[m]
α	Overhang angle	[°]
α_s	Solar altitude angle	[°]
β_l	Left fin angle	[°]
β_r	Right fin angle	[°]
γ_s	Solar azimuth angle	[°]
γ'_s	Solar pseudo azimuth angle	[°]
δ	Earth declination angle	[m^2]
θ	Wall cavity	[%]
θ_{air}	Air temperature	[°C]
$\theta_{air,0}$	Air temperature without heating/cooling	[°C]
$\theta_{air,10}$	Air temperature with heat supply of 10 W/m^2	[°C]
$\theta_{int,C,set}$	Set point temperature for cooling	[°C]
$\theta_{int,H,set}$	Set point temperature for heating	[°C]
θ_m	Thermal mass temperature	[°C]
$\theta_{m,t}$	Actual thermal mass temperature	[°C]
$\theta_{m,t-1}$	Thermal mass temperature of previous time step	[°C]
θ_s	Temperature internal surface	[°C]
θ_{sup}	Ventilation supply temperature	[°C]

Symbol	Description	Unit
κ_{j}	Internal heat capacity of the building element j	[Wh/m^{2}K]
λ_{i}	Thermal conductivity	[W/mK]
ρ_{i}	Density of layer i	[kg/m^3]
τ_{s}	Solar time for a specific location	[h]
ϕ	Latitude	[°]
$\phi_{\mathrm{HC,nd}}$	Heating/cooling need with unrestricted power	[W]
$\phi_{\mathrm{HC,nd,ac}}$	Actual heating/cooling demand	[W]
ϕ_{sol}	Solar heat gains in thermal zone	[W]
ψ	Linear thermal transmittance	[W/m^{2}K]
ψ	Linear thermal transmittance between wall and window	[W/mK]
ψ	Horizon angle	[°]
ω	Hour angle	[°]

Contents

1 Heat consumption in domestic buildings in Europe

1.1 An overview of the heat consumption of domestic buildings

The reduction of energy consumption and the elimination of energy wastage are major goals of the European Union (EU). Within the EU it is committed to decrease the annual primary energy consumption by 20 % in 2020 [Summaries of EU legislation, 2014a] to the consumption of year 1990. A significant potential is given in the energy intensive consumers like buildings, especially of domestic and tertiary sector, as well as transport and industrial processes [Glas for Europe, 2014]. The building sector is responsible for around 40 % of the overall energy consumption in the EU, seen in figure 1.1 and therefore a priority [Summaries of EU legislation, 2014b]

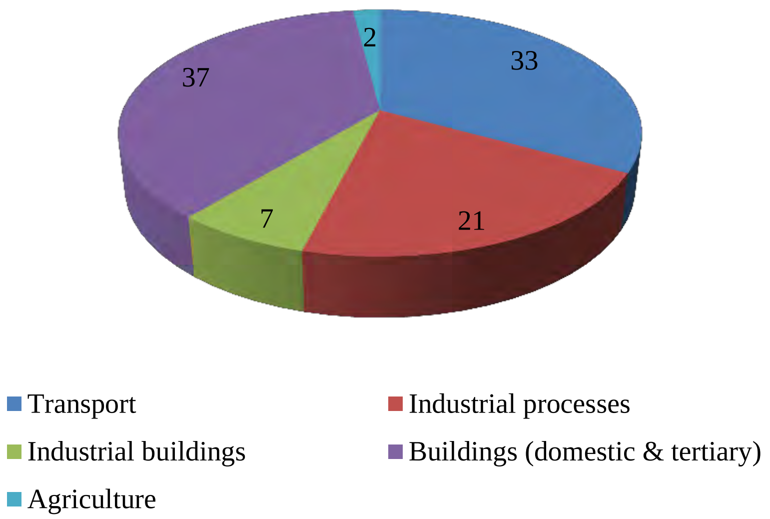


Figure 1.1. Energy consumers in European Union [Glas for Europe, 2014].

To achieve this goal, guidelines regarding the energy performance of buildings are proposed for the member states. Every nation is encouraged to apply a method for calculating the energy efficiency for buildings as well as to establish minimum requirements. Denmark implemented the building regulation BR10 and for Germany it is the EnEV 2014 that stipulates the suggestions of the European Union into German regulation. Next to restraints about the annual primary energy demand and instructions about the thermal insulation of the building envelope, EnEV [2014] regulates in §5 the accounting of electricity from renewable energies.

In new buildings, the electricity generated in direct spatial vicinity and mainly used for the building itself, can be deducted from the final energy demand [EnEV, 2014]. This gives potential for the so called smart grid to be applied in buildings to comply with the more and more stricter becoming regulations.

1.2 The idea of the smart grid building

A smart grid is "a network of electricity consumers and electricity generators in order to optimize a local control of electricity supply and consumption over time" [Lackes and Siepermann, 2014]. A common variant and therefore presented in this report, is a smart grid containing a photovoltaic system and a heat pump. In buildings with these two renewable energy devices, but without a smart grid, there are big differences between generator and consumer. To visualize this, a fictive electricity demand is designed, next to a fictive possible photovoltaic performance, seen in figure 1.2.

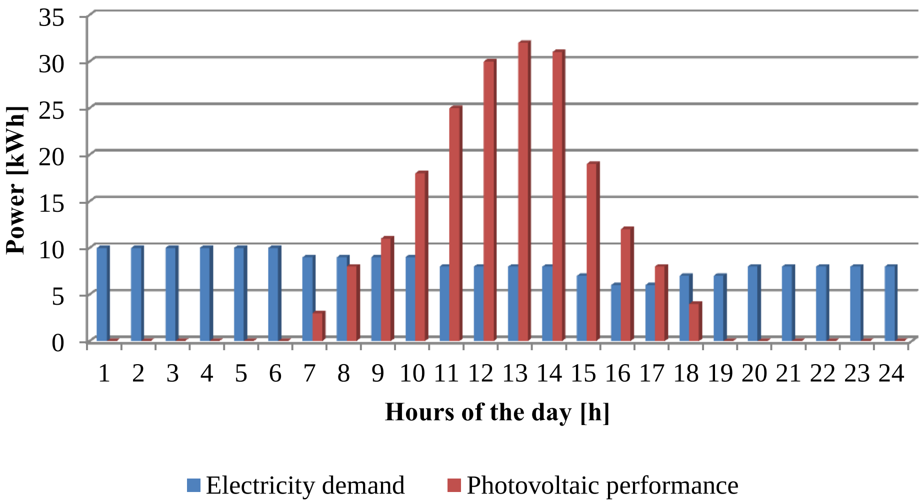


Figure 1.2. Sketch of fictive electricity demand in accordance to fictive photovoltaic performance in buildings without smart grid.

If a smart grid is integrated into a building, will the electricity generator, the photovoltaic system, be in continuous contact with the electricity consumers, inter alia, the heat pump. An overall controller simulates beforehand, what the performance of the electricity generator will be. In accordance to that it is planned when the user-independent electricity devices are to be used on the next day, as exemplary visualized in figure 1.3 on the facing page.

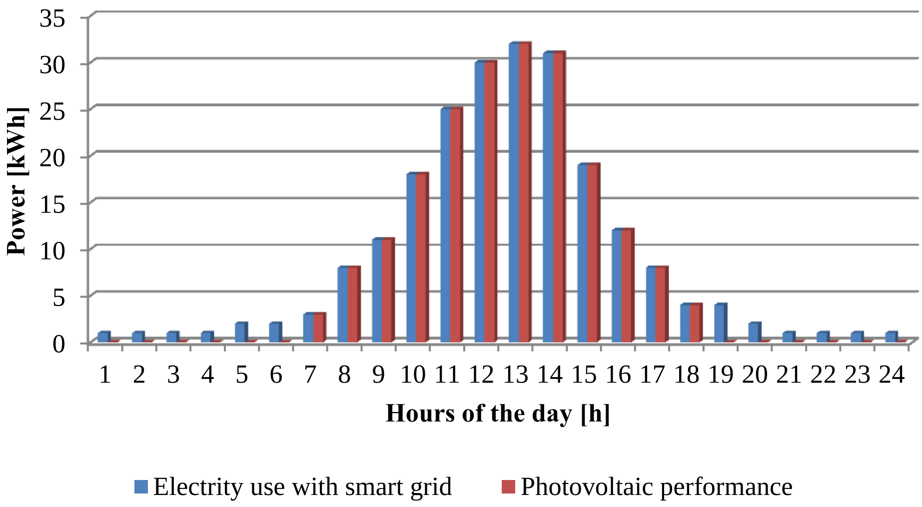


Figure 1.3. Sketch of electricity consumption in accordance to photovoltaic performance in smart grid buildings.

As the figure 1.3 indicates, does the photovoltaic system show a high performance in the afternoon, in this time the heat pump can be activated to deliver heating energy to the building. But also other consumers, that are to a certain degree independent from the user, as washing machines, dish washers, etc. can be utilized in this period of high electricity generation, if the users tolerate. It is seen that the photovoltaic does not cover all the electricity demand, as some needs are independent and have to be utilized irrespective of a given electricity supply of the photovoltaic. In this project focus is given to the heat pump, as the biggest electricity consumer, when providing a building with heating (and cooling).

In the above shown figure it is not integrated, what effect a limited period of heating has on the internal temperatures. Heavy buildings with a high amount of thermal mass can store heat and therefore keep the temperature in a comfortable region longer than light buildings with no thermal mass. Also does the quality of the building effect the temperature drop, when the heat pump is turned off due to a missing photovoltaic supply availability. Parameters that can be mentioned are air tightness, heat recovery rate of the ventilation and insulation thickness.

To convert a smart grid into reality, a prognosis of the expected performance of the electricity generator and the expected electricity demand of the building have to be made. When the generator is a photovoltaic system, then it is with technical data of the photovoltaic and solar radiation forecast possible to obtain a tolerably reliable predication of the performance fast. But a prognosticating of the electricity demand, especially of a heat pump used for covering the heat demand, is not easy. The difficulties of prognosticating the heat demand are described in the following section.

1.3 Difficulties in prognosticating the heat demand of a building

The heat demand of a building and therefore the electricity demand of a heat pump varies much from day to day. To demonstrate this, a typical low energy building of 2014 standard, meaning it fulfils the requirements of both EnEV and BR10, is built and simulated in Polysun. The building is located in Denmark and the used weather file is from Meteonorm [PR Web Online Visibility, 2014]. The building has a total heating energy demand of 9081 kWh. The sum of transmission and ventilation losses is 12580 kWh at a heating set point temperature of 20 °C and a conditioned floor area of 145 m^2.

The varying daily heat demand as well as the minimum and maximum hourly values of a day are shown for the months January and February in figure 1.4.

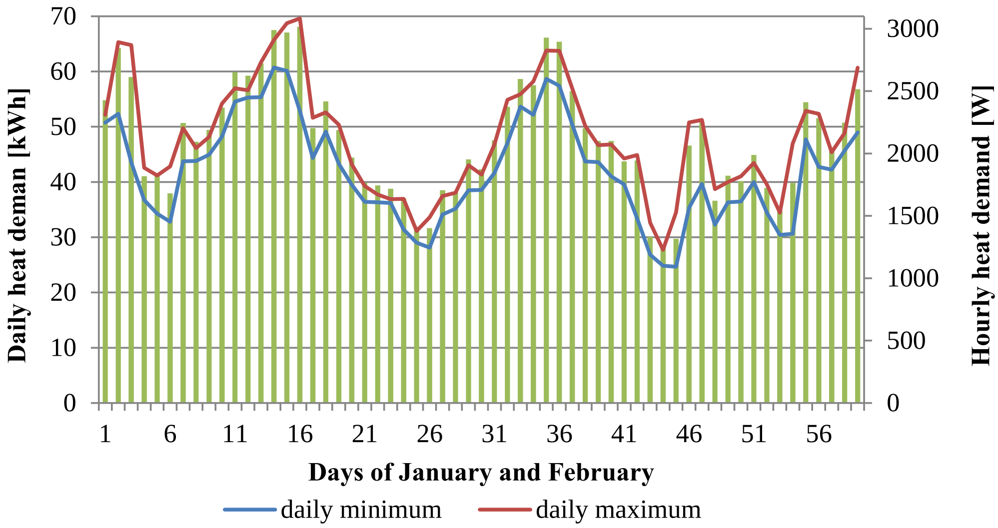


Figure 1.4. Daily heat consumption of a low energy house after actual building regulation [EnEV, 2014] and [BR10, 2010] in January obtained from Polysun simulation.

Within these 59 days of January and February the heating demand varies between 28 kWh and 68 kWh with a factor of 2.5. Hourly values vary between 1100 and 3100 W. The reason for the big differences in the relatively small period is, that many factors influence the heat demand of a building and therefore the electricity demand of a building. First of all, parameters of the weather situation are to be mentioned, which might influence the heat demand, some probably more and other less. Parameters are outdoor temperature, wind speed and direction, all versions of solar radiation, air humidity and albedo. Additionally, the characteristic of the building, as well as internal loads affect the heat demand. If a reliable prognosis is wished, a model is needed, that considers all parameters, that influence the heat demand to a large amount.

1.4 Project description

Smart grid buildings with a network between energy generator and energy consumer are one possibility to meet the more and more tight requirements. When implementing a smart grid in buildings with heat pump and photovoltaic, where the heat pump demonstrates the biggest electricity consumer as it delivers heating energy, a high heat storage potential is advantageous, as the photovoltaic's energy is only available in limited periods during a day. In conclusion, especially in heavy buildings with a high internal heat capacity and low heat losses, smart grids improve the energy performance of buildings as the generated renewable energy can be accounted to the final energy demand. In which building types integrating a smart grid is most rational is investigated in chapter 2. Four different variations of building heavinesses are investigated from extra light to extra heavy, classified by their building heat capacity. To integrate the different quality of building standards, actual requirements of the year 2014 are compared to passive houses, leading to eight different variations, that are designed and compared:

- Extra light building of 2014 standard
- Medium light building of 2014 standard
- Medium heavy building of 2014 standard
- Extra heavy building of 2014 standard
- Extra light building of passive house standard
- Medium light building of passive house standard
- Medium heavy building of passive house standard
- Extra heavy building of of passive house standard

The goal is to make a statement about which building variations are recommendable when implementing a smart grid and where a virtual border regarding reasonableness can be drawn.

The basis of a well functioning smart grid system are the prognosis of the expected generator performance as well as the expected consumption. In this thesis it is concentrated to prognosticate the heating energy demand of the building, so that a heat pump can be utilized when a photovoltaic supply is available.

The utilized calculation method for the heat energy prognosis is the simple hourly method after EN ISO 13790. The Excel sheet from [Homics and Kirkedahl, 2013] is utilized and further developed. Special intention is given to the input parameters according to the weather. To keep the computation time to a reasonable limit, a sensitivity analysis is made regarding the different weather parameters available from the weather forecast. The implemented calculation model is changed due to that the existing sheet can only calculate internal air temperature on basis of no existing heat device. After integrating heating and further features as a heat recovery unit for ventilation, the further developed calculation tool is both able to calculate heating demand for an implemented set point temperature, as well as resulting air temperature with given heating power. Further it is possible to insert measured data from a smart grid building to the Excel sheet to overcome differences between prognosis and actual behaviour. The output of the calculation tool will be the prognosticated heat demand in [W/h] of the next day. This can be used for the overall controller of a smart grid to divide up the expected power from photovoltaic to the energy consumers. Further can then the allocated power from the photovoltaic be implemented in the Excel spread sheet to see, if full covering is achieved, or at what time of the day additional heating has to be activated.

To validate the calculation model full-scale measurements from the Danish comfort house project are taken and compared to the simulated results. As the calculation tool is both able to simulate heating demand based on set point temperature and internal air temperature based on input heating demand, both variations are simulated and compared to measured values.

Buildings' capacity of heat storage 2

2.1 Introduction

The idea of smart grid buildings and using the electricity produced by the photovoltaic for the heat pump for heating purposes makes most sense, when the building has the capacity to store the heat energy in the time, when the photovoltaic's electricity is not available. A specific comfort temperature should be kept all day, even when the heating is shut off for several hours. But different building types have varying capacity of keeping the heat due to different levels of heaviness of their components. Also the losses, namely transmission, ventilation and infiltration losses, play an important role in heat storage of heating energy. Furthermore, is the heating system an important factor as a floor heat system activates thermal mass directly, whereas a radiator heats up internal air first, which then passively activates thermal mass. Recently may be mentioned that different weather conditions might lead to a different efficiency of utilizing capacity of heat storage. Having two identical buildings, one in a cold and one in a warmer climate, differences in heat storage capacity are likely, even though the actual heat capacity of both buildings is equal.

It is shortly mentioned, that in this report mainly a smart grid system regarding heating phase is considered. The possible consequences of heat capacity in summer, with a need of cooling are not further analysed.

The ability of storing heat in different building types regarding the above mentioned factors is investigated in this section with BSim simulations. The goal is to make a statement about which building types are to be preferred when thinking about implementing a smart grid and where a virtual border regarding a rational implementation can be drawn, schematically presented in figure 2.1.

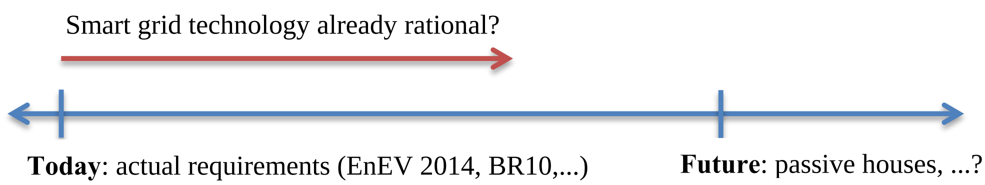


Figure 2.1. Simplified timeline of building types and requirements.

The general tendency of the last years was that buildings got more and more insulated due to stricter becoming requirements as mentioned in section 1.1, which reduced the transmission losses. Also the air tightness increased simultaneously, which leads to a reduced amount of infiltration losses. Heat recovery rates of ventilation systems got better due to higher technical standards as well. It is decided to focus this investigation within a specific frame, having the passive house as upper end, demonstrating best, today achieved technology standard. As the lower end, a today actual building, which just fulfils actual requirements of Germany and Denmark regarding transmission, ventilation and infiltration losses, hereafter called 2014 standard, is chosen. Both standards are further investigated with different heat capacities representing the heaviness of their building structures, as heavier buildings have a higher heat capacity than light constructions. The geometry of a building from the comfort house is chosen, to reflect ratios of a realistic building.

2.2 Description of chosen comfort house

For the heat capacity investigation, and later in the report for the verification of the calculation tool in chapter 5 on page 55, a building from the comfort house project is chosen. The building is located in Stenagervænget 12, 7100 Vejle in Denmark. A view from East, as well as an aerial view are seen in 2.2.

(a) View from East. (b) Aerial view.

Figure 2.2. View on Stenagervænget 12 [Google maps, 2014].

A top view is shown in following figure 2.3 on the facing page.

