2014

[Type houses with optimal energy use in relation to an energy system without the use of fossil fuels]

Master Thesis – Building Technology

Nikolai Leth – S082470

Technical University of Denmark

Title page

Title: Type houses with optimal energy use in relation to an energy system without the use of fossil fuels

Author: Nikolai Leth

Student number: S082470

Supervisor: Svend A. Svendsen
Lies Vanhoutteghem

DTU•BYG
Department of Civil Engineering
Technical University of Denmark
Brovej
Building 118
2800 Kgs. Lyngby
Denmark

http://www.byg.dtu.dk
Tel: (+45) 4525 1700
E-mail: byg@byg.dtu.dk

Period: 16 September 2013 – 22 March 2014

Project type: Master Thesis DTU BYG

Weight: 35 ECTS Points

Preface

This Master thesis is a part of the fulfilment of my studies in Building Technology at the Technical University of Denmark. The project lasted from September 2013 until March 2014.

I would like to thank Professor Svend A. Svendsen for providing inspirational ideas and supervision throughout the project. I would also like to thank Ph.D. Lies Vanhoutteghem, for invaluable help with WinDesign and general guidance.

____

Nikolai Leth

Lyngby, 22nd of March 2014

Abstract

The aim of this project is to investigate the viability and consequences of supplying a low energy single family house with space heating and domestic hot water from electricity consumed only in the off-peak period between 00:00 and 06:00, by storing enough heat for use during the rest of the day. From an economic perspective it is examined whether a simple installation of electric heating elements in a concrete floor and in the hot water tank can be a viable alternative to a more expensive pump setup if the house has a low demand for space heating.

Different investigations were carried out in order to determine the relevance of an electric off-peak heating system in regard to the strain on the electric grid, the temperature rise in the concrete slab due to the storage of heat for the entire day. The necessary domestic hot water tank size was also investigated along with the potential economic gains of consuming the electricity at night. To supplement this, a second building design was developed with the aim of achieving a lower heating demand than is typically used in a low energy single family house, and to evaluate the potential advantages and disadvantages in relation to the 2020 reference house.

Investigations between the low energy 2020 reference house and the improved version, Design 2, which has a 36% lower space heating demand showed that the reference house was found to perform adequately, but the lower heating demand of Design 2 had some notable improvements regarding e.g. the strain on the grid and temperature rises in the concrete slab. Due to this lower heating demand, the Design 2 house is also economically interesting despite higher initial component costs.

The results show a necessary heating power of 5.1 kW for the 2020 reference house in order to store enough heat to be stored in the concrete slab on the coldest day in the DRY reference year by supplying it directly with electricity in the off-peak period from 00:00 to 06:00, where the national strain on the electric grid and subsequent price is lowest. This can be seen as an acceptable strain on the electric grid that can potentially be replicated in thousands of low energy houses in Denmark without access to district heating.

The temperature rises in the concrete slab and subsequent room temperature rises caused by the storage of heat in the period 00:00-06:00 for an entire day were found to be in the excess of 2.5 °C on the cold winter days, which were deemed acceptable since it primarily occurred in a north facing room and not for more than 10 days each year. The storage of heat in the concrete slab for heating purposes was found to be a problem in bedrooms, and especially children's bedrooms, which are often occupied during the day. This is due to the greater need for temperature flexibility in these rooms. A storage heater or similar device is needed to reduce this problem.

Investigations regarding the domestic hot water tank showed that it was not feasible to supply the tank with enough hot water to cover the demand on a demanding day without charging due to the necessary size, temperature and subsequent stationary heat loss. A compromise was found in a 300 L tank heated to 60 °C, which could likely cover the necessary hot water demands on most days and charge as necessary on a demanding day.

In regard to the direct economic aspect of consuming electricity only at night, little benefit was found in the way of reduced energy prices at night, which is mostly due to the current large fraction of the electricity price consisting of taxes. More potential for savings was imagined for the future - as wind turbines become more prevalent, so does the potential for savings by night consumption.

In regard to the economic aspect of acquiring a heat pump versus utilizing direct electricity heating, little economic incentive was found to acquire a heat pump. Depending on the heat pump setup, the investment was barely able to be returned after 20 years, which is the expected lifetime of a heat pump. A solar heating system was found to be viable from an economic perspective due to the long lifetime. In regard to the energy frame, compensation is required in the form of a lower primary energy factor for off-peak electricity, in order for the Design 2 house to be able to comply with the low energy frame 2020. In this regard the solar heating system is a useful way to reduce the energy frame. It can be concluded that for very low energy houses, supplying heat directly with off-peak electricity can be seen as a viable alternative to e.g. investing in a heat pump for houses without access to district heating.

Contents

1. Introduction

Background

The Danish long term climate strategy is for energy supply in Denmark to be entirely renewable by the year 2050. Leading up to this are milestones in 2020, 2030 and 2035, as can be seen on figure 1.

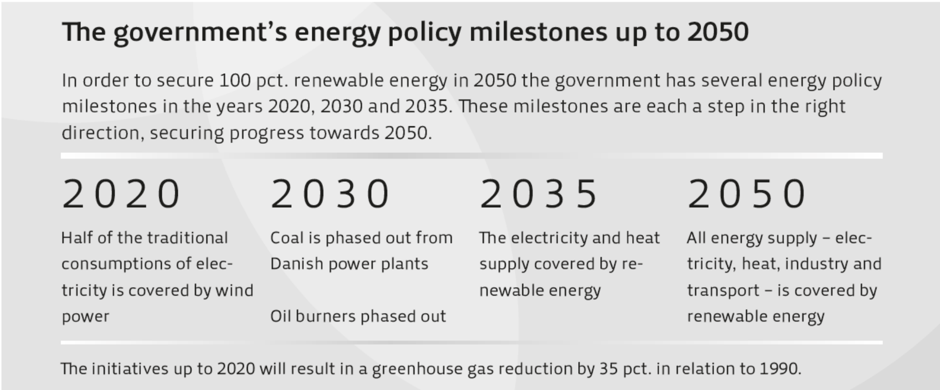


Figure 1 – The climate policy milestones of the Danish government up to the year 2050 [1]

Already by the year 2035, all electricity and heat is to be supplied only by renewable sources, which is an ambitious goal, and presents numerous challenges, not least for the electricity supply, the majority of which is to be covered by wind turbines.

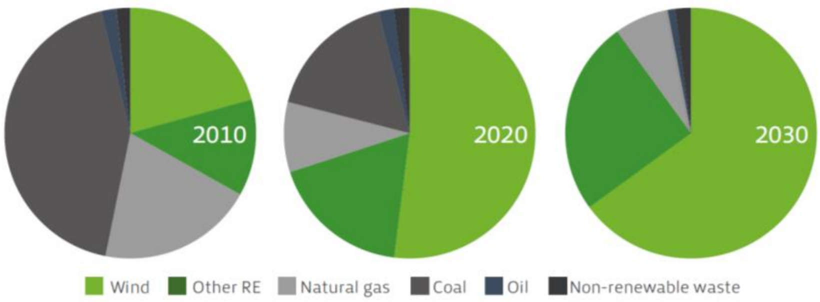


Figure 2 – Electricity production by energy source [1]

As can be seen from figure 2, the cheap and flexible, but highly polluting electricity from coal-fired power plants is to be phased out by 2030, and is to be replaced in large part by the somewhat less predictable, less flexible wind turbines. This transition will present major challenges for the building sector and demands the transition towards a more intelligent electricity system where consumers and appliances are able to adapt according to the availability of electricity. In order to incentivize this, by 2020 all Danish houses are to be fitted with an intelligent electric meter by capable of differentiating between the hours at which the electricity is consumed.

At the same time, oil and gas-fired boilers are to be phased out, with no such installations allowed in new buildings currently, and 2015 oil-fired boilers are not to be installed in existing buildings as well. The goal is for half of all oil-fired boilers to be phased out by 2020, compared to 2010 numbers and for them to be completely phased out by 2030.

Objective

The objective of this task is to assess the viability of off-peak electric heating in a low energy house in a way that could perhaps take advantage of this increased electricity production from wind turbines.

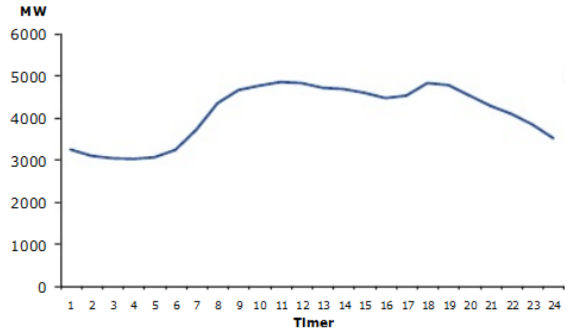


Figure 3 – The average daily variation of the Danish electricity consumption [3]

As can be seen on figure 3, there is a six hour off-peak period from approximately 00:00 to 06:00 in the Danish national electric consumption. It could therefore be interesting to investigate the viability of supplying the heat for a low energy house, located outside the range of a district heating plant, with direct electric heating consumed only in this off-peak period of approximately six hours, by storing enough heat for the day in the concrete slab. Electric heating is generally more expensive than other heating methods, and this expense could perhaps be reduced if the heat could be supplied only in this off-peak period at night where the electricity is generally cheaper and more readily available.

As the production of electricity from the somewhat inflexible wind turbines increases, it is more likely that excess electricity in the off-peak period between 00:00 and 06:00 will be more plentiful. Therefore it is likely that he benefit of off-peak consumption will increase, both for the consumers in the form of lower tariffs and for the grid system as a whole due to the smoothing of the daily consumption curve, reducing the need for overproduction of wind turbines in order to be able to cover the electricity consumption in peak the peak hours. Since installing an electric heating system presents a low investment cost with little or no maintenance, it could potentially be a more economically interesting method of heat supply compared to e.g. an expensive heat pump, for a low energy house.

One potential problem with electric off-peak heating could be an increased interior temperature due to the storage of heat in the concrete slab for a whole day, and it could perhaps also be a problem that the electricity needed to store enough heat for a cold winter day could cause an unwanted strain on the electric grid.

It is the objective to investigate the impact and relevance of an electric off-peak heating system in a low energy 2020 house, and to also develop a house where a higher focus will be put on reducing the annual heating demand as well as the heating demand on a cold winter day, than would ordinarily be put on a low energy 2020 house, to determine if that could make a relevant difference in regard to the use of electric off-peak heating.

Method

The relevance of electric off-peak heating will be investigated on the basis of an existing low energy 2020 house design, previously developed by Matilde Grøn and Susanne Roed for their Master thesis [20]. Based on that house, a design with a lower heating demand will be developed. This process will include the investigation of better components, such as windows, and their impact on the house and the heating demand in the WinDesign program. Ways to optimize the daylight will be investigated with the use of tapered window reveals, which could reduce the heating demand on a cold winter day as well as the overheating hours. Different window sizing and placement parameters will be investigated in order to achieve an optimal daylight intake and good daylight conditions for the occupants. The daylight will be evaluated with the Velux Visualizer program on the basis of three daylight requirements from [20], of a daylight factor of 3% in the center of a room, 2% across and 1% elsewhere. This should ensure a good spread of daylight around the room and a general high quality of daylight intake. In addition, different ways of optimizing the windows and doors in regard to the heating demand will be investigated.

With the WinDesign program, the houses will be evaluated both on the basis of the room based heating demand and overheating hours, as well as the heating demand on the cold winter day and the temperature increase in the concrete due to the storage of heat for a whole day in the concrete slab.

The walls, floor and roof will be optimized from an economic perspective in regard to the insulation thickness with the use of Cost of Conserved Energy calculation. This ensures that the components have a similar marginal energy price, which means that the energy saving price for the last cm of insulation is the same.

Disposition

First the reference house will be investigated in WinDesign in terms of the annual heating demand, the heating demand on a cold winter day and the temperature rise of the concrete slab due to the storage of heat for the rest of the day.

Based on that, a house with a focus on a lower heating demand will be developed, referred to as Design 1, with the use of very thick insulation, better glazing and tapered reveals and the results will be investigated in WinDesign. Based on that, numerous different design changes will be proposed and investigated with the purpose of achieving a design where an additional focus has been put on reducing the heating demand without extraordinary insulation thicknesses. The most relevant of these design changes will be used and the insulation thicknesses will be balanced according to CCE, and the resulting deisng will be called Design 2.

Next, more realistic inputs will be introduced, and an improvement to WinDesign will be developed, allowing the input of a variable internal load which varies according to the room type and time of day. This should result in results more representative of a real house.

After that the relevance of electric off-peak heating will be investigated for the reference house as well as Design 2. Among that, the possibility of heating the domestic hot water with electricity in the off-peak period will be investigated. In addition, the potential savings due to supplying the houses with heat from electricity in the off-peak period will be investigated. An economic comparison between heating with direct electricity and investing in a heat pump will also be carried out, and the use of solar heating for the domestic hot water will also be investigated. Then the energy frame of the buildings will be investigated, and lastly the future possibilities in window technology will be investigated in regard to the possible window design and space heating demand in the future.