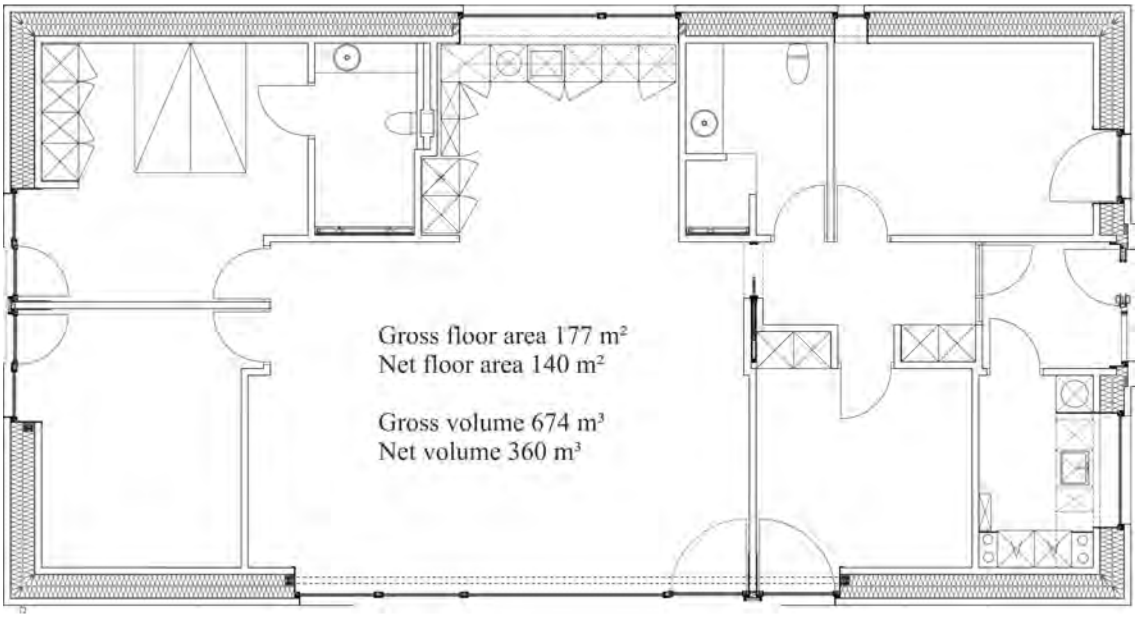


Figure 2.3. Top view of comfort house, which geometry is taken over for heat storage investigation.

The comfort house consisting of one storey has a gross floor area of 177 m^2 and a gross volume of 674 m^3. Corresponding net values are a floor area of 140 m^2 and a volume of 360 m^3.

An overview of the area of the different building elements is given in table 2.1.

Building element	**Area** [m^2]
Floor	140
Roof	140
External walls	89
Internal walls	128
Windows	40

Table 2.1. Areas of building elements.

The different factors, heat capacity and different types of heat losses, leading to a varying heat storage ability are described in detail in the following sections, starting with the heat capacity due to varying building heaviness in the next section.

2.3 Heat capacity

The internal heat capacity of a building can be calculated with the sum of the internal heat capacities of those building elements, that are in direct thermal contact with the internal air of the building, seen in equation 2.1 [EN ISO 13786, 2008].

$$C_m = \frac{\sum \kappa_j \cdot A_j}{A_{floor}} \, [Wh/m^2K] \tag{2.1}$$

Where:

C_m	Internal heat capacity of the building [Wh/m^2K]
κ_j	Internal heat capacity of the building element j [Wh/m^2K]
A_j	Area of the element j [m^2]
A_{floor}	Area of the floor [m^2]

The values of the internal heat capacity can vary between different building types from very light buildings, that cannot store heating energy very well to extra heavy buildings, which need a longer time to get heated, but can therefore also store the heating energy very well. In this master thesis these buildings are divided into four categories and typical values for these categories, suggested from [SBi, 2011a], are seen in table 2.2.

Category	**Characteristic**	**C_m** [Wh/m^2K]
Extra light	Light walls, floors, roofs of such skeleton with slabs or boards, with no heavy parts	40
Medium light	Individual heavier elements such as concrete deck with a wooden floor or porous concrete	80
Medium heavy	More heavy elements such as concrete slab with tile and brick or tile and concrete	120
Extra heavy	Heavy walls, floors and roof of concrete, brick and tile	160

Table 2.2. Description of different building heat capacity categories after [SBi, 2011a].

The building elements are, in a first rough division, split up in heavy and light elements, as shown in table 2.3.

Category	**Heavy elements**
Extra light	[-]
Medium light	Floor
Medium heavy	Floor, external and internal walls
Extra heavy	Floor, external and internal walls, roof

Table 2.3. Rough division of light and heavy building elements into different heat capacity categories.

While the entire envelope of the extra heavy building consists of heavy material like brick and concrete, is the extra light building constructed as a skeleton having a wooden framework with mainly supporting function. The medium light and medium heavy building categories have partly heavy elements and partly light elements. Also windows and internal walls have to be taken into consideration, as they also are in direct contact with internal air temperature.

In the following the components of the different capacity categories will be described. Four different versions of building elements are necessary for this investigation, two light constructions and two heavy constructions that are combined regarding table 2.3 on the facing page. An overview is given in table 2.4.

Element	**Heavy 2014**	**Heavy passive**	**Light 2014**	**Light passive**
External wall	√	√	√	√
Floor	√	√	√	√
Floor	√	√	√	√
Internal wall	√		√	

Table 2.4. Overview of necessary building element variations.

Each light building element and each heavy building element is once constructed as 2014 standard and once as passive house standard. Further information regarding heat transfer coefficient will be described in subsection 2.4.1 on page 20. Internal walls are only constructed in one heavy and one light construction version, as there are no differences between 2014 standard and passive house standard. Windows are implemented once as passive house standard and once in 2014 standard, seen in table 2.5.

Element	**2014 standard**	**Passive house standard**
Windows	√	√

Table 2.5. Overview of necessary window variations.

To validate that this rough division is close to the in table 2.2 on the facing page mentioned values, the internal heat capacities of the buildings are determined by identifying the internal heat capacities of each building element κ_j, calculated with equation 2.2 [EN ISO 13786, 2008].

$$\kappa_j = \frac{\sum d_i \cdot \rho_i \cdot c_i}{1000 \cdot 3.6} \, [Wh/m^2K] \tag{2.2}$$

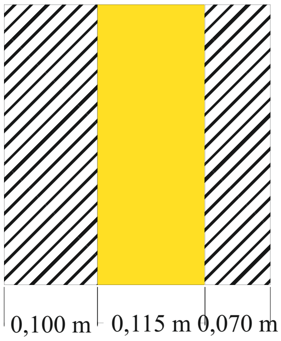
Where:

κ_j	Internal heat capacity per area of the building element [Wh/m^2K]
d_i	Thickness of layer i [m]
ρ_i	Density of layer i [kg/m^3]
c_i	Specific heat capacity [J/kgK]

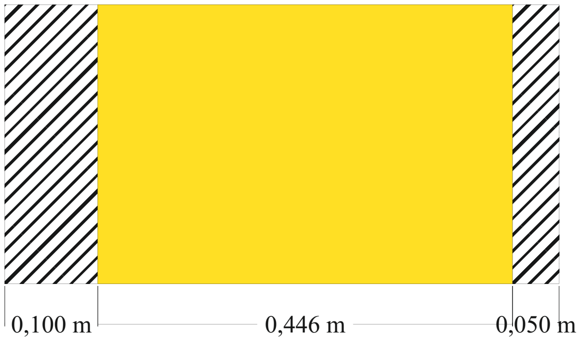
EN ISO 13790 [2008] specifies that maximum the first 0.1 m facing internal air of each component may be used in the calculation of internal heat capacity. If an insulation layer starts within the first 0.1 m, then only the thickness until the insulation may be inserted [EN ISO 13790, 2008]. To give an overview of the structure of the different building elements, all layers will be listed. The values that are implemented into the heat capacity calculation will be marked in red.

2.3.1 External wall construction

First, the different versions of external walls are presented, starting with the two heavy external wall constructions , shown in figure 2.4.



(a) Heavy 2014 standard.



(b) Heavy passive house standard.

Figure 2.4. Heavy external wall constructions, where left side faces internal and right side faces external conditions.

The heavy external walls consist of two brick layers with an insulation layer between. The values taken into consideration in the heat capacity equation are shown in table 2.6 and are marked in red.

External wall	**Layer**	ρ	**c**	**d for 2014**	**d for passive**
Heavy	[-]	[kg/m^3]	[J/kgK]	[m]	[m]
Brick	1	1840	800	0.10	0.10
Stone wool	2	21	800	0.115	0.446
Brick	3	1840	800	0.07	0.05

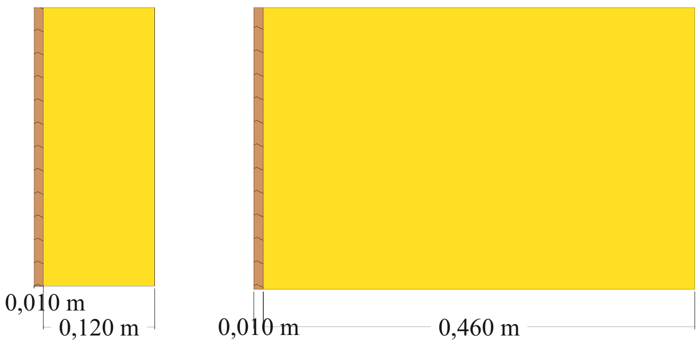
Table 2.6. Structure heavy external wall.

The difference in thickness of the second brick layer is due to the arrangement that all four versions: *heavy 2014*, *heavy passive*, *light 2014* and *light passive* standard have to have the same thermal heat transfer coefficient to be able to mix the individual elements by still keeping the calculated heat capacity within a range close to the suggested values of table 2.2 on page 10 after [SBi, 2011a]. In an iterative process the different layer thickness were changed, until all heat capacities values were close to the table 2.2 on page 10 and all elements had the same U-value.

Applying the internal heat capacity equation 2.2 on page 11 to the heavy external wall, while only considering the first 0.1 m, the value of κ_{ext} is determined to be 40.9 $\text{Wh/m}^2\text{K}$ as seen in equation 2.3.

$$\begin{aligned}
\kappa_j &= \frac{\sum d_i \cdot \rho_i \cdot c_i}{1000 \cdot 3.6} \, [Wh/m^2K] \\
\kappa_{ext} &= \frac{d_{brick} \cdot \rho_{brick} \cdot c_{brick}}{1000 * 3.6} \, [Wh/m^2K] \\
\kappa_{ext} &= 40.9 \, Wh/m^2K
\end{aligned} \tag{2.3}$$

Next the light external walls are presented, seen in figure 2.5.



(a) Light 2014 standard.

(b) Light passive house standard.

Figure 2.5. Light external wall constructions.

As already mentioned, are light external wall constructions often built with a wooden skeleton frame and filled up with insulation in between. To integrate the thermal capacity effect of the wooden frames, they are implemented as a small wooden layer, as the simplified equation 2.2 on page 11 after EN ISO 13786 [2008] can only be applied to homogeneous constructions.

Properties of the construction, as well as values used for heat capacity equation are listed in table 2.7.

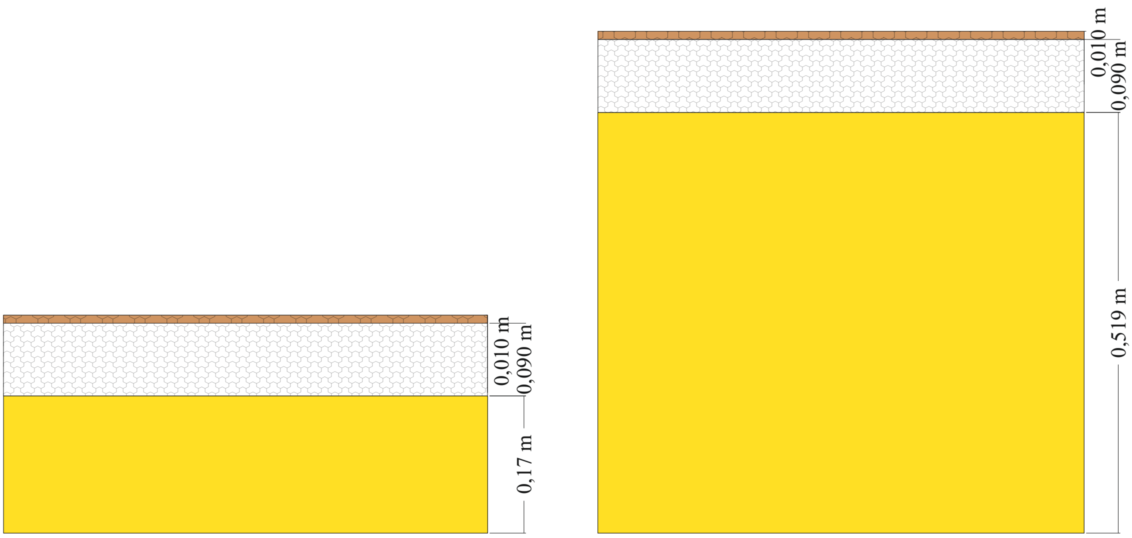
External wall	**Layer**	ρ	**c**	**d for 2014**	**d for passive**
Light	[-]	[kg/m^3]	[J/kgK]	[m]	[m]
Wood	2	950	1800	0.01	0.01
Stone wool	1	21	800	0.12	0.46

Table 2.7. Structure light external wall.

The internal heat capacity of the light external wall is 4.8 $\text{Wh/m}^2\text{K}$ for both standards.

2.3.2 Floor construction

An overview of the construction of the heavy floor is shown in figure 2.6.



(a) Heavy 2014 standard. (b) Heavy passive house standard.

Figure 2.6. Heavy floor constructions.

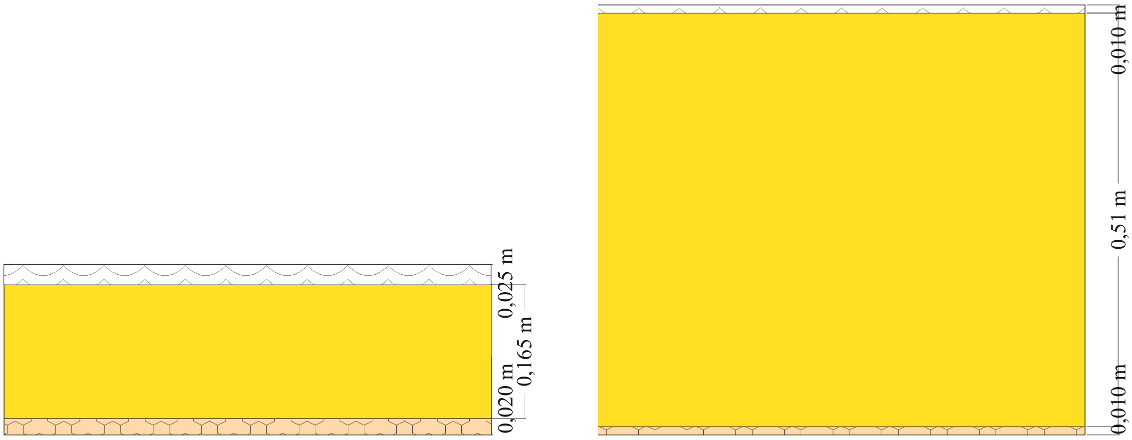
The heavy floor consists of a thin wooden layer on top, which is placed on concrete. Properties of the layers, as well as the structure and the parameters taken for the internal heat capacity equation are shown in the following table 2.8.

Heavy floor	**Layer**	ρ	**c**	**d for 2014**	**d for passive**
	[-]	[kg/m^3]	[J/kgK]	[m]	[m]
Wood	1	950	1800	0.01	0.01
Concrete	2	2400	800	0.09	0.09
Stone wool	3	21	800	0.17	0.519

Table 2.8. Structure heavy floor.

The internal heat capacity of the heavy floors is 52.8 Wh/m^{2}K in both building standards.

Next, the light floor constructions are shown in figure 2.7 on the next page.



(a) Light 2014 standard. (b) Light passive house standard.

Figure 2.7. Light floor constructions.

The light floor consists of a thin layer of linoleum on insulation and beech. Properties of the construction are shown in table 2.9.

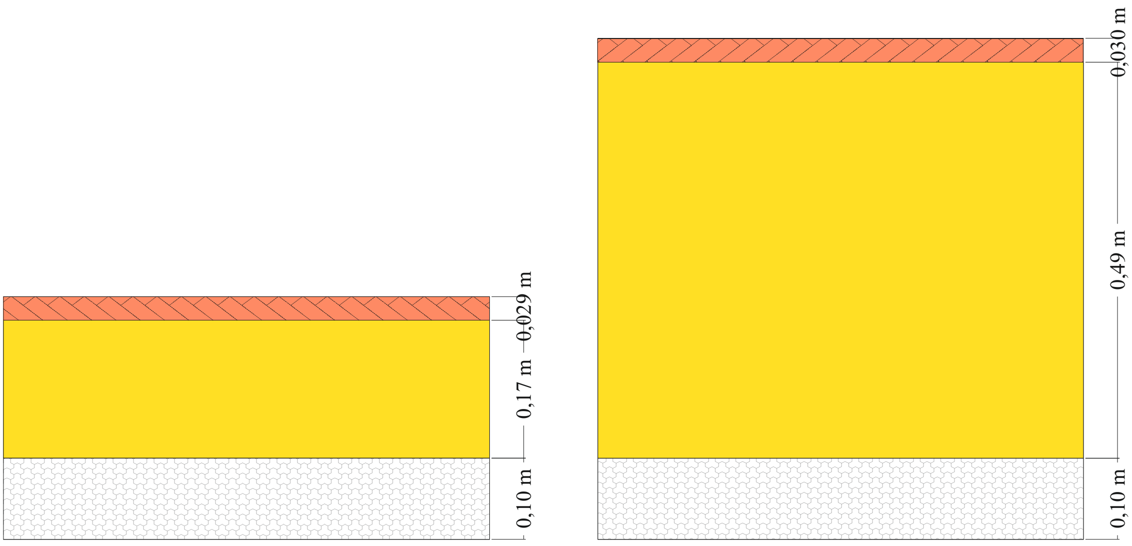
Light floor	**Layer**	ρ	**c**	**d for 2014**	**d for passive**
	[-]	[kg/m^3]	[J/kgK]	[m]	[m]
Linoleum	1	1200	1260	0.025	0.01
Stone wool	2	21	800	0.165	0.51
Beech	3	600	1800	0.02	0.01

Table 2.9. Structure light floor.

The light floors have internal heat capacities of 10.5 Wh/m^{2}K in 2014 standard and 4.2 Wh/m^{2}K in the passive house variation.

2.3.3 Roof construction

The different heavy roof constructions are shown in figure 2.8 on the next page.



(a) Heavy 2014 standard

(b) Heavy passive house standard.

Figure 2.8. Roof constructions.

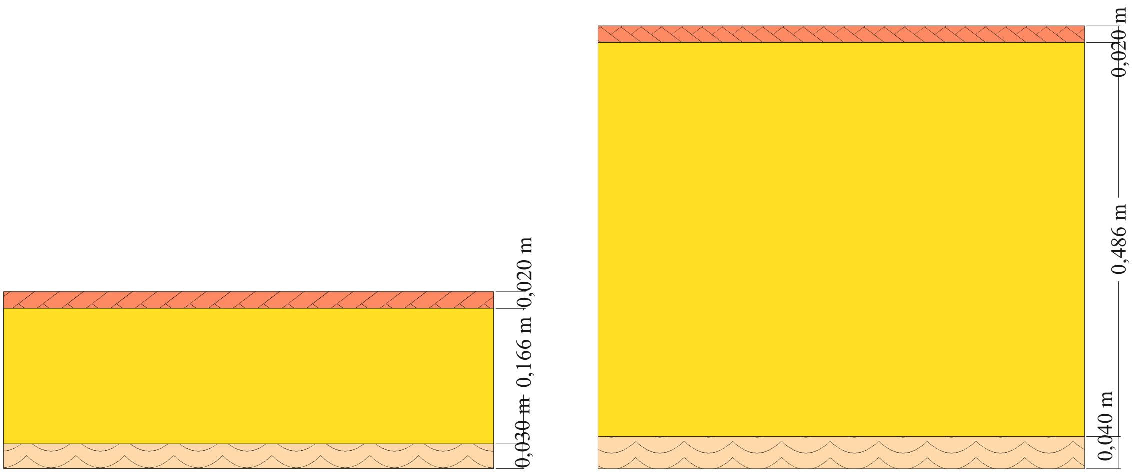
The heavy roof consists of concrete, insulation and roof tiles. The parameters used for the calculation of the internal heat capacity for the heavy roof constructions are shown in the following table 2.10.