2. State of the Art

Window design in low energy class 2015 and 2020 dwellings

By Svend Svendsen and Lies Vanhoutteghem (2010) [4]

This article is a design guide which shows methods of achieving optimal window sizes and window distribution in a low energy house, in relation to thermal indoor environment, energy performance and daylight intake, with the use of simulation programs. It states that in low energy houses it is not as advantageous as previously believed to utilize large amounts of south facing window area in the attempt to take advantage of the solar gains, and that windows can be distributed more evenly across the facades.

It also demonstrates how it can be beneficial to merge small windows and place glazing area higher on the façade.

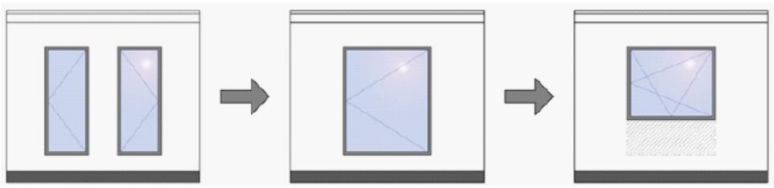


Figure 4 - possible ways to optimize the window design in a house [4]

As can be seen on figure 4, by merging small windows a lower heating demand can be achieved due to the reduction of frame area. Similarly, the amount of overheating can be reduced by reducing the amount of low glazing area, since low glazing area contributes less to the daylight factor in the room. These considerations will be taken into account when evaluating the window design and optimizing the daylight.

Reducing the energy consumption in window-wall assemblies by combining wide unsealed windows and tapered reveals

By Jeppe Szameitat and Svend Svendsen [23]

In order to achieve low heating demands, low energy buildings often utilize wall thicknesses in the excess of 600 mm, which can have a negative impact on the daylight intake in a building. This report investigates the advantages of using tapered reveals as a way to counteract the decrease of daylight intake as a result of the thick walls. Different angles and positions were investigated and it is interesting for this report as a way to achieve optimal daylight conditions while still utilizing a thick wall.

Mapping of innovation in building components

By Svend Svendsen et al. (2011) [2]

This report presents the possible innovation of building components in regard to low energy building complying with the 2020 low energy frame. The evaluation of possible development is based on information from Danish and international companies regarding the newest products, emerging as a result of previous research as well as a general tightening of energy requirements. This was relevant in this report regarding the expected performance of certain building components in the near future, for example in relation to the expected innovations regarding windows, where it provided an overview of different window types which could be considered relevant for a low energy house.

3. Simulation tools

In this report the programs WinDesign, Velux Daylight Visualizer and Sketchup is used in order to document the heating demand, overheating and the daylight conditions of the houses. This section will briefly describe these programs.

WinDesign

WinDesign is an Excel-based program that has been developed by the building department of the Technical University of Denmark. It utilizes requirements and methods from EN13790 [8] to conduct hourly calculations, and it is also capable of conducting room-based calculations. It works in steps: in Step 1, different sizes of windows can be defined where upon the net energy gain can be seen for different combinations of glazing and frames. In Step 2, the energy consumption of the windows is used in the seasonal calculation for different scenarios. In Step 3, the results from the hourly calculation can be seen for each room such as heating demand, cooling demand and hours of overheating.

Sketchup

Sketchup is a free 3D-modelling program with a wide range of uses and in this project it is utilized to manually model the house, its window geometry and the tapered reveals. As it was not possible to model the tapered reveals in Velux Daylight Visualizer walls, the house is instead modelled manually in Sketchup and then imported into Visualizer.

Velux Daylight Visualizer

Visualizer is a free program from Velux with the purpose of performing daylight calculations in a building. When a Sketchup model is imported, so are the surface materials, which can then be assigned different visual properties such as reflectance and transmittance. After simulation, a picture of either the whole building or a smaller section can be rendered to display e.g. luminance or daylight factor on a given plan height with the relevant contour lines.

4. Requirements for indoor environment and energy

People spend 90% of their time indoor, and it is therefore important to set up a list of requirements that will ensure a healthy and pleasant indoor environment. In this section, the different requirements for the indoor environment will be established and explained.

Daylight requirement

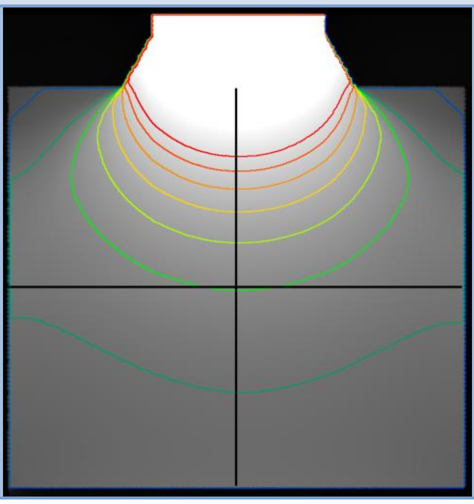
A good intake and distribution of daylight is a necessity, in order to create a bright and stimulating indoor environment. It is therefore important to try and achieve a high daylight factor, and it is also very important that the occupants can get a good view out. The Danish Building Regulation can be seen as somewhat vague on this point, stating that rooms should be well lit, should avoid unnecessary overheating and glare, and that this can be deemed acceptable for primary rooms if the glass-to-floor ratio is 10%, although this requirement is increased to 15% in the 2020 version of the Danish Building Regulation. Both glass-to-floor requirements are based on the use of at least a 75% light transmittance of the glass and should be adjusted proportionally if a lower transmittance is used.

There are different ways to evaluate the daylight conditions in a room, such as evaluating the center daylight factor or an average of the whole room, but here are some problems with these. For example, even though a room has a high daylight factor in the center, the back wall and corners could still be very dark. Measuring the average daylight factor can be unreliable, as just moving the measured area slightly toward the window sill will increase the overall daylight factor, thus creating a false representation of the average daylight factor. Therefore these concepts are not used to evaluate the daylight conditions in this project. Instead it is chosen to abide by some stricter, more thorough daylight requirements, consisting of three requirements which have been developed by Matilde Grøn and Susanne Roed [20]:

- A daylight factor of at least 3 % in the middle of the room.
- A daylight factor of at least 2 % on a line across the middle of the room.
- A daylight factor of at least 1% elsewhere in the room

Meeting these three requirements will ensure a high quality of well distributed daylight in a room. An example of a room optimized for these requirements can be seen on table 1.

Table 1 – an example of a room complying with the daylight requirements

Room	Nomenclature
	

It can be seen that the requirements are an effective way to ensure a good distribution of daylight. The only place where the requirement is not met is in the corner nooks, where the daylight factor will drop below 1%. This can still be considered acceptable, since it is very difficult to completely avoid dark corners beside the window without skylights. If it occurred near the back wall or in the back corners, then it would be unacceptable. In general it can be said that following these three requirements, the evaluation of daylight should become more reliable, and in general the daylight conditions in the room are held to a higher and more specific standard than is required by regulation.

Thermal indoor environment

While large windows might be desirable from a daylight point of view, one downside to this is that too large windows can increase the risk of overheating in the room. Therefore it is important to have a good thermal indoor environment - to avoid negative effects such as headache, concentration difficulties and general discomfort. Therefore the room temperature should neither be too hot nor too cold, which is why the following requirements are implemented from DS EN 15251 Class II [24].

- Indoor operative temperature range: 20 - 26 °C.
- No more than 100 hours above 26 °C
- No more than 25 hours above 27 °C

According to [2], one way to reduce the risk of overheating is to reduce the amount of glazing below a certain height, such as the working plane height of 0.8m, since low window area contribute less to the daylight conditions.

Ventilation requirement

In order to ensure a certain air quality without too many pollutants, it is important to supply fresh air with natural or mechanical ventilation. The Danish Building Regulations have set up the following requirements for ventilation in houses, as seen in table 2.

Table 2 – The different ventilation requirements from the building regulation.

Requirement 1		Requirement 2	
Minimum ventilation for heated floor area	0.3 l/(s m^2)	Kitchen exhaust	20 l/s
		Bath exhaust	15 l/s
		Toilet/utility exhaust	10 l/s

In addition to the ventilation rates, according to the Danish Building Regulation 2020, the requirements for the ventilation system itself is as follows:

- Heat recovery systems for residential buildings must have an efficiency of no less than 85%
- The specific fan power for ventilation in residential building must not exceed 800 J/m^3

Energy frame

The reference house is a house which is designed to comply with low energy class 2020, which as can be seen on Table 3 corresponds to an energy frame of 20 $\frac{kWh}{m^2}$.

Table 3 – Energy frames and primary energy factors

Year	Energy frame	Electricity factor	Heat factor
Danish Building Regulation 2010	$52.5\frac{kWh}{m^2}+\frac{1650}{A}$	2.5	1
Energy Class 2015	$30.0\frac{kWh}{m^2}+\frac{1000}{A}$	2.5	0.8
Energy Class 2020	$20.0\ \frac{kWh}{m^2}$	1.8	0.6

Table 3 shows that the energy frames and corresponding primary energy factors for electricity, district heating and natural gas. It can be seen that the primary energy factors do decrease somewhat, which helps to reach the low energy frame of 20 kWh/m^2. However, the factor for electricity is still three times higher than for heat, which makes it much more difficult for an electrically heated building to abide by the building code.

Therefore, the reference house for this report which was originally designed to be abide by energy class 2020 using the primary factor for heat of 0.6, which means it will no longer abide by energy class 2020 if it is heated with electricity.

It can be said that the energy frame is not the focus of this project, but it means that it is not legal to construct the reference house with electrical heating in the year 2020. Given the assumption that heating with electricity can be supplied in a way that is not harmful for the electricity grid by only consuming in the off-peak period, it can be said that the validity of the electricity factor of 1.8 is perhaps not entirely reasonable in regard to well insulated houses with a low heating demand. It can therefore be argued that some kind of exception to the energy frame would be necessary in order for a house heated by electricity only in the off-peak period to be able to comply with energy class 2020.

5. Reference house

The reference house of this project is based on a 159 m^2 type house from Lind & Risør, the sketch of which can be seen on figure 5:

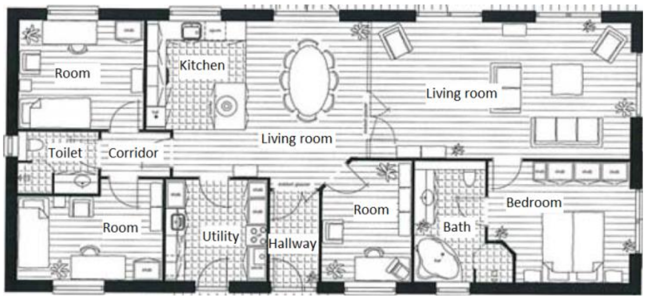


Figure 5 – Sketch of the ground plan of the house.

This house was optimized for an energy frame of 20 $\frac{kWh}{m^2 year}$ by Matilde Grøn and Susanne Roed [20], and it is this optimized version that serves as the reference house for this project. In the following a short description of the optimized building components and systems is given.

Building envelope

The envelope parts and insulation thicknesses are as follows.

Table 4 – The wall, roof and floor construction of the reference house

Wall	Thickness	λ	R
	m	W/(m K)	m2K/W
			0.04
Plaster	0.010	0.460	0.02
Lightweight Concrete	0.050	0.170	0.29
Insulation	**0.400**	**0.032**	**12.50**
Lightweight Concrete	0.100	0.170	0.59
			0.13
Total	0.560		13.57
		U-value	**0.074**

Roof	Thickness	λ	R
	m	W/(mK)	m^2K/W
			0.04
Roof and roof space	-	-	0.30
Insulation	**1.000**	**0.040**	**25.00**
Wooden parts	0.025	-	0.16
Plasterboard	0.026	0.250	0.10
			0.1
Total	1.051		25.70
		U-value	**0.039**

Floor	Thickness	λ	R
	m	W/(m K)	m^2K/W
			1.5
Lightweight Concrete	0.100	1.30	0.08
Insulation	**0.750**	**0.036**	**20.83**
Singles 32/64	0.150	0.88	0.17
			0.17
Total	1.000		22.75
		U-value	**0.044**

As can be seen on table 4, the exterior wall has a thickness of 560 mm and consists of a somewhat heavy concrete construction. The wooden frame roof has 1000 mm of insulation and the floor consists of a slab of lightweight concrete, 750 mm insulation and a capillary layer.

The values of the line losses have been established according to DS418 [25] as follows:

Table 5 – Line loss values from DS418

	Line loss [W/mK]
Wall/roof	-0.06
Vall/floor	0.13
Wall/windows	0.01
Corner	-0.06

The line loss for the corners is found from Annex M in DS 418. With continuous insulation throughout the outside bending corner, the value negative and is therefore a compensation for using outside measures, which would otherwise lead to an overestimated heat loss due to increased transmission areas. Similarly, the line loss from Wall/roof joint is found to be negative due to outside measures, with the assumption that the insulation in the roof is not cut off.