Heavy roof	**Layer** [-]	ρ [kg/m^3]	**c** [J/kgK]	**d for 2014** [m]	**d for passive** [m]
Concrete	1	2400	800	0.1	0.1
Stone wool	2	21	800	0.17	0.49
Roof tiles	3	1609	800	0.029	0.029

Table 2.10. Structure heavy roof.

The internal heat capacity of the heavy roof constructions is calculated to be 53.3 Wh/m^{2}K.

A visualization of the roof in light construction is given in figure 2.9 on the next page.



(a) Light 2014 standard. (b) Light passive house standard.

Figure 2.9. Roof constructions.

The light construction of the roof differs in comparison to the heavy roof construction only in the third layer, which is changed to beech. Properties of the structure and parameters used for heat capacity equation are shown in table 2.11.

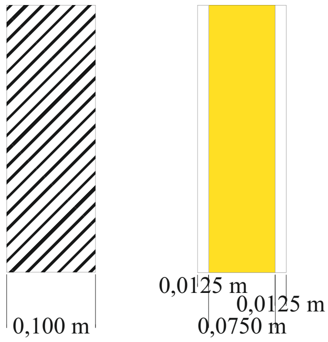
Light roof	**Layer** [-]	ρ [kg/m^3]	**c** [J/kgK]	**d for 2014** [m]	**d for passive** [m]
Beech	1	600	1800	0.03	0.04
Stone wool	2	21	800	0.166	0.486
Roof tiles	3	1609	800	0.02	0.02

Table 2.11. Structure light roof.

The internal heat capacity of the light roof is 9 Wh/m^{2}K in 2014 standard and 12 Wh/m^{2}K in the passive house.

2.3.4 Internal wall construction

Two different internal walls were constructed, one heavy and one light construction, shown in figure 2.10 on the next page.



(a) Heavy version. (b) Light version.

Figure 2.10. Light wall constructions, used for both building standards.

Properties of the structure and parameters used for the calculation of the internal heat capacity of the light internal wall are shown in the following table 2.12.

Internal wall Light	**Layer** [-]	**ρ** [kg/m^3]	**c** [J/kgK]	**d for 2014** [m]	**d for passive** [m]
Plasterboard	1	881	1000	0.0125	0.0125
Stone wool	2	21	800	0.075	0.075
Plasterboard	3	881	1000	0.0125	0.0125

Table 2.12. Structure internal wall light construction.

Considered are both plasterboards as both sides face internal air. Its internal heat capacity is calculated to be 6.1 Wh/m^{2}K. Values for the heavy internal wall are shown in table 2.13.

Internal wall Heavy	**Layer** [-]	**ρ** [kg/m^3]	**c** [J/kgK]	**d for 2014** [m]	**d for passive** [m]
Lightweight concrete	1	1200	1000	0.1	0.1

Table 2.13. Structure internal wall heavy construction.

The heavy internal wall has a heat capacity of 33.3 Wh/m^{2}K.

2.3.5 Window construction

Lastly, a simplified parameter overview of the windows is shown in table 2.14.

Internal wall	**Layer** [-]	**ρ** [kg/m^3]	**c** [J/kgK]	**d for 2014** [m]	**d for passive** [m]
Glass	1	30	840	0.01	0.01

Table 2.14. Parameter glass of window.

Whereas in reality windows do consist of different layers of glass, filled with gas, it was seen sufficient for this investigation to combine mentioned layers, as the expected heat capacity is low anyway. This is confirmed, as calculated heat capacity of the window is 0.1 Wh/m^{2}K. Thermal heat transfer coefficients vary and will be presented later in subsection 2.4.1 on the next page, as they contribute to transmission losses.

2.3.6 Result heat capacity calculation

Inserting all heat capacities of the different building elements into the heat capacity equation 2.1 on page 10, the following values for C_m are obtained and compared to the suggested values from [SBi, 2011a], presented in table 2.15.

Category	**C_m 2014 standard** [Wh/m^{2}K]	**C_m passive house** [Wh/m^{2}K]	**C_m SBI** [Wh/m^{2}K]
Extra light	28.3	25.2	40
Medium light	70.5	73.7	80
Medium heavy	119.1	121.5	120
Extra heavy	163.4	162.8	160

Table 2.15. Internal heat capacities of the different buildings of 2014 standard and passive house standard.

The values for the heavy building types come very close to the from SBi [2011a] suggested values. It is though noticed, that light ones lay a bit below suggested values, but still in an acceptable range. Furthermore, it is more important for the comparison of the different heat capacities, that the deviations between the different categories are equally distributed, which they are.

2.4 Heat losses

Heat losses are composed from transmission, ventilation and infiltration losses, seen in equation 2.4 [The Engineering ToolBox, 2014].

$$H = H_t + H_v + H_i \,[W] \tag{2.4}$$

Where:

H_t	Heat loss due to transmission [W]
H_v	Heat loss caused by ventilation [W]
H_i	Heat loss caused by infiltration [W]

German EnEV [2014] and Danish building regulation BR10 [2010] formulate actual requirements regarding maximum heat losses. A more detailed description of the individual heat losses is given in the following, where the actual requirements of both Germany and Denmark are stated and, if available, guidelines about passive house standard. First, a closer look to the transmission losses is given.

2.4.1 Transmission losses

Heat transmission losses are losses through common building elements due to a temperature difference between inside and outside. They depend on the exposed area and on the heat transfer coefficient, the U-value, of the building elements. [The Engineering ToolBox, 2014]. Danish BR10 [2010] and German building regulation EnEV [2014] require a maximum values of those. The chosen U-values for the investigation of buildings' capacity of heat storage are oriented on the stricter value to fulfil both regulations. The maximum allowed U-values, as well as the ones utilized for this investigation, which are marked in red, are shown in table 2.16.

	Requirement		**Chosen for simulation**	
Element	EnEV 2014 [W/m²K]	BR10 [W/m²K]	2014 [W/m²K]	passive [W/m²K]
External wall	0.28	0.30	0.28	0.07
Floor	0.35	0.20	0.20	0.07
Roof	0.20	0.20	0.20	0.07
Windows	1.30	1.80	approx. 1.20	approx. 0.8

Table 2.16. Requirements and chosen values for simulation regarding U-values.

Care was taken to that each the light and the heavy construction have the same U-value, so that light and heavy constructions can be mixed by virtue of getting different heat capacities of the building.

The specific transmission heat losses can be calculated with equation 2.5 [The Engineering ToolBox, 2014].

$$\frac{H_t}{t_i - t_o} = \sum_i A_j \cdot U_j \, [W/K] \tag{2.5}$$

Where:

H_t	Heat loss due to transmission [W]
t_i	Internal air temperature [°C]
t_o	External air temperature[°C]
A_j	Area of exposed surface of building element j [m²]
U_j	Overall heat transmission coefficient of building element j [W/m²K]

By integrating the in table 2.16 stated U-values into the equation and utilizing the different areas of the building structures, presented in table 2.1 on page 9, the following specific transmission heat losses are obtained, seen in table 2.17.

	2014 standard [W/K]	**passive house standard** [W/K]
H_t	128.7	57.6

Table 2.17. Specific heat transmission losses.

The specific heat loss by transmission is twice as large in the building after actual building regulation as the resulting loss with a passive house standard.

2.4.2 Infiltration losses

"Infiltration is unintended or uncontrolled air penetration through leaks in the building envelope" [SBi, 2011b]. First, a closer look is given to actual requirements.

German EnEV [2014] specifies a maximum infiltration of 1.5 h^{-1} at 50 Pa pressure difference, which can be determined by means of a blower door test. This value means, that the air within a building or room is entirely exchanged 1.5 times within one hour. Danish BR10 [2010] states a maximum infiltration rate of 1.5 $l/s/m^2$ also at a pressure difference of 50 Pa. In the investigated building with a gross area of 170 m^2 this results in a value of 1.4 h^{-1}. Therefore the Danish building regulations are followed regarding maximum infiltration as they represent the stricter value. To come from this air change at 50 Pa to a basic air change rate, representing ambient conditions, the following equation 2.6 after [SBi, 2011a] is utilized.

$$n_0 = 0.04 + 0.06 \cdot q_{50} \tag{2.6}$$

Where:

n_0	Basic air change rate [h^{-1}]
q_{50}	Air change at 50 Pa pressure difference [h^{-1}]

For the in BR10 [2010] stated maximum allowed value applied to the investigated building, a basic infiltration air change rate of n_0 = 0.123 h^{-1} is determined. This value is utilized for the building variations after 2014 standard.

For the passive house standard the stricter value of 0.6 h^{-1} for 50 Pa pressure difference is chosen [Passivhaus Institut, 1998-2007], demonstrating a higher air tightness of the building. The basic air change rate for the passive house is calculated to be n_0= 0.076 h^{-1}.

The specific infiltration losses are calculated as in equation 2.7 [The Engineering ToolBox, 2014].

$$\frac{H_i}{t_i - t_o} = c_p \cdot \rho \cdot n \cdot V \, [W/K] \tag{2.7}$$

H_i	Specific infiltration loss [W/K]
c_p	Specific heat capacity of air [J/kgK]
ρ	Density of air [kg/m^3]
n	Air change [s^{-1}]
V	Gross volume [m^3]

Implementing the two determined basic air changes, the following specific infiltration losses are obtained in table 2.18.

	2014 standard [W/K]	**passive house standard** [W/K]
H_i	316.1	135.5

Table 2.18. Specific infiltration losses.

2.4.3 Ventilation losses

Basis for the ventilation losses is the “need [of] a constant supply of fresh air” [Backwoodsman, 2014]. In heating period this means that fresh cold air has to enter the building to be heated up just to be lost again. [Backwoodsman, 2014]. It can be differentiated between natural ventilation by means of venting and mechanical ventilation due to an implemented ventilation system, which is required both in Denmark [BR10, 2010] and Germany [EnEV, 2014], where Danish building standard even requires the implementation of a heat recovery unit.

Mechanical ventilation systems have the advantage that, if a heat recovery unit is implemented, a specific part can be recovered, which lowers the amount of heat losses. An example can be seen in figure 2.11.

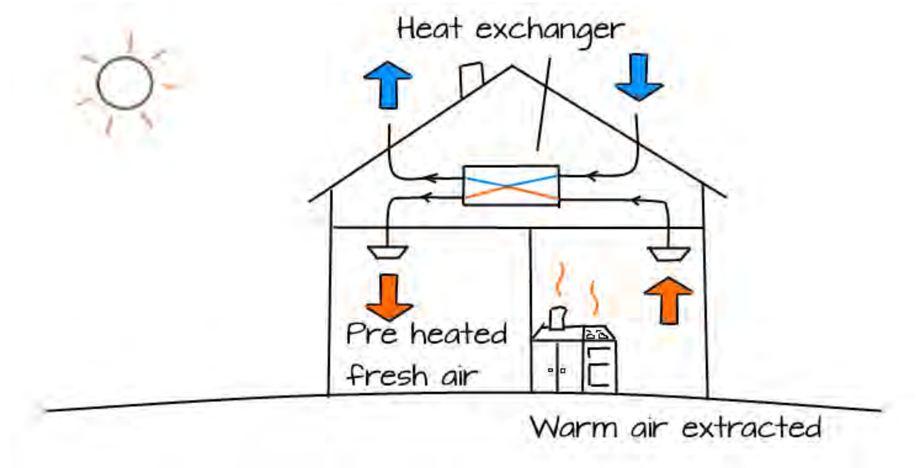


Figure 2.11. Example of ventilation system with heat recovery. [Centre for Sustainable Energy, 2014]

The figure shows, that the cold outside air is preheated in a heat exchanger, instead of just entering the building directly. It is decided to give the 2014 standard a heat recovery efficiency of 80 % based on current technical state and minimum requirement after BR10 [2010]: when the “ventilation installations [...] supply one dwelling”. The passive house is given a higher heat recovery efficiency of 90 %, seen as maximum today possible efficiency [Jensen, 2014].

The minimum supply of fresh air is stated to be 0.3 l/sm^2 in Danish buildings [BR10, 2010]. This results for the investigated building with a gross volume of 674 m^3 in a minimum fresh air supply of 0.051 m^3/s. German building regulation specifies the minimum air change rate in dependency of the air change rate a building has at a pressure difference of 50 Pa [EnEV, 2014]. An excerpt from the German building regulation regarding minimum air change is seen in table 2.19.

q_{50} [h^{-1}]	**Minimum air change** [h^{-1}]
>1.5	0.7 (mechanical ventilation, requirements are not met)
$\leq$ 1.5	0.6 (depending on mechanical ventilation system)

Table 2.19. Minimum required air change rates [EnEV, 2014].

It is noticeable, that for an air tight building with an air change at 50 Pa less or equal 1.5 h^{-1}, the requirement regarding minimum air supply is less strict, than when having a less air tight building, even though the opposite would have been expected.

The infiltration air change of the to be examined building is after Danish building regulation 1.4 h^{-1}, as mentioned in 2.4.2 on page 21. Therefore is the minimum air change after German EnEV 2014 0.6 h^{-1} as stated in table 2.19.

Using this time the net volume [EnEV, 2014] of 360 m^3, is the minimum air change rate for the to be investigated building calculated to be 0.06 m^3/s. Applied to the utilized building, the German requirement with a minimum air supply of 0.06 m^3/s is stricter than the calculated 0.051 m^3/s after Danish building regulation, and therefore is the value after German regulation chosen for this investigation.

Specific ventilation heat loss is calculated, assuming that the minimum air supply is equal to the air volume flow of the mechanical ventilation system, with equation 2.8 [The Engineering ToolBox, 2014].

$$\frac{H_v}{t_i - t_o} = c_p \cdot \rho \cdot q_v \cdot \left(1 - \frac{\eta}{100}\right) \; [W/K] \tag{2.8}$$

H_v	Specific ventilation loss [W/K]
c_p	Specific heat capacity of air [J/kgK]
ρ	Density of air [kg/m^3]
q_v	Air volume flow [m^3/s]
η	Efficiency heat recovery unit [%]

The air change rate is calculated with the above mentioned set heat recovery rates of 80 % for 2014 standard and 90 % for passive house standard, and a gross volume of 674 m^3 and the following specific ventilation losses are obtained, presented in table 2.20 on the following page.

	2014 standard [W/K]	passive house standard [W/K]
H_v	14.5	7.2

Table 2.20. Specific ventilation losses.

The specific ventilation heat loss of the 2014 standard with a heat recovery efficiency of 80 % is twice as large as the value for passive house with an heat recovery efficiency of 90 %, but still on a much lower level as remaining specific heat losses. An overview of the resulting heat losses through ventilation, infiltration and ventilation is presented in the following subsection.

2.4.4 Overview of resulting heat losses

First, an overview of the specific heat losses are given, followed by an overview of the absolute losses. In the end a resume is given.

2.4.4.1 Specific heat losses

Figure 2.12 gives an overview of calculated specific heat losses.

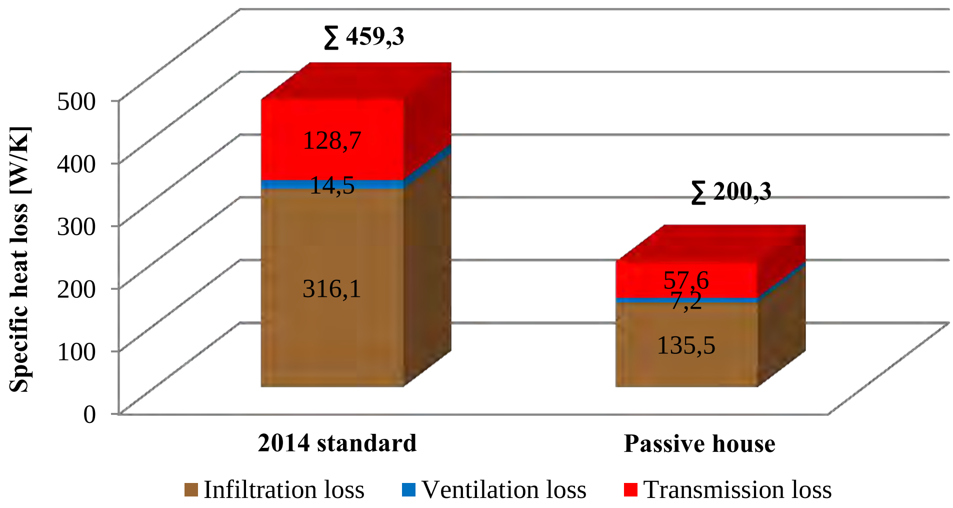


Figure 2.12. Overview of specific heat losses.

The overall specific heat loss is more than twice as large in the building after 2014 standard with 459.3 W/K in contrast to 200.3 W/K in the passive house. Infiltration losses take up the largest part with an amount of two thirds in both building standards. The specific ventilation loss with its high heat recovery rate is small in contrast to others with a ratio of around 3 % of the entire specific heat loss. The transmission losses take up around 28 % of entire heat losses. It is noticeable, that the ratio of the individual losses do not change in the both standards, only the absolute values do. As presented heat losses are specific ones, which do not take into consideration the actual temperature difference between inside and outside, it is interesting to see the actual effect and the ratios of the individual losses, when applied to an entire year.

2.4.4.2 Absolute heat losses

It is chosen to implement Danish weather conditions of SBi [2014]. The result, this time further split up into the different heat capacity categories, are seen in following table 2.21,

Heat capacity category	H	2014 [kWh]	Change	Passive house [kWh]	Change [kWh]
Extra heavy	**H**	**21174**	↘ 26 %	**15589**	-5585
	H_t	15603	↘ 37 %	9876	-5727
	H_v	3356	↗ 43 %	4791	+1435
	H_i	2215	↘ 58 %	922	-1293
Medium heavy	**H**	**21092**	↘ 26 %	**15589**	-5503
	H_t	15537	↘ 36 %	9870	-5667
	H_v	3352	↗ 43 %	4797	+1445
	H_i	2203	↘ 58 %	922	-1281
Medium light	**H**	**21005**	↘ 25 %	**15662**	-5343
	H_t	15383	↘ 36 %	9842	-5541
	H_v	3425	↗ 43 %	4893	+1468
	H_i	2197	↘ 58 %	927	-1270
Extra light	**H**	**20988**	↘ 25 %	**15696**	-5292
	H_t	15305	↘ 34 %	9840	-5465
	H_v	3494	↗ 41 %	4928	+1434
	H_i	2189	↘ 58 %	928	-1261

Table 2.21. Overview of resulting absolute heat losses.

The absolute heat losses are reduced from 2014 standard to passive house standard around 26 % from around 21100 kWh to 15600 kWh.

The difference in transmission losses between 2014 standard and passive house is large both in percentage and in absolute values. The reduction is around 36 % from 2014 standard to passive house, leading to an absolute reduction between 5300 and 5600 kWh. As values for U-values were kept similar in all building structures, it can be seen, that the transmission losses lay close to each other within the specific building standard. But it is further noticed that the transmission losses of the heavier building categories are a bit higher, than in the lighter building variations in the 2014 standard. This might be due to the fact, that when having more thermal mass, also more has to be heated up.

Even though a higher heat recovery efficiency of the ventilation system of 90 % was implemented in the passive house, leading to a lower specific ventilation loss, in contrast to the efficiency of 80 % in the 2014 standard, the value of heat losses by ventilation is bigger in the passive house. The value rises with 43 % from 2014 standard to passive house standard with an absolute change of additional 1434 to 1468 kWh. The reason for this are higher temperatures in summer in the passive house than in the 2014 standard. Even though the ventilation system is more efficient, it has to derive more heat in summer in the passive house, and therefore absolute ventilation losses are bigger.