Mechanical ventilation

The reference house utilizes a balanced mechanical ventilation system supplied by a Nilan Comfort 300 with a specific fan power of 800 J/m^3 and a heat recovery efficiency of 91% with bypass, in order to supply fresh air with low ventilation loss and electricity consumption. The two requirements from the Danish Building code yield the following ventilation rates:

Table 6 – The ventilation requirements according to the building regulation

Requirement 1		Requirement 2	
Minimum ventilation for heated floor area	0.3 l/(s m^2)	Kitchen exhaust	20 l/s
		Bath exhaust	15 l/s
		Toilet/utility exhaust	10 l/s
Total	50.2 l/s	Total	**60 l/s**

It can be seen that requirement 2 is the dimensioning one, at 60 l/s, but that does not necessarily mean that the ventilation system should exchange air at 60 l/s at all times, only that it should be able to increase the exhaust rates in the given rooms to the given amount.

Distribution of ventilation

In addition to finding the required ventilation rate, it is important to decide how this ventilation should be distributed between the rooms. According to the Danish building code, transfer of air must not occur from a polluted room to a less polluted room. This makes sense as it would be unfortunate if the damp kitchen air seeped into the neighboring bedroom and it is therefore also important to decide from which rooms the air should be exhausted and supplied to, in addition to the actual rates. One way to do this is to let fresh air be supplied in the primary rooms such as living rooms and let it be exhausted from secondary rooms, which would create a flow as illustrated on figure 6.

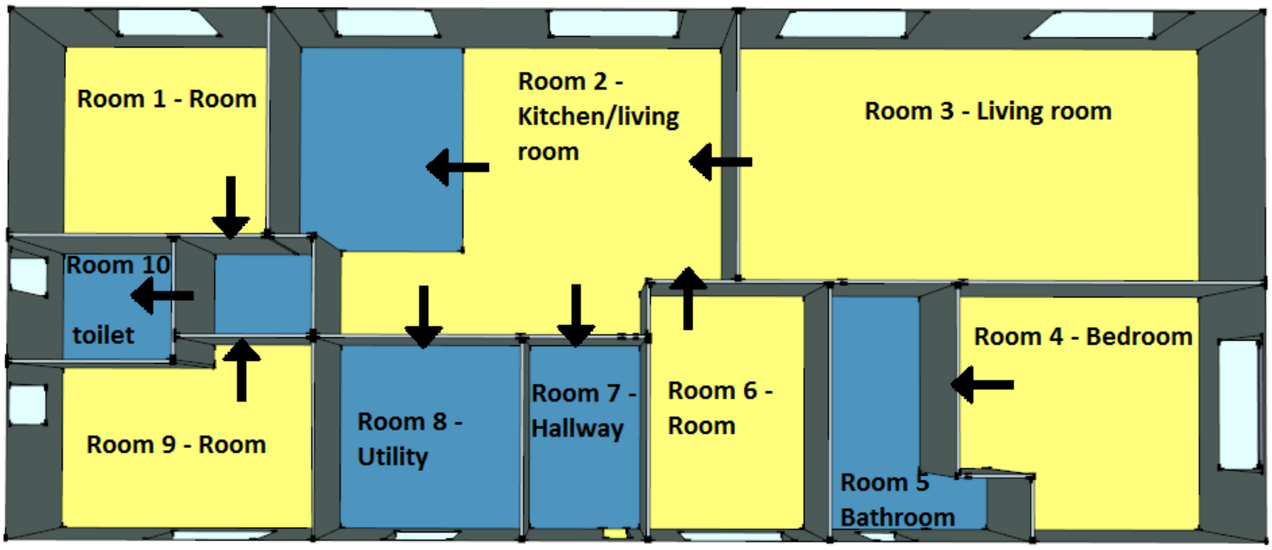


Figure 6 – The ventilation flow for the house, with blue marking rooms with exhaust and yellow marking rooms with supply

As can be seen, by supplying in primary rooms and exhausting in secondary rooms, the fresh air is supplied where occupants are most likely present.

A next step is to decide the actual supply rates of each room. In the reference house this is done by weighing each room according to the assumed relative occupancy [20].

Table 7 – The assumed occupancy and corresponding air supply rate

	Assumed occupancy	Supply rate
	[h/day]	[l/s]
Room 1 – Room	15	12.1
Room 2 – Living room/kitchen	12	9.7
Room 3 – Living room	12	9.7
Room 4 – Bedroom	18	14.6
Room 6 – Small room	4	3.2
Room 9 – Room	15	12.1

As can be seen on table 7, a higher priority has been given to rooms where occupants are present and sleeping, which should help to achieve a higher indoor air quality. This method stands in contrast to for example assigning supply air according to room area, which would have given a higher supply air rate to the large living rooms, thus perhaps neglecting the bedrooms where higher concentrations of bio effluents can build up at night due to one or more occupants sleeping in a bedroom a night.

One thing is how the air is supplied and exhausted from the different rooms; another thing is how this is implemented into a program like WinDesign, since it uses the ventilation only for thermal purposes of the calculations. It is therefore important to implement the ventilation in WinDesign with the thermal aspect in mind. This makes the exhaust unnecessary, as the actual thermal impact of it is insignificant. This is due to the assumption that the ventilation is balanced and the fresh air is supplied into the primary rooms at a lower temperature, but the air that is flowing from the primary to the secondary room to be exhausted will likely have reached room temperature. Therefore only the supply ventilation is implemented into WinDesign.

Venting

The venting rates in each room is estimated according to SBi-213 [11], which states that for houses with manually controlled windows, the venting can be estimated to 0.9 l/(s m^2) or approximately 1.3h^{-1}. This can be proportionally increased if the effective opening area is larger than 1.5% of the floor area for cross ventilation or 4% for single-sided window placement. This means that the drafts created by opening windows on several facades allow for a much higher venting rate than if e.g. only a single window is opened in a room. The effective opening area is assumed to be 30% and the exterior doors are assumed closed.

Table 8 – Estimated venting rates according to SBi-213

Venting	Estimated venting [h^{-1}]	
	Single-sided opening	Cross ventilation
1 – Room	2.0	5.4
2 – Living room/kitchen	1.9	5.0
3 – Living room	2.1	5.6
4 - Bedroom	1.7	4.5
5 – Bath	1.2	3.2
6 – Room	2.6	6.9
7 – Hallway	1.5	4.0
8 – Utility	1.8	4.8
9 – Room	2.9	7.6
10 - Bathroom	2.2	5.9

As can be seen on table 8, the estimated venting rates are greater if cross-opening is achieved; either by opening two windows on two different facades of a corner room, or by opening interior doors between rooms, allowing for a higher venting air flow.