The infiltration losses decrease with 58 % from 2014 standard to passive house standard. When considering changes in percentage, then the difference between the two standards is highest regarding infiltration losses. The biggest absolute change is though seen in differences in transmission losses between 2014 standard and passive house standard.

2.4.4.3 Resume

Specific heat losses indicate that the individual heat loss through infiltration takes up the largest part. After an application to an entire year, it is seen that transmission losses represent the biggest absolute losses. When it is wished to improve an available building of 2014 standard with as little effort as possible, then an improvement in insulation quality reducing transmission losses will have the biggest impact on absolute heat losses. An improvement of ventilation system is possible, but consequences are minimal due to an already very high efficiency standard of those nowadays. Infiltration losses show highest impact when presenting specific heat losses, but absolute values are in a lower range than transmission losses. This might be due to the fact that buildings after actual standard are already very air tight and difference to passive house air tightness is not big. Furthermore can the conclusion be drawn, that when reducing all three heat losses, the consequence will be a higher internal air temperature in summer, seen in the increased amount of ventilation need.

Another parameter, which has influence on buildings' capacity of heat storage is the outdoor condition, which is described in the next section.

2.5 Influence of weather condition

The outdoor conditions have a big influence on the heat capacity efficiency of a building as all heat losses depend on the temperature difference between inside and outside. In warmer climates with winters that do not get extremely cold, it should be easier to keep a certain comfort temperature, when the heating system is shut off for some hours. As the entire master thesis both comprises Danish and German circumstances, also these two environments are taken into consideration. A visualisation of the monthly average temperatures is seen in figure 2.13 on the next page.

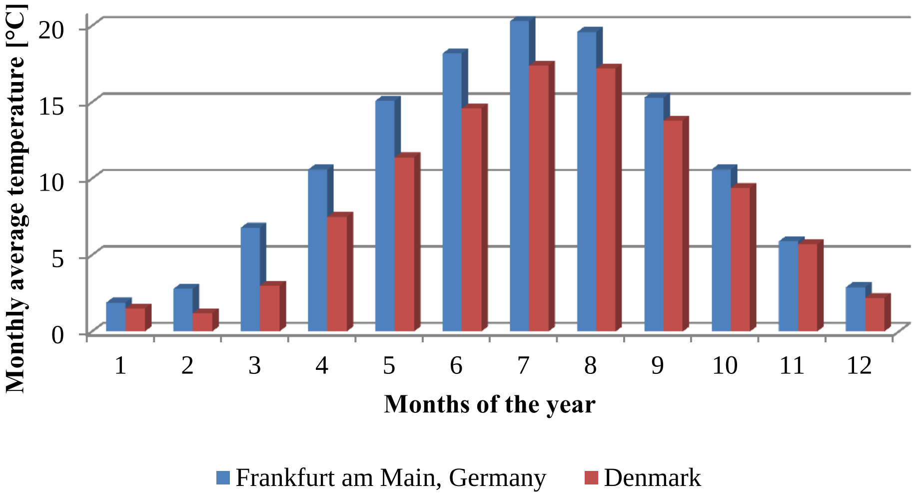


Figure 2.13. Monthly average temperatures for Denmark (entire country) and Germany (Frankfurt). [DMI, 2014] and [DWD, 2014]

The Danish climate with a yearly average temperature of 8.8 °C [DMI, 2014] is 2 °C colder than the average yearly temperature of 10.8 °C in Frankfurt am Main [DWD, 2014]. Therefore it is decided to implement all investigations with Danish weather conditions, representing harder circumstances for heat storage. Two selected examples of building categories are further simulated with both Danish and German weather conditions, with the goal to show the effect on heat storage of two slightly different climate circumstances.

2.6 Influence of implemented heating system

It is decided to implement the investigations of buildings' heat capacity with floor heat as this is the more likely variation, in a building with heat pump regarding the efficiency of the heat pump. Further does a floor heating system activate thermal mass directly and not passively like radiators, who first heat up internal air which then warms thermal mass. But two building categories are chosen to show the effect of radiators.

2.7 Implementation in BSim

The geometry of a building from the comfort house project with a gross area of 177 m^2 is chosen to come as close to a realistic building as possible. The structure of the simulated building elements is changed according to the mentioned different internal heat capacity categories, presented in section 2.3 on page 9.

Several BSim models corresponding to each heat capacity category and building standard have been made to investigate how fast the internal air temperature goes down, when the heating is shut off. The BSim model seen from side is presented in figure 2.14.

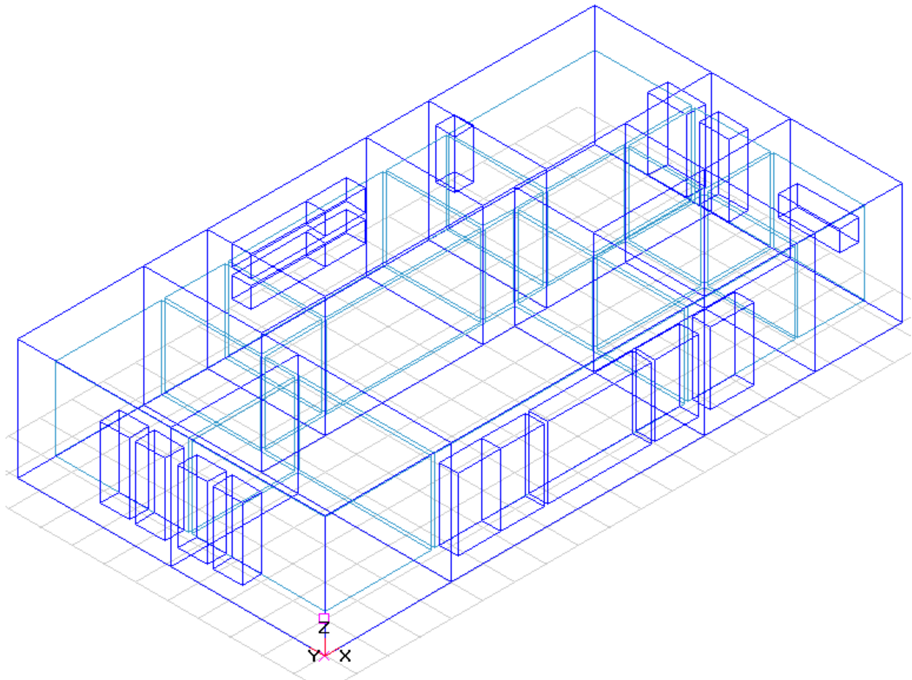


Figure 2.14. BSim building model seen from the side.

The model contains eleven thermal zones, each demonstrated by one room, seen in 2.15.

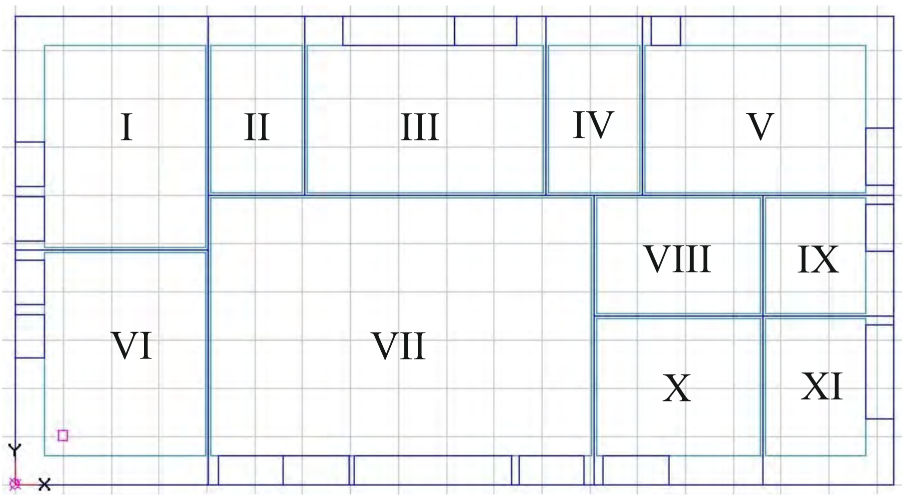


Figure 2.15. Top view BSim building model.

The structure of the different building elements is as described in section 2.3 on page 9. One change was made due to a peculiarity in BSim. The original thicknesses of the building elements are large. The external wall is for example 0.596 m in the comfort house, while the in subsection 2.3.1 on page 12 described external wall thicknesses are lower in some versions (*heavy 2014*, *light 2014* and *light passive*). To overcome this difference, the geometry is kept to be 0.596 m in the BSim models and instead filled with an empty layer. This was done to all constructions that were designed smaller than the originally thickness of the comfort house.

As an example, the heavy external wall from 2014 standard, simulated in BSim, is shown in figure 2.16.

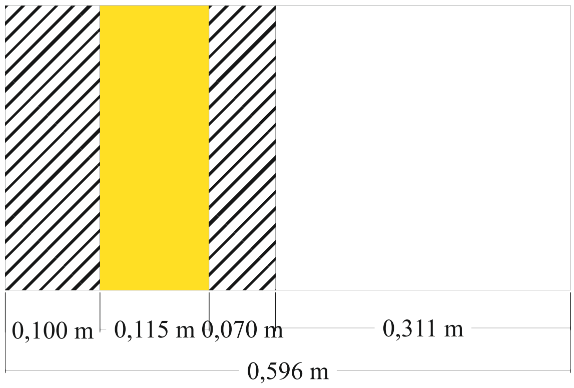


Figure 2.16. Heavy external wall with empty layer in BSim model.

The empty layer fills the remaining space, so that the same gross area and gross volume are kept in all variations.

Implemented parameters for the windows are shown in table 2.22.

	2014 standard	**passive house**
Glass	4-9Ar-SLwE4	Silverstar
Glass LinTrCoeff/Width/Pct	0.06	0.028
heat transmittance	0.63	0.54
Light transmittance	0.79	0.75
U-value center glass	1 W/m^2K	0.6 W/m^2K
Frame	alu-træ	Optiwin_komfort
Frame LinTrCoeff/Width/Pct	0.1	0.1
U-value frame	1.15 W/m^2K	0.95 W/m^2K

Table 2.22. Input values in BSim for windows.

In the BSim model further systems need to be implemented regarding internal gains from people, equipment and lighting, infiltration, heating and ventilation system. An overview of the utilized systems is shown in table 2.23 on the next page, where values in black are used for both standards, blue parameters are used for 2014 standard and red parameters were input for the passive house standard.

System	Description	Control	Indication of time
People load	4 persons 0.32 kW	full load	Mon-Fri 0-8; 16-24 Sat-Sun 0-24
Equipment	Heat load 0.619 kW* Part to air 0.5	full load	always
Infiltration	n_0 0.123 h^{-1} n_0 0.043 h^{-1}* Tmp factor 0 1/h/K Tmp Power 0 Wind factor 0 s/m/h	full load full load	always always
Lighting	Task Lighting 0.048 kW* Gen Lighting 0.048 kW* Gen Lighting Level 200 lux Lighting type fluorescent Solar limit 0.2 kW Exhaust part 0	Factor 1 Lower limit 0 kW Temp max 24 °C	Mo-Fr 6-8; 16-22 Sa-Su 16-22
Heating	Max power 100 kW Fixed part 0 Part to air 0.6	FloorHtCtrl Factor 1.0 Set point 24 °C Max Surface 30 °C Design Temp -12 °C Min Pow 100 kW Te Min 20 °C	Mon-Sun 8-16
Ventilation	**Input:** Supply 0.06 m^3/s Pressure rise 300 Pa Total Eff. 0.7 Part to air 1 **Output:** Return 0.06 m^3/s Pressure rise 200 Pa Total Eff. 0.7 Part to air 0 **Recovery Unit:** Max heat rec 0.8 Max heat rec 0.9 Min heat rec 0 Max Cool rec 0.8 Max Cool rec 0.9 Max Moist rec 0 **Heating Coil:** Max Power 0 kW	Inlet control Part of nominal flow 1 Point 1 Te1 -12 °C Tin1 24 °C Point 2 Te2 8 °C Tin2 20 °C Slope before 1: 0 Slope after 2: 0 Air hum 0.07 kg/kg	always

Table 2.23. Systems. Differences are marked in blue (2014 standard), red (passive house). Emphasised values are split up in zones regarding floor area. Values with* from [Feist, 2008].

All described building types are simulated to get heated up until an assumed maximum comfort temperature of 24 °C, but the heating is only activated between 8.00 and 16.00. In case of a smart grid building using a photovoltaic, it is presumably that free electricity is produced in this time and therefore also the heat pump activated. The heating device is simulated generously with 100 kW in each building zone to guarantee, that the set point temperature of 24 °C is achieved fast in the short heating period. In reality it has to be considered that a wished fast achievement of a high temperature like 24 °C comes along with a demand of a larger heat pump as well, as a high peak heat demand will be extant. It is investigated, how fast the temperature drops after the heating is shut off and if a minimum assumed comfort temperature of 20 °C can be kept until the next heating period.

2.8 Results

An overview of the different building heat capacities within the two different building standards is given first. Hereafter, a short outlook is made regarding changes in heating system from floor heat to radiator with two selected building variations as well as a change in location from Denmark to Germany.

2.8.1 Overview

First, the temperature distribution over one day is presented for the four different building categories of 2014 standard with floor heat and location in Denmark, seen in figure 2.17.

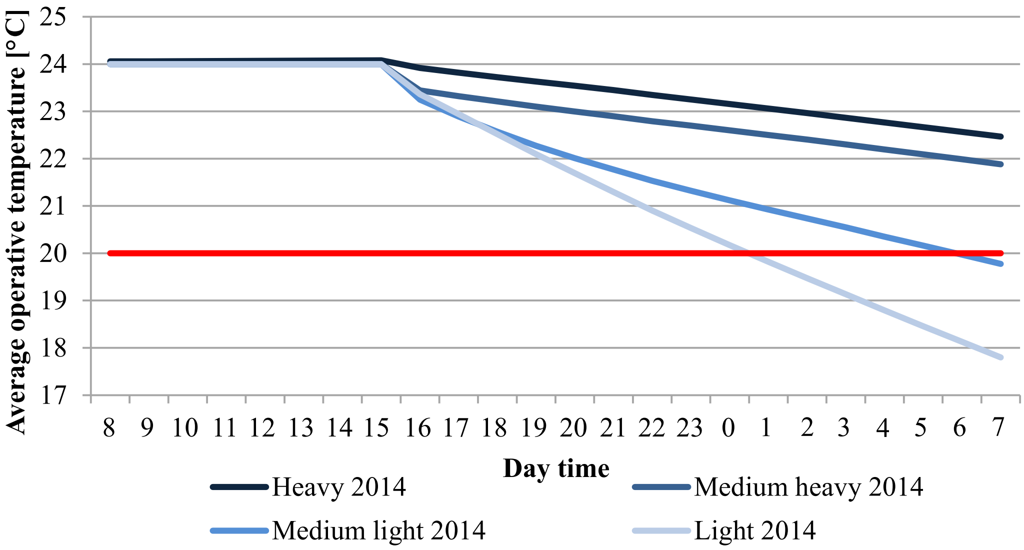


Figure 2.17. Temperature distribution of 4th January for different building categories after 2014 standard variations starting in the beginning of heating period at 8.00.

When the heating was started again at 8.00, the wished temperature of 24 °C was achieved already within the first hour of heating due to the large heating system. This was done to guarantee that all buildings within the different heat capacity categories are heated up the same period of time, meaning over 8 hours, which is exaggerated in comparison to reality. What consequences this has, is described in section 2.9 on page 39 after all building categories in both building standards are presented.

The temperature drops after 8 hours of heating very fast for the building variations *light 2014* and *medium light 2014*. This leads to that they both lay below the chosen minimum comfort temperature of 20 °C after 16 hours, meaning before the next heating period starts. Variations with a majority of heavy building elements, namely, *medium heavy 2014* and *heavy 2014* lay both above the minimum comfort temperature for the entire day. The difference between both heavy variations is relatively small and not as big as the difference within the light variations. After an analysis of the temperature distribution of one day, the entire January is taken into consideration in figure 2.18.

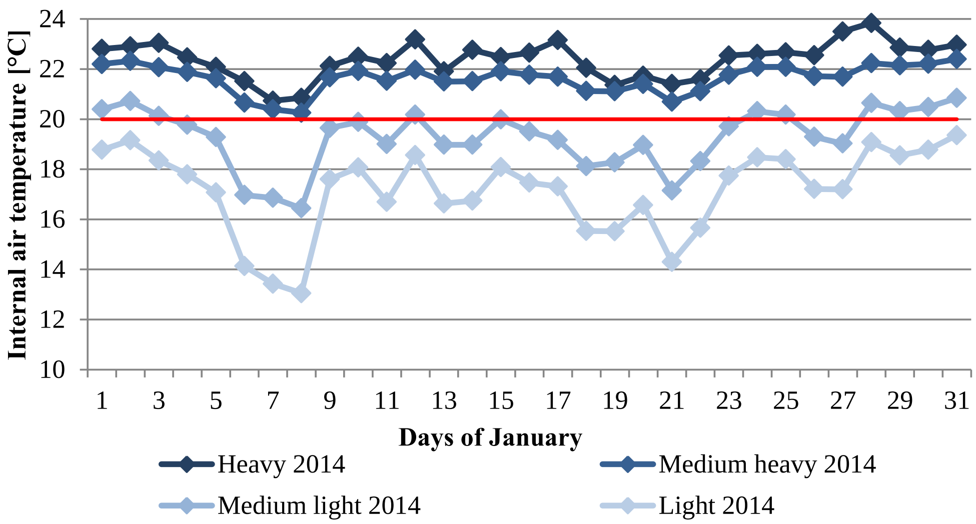


Figure 2.18. Temperature distribution at 8.00 every day, demonstrating the hour, when heating is shut off for 16 hours in the buildings after 2014 standard.

Due to an easier visualization, only the temperature at 8.00 of every day in January is plotted and then connected by means of a better comparison ability. It is seen, that the temperatures at 8.00 in the heavy and medium heavy construction vary between 20 and 22 °C. The medium light and light variation of the 2014 standard buildings lay below minimum comfort temperature line of 20 °C most of the time at 8.00.

Next, a yearly overview is shown in figure 2.19 on the next page, where results are presented in percent of days in a month where the specific building was able to keep comfort temperature until 8.00 in the next morning, meaning for 16 hours.

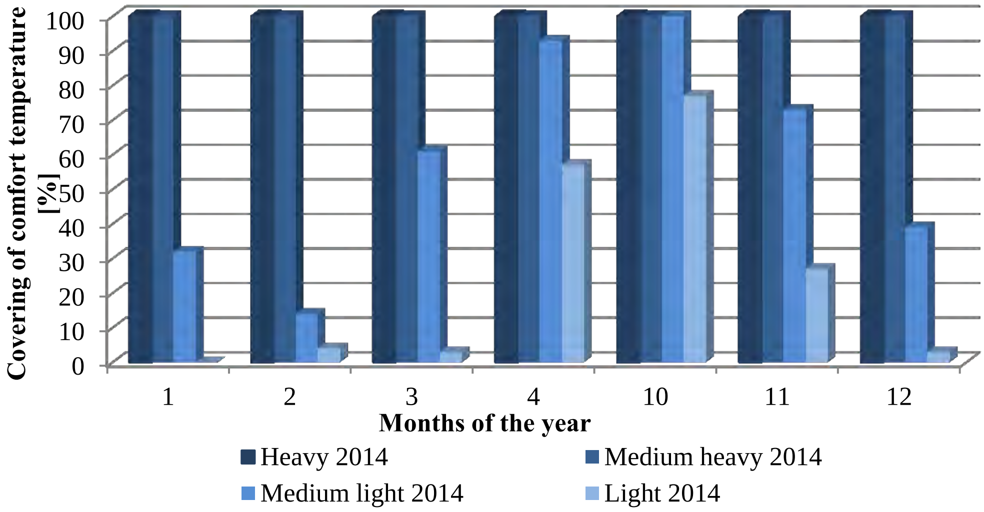


Figure 2.19. Monthly covering of comfort temperature in different heavy buildings of 2014 standard.

Shown months are October until April, as remaining months show full covering in all variations. The figure 2.19 shows, that both the heavy building and the medium heavy building after 2014 standard can keep the temperature within a frame of 24 to above 20 °C for minimum 16 hours in all months of the year. The medium light building with only a heavy floor, keeps the comfort temperature to a certain percentage, whereas the light building has nearly no covering of comfort temperature in four months of the year, namely December to March.

The shown results lead to the assumption that building categories with a majority of heavy building elements keep comfort temperature for a sufficient enough time and are therefore recommended when implementing smart grid. A border until where a smart grid is rational is given by the medium heavy building of 2014 standard.

All investigations were also implemented with the different passive house variations, shown in the following. First, the temperature distribution of one specific day in January is given in following figure 2.20 on the next page.

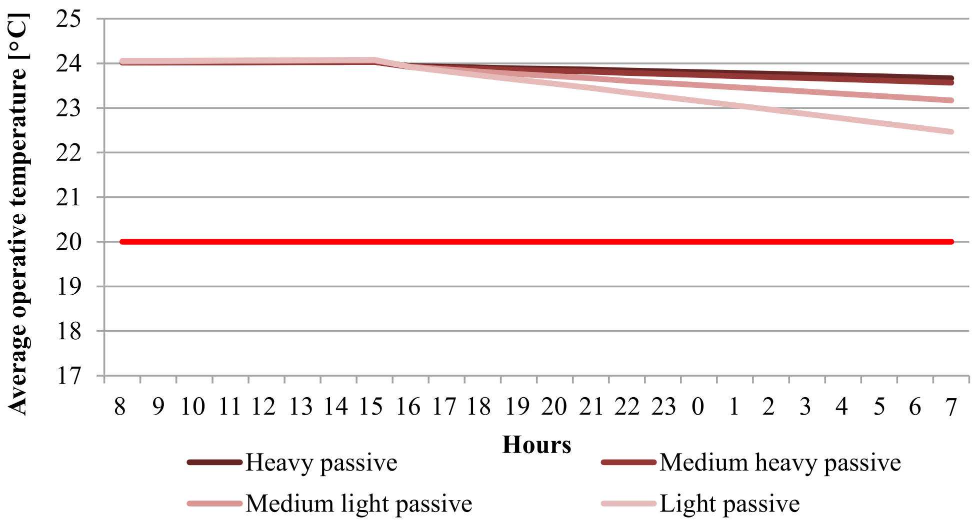


Figure 2.20. Temperature distribution of 4th January of DRY for different building categories of passive house standard.

All passive house variations keep comfort temperature in the 16 hours of switched off heating system on the shown day. It can be seen that in the passive house standard the temperature drop is very small, especially in the variations with heavy building elements. When implementing a smart grid into a passive house it is probably sufficient to set the heating temperature in times with electricity surplus to a value slightly above minimum comfort temperature, as indoor air temperature is even after 16 hours of no heating above 22.5 °C. To verify that, the temperature at 8.00 of every day in January is shown in following figure 2.21.

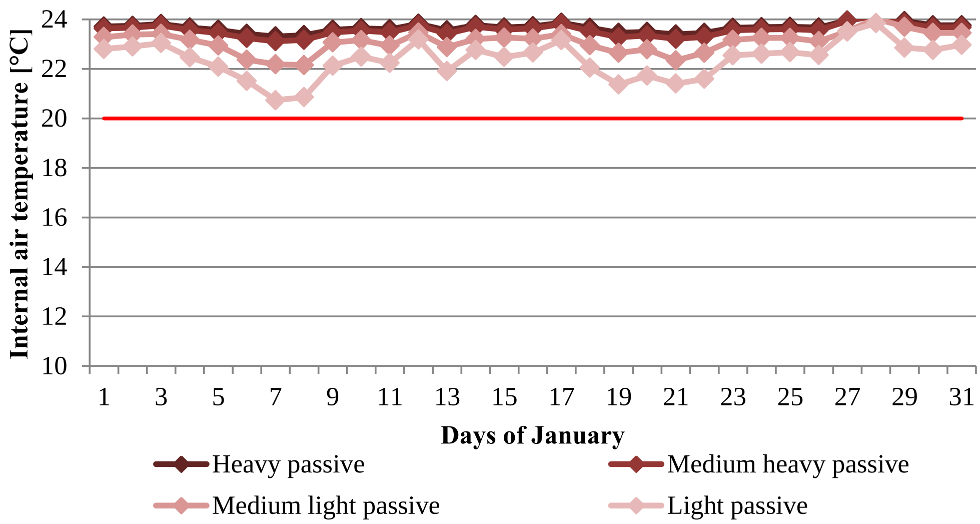


Figure 2.21. Temperature distribution at 8.00 every day, demonstrating the hour, when heating is shut off for 16 hours in the passive houses.

Differently to the 2014 standard, where the temperature even of the heavy building categories dropped to 20-22 °C, does the temperature not fall below 22.5 °C in all variations of passive house standard in the entire January. The temperature drop in the variations *heavy passive* and *medium heavy passive* is with 0.5 °C so small, that the heating set point temperature of 24 °C should be decreased to a temperature slightly over minimum comfort temperature, when implementing a smart grid.

Lastly, an overview of the monthly covering in percent of covering comfort temperature is visualized in 2.22.

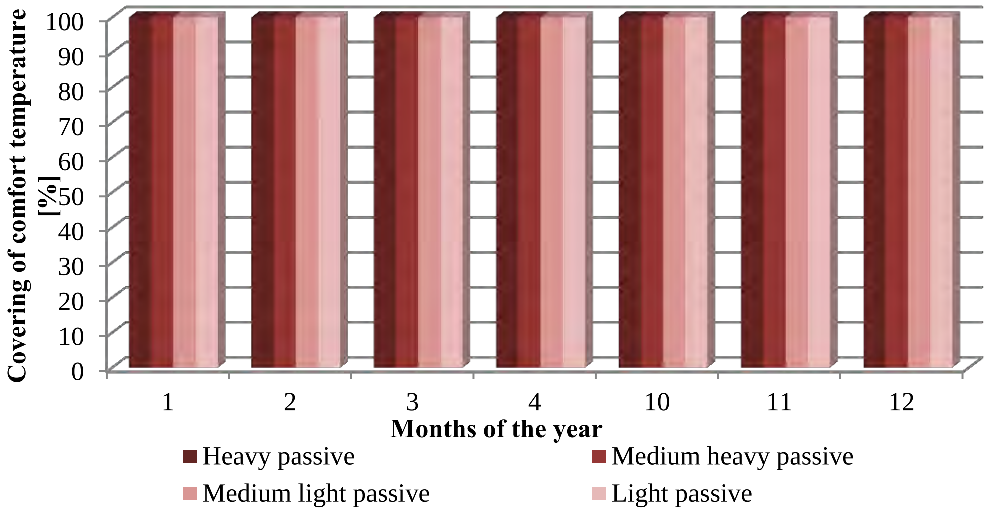


Figure 2.22. Monthly covering of comfort temperature in different heavy passive houses.

As supposed from the earlier figures, do the investigated passive house variations have a 100 % covering of comfort temperature in all months of the year.

A comparison of the exact values of covering comfort temperature in percent for both standards and all heat capacity variations is seen in table 2.24 on the following page, where it is marked in red when the percentage of covering within a month lies below 75 %.

	heavy 2014 [%]	**med.heavy 2014** [%]	**med.light 2014** [%]	**light 2014** [%]
Jan	100	97	32	0
Feb	100	100	14	4
Mar	100	100	61	3
Apr	100	100	93	57
Oct	100	100	100	77
Nov	100	100	73	27
Dec	100	100	39	3
	heavy passive [%]	**med.heavy passive** [%]	**med.light passive** [%]	**light passive** [%]
Jan	100	100	100	100
Feb	100	100	100	100
Mar	100	100	100	100
Apr	100	100	100	100
Oct	100	100	100	100
Nov	100	100	100	100
Dec	100	100	100	100

Table 2.24. Results of 2014 standard and passive house.

It is seen, that all passive house versions are unrestricted recommendable for a smart grid system. Even though there is no heavy material available that could store heat as in the light passive house construction, the buildings are so well insulated and air tight, that the heat does not drop fast.

Which of the above mentioned factors play a more and which a less important role is an interesting investigation, but could due to a time limitation not be further investigated. But it is noticed, that the differences in the 2014 standard itself (from *heavy 2014* standard to *light 2014* standard) is much higher, than in the different passive house variations with only small differences between *heavy passive* and *light passive*. Therefore it is assumed, that the heat capacity of a building has only a big effect in buildings which just fulfil actual building regulations or are worse. In highly insulated buildings with high efficient technology, does the heat capacity has nearly no influence. Further does a review on 2.4.4.3 on page 26 lead to the assumption that transmission losses, representing the highest amount of heat losses, have also a big effect on building's capacity of heat storage.

In summary it can be stated that, when having a floor heating system and considering the Danish weather all passive house versions are recommendable for implementing a smart grid. When only actual requirements of 2014 standard are targeted, then the building should have heavy building structures in majority.

2.8.2 Floor heating versus radiator

A short outlook is given now to the consequences radiators have in contrast to floor heating. Instead of the system floor heat, the following values for a heating system with radiators were implemented in BSim, seen in table 2.25.

System	Description	Control	Indication of time
Heating	Max power 100 kW	HeatCoolCtrl	Mon-Sun 8-16
	Fixed part 0	Factor 1.0	
	Part to air 0.6	Set point 24 °C	
		Design Temp -12 °C	
		Min Pow 100 kW	
		Te Min 20 °C	

Table 2.25. Heating systems and their control.

It is decided to analyse only *medium heavy 2014* and *medium light 2014* in this investigation, due to that the medium heavy variation was the first one that showed full covering and therefore assumed as a border of a rational implementation of a smart grid. Results, again in percent of covering comfort temperature after the heating was shut off for 16 hours, are shown in figure 2.23.

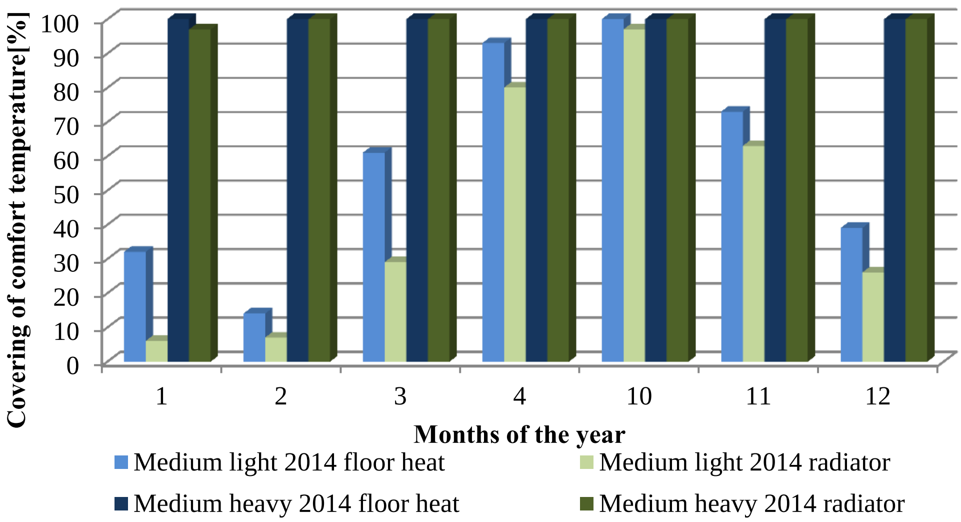


Figure 2.23. Comparison covering of comfort temperature of *medium heavy 2014* and *medium light 2014* each once with floor heat and radiator.

Floor heating activates thermal mass in the floor structure directly and actively, whereas a radiator mainly heats up internal air, which then secondly warms the thermal mass. A better performance of the floor heating system was therefore expected. The difference between the two heating system is though negligible small in the medium heavy variations. The differences in the medium light variations are bigger, especially in the first three months of the year, where the medium light variation with floor shows a much higher percentage of covering comfort temperature, than the corresponding building with radiators. The covering percentage is twice as high for floor heat in February and March and even four times as high for the month January. The difference in the other months is not as big, but the percentage of covering comfort temperature with floor heat is always higher than in the corresponding building with radiators.

2.8.3 Danish weather versus German weather

Finally a short outlook to different weather situations is given. As all implemented simulations were until now carried out in Danish conditions, it is interesting to see the difference to a simulation in German weather conditions. Frankfurt am Main is chosen as example of a German weather condition, due to a relatively far distance to Denmark. The weather file implemented for this investigation is DRY [SBi, 2014] for Denmark, as in all previous investigations as well. The weather file for Frankfurt am Main is downloaded from the internet [US Department of Energy, 2014]. Average monthly temperatures of these weather files, seen in 2.13 on page 27 indicate a better covering of comfort temperatures for Frankfurt due to higher outdoor temperatures leading to smaller heat losses. When plotting daily average temperatures of the two mentioned weather files, then it can be seen, that also the daily averages lay often higher in Frankfurt than in Denmark, seen in figure 2.24.

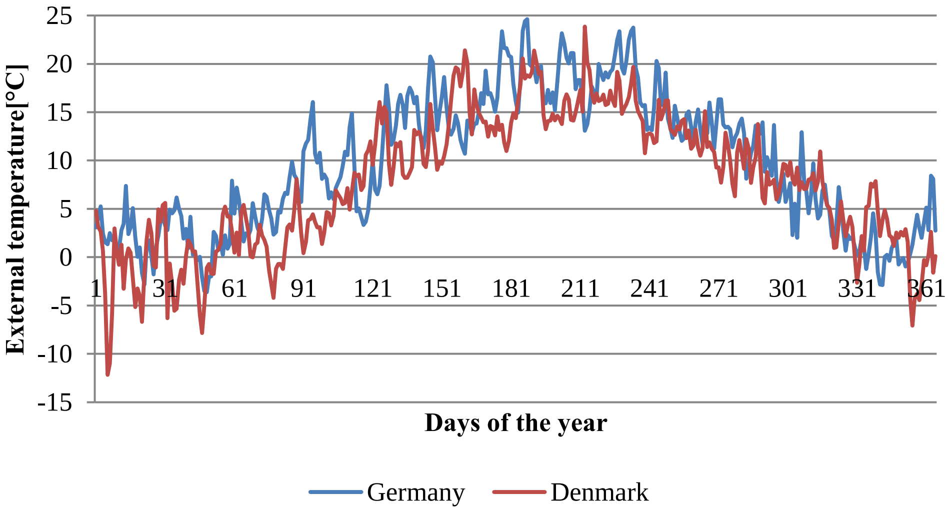


Figure 2.24. Average monthly temperatures of weather data files implemented in BSim for Frankfurt am Main [US Department of Energy, 2014] and Denmark [SBi, 2014].

The comparison is again made with the medium heavy and medium light building of 2014 standard and the results are seen in 2.25 on the facing page.

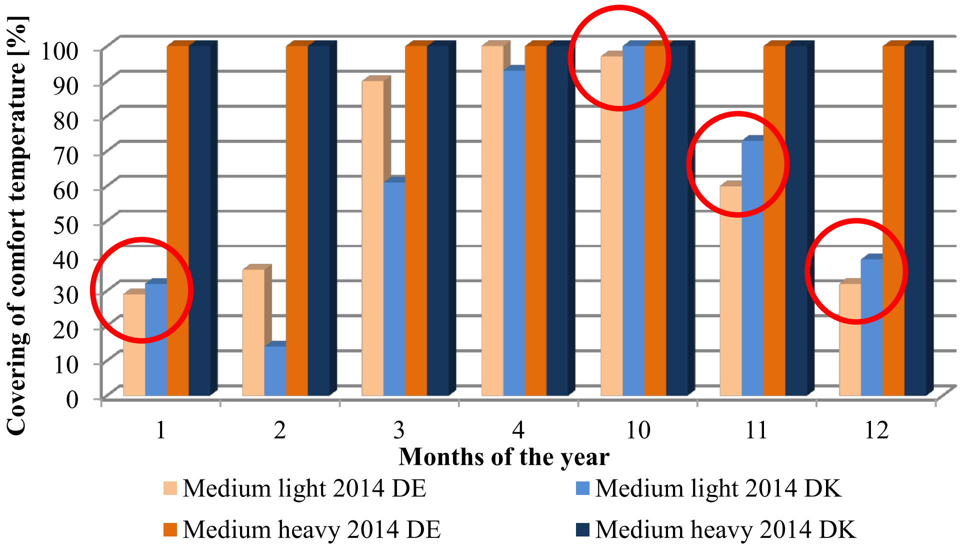


Figure 2.25. Comparison covering of comfort temperature of medium light building 2014 standard in Germany (DE) and Denmark (DK).

No differences between medium heavy variations are visible between Denmark and Germany, differently to medium light variations, which have small variations in all shown months. Even though the earlier mentioned daily and monthly average temperatures indicate opposite, does the medium light variation show a higher percentage of covering comfort temperature from October to January. Differences are though small. In February and March does the medium light variation with location in Frankfurt show a better performance, this time with a bigger difference between German and Danish location. Differently than assumed, is Denmark not unambiguously the colder country, as monthly average values from [DMI, 2014] and [DWD, 2014], as well as the plot of the weather files used for BSim, showing daily average temperatures, might have indicated. Reasons for this phenomena might be colder night temperatures in Germany or lower solar radiation. The simplified investigation only indicates that the yearly covering of comfort temperature is pretty similar for Germany and Denmark, even though the separate monthly values are different.

That Denmark with a slightly colder climate is worse for implementing a smart grid cannot be validated. Therefore the earlier mentioned recommendation, having a rational border at a medium heavy building construction built after 2014 standard can be extended to German conditions as well.

2.9 Discussion

As already indicated, are the results and the stated border for a rational implementation of a smart grid valid with the generously planned heating device of 100 kW per room. The reason for this over dimensioned heating device was to ease the comparison ability of the different heat capacity versions. With this assumption, it was simulated that the all buildings reach the set maximum comfort temperature of 24 °C fast, and can use the entire 8 hours for the accumulation of thermal mass. In reality this will be different. The lighter versions will likely heat up to the maximum comfort temperature fast, but the heavier buildings will need some more time, depending on the size of the heating device. With the over dimensioned size the heavier building categories were therefore given an advantage and their heat storage ability is likely a bit below stated results, depending on the actual size of the heating device.

Further it has to be considered, that in smart grids, when it is wished to heat up the building in a period to a maximum comfort temperature, this will come along with the need of a bigger sized heating device, as when the building is kept at a constant temperature.

In conclusion, the large heating device was a simplified variation, that does not include the different time the different buildings need to be heated up, which exaggerates the results of the heavier building categories to a certain degree. Still it is kept to the virtual border of a rational implementation of smart grids in building after actual standard, when they consist of heavy materials in majority, as figure 2.18 on page 32 showed. Further are all passive house variations recommendable when integrating a smart grid system.

Theory of simple hourly method after EN ISO 13790 3

After it is found out that integrating a smart grid gives good sense in most of building types, especially passive houses, the next step is to make a prognosis of the heat consumption. This is needed to schedule the available electricity from a photovoltaic with the expected electricity consumption of the heat pump in an optimal way. Several computer programs exist, that can prognosticate the expected heat demand in a very precise form, like the just used BSim program. These extensive programs have however the disadvantage, that they are accompanied with a high computational process. To be able to implement the prognosis of heat demand in a heat pump controller, the computational process, as well as input parameters should be kept to an absolute minimum. Further shall it be possible to integrate hourly values of measured parameters of the smart grid building, like air temperature and actual heat demand, which can then be used as new improved starting point for further prognosis. With an additional self learn function of the controller it is possible that measured and prognosticated values are compared and aligned for further prognosis.