Room based calculation

Building simulation might be performed by considering the whole building as a single thermal zone, and this might yield favorable results with regard to e.g. overheating and heating demand. This is because such simulations might hide potential problems such as e.g. overheating in a south room by assuming the entire building as one thermal zone.

To avoid this, this study utilizes room based simulation in WinDesign i.e. the heating demand and overheating hours are calculated for each room separately, and the total heating demand of the building is then found from the weighted average in each room. This will yield slightly pessimistic results, as in reality, the rooms will exchange heat to some degree, but it is much preferable since it is better at highlighting potential problems in the design. As an addition, individual ventilation and venting is also utilized in WinDesign, which is only for advanced users.

Internal load

One very important factor in the calculation of heating demand is the internal heat load. A value of 5 W/m^2 is common, which according to SBi-213 [11] accounts for 1.5 W/m^2 from occupants and 3.5 W/m^2 from appliances.

For this study, a lower value of 3 W/m^2 is assumed, which can be seen as more realistic for a house that is meant to be correspond with the climate goals of 2035. This is due the likelihood that future appliances will be more energy efficient; hence less of their electricity consumption will be spent on heat. This is a good thing, since the emitted heat from appliances can not necessarily always be utilized well, but a value of 3 W/m^2 does increase the heating demand by a noticeable amount compared to using 5 W/m^2.

Preliminary results

This chapter introduces the preliminary results of the reference house from with regard to the annual heating demand, the heating demand on a cold winter day and the concrete temperature rise due to the storage of heat for the whole day. The set points used will be 20 °C for heating and 23 °C for venting.

Annual heating demand

The annual heating demand is found in WinDesign.

Table 9 – The heating demand and overheating hours for the reference house

Results			Heating demand	Overheating hours
Room	Orientation	Room type	[kWh/m^2 year]	$T_i > 26$ °C
Room 1	South	Room	6.6	72
Room 2	South	Living room/kitchen	1.7	63
Room 3	South	Living room	3.0	63
Room 4	West	Bedroom	16.5	40
Room 5	North	Bathroom	6.6	0
Room 6	North	Room	9.2	24
Room 7	North	Hallway	28.9	0
Room 8	North	Utility	6.4	2
Room 9	North	Room	17.9	25
Room 10	East	Bathroom	7.3	211
		Total - weighed	**8.1**	

As can be seen on table 9, the reference house simulated with room-based calculation in WinDesign and an internal load of 3 W/m^2 yields a heating demand of $8.1\,\frac{kWh}{m^2 year}$. It can be seen that overheating is not an immediate problem, as the amount of hours above 26 °C is below the limit of 100 for all the primary rooms. This is because it was designed from [20] to have a good indoor environment. Room 10 has 211 hours above 26 °C, which can be seen as acceptable since it is a bathroom, hence a secondary room and not subject to the same requirements due to people not spending a lot of time there.

Heating demand – cold winter day

As an addition to the yearly heating demand, is it also important to determine the daily heating demand of a cold winter day, since this is what determines how large a strain is put on the electricity grid by the electric heating.

In order to find the most demanding day in terms of heating demand, first the days with the highest heating demand are found for each of the rooms. For room 1, the 10 worst days along with the corresponding heating demand can be seen on table 10.

Table 10 – The ten days with the highest heating demand over a period of 24 hours - south

Daily heating demand			
Room 1		South room	
Rank	[kWh]	Month	Day
1	2.8	12	21
2	2.6	12	22
3	2.6	12	25
4	2.4	1	19
5	2.4	1	8
6	2.3	12	20
7	2.3	12	23
8	2.3	12	24
9	2.2	12	26
10	2.0	12	27

It can be seen on table 10 that the worst day in terms of heating demand is the 21st of December with a demand of 2.8 kWh. Further investigations showed that this is characteristic for south rooms but different from the north rooms, as is seen on table 11.

Table 11 - The ten days with the highest heating demand over a period of 24 hours - north

Daily heating demand			
Room 9		North room	
Rank	[kWh]	Month	Day
1	4.2	1	6
2	4.1	1	7
3	3.9	1	8
4	3.8	12	21
5	3.4	1	21
6	3.3	12	22
7	3.2	12	24
8	3.2	2	4
9	3.2	1	18
10	3.1	12	25

The days with the highest heating demand more often occur in January for south rooms, as opposed to the north rooms, where they occur in December.

One reason for this can be seen by investigating the Design Reference Year (DRY) hourly data that WinDesign utilizes for the simulation. Below, the worst days in January and December are compared in terms in terms of exterior temperature and total solar radiation.

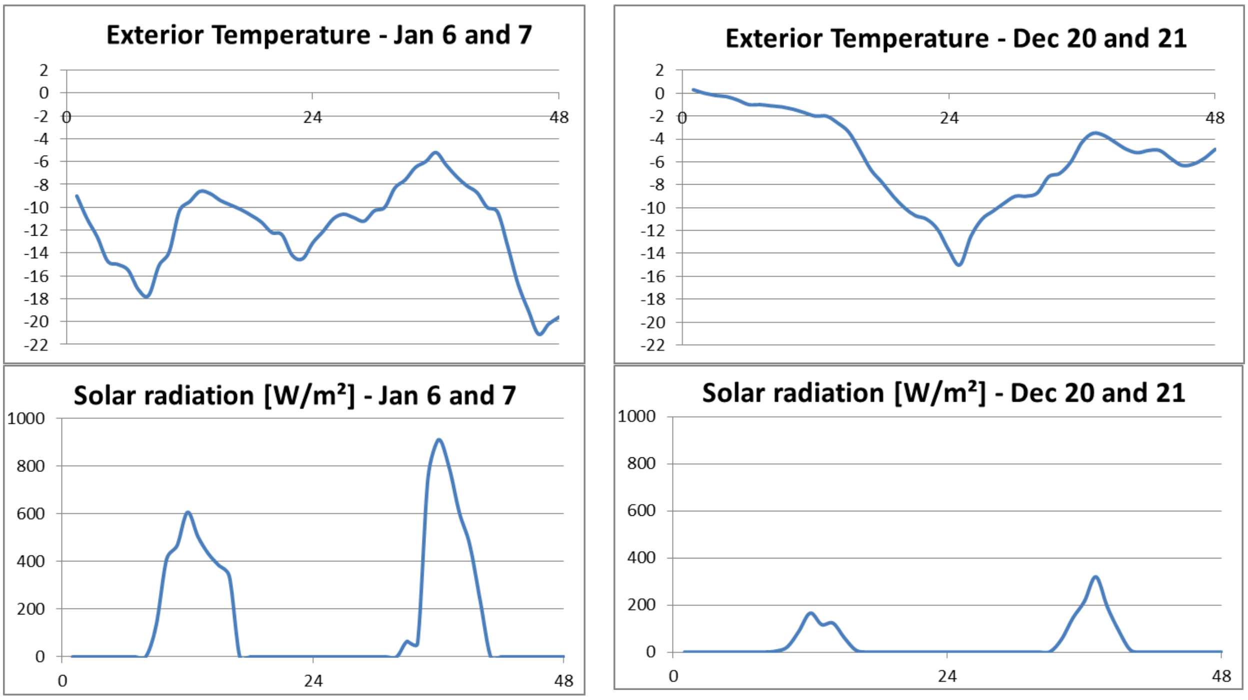


Figure 7 – variations of exterior temperature and solar radiation for periods in December and January