The standard EN ISO 13790 [2008] specifies three different calculation methods. The monthly quasi-steady-state calculation method is omitted due to a monthly output, instead of the wished hourly output. The detailed hourly dynamic simulation method might be an option, but due to the wish to keep the computational process to a minimum, the simple hourly method seems to be the ideal choice. The theory of the simple hourly method is described in this chapter. As the calculation method is not as simple as the name indicates, only the idea of the method is presented and an overview of the interrelation of all contained equations is given in appendix B. The following descriptions of the theory are based and rendered in a reduced version after EN ISO 13790 [2008].

3.1 Overview of simple hourly method

The simple hourly method presents a simplification of a dynamic situation with a chosen limited amount of equations with the intention to reduce the amount of input data as much as possible. It is possible to integrate new development easily as the physical behaviour of the building can be implemented directly. The simple hourly method is based on a resistance-capacitance model, seen in figure 3.1 on the following page.

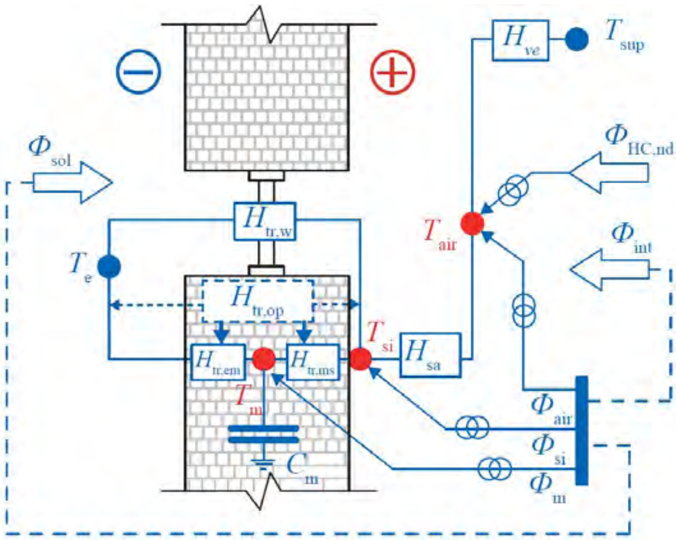


Figure 3.1. Scheme of simple hourly method redrawn from [Homics and Kirkedal, 2013] after [Narowski et al., 2010].

The figure gives an overview of how the different temperature nodes interact with each other. Differently than in EN ISO 13790 [2008], temperatures are in the figure named with T, and in the standard as θ. The different parameters are in this master thesis called identical to the ones described in EN ISO 13790 [2008].

The time step is one hour, so all input data from the building and system can be implemented using hourly time schedules. It is differentiated between internal air temperature θ_{air} and a mean temperature of internal surfaces θ_s. By this, radiative and convective parts of the different heat gains can be accounted.

The simple hourly method is based on heat transfer between internal and external environment. The heating or cooling need $\phi_{HC,nd}$ is calculated by finding the power, that needs to be added or subtracted from the internal temperature node, to fulfil a certain set point temperature. Heat transfer through ventilation is related straight with the internal air temperature node θ_{air} and the supply air temperature node θ_{sup}. Heat transfer by transmission is split up into transmission through windows and through opaque elements, in which the thermal mass is situated. The later is again split up into heat transfer between external air and thermal mass, $H_{tr,em}$, and heat transfer between internal surface and thermal mass, $H_{tr,ms}$. Heat gains from solar radiation and internal heat gains are dispersed on the three temperature nodes θ_{air}, θ_s, and θ_m. The later is the thermal mass temperature node, constituted by one thermal capacity C_m.

In this master thesis the main focus is given to the calculation of the needed heating or cooling power including the resulting actual temperature, so a closer look is given to the calculation process of $\phi_{HC,nd}$, which in general can be divided into four main steps. The first step is to check, if there is a conditioning demand at all.

3.2 Checking the demand of heating or cooling

In the first step it is assumed that there is no heating or cooling demand and therefore the calculation process is accomplished with a heating/cooling demand of $\phi_{\text{HC,nd}} = 0$. An overview of all equations is given in appendix B.

The calculation model is on basis of Crank-Nicholson-scheme, where it considers one hour as one time step. All temperatures are of an hourly averaged value, except the temperatures for thermal mass, which are instantaneous values at the time t and t-1.

The thermal mass temperature calculation computes the actual time step $\theta_{\text{m,t}}$ at its end from the previous time step $\theta_{\text{m,t-1}}$. The resulting air temperature is $\theta_{\text{air,0}}$ and symbolises the temperature that the building gets, when there is no heating. Now it is checked, if the $\theta_{\text{air,0}}$ is between the heating and the cooling set point temperature. When it is in between, the calculation can already be stopped at this point, else it is continued as described in the next section.

3.3 Choosing the set point and calculating the heating or cooling need

If the temperature with $\phi_{\text{HC,nd}} = 0$ is not in the area between the two set points, it is checked, which set points becomes valid. If $\theta_{\text{air,0}}$ is higher than the cooling set point temperature $\theta_{\text{int,C,set}}$, then the valid set point temperature is $\theta_{\text{int,C,set}}$,

if $\theta_{\text{air,0}}$ is lower than the heating set point temperature $\theta_{\text{int,H,set}}$, then the valid set point temperature is $\theta_{\text{int,H,set}}$.

Now the calculation process is made with a heating supply equal to 10 W per m^2 floor area, seen in equation 3.1.

$$\phi_{\text{HC,nd}} = 10 * A_{\text{F}}[W/m^2] \tag{3.1}$$

Where:

A_{F}	Conditioned floor area [m^2]

The resulting air temperature is to be called $\theta_{\text{air,10}}$, which symbolises the air temperature that is obtained with a heating or cooling power of 10 W/m^2. The unrestricted heating/cooling power demand can now be calculated with the help of the beforehand calculated two temperatures, seen in equation 3.2.

$$\phi_{HC,nd,un} = \phi_{HC,nd,10} * \frac{\theta_{air,set} - \theta_{air,0}}{\theta_{air,10} - \theta_{air,0}} \tag{3.2}$$

The result is positive for heating and negative for cooling.

3.4 Checking sufficiency of available heating or cooling power

In the next step it is necessary to check, if the just calculated heating/cooling power is in the frame of the given possibilities. If the unrestricted $\theta_{\mathrm{HC,nd,un}}$ is between the given maximum heating power and maximum cooling power, then the given set temperature with the calculated power is also the actual room temperature and the calculation can be stopped. Else the fourth and last step has to be applied.

3.5 Calculating the internal temperature

If $\theta_{\mathrm{HC,nd,un}}$ is positive, then the calculation process is repeated, this time with $\phi_{\mathrm{HC,nd,ac}}$ equal to the maximum heating power $\phi_{\mathrm{H,max}}$. With a negative $\phi_{\mathrm{HC,nd,un}}$, $\phi_{\mathrm{HC,nd,ac}}$ has to be taken, which is equal to the maximum cooling power $\phi_{\mathrm{C,max}}$.

Design of calculation tool for prognosticating heat demand 4

With the help of the Excel sheet [Homics and Kirkedahl, 2013] of the simple hourly method after [EN ISO 13790, 2008] the actual internal temperature in the building can be calculated with a given heat demand of 0. For a smart grid building it is though wished to prognosticate the actual heating or cooling demand on basis of a defined heating or cooling set point temperature. Therefore, is the given Excel sheet further developed and changed in the calculation method. Most input parameters could be taken over, but some were also added. This chapter contains first a sensitivity analysis to eliminate negligible weather parameters. Afterwards a short overview of the structure of the designed calculation tool is given. A comprehensive guidance about the different necessary input parameters that have to implemented into the Excel sheet is given in appendix B.

4.1 Which progressive weather input parameters are indispensable?

As progressive input parameters, which are described in this section, these input data are meant, that can be put into the Excel sheet ongoing. These are first of all the weather parameters. Every hour, or as soon as new data is available, they are put into the calculation tool. But which of the many weather parameters available are indispensable is investigated in this section, as it has to be remembered that the input is wished to be kept to minimum. Further does every weather parameter need to be bought, which increases the request of restricting the amount. Measured data in the building, like internal air temperature and actual heating demand are also progressive parameters, meaning as soon as new, actualized data is available, they are implemented into the model. But as their input is free of charge and further obviously improve the calculation tool, are they not further analysed here. Occupancy is implemented fixed, assuming no occupancy between 8.00 and 16.00 on weekdays and full occupancy the remaining time. But, if wished, this can also be changed to a progressive input parameter.

For the simple hourly method after EN ISO 13790 [2008] at least the external air temperature, the incident solar radiation, as well as the solar height and azimuth need to be implemented. Moreover, does the standard specify, that further weather data like wind speed, wind direction and relative humidity of the external air can be inserted, “if relevant” [EN ISO 13790, 2008]. After an exemplification of the indispensable weather parameters, a simplified sensitivity analysis is made to show the significance or insignificance of the remaining factors.

4.1.1 External temperature

Even though EN ISO 13790 [2008] documents the demand of implementation of external air temperature, a short investigation is made to show the high connection between heating demand and external temperature. Exemplary the dependency of the weather parameter to the heating demand is shown for the typical low-energy house, as already used in section 1.3 on page 4.

Again is the geometry of the comfort house chosen, to depict a realistic building structure.The individual building elements are though changed according to the in section 2.3 on page 9 described standard of a heavy building after 2014 standard.

It is chosen to implement this sensitivity analysis in Polysun, which "relies on the well-established, extensive Meteonorm weather-database. As Polysun is connected to Google maps [2014], the user is able to enter any address and hourly weather data will be subsequently incorporated for the selected location [PR Web Online Visibility, 2014]. Copenhagen is chosen as location for sensitivity analysis.

The total heating energy demand of the building excluding domestic hot water is 9081 kWh. Energy losses from transmission and ventilation are 18162 kWh and the heating set point temperature is chosen to be 20 °C. The values are calculated from BSim and then put into Polysun.

The external air temperature in connection to the heating demand is presented in figure 4.1.

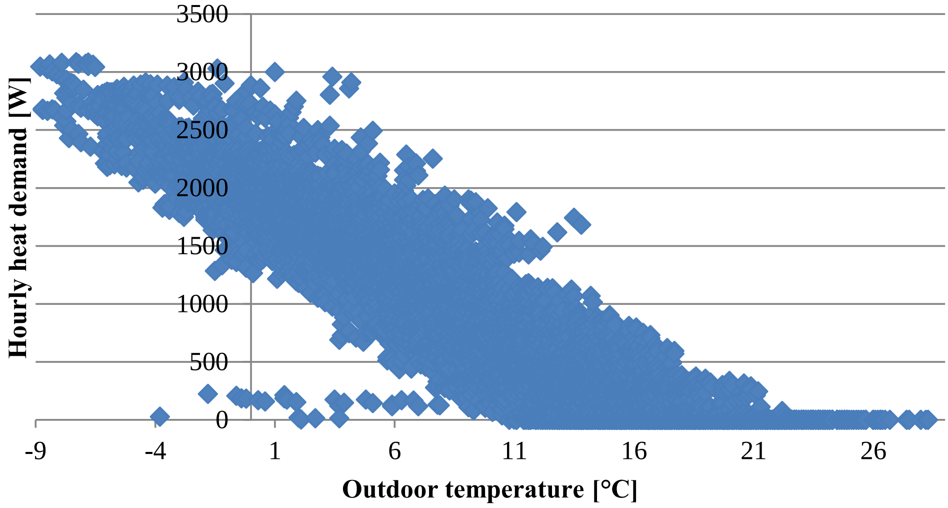


Figure 4.1. Hourly heating demand over outdoor temperature.

A strong dependency is visible between outdoor temperature and heating demand.

4.1.2 Solar radiation

The same investigation is made for global solar radiation, as this is the most likely value, which is available from weather services. Further division in direct and diffuse radiation is not implemented. It is seen sufficient, that one value of radiation is obtained from weather services. Because, if wished, the global radiation can be split up into diffuse and direct radiation, anyway by means of calculation tools.

The results for global solar radiation are shown in figure 4.2.

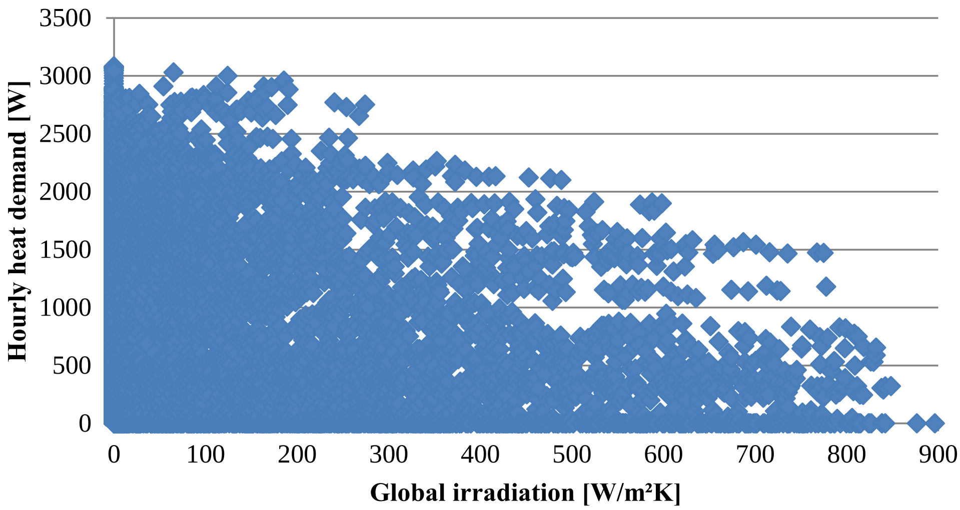


Figure 4.2. Hourly heating demand over global solar radiation.

Also here, a strong dependency between global solar radiation and heating demand is visible.

4.1.3 Wind

The heating demand in dependency on the wind speed is shown in figure 4.3 on the next page.

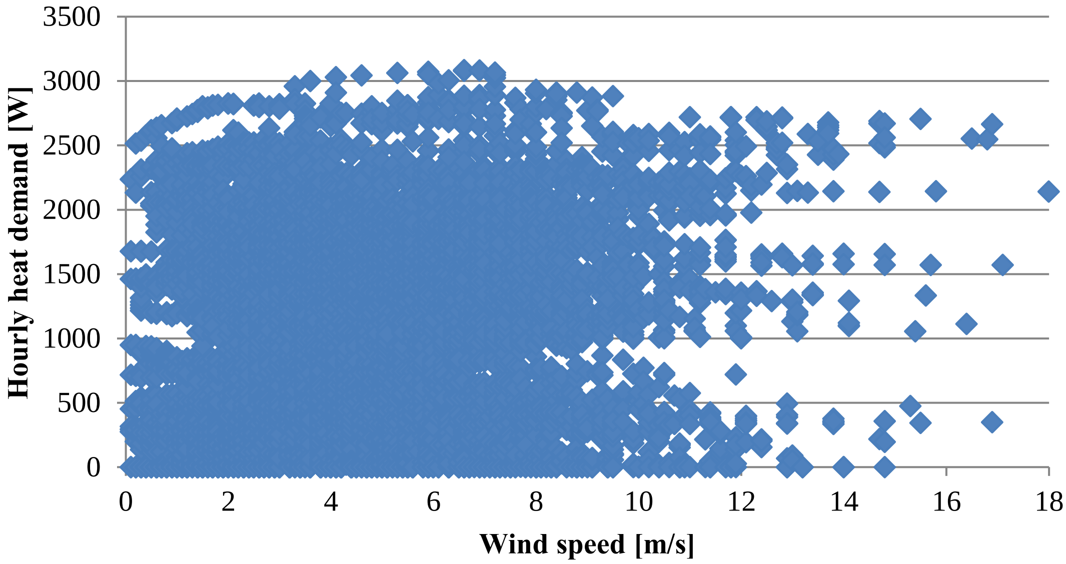


Figure 4.3. Hourly heating demand over wind speed.

The obtained results from the above shown figure are not conclusively. It can be, that when having a high wind speed, also the average heat demand is higher, but it also cannot be clearly excluded. Therefore it is decided to implement another investigation for analysing a possible indispensability of wind speed in the following.

The wind influences the heat transfer coefficient U of the different constructions by means of the external thermal resistance, therefore the transmission losses and thus the heating energy demand. The significance of this influence is investigated in this section. Therefore the calculation of the heat transfer coefficient, seen in equation 4.1 is examined, where the wind has an impact on the external thermal resistance R_{se}.

$$U = \frac{1}{R_{si} + R + R_{se}} \, [W/m^2K] \tag{4.1}$$

Where:

U	Heat transfer coefficient [W/m^2K]
R_{si}	Internal thermal resistance [m^{2}K/W]
R	Thermal resistance of the construction [m^{2}K/W]
R_{se}	External thermal resistance [m^{2}K/W]

The thermal resistance of the construction is calculated with equation 4.2 .

$$R = \sum_{i=1}^{n} \frac{d_i}{\lambda_i} = \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + ... \, [m^2K/W] \tag{4.2}$$

Values for R_{se} and R_{si} can be found in technical reports, etc. One example is shown in figure 4.4.

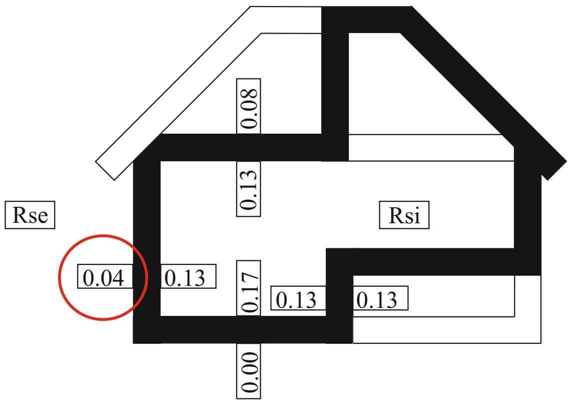


Figure 4.4. Thermal resistances redrawn after [Bruns, 2010]

The shown values for R_{se} are for "standard cases without a consideration of wind speed or surface characteristic" [Bruns, 2010]. This simplified value for the external thermal resistance R_{se} for outer walls is 0.04 m^2K/W.

It is investigated what consequences appear to the U-value, when the external thermal resistance value is changed, making the number both smaller and bigger, demonstrating the influence of wind, seen in figure 4.5.

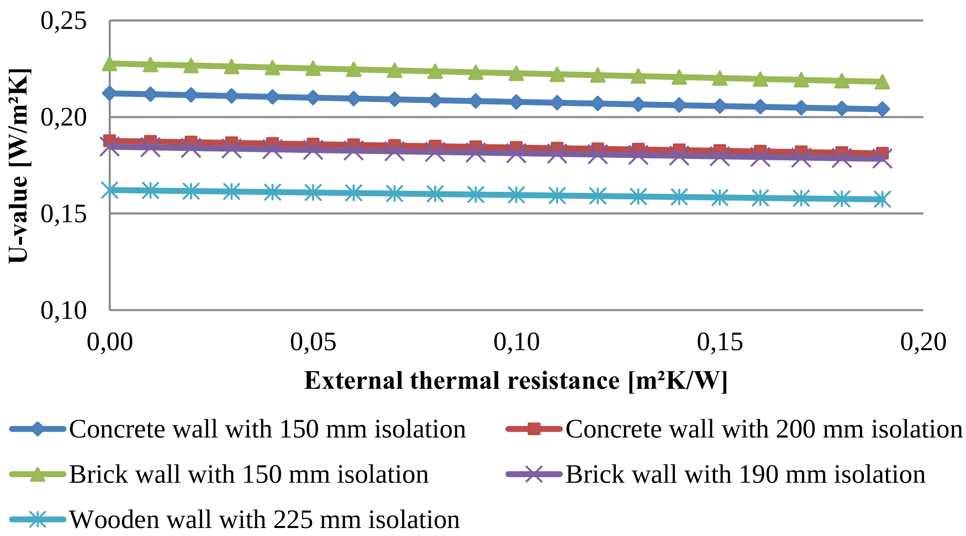


Figure 4.5. U-value as function of external thermal resistance with well insulated external walls.