As can be seen on figure 7, the temperatures in January days are lower than the temperatures in December. In contrast, the solar radiation is higher in January than in December.

South facing rooms have greater access to solar gains, which explains why a south facing rooms has a higher heating demand in December, when the solar gains are much lower, even though the exterior temperatures are higher. Since the north facing rooms do not have the same access to solar gains, their heating demand is more influenced by the exterior temperature. Accordingly, they generally have a larger heating demand in the cold January days.

In terms of the viability of heating with electricity in the off-peak period between 06:00, it is interesting to know which days are the worst in terms of heating demand for the house as a whole. This is found by summing the heating demand of each room for each day, see table 12.

Table 12 – The ten days with the highest heating demand for the whole house

Daily heating demand			
Entire house			
Rank	[kWh]	Month	Day
1	24.7	12	21
2	21.7	12	22
3	21.4	12	25
4	20.0	12	24
5	19.9	12	23
6	19.3	1	8
7	19.2	12	20
8	18.9	1	19
9	17.8	12	26
10	17.6	1	7

It can be seen on table 12 that the worst day in terms of heating demand for the entire house is the 21st of December with a heating demand of 24.7 kWh. This could be due to the fact that it was the most demanding day for south facing rooms, which take up a larger area of the house than the north facing rooms. In order to supply the 24.7 kWh of heating with electricity for six hours during the night, it requires a heating power of $\frac{24.7\ kWh}{6h} = 4.1\ kW$.

In order to put this into perspective, an example of the average daily variation in electricity consumption for appliances of a regular single family house in Austria can be seen as the blue line on figure 8.

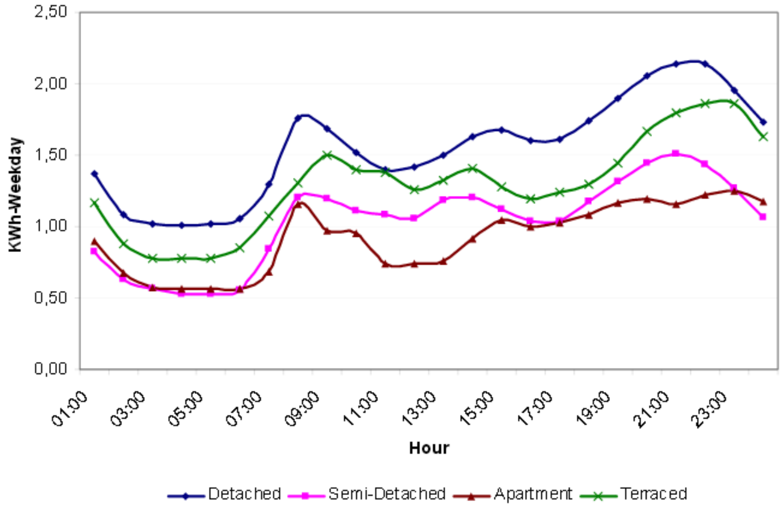


Figure 8 – The daily variation in electricity consumption measured in different houses in Austria [5]

As can be seen, the consumption is in the excess of 1 kWh during the night and approximately 1.75 kWh during the day. In the light of this, an additional consumption of 4.1 kW can perhaps seem like a not insignificant additional consumption to have during the night. Still, the electric consumption for general appliances cannot be directly compared to an electric heating demand. It can be seen from figure 8 that the consumption for appliances is lowest during the night. Therefore it could it could be more beneficial to utilize electric heating during the off-peak period of the night where the demand is otherwise lowest, in order to reduce the strain on the electric grid in general.

It could be important to see what sort of strain the off-peak electric heating would have on the grid as a whole if it was utilized by a large number of houses. In order to do so, figure 9 illustrates the average daily variation of the Danish electricity consumption.

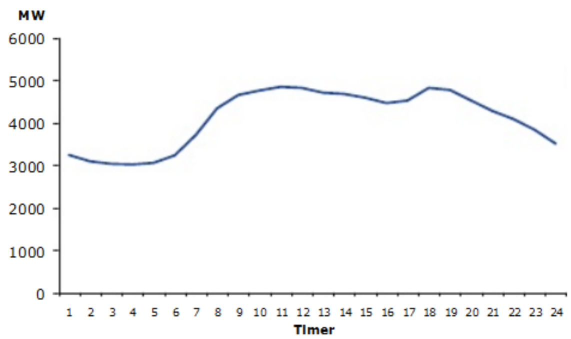


Figure 9 – The average daily variation of the Danish electricity consumption [3]

As can be seen on Figure 9, the difference between consumption at night and day in Denmark is approximately 1800 MW. Therefore, a reasonable amount of strain can perhaps be defined as not increasing the national night electricity consumption above the daily consumption. By that definition, assuming no other inherent national increase in night consumption, the grid could feasibly support $\frac{1800\ MW}{4.1\frac{kW}{dwelling}} = 437{,}000\ houses$

This can be seen in relation to numbers from Danish Statistics, according to which there were 700,000 single family detached homes in Denmark in 2013 without access to district heating, which means possibly 60% of the houses without access to district heating could feasibly be heated electrically at night if they were low energy buildings. This is a simplistic assumption, but it illustrates that from a national grid strain point of view, the night heating method seems viable at first glance.

There are additional factors to take into consideration when evaluating the viability of the off-peak electric heating. For example, according to Our Future Energy [1], it the ambition of the Danish government to achieve an overall more intelligent electricity grid, and a part of this is to implement intelligent electric meters and dynamic tariffs. This is beneficial with regard to the potential of electricity heating in the night for low energy buildings, but it also means that in the future there might not be the same low off-peaks in the national electric consumption. This could be a factor as intelligent and flexible systems start to take advantage of the cheaper electricity at night.