The lower the value for the external thermal resistance number, the higher the wind speed that is integrated. When having well insulated external walls as shown in the figure 4.5, it is observed that there is no big influence of the U-value.

In the next investigation the focus is given to an uninsulated external wall and to a smaller insulation thickness in figure 4.6 on the next page.

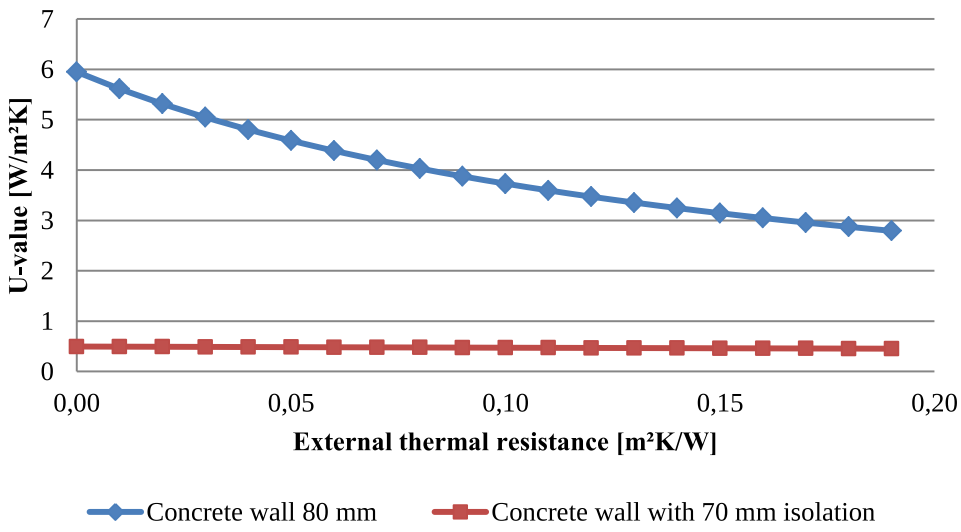


Figure 4.6. U-value as function of external thermal resistance with an uninsulated external wall and with 70 mm insulation.

A significant influence is seen in the change of U-value for the uninsulated external wall, varying from 5.95 W/m^{2}K with an external thermal resistance number of 0.00 m^{2}K/W to 4.81 W/m^{2}K with 0.04 m^{2}K/W. But as soon as there is a small layer of insulation, the influence of a changing external thermal resistance number is negligible. This simple investigation shows that the influence of wind is not important as long as the external walls are insulated. The exact values and further information about the insulation can be seen on appendix CD.

As the wind speed does not show a strong dependency on the heat demand, it is assumed, that neither the wind direction does. Therefore will these wind parameters not be included in the Excel calculation tool.

4.1.4 Relative humidity

The simplified sensitivity analysis of the heating demand in function over the air humidity is shown in 4.7 on the facing page.

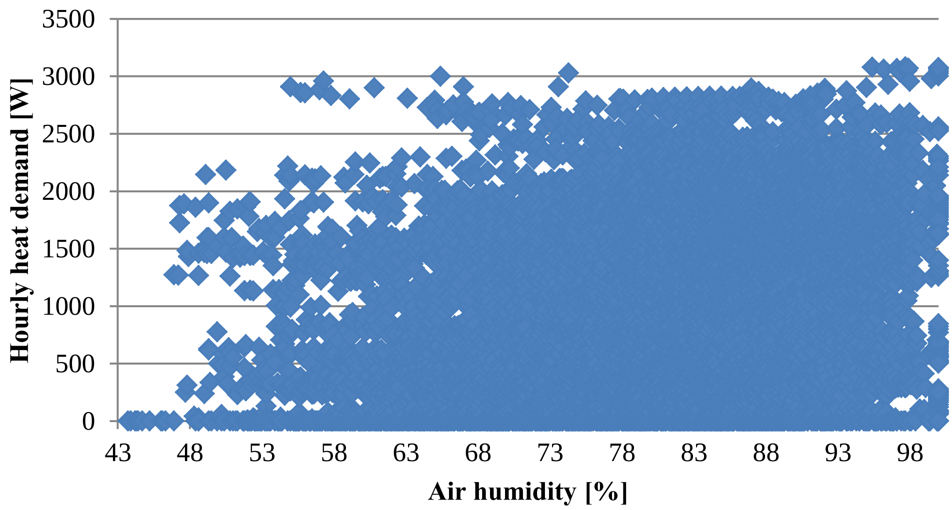


Figure 4.7. Hourly heating demand over air humidity.

No direct connection between air humidity and heating demand is detected. Therefore it is decided to neglect air humidity and not use it as input parameter in the Excel model.

Summed up, it can be said, that next to the required weather information EN ISO 13790 [2008] specifies, no further weather parameters as wind speed and direction and air humidity have to be taken into consideration as their influence is negligible.

4.2 Input data

After weather parameters wind and air humidity are delimited, the design of the calculation tool with implementation of the simple hourly method is shortly presented in this section. An extensively description of all necessary input parameters is found in appendix C, which can be seen as a guidance for using the calculation tool.

4.2.1 Building characteristics

The input of building characteristics allows the model to be adapted to different building types. But as already mentioned in chapter 3 on page 41 it is still wished to keep these input data to a minimum. Indispensable is information about the building construction, windows, doors, shading devices and ventilation system.

4.2.2 Solar gains

For simulating solar gains for the purpose of the prediction of heating demand, rather detailed knowledge according to the sun is necessary, as it is the sun, which is solely responsible for solar gains. Depending on the location of the building, the sun will be in another position, defined by azimuth and altitude. Definition and calculation process is described in appendix C.

The solar incidence arrives at the surface of the building and consists of different solar radiations, seen in equation 4.3.

$$I_{\mathrm{sol}} = I_{\mathrm{dir}} + I_{\mathrm{dif}} + I_{\mathrm{ref}} \tag{4.3}$$

Where:

I_{sol}	Total solar incidence [W/m^2]
I_{dir}	Direct solar radiation [W/m^2]
I_{dif}	Diffuse solar radiation [W/m^2]
I_{ref}	Reflected solar radiation [W/m^2]

The designed Excel sheet requires the input of direct solar radiation and diffuse solar radiation. The reflected solar radiation may in calculations be considered as diffuse after [ASHRAE, 2009].

The solar heat gains in a thermal zone are calculated after EN ISO 13790 [2008] by the sum of solar energy which is transmitted through collective elements. A simplified version is integrated in the Excel file, which neglects radiation from the sky to building elements [Homics and Kirkedal, 2013], seen in equation 4.4.

$$\phi_{sol} = \sum_{j=1}^{n} I_{sol} \cdot A_w \cdot g_{gl} \cdot f_g \cdot f_c \cdot f_{sh} \tag{4.4}$$

Where:

ϕ_{sol}	Solar heat gains in thermal zone [W]
I_{sol}	Total solar incidence [W/m^2]
A_w	Window area [m^2]
g_{gl}	Solar energy transmittance of transparent [-]
f_g	Glazing area fraction [-]
f_c	Shading factor [-]
f_{sh}	Shading factor [-]

The calculation of the above mentioned parameters is found in appendix C.

4.2.3 Internal gains

Internal heat gains play an important role within the prognosis of heat consumption and are not easy to predict. An investigation was implemented from [Homics and Kirkedal, 2013] in which they compared different internal heat gain calculation methods and came to the conclusion that the method after SBi 213 [Aggerholm and Grau, 2008] is the most optimal. In SBi 213 it is specified, that expected heat load from people is 1.5 W per m^2 of heated area [Aggerholm and Grau, 2008]. Per household a minimum of 90 W and a maximum of 360 W is assumed, corresponding to one to four persons. The assumed heat gains from appliances, including lighting is 3.5 W per m^2 of heated area [Aggerholm and Grau, 2008]. The minimum internal heat gain from appliances per household is expected to be 210 W and the maximum is assumed to be 840 W, again corresponding to one to four persons [Aggerholm and Grau, 2008].

In the Excel model a further distribution over the day regarding internal heat gains from both people and appliances is integrated. The wished complexity is up to the user. It can be differentiated between different rooms, so that a probably higher heat gain from some rooms (living room, kitchen, etc.) can be included as well. Else, can an average value for the entire building be chosen. Further it is possible to differentiate between internal loads on week days, weekends and holidays.

4.3 Self learn function

For a well functioning smart grid building, consecutive measurements of the building development are to be implemented. Necessary measurements are the internal room temperature and the actual used heating/cooling power. By implementing these values progressively into a controller, the controller will be able to learn and to adapt the information for further prognosis.

Verification of Excel model after simple hourly method with real life measurements 5

5.1 Input parameter in Excel model

The construction of the comfort house is of passive house standard, where the geometry was already presented in section 2.2 on page 8. The description of the input parameters orientates gradually on the different sheets of the Excel file and starts with the building construction. A more detailed description and guidance of the input parameters is given in appendix C.

5.1.1 Building construction

The building construction is taken over from the passive house calculation sheet [Feist, 2008], where only the first 0.1 m are considered for accumulation after EN ISO 13790 [2008], seen in table 5.1.

	Layer [-]	**ρ** [kg/m^3]	**c** [J/kgK]	**d** [m]
Floor	Wood on concrete	1440	1200	0.019
	Concrete	2385	800	0.081
External wall	Brick	1850	800	0.1
Ceiling	Wood on joists	450	1600	0.019

Table 5.1. First 0.1 m of building construction.

The heat capacity of the building results with the in the table mentioned values in 84.9 Wh/m^{2}K. When comparing this result to in table 2.2 on page 10 suggested values from [SBi, 2011a], then it can be seen, that the building belongs to the category *medium light*. It has to be mentioned, that the Excel sheet does not consider internal walls nor windows into the heat capacity calculation. What consequences this has to the simulation of accumulation in buildings is outlined in appendix C.4.

5.1.2 Windows

Input parameters for windows are shown in table 5.2 on the next page

Window	n	h	w	U_w	Orientation	f_g
W1	4	2.25	1.36	0.74	180	0.78
W2	1	2.25	3.28	0.68	180	0.88
W3	1	0.66	1.93	0.87	90	0.66
W4	1	2.25	0.95	0.78	90	0.75
W5	1	2.25	1.21	0.79	90	0.72
W6	2	0.66	1.28	0.89	0	0.64
W7	2	0.66	2.33	0.86	0	0.68
W8	1	1.53	0.6	0.91	0	0.62
W9	4	2.25	0.92	0.79	270	0.725

Table 5.2. Input parameters for windows.

The linear thermal transmittance for the comfort house was specified with 0.014 W/mK and the declination of all windows is 90 °C. Solar heat gain coefficient is equal to 0.54. [Feist, 2008]

5.1.3 Shading devices

The comfort house has overhangs with a length of 1.35 m on southern and northern side and with a length of 0.57 m on western and eastern side. Therefore, the belonging overhang angle has to be calculated as described in appendix C.2.2. Northern side was neglected due to the assumption that solar heat gains are very small at northern side anyway. Further are windows on northern side mounted in different heights which increases computational process in a way that is not according to gained results. Overhang angles for the remaining orientations are shown in table 5.3.

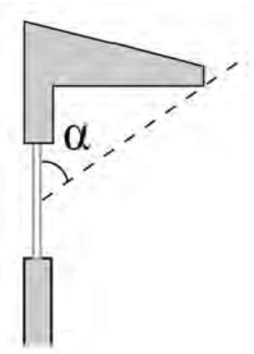
Window	α [°]	Visualization
W1	50.2	
W2	50.2	
W3	12.2	
W4	8.5	
W5	10.6	
W6	[-]	
W7	[-]	
W8	[-]	
W9	8.9	

Table 5.3. Input parameters for overhang.

5.1.4 Ventilation system

Mechanical ventilation is integrated in the comfort house with a basic ventilation rate of 0.236 $l/s/m^2$ [Feist, 2008] and no further distribution during the day.

Proportional band is equal to one and the ventilation set point temperature is set to 24 °C with a supply temperature of 19 °C. The fraction of air flow elements that goes through the heat recovery unit is set to 1 with an efficiency of the heat recovery unit of 0.753 [Feist, 2008].

5.1.5 Weather condition

Measurements of the external weather temperatures were conducted around the comfort house, but failed. Therefore weather data was bought from Aalborg University for the time during the measurements.

External air temperature can be implemented directly into the sheet *Model*. Though was only one global radiation per hour given. The Excel sheet allows the input of radiation values split up in direct and diffuse, as well as the possibility to split it up into different orientations in the sheets *Direct radiation* and *Diffuse radiation*. But as only one value has been given, this value was input completely as direct radiation from southern side, instead of splitting it up. This was due to the assumption, that most solar radiation comes from the souther side anyway and will likely also affect the southern windows most. Though is this an uncertainty that has to be taken into consideration when evaluating the results.

5.1.6 Internal gains

As already mentioned in subsection 4.2.3 on page 52, the internal gain approximation method after SBi 213 [Aggerholm and Grau, 2008] is used with an assumed internal heat gain of 5 W/m^2. Though an individual distribution of this overall value is applied after [Homics and Kirkedal, 2013]. The internal heat gains are split up into common habits from people, going to work during weekdays and being home the rest of the day and the weekend. Also the internal gains represent an uncertainty. Even though it is tried to come as close to occupants' habits, deviations between simulated and realistic internal gains are likely and can hardly be avoided.

5.1.7 Shadows

The latitude and longitude are defined for DRY as 55.46 ° and 12.19 °, respectively [SBi, 2014]. The remaining parameters are all calculated within the Excel sheet as described in appendix C.3.

5.1.8 Photovoltaic performance

A photovoltaic system is not available in the comfort house. Though was a fictive photovoltaic performance simulated in Polysun and added to the Excel to demonstrate the ability of the Excel sheet of utilization in smart grid buildings.

5.2 Output

The Excel model is both able to prognosticate the heat demand for common heating systems and buildings with smart grid. An overview of the different possible outputs of the Excel model of the simple hourly method after EN ISO 13790 [2008] is given in the following. As mentioned above, is the performance of the photovoltaic only fictive and will be removed in the verification, as no photovoltaic is available in the original comfort house.

The first output presented is the heating demand split up for every hour in kW per hour, combined with the fictive generated power from the photovoltaic, when no smart grid is available, visualized in figure 5.1.

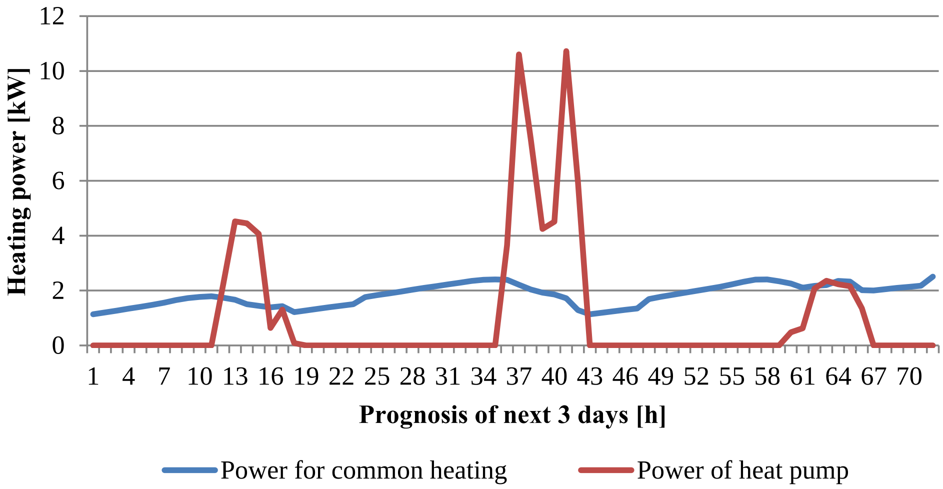


Figure 5.1. Hourly heating demand in contrast to photovoltaic's power generation.

The figure shows clearly, that when a common heating system is used without the technique of smart grid, big deviations between actual need and supply are present. High peaks of the photovoltaic are available, but cannot be utilized for the heating. The belonging temperature curve for the internal air temperature in the building with no smart grid is visualized in figure 5.2 on the next page.

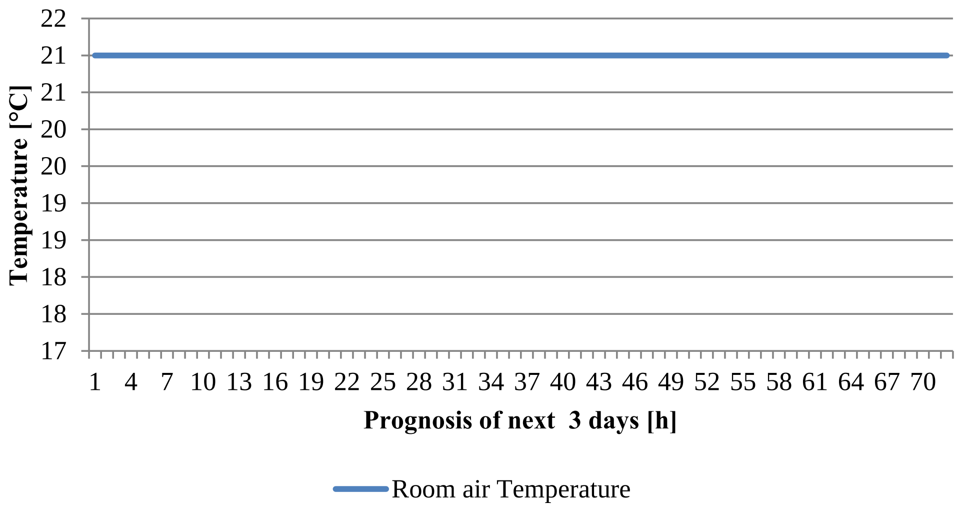


Figure 5.2. Internal air temperature with common heating system.

When a normal heating system is implemented, does the Excel sheet prognosticate that there will be no fluctuations and the set point temperature can be kept all the time. Here it has to be mentioned, that the output does not completely represent reality, as in real buildings small fluctuations will be present. The reason of the total straight temperature curve is due to the specification in the calculation tool, which defines, as long as simulated heating demand lays below maximum available heating power, the internal room temperature is equal to set temperature [EN ISO 13790, 2008].

The next output graph shows the heating power within a smart grid system. The set temperature of the internal room air temperature is changed to 24 °C, but maximal heating power for the smart grid is equal to available photovoltaic power generation, seen in figure 5.3.

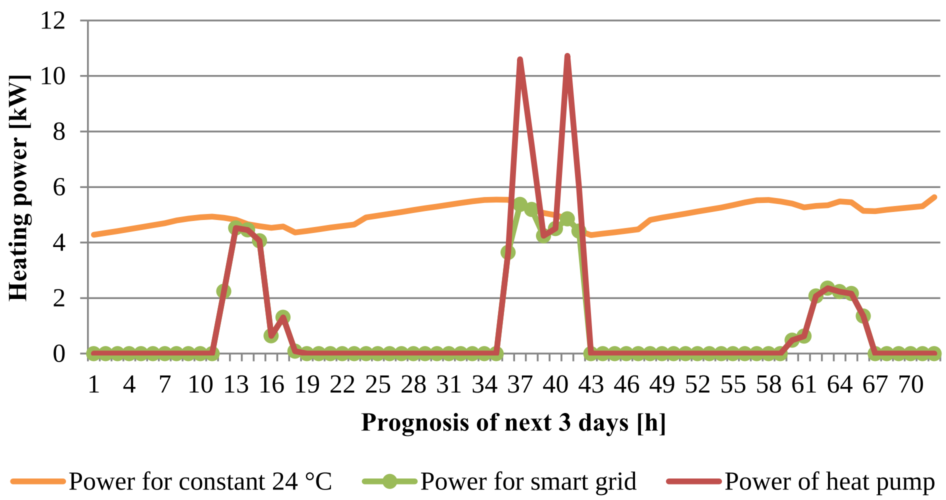


Figure 5.3. Necessary power for set point temperature of 24 ° with common heating, available heat pump power, power utilized in smart grid.

The orange curve represents the heating power that is necessary to keep the room to the constant high set point temperature of 24 °C. This is seen as the limit for the available photovoltaic power, shown as red curve, to guarantee that the internal air temperature does not exceed the set limit. This leads to the power that is then actual available for the smart grid, demonstrated in green.

The belonging temperature curves of the internal air temperature, as well as the operative temperature in the building with smart grid are shown in 5.4.

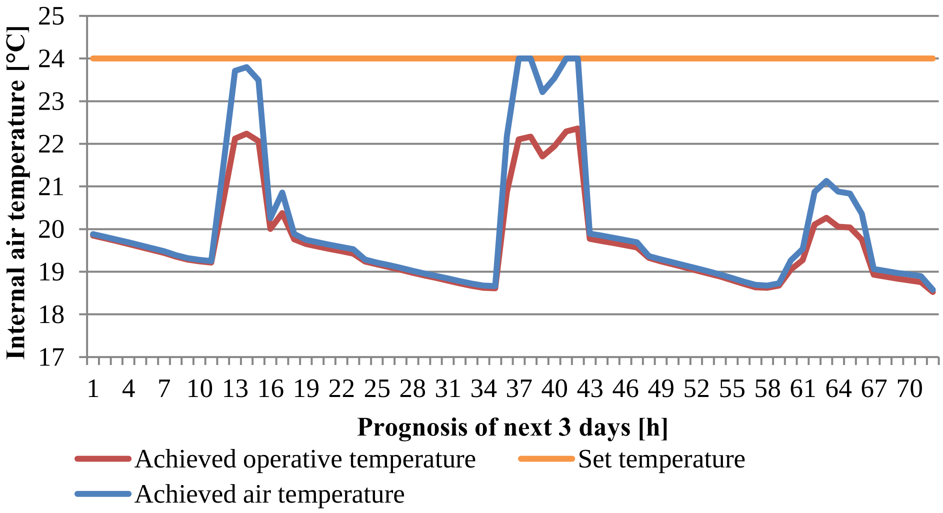


Figure 5.4. Internal air temperature with smart grid system

With this output it can be seen, if the solely photovoltaic's energy supply is sufficient or if additional energy supply is necessary. It is noticeable, that the resulting temperature of this light medium passive house declines rapidly within the first hour after the heating is stopped. The further temperature drop is small and even. This is in strong contrast to the results, which were achieved with the advanced simulation tool BSim in subsection 2.8.1 on page 34, where the temperature dropped evenly and not more than maximum 2 °C in the course of 16 hours. Though does also the temperature in the Excel simulation does not drop more than 1 °C from the second hour of heating stop of the first day to hour 35, for example. This is also a frame of 15 hours with only a small temperature drop. The fluctuations of the operative temperature are less intense, which is expected due to the influence of thermal mass, included into the calculation. But the high drop within the first hour is not realistic and must occur due to a calculation phenomena within the simple hourly method. EN ISO 13790 [2008] elucidates about the simple hourly method: "This method produces hourly results, but the results for the individual hours are not validated an individual hours can have large relative errors." An implementation error due to a too less regarded inclusion of accumulation of thermal mass can though be excluded, because of the fact, that the temperature drops only a bit in the following hours, after the rapid fall of the first hour. How much this calculation phenomena effects the results of the calculation tool is analysed, when compared to real life measurements in section 5.4 on the next page.

5.3 Results of measurements

Operative internal air temperature is measured in four different spots within the building, seen in figure 5.5.

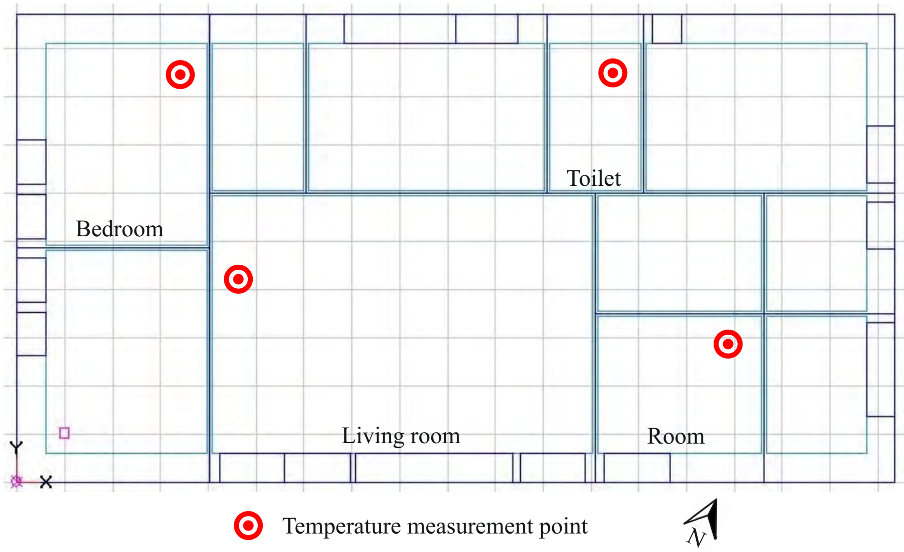
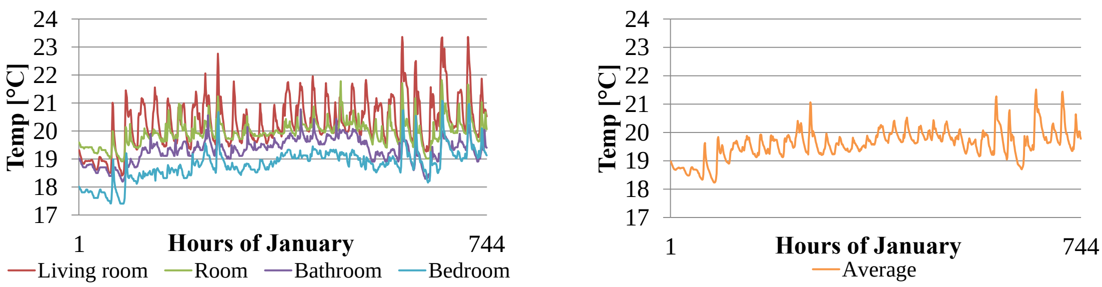


Figure 5.5. Temperature measurement points.

It is decided to use the average temperature of the four measured temperatures as this takes out temperature peaks. This average temperature as well as the four measured temperatures of the different rooms are shown for January 2010 in following figure 5.6.



(a) Room temperatures.
(b) Average temperature.

Figure 5.6. Measured room temperatures and average temperature.

Heating energy is supplied from floor heating system and a heating coil. The month that is chosen to be investigated is January 2010. Measured values of the floor heat and heating coil are seen in figure 5.7 on the following page.

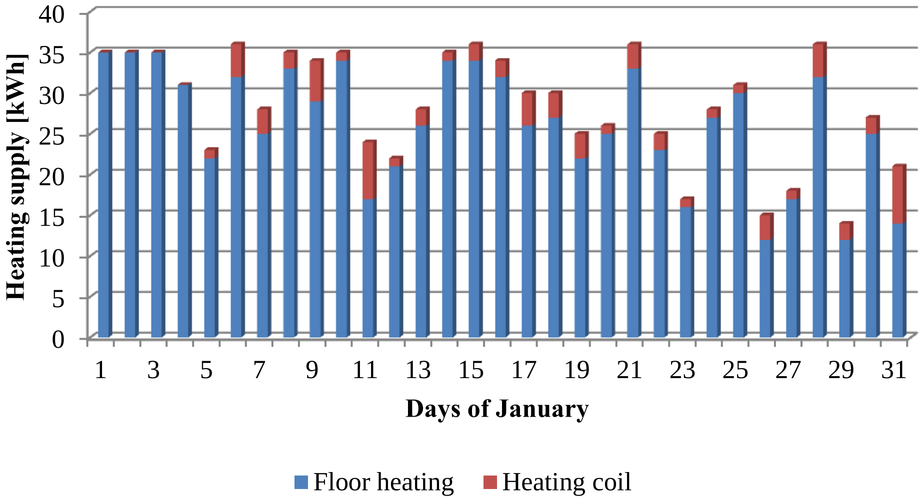


Figure 5.7. Measured daily heating energy.

Heating supply varies in January 2010 for the passive house between 13 kWh and 36 kWh. The average heating demand of the month is 28.5 kWh.

5.4 Comparison of Excel model to measured data

As the calculation tool is able to prognosticate the heating demand, when a set temperature for heating (or cooling) is defined, as well as to prognosticate the air temperature, when a given heating demand is defined, both variations are verified by juxtaposing to measured values. The beginning is made by a comparison of measured operative temperatures and simulated operative temperatures.

5.4.1 Measured operative temperature versus simulated operative temperature

To obtain operative temperature, an hourly input of the heating supply is sufficient for the Excel calculation tool. As above mentioned, the heating supply was measured for an entire day. Therefore was it necessary to split up the heating supply into hourly values. For the sake of simplicity it is decided to divide daily heating supply in kWh by 24 hours to get the heating power per hour in kW without further distribution, about when the heating is demanded more or less. The resulting simulated operative temperature, the measured operative temperature, as well as the hourly heating power is shown in figure 5.8 on the next page.

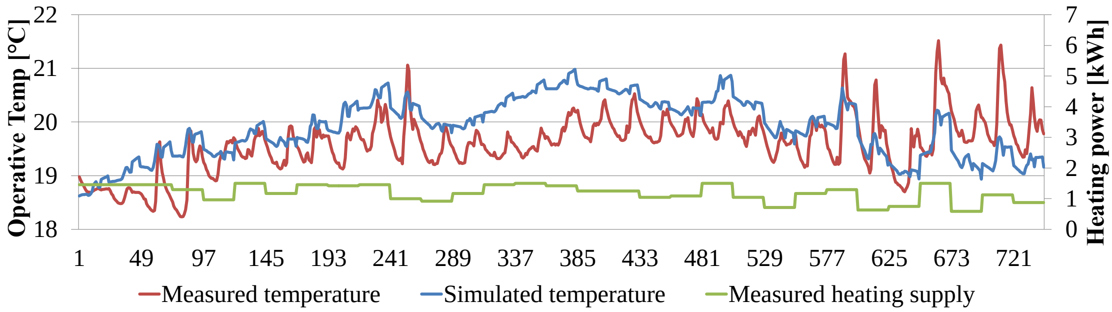


Figure 5.8. Comparison measured operative temperature with simulated operative temperature plotted next to hourly heating supply.

The figure indicates that the simulated and measured temperature show an acceptable variance. It is though noticeable, that the fluctuations within the curve of the simulated temperature are smaller, than the fluctuations of the measured temperature. A possible reason for this difference might be the hourly even input of heating power, whereas the real hourly heating supply is unknown and might be subject to large fluctuations. Further are the internal gains defined after common habits of people. As no information about people behaviour and equipment was recorded, this is a large uncertainty factor within the simulation of the calculation tool. Also was the solar global radiation only input as one value and input as direct radiation solely coming from south. However, it can be noticed, that the difference between simulated and measured operative temperature is in the shown month not bigger than 1 °C. This indicates, that the Excel model in general, meaning over a longer period, depicts the temperature behaviour of a building in a realistic way.

Next, the other possibility of the Excel sheet, obtaining a heating demand with a given set temperature is presented.

5.4.2 Measured heating supply versus simulated heating demand

As the temperature measured in the comfort house is the operative temperature, one difficulty occurs when it is wished to simulate the heating demand. The operative temperature depends on air temperature and surface temperature. The surface temperature in turn depends on the actual heating demand. Therefore it is assumed in the beginning that the operative temperature, which is measured, is equal to the air temperature. This is then input into the Excel sheet, which can on that basis prognosticate heating demand. The thus determined simulated operative temperature is juxtaposed with measured one. It is found out that the air temperature lays a bit above operative temperature and therefore is the input set air temperature adjusted, so that the resulting operative temperature is similar to measured one. The with help of the adjusted air set temperature obtained simulates operative temperature is plotted next to the measured operative temperature in figure 5.9 on the following page.

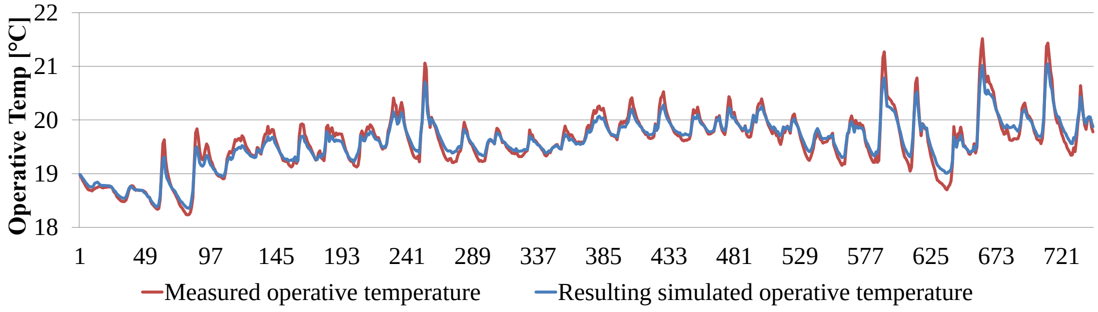


Figure 5.9. Adjusting air temperature with operative temperature.

In average lays the internal air temperature 0.5 °C above operative temperature, which was then used as adjustment to the internal temperature. This might be due to the fact that the comparison is made for January, meaning in the heating phase. In cooling phase the internal air temperature would likely be below operative temperature. With this adjusted air set temperature the heating demand is determined and compared in figure 5.10.

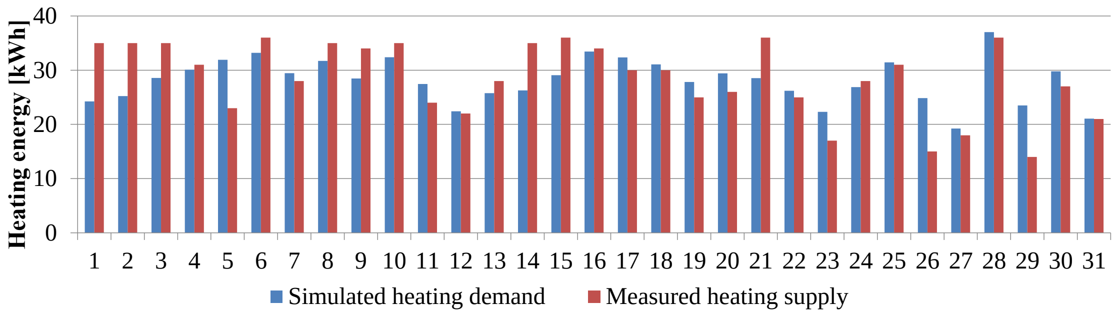


Figure 5.10. Comparison measured operative temperature with simulated operative temperature.

Simulated and measured heating demand lay in the same range, where around half of the days the measured heating demand lays above simulated and half of the days the other way. The differences in the beginning can be explained due to initial conditions that have to be implemented into the Excel sheet, namely an initial thermal mass temperature. For a simplified calculation method with a minimum of input parameters, this is considered to be an acceptable variance. The average deviation between measured and simulated heating energy is calculated to be 4 kWh.

5.5 Discussion

The Excel sheet does not reflect the temperature distribution of every hour of a day in a realistic manner. Even though the accumulation is properly used in most of the hours, seen by a relatively flat temperature curve over most of the day after the heating is shut off, does the temperature of the first hour drop so fast, that it delivers therefore a wrong starting point for the remaining hours. As the EN

ISO 13790 [2008] already indicates, does the simple hourly method come along with some huge hourly errors. Therefore it is not recommended to use the Excel sheet when an exact hour wants to be prognosticated.

The comparison with real life data over an entire month showed though that the resulting simulated temperature is not far from measured results. The deviation in the shown month January 2010 was never more than 1 °C. Also the measured heating demand was in an acceptable range compared to the simulated heating demand.

The deviations in the verification can be explained by the two main uncertainties internal heat gains and solar heat gains. Even though it is assumed that the input internal heat gains lay in a realistic range, as sometimes the simulated results were higher than measured and sometimes the other way, it is hard to prognosticate the real internal gains, as occupants do not always follow the implemented habits, as going to work between 8.00 and 16.00. Every time there is a deviation between realistic and simulated input internal gains, this will also lead to a deviation in the prognosticated heat demand. This deviation can be counteracted, when the occupants put in their individual schedule. The more precise this is done, the more precise can then the calculation tool be.

Further uncertainty are the solar heat gains. First of all, it cannot be guaranteed that the prognosticated radiation will also be the real one. Secondly, was the simplification made that instead of splitting up the global solar radiation into diffuse and direct radiation, it was input as direct radiation on southern side. A more exact breakdown of global radiation would further improve the accuracy of the calculation model.

Conclusion 6

Investigation of smart grid buildings' heat capacity in periods of the day with no heating supply were conducted. Investigated were eight buildings, which had varying heat capacity due to a different heaviness of their building elements and were of different building standard. The analysis was conducted in BSim, where the variations were heated up to an assumed maximum comfort temperature of 24 °C in eight hours of the day, to investigate the effect in the remaining 16 hours. It was found out, that all passive house can store heat for more than 16 hours with a maximal temperature drop of 2 °C, whereas the different building after actual building regulations showed varying ability of doing that. The light and medium light variation of 2014 standard, could not cover an assumed minimum comfort temperature of 20 °C in most of the heating period. Medium heavy and heavy variation built after actual standard, had a covering percentage of 100 % in all months of the year, with temperature drops of 2 to 4 °C within the analysed 16 hours after heating stop.

Due to an oversized heating device were the performances of the heavier building versions presented a bit too good, as they would probably not reach the maximum set point temperature of 24 °C right away, due to the longer time of heating up thermal mass. It is assumed that a virtual border of a reasonable implementation of smart grids can be drawn for buildings of actual standard, which in majority consist of heavy building materials, as brick and concrete.

A short analysis of the resulting heat losses showed, that reducing transmission losses by means of improving U-values of the building elements, will have the biggest effect regarding a better heat capacity for purposes of implementing a smart grid. Ventilation systems are already today of such advanced efficiency, that improving them, will not lead to high changes. Further was it noticed, that when reducing all heat losses, a higher need of ventilation need is likely, due to higher internal temperatures in summer in houses of an extraordinarily quality, as passive houses.

The simple hourly method after EN ISO 13790 [2008] was used and a calculation tool from [Homics and Kirkedahl, 2013] was further developed with the goal of a prognostication of the heating demand. Due to a simplified sensitivity analysis the weather parameters wind speed, wind direction and air humidity could be delimited as possible input parameters, as their influence on buildings' heat demand is negligible.

An hourly prognosis of the expected internal air temperatures on basis of implemented heating supply showed unrealistic results, as the temperature drop within the first hour was extraordinarily high in contrast to all other temperatures. The reason for this is not entirely enlightened, though can a wrong inclusion of thermal mass probably be neglected, as the remaining temperature curve was comparable with results obtained from BSim.

However showed a verification with measured results from a building from the comfort house project that the deviation between measured and simulated values lay in an acceptable range, which enables the usage of the created calculation demand in heat pump controller.

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