It is difficult to predict the specific conditions of e.g. the year 2035, but it can be said that it is unlikely that low energy houses heated with off-peak electricity will have a significant impact on the grid as a whole unless a very large amount of them is built. The increase of wind power towards approximately 65% in the year 2030 will perhaps yield a more inflexible system in general, which could increase the potential of off-peak electric heating.

Concrete temperature rise

In addition to the actual daily heating demand and the strain on the grid system, it is also important to determine which temperature rise the night heating towards the whole day will lead to in the concrete slab and subsequently in the rooms. The main concern is that heating only during the night will lead to too high room temperatures. This is investigated in the following.

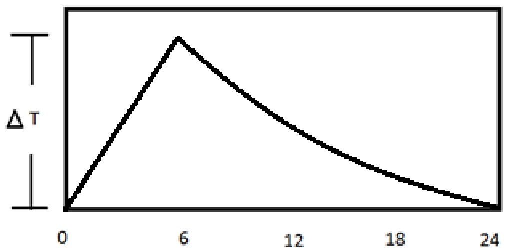


Figure 10 – A sketch showing the possible variation in the temperature of the concrete slab due to off-peak night heating

As can be seen on figure 10, if the heating occurs in the concrete slab between 00:00 and 06:00, the highest temperature rise will occur at 06:00, at which point the concrete should have stored the necessary heat for the rest of the day. Therefore, the temperature rise in the slab is calculated from the heating demand of the remaining 18 hours of the day. This is done under the assumption that $T_{concrete} = T_{air,room}$, which is assumed to be reasonable if the floor cover is thin, allowing the transfer of heat from the concrete to the room, given the fact that it is a very well insulated building.

An example of the results regarding temperature rise in the concrete at 06:00 can be seen in table 13 for a north facing room.

Table 13 – The estimated temperature rise in the concrete slab as a result of the heating in the off-peak period of 00:00-06:00 and the corresponding number of occurring days, with a concrete slab of 10 cm in thickness

Room 9	North room				
Temperature rise [K]	0.5	1	1.5	2	2.5
Days each year	132	93	41	13	2

As can be seen from table 13, with a concrete slab of 10 cm in thickness, the highest temperature rise is 2.5 K, which occurs two days each year, while an increase of 0.5 K happens 132 days corresponding to roughly one third of the year.

In order to better compare the different rooms, it is chosen to dismiss temperature rises which occur less than five times each year. Thereby each room can be represented with a single number, representing the highest temperature increase which the occupants will experience more than five times each year. For room 9 from table 13, this would be 2 K.

Table 14 – Maximum temperature rise in the concrete for different rooms occurring more than five days each year

	Orientation	Room type	Temperature rise [K]
Room 1	South	Room	1.5
Room 2	South	Living room/kitchen	0.5
Room 3	South	Living room	0.5
Room 4	West	Bedroom	2
Room 5	North	Bath	1
Room 6	North	Room	1
Room 7	North	Hallway	2.5
Room 8	North	Utility	1
Room 9	North	Room	2
Room 10	East	Bath	1

As can be seen on table 14, the highest temperature rise occurs in room 7, which is the hallway, so regardless of whether or not the temperature is acceptable; it is perhaps not a significant problem if it only happens in the hallway, where occupants are only present for short periods of time. It can be seen that the night heating towards the south facing living rooms yield the lowest temperature rise of only 0.5 K. This is due to the higher solar gains and subsequent lower heating demands of these rooms, which is fortunate since these are primary rooms where occupants often spend time.

On the other hand the master bedroom (room 4) and room 9, which could be a children's bedroom, both see a temperature increase of 2 K. Depending on the viewpoint, this can either be a problem for a bedroom or not so much. On one side, occupants generally prefer a lower interior temperature when sleeping, which contrasts with the idea of off-peak night heating. On the other side, this also means that heating is perhaps not as necessary in the bedroom, in which case there is perhaps not much reason to worry about the night heating in Room 4. Slightly more worrying is room 9, which could be a children's bedroom. The problem here is that the occupant might not be happy about the higher temperatures in the night and in the morning while sleeping. A lower room temperature in general is perhaps not a solution here, since that same occupant will likely occupy the room during the day or in the evening, where a lower temperature of e.g. 17 °C for sleeping purposes would not be appreciated.

This inflexibility can be seen as a disadvantage of off-peak heating in bedrooms. One way to diminish this could be to implement a thicker concrete slab of e.g. 15 cm or 20 cm, which could reduce the temperature increase in the concrete. This is illustrated in table 15.

Table 15 – Maximum temperature rise for the different rooms, with 15 cm and 20 cm concrete slabs

	Orientation	Room type	Temperature rise 15 cm concrete [K]	Temperature rise 20 cm concrete [K]
Room 1	South	Room	1	0.5
Room 2	South	Living room/kitchen	0	0
Room 3	South	Living room	0.5	0
Room 4	West	Bedroom	1	1
Room 5	North	Bath	0.5	0.5
Room 6	North	Room	0.5	0.5
Room 7	North	Hallway	1.5	1
Room 8	North	Utility	0.5	0.5
Room 9	North	Room	1.5	1
Room 10	East	Bath	0.5	0.5

As can be seen, with a 20 cm concrete slab the temperature rise experienced by the occupants more than 5 days each year is reduced to 0 or 0.5 K for most rooms and 1 K for the teenage bedroom, room 9. So it can be seen that the temperature rise can be diminished. Sleeping with an open window would not solve the problem since it would cause a large heat loss and result in inadequate heating during the day if no additional heating is supplied after the off-peak period.

With a 20 cm concrete slab, the sleeping temperature of the teenage bedroom would be 21 °C for a few days, with a heating set-point of 20 °C, and closer to 20.5 °C on most days in the heating season, which is not optimal for sleeping for all occupants, but perhaps not a large problem overall, as it can potentially be solved by sleeping with a thinner duvet.

The indication from these preliminary results regarding strain on the electricity grid and temperature rise in the concrete is that off-peak heating with electricity is potentially feasible.

6. Preliminary examination of daylight

Now that the reference house has been established, with the indication that night heating is feasible the next step is to try and develop a house with a lower heating demand that could potentially be even more accommodating towards electric off-peak heating. However, first some preliminary examinations of the daylight conditions in the rooms will be carried out in order to try and estimate what is possible to ensure enough daylight access, in regard to wall thicknesses, tapered reveals etc. All tests have been carried out in Velux Daylight Visualizer with the default surface parameters as indicated in table 16.

Table 16 – Surface properties for the daylight simulations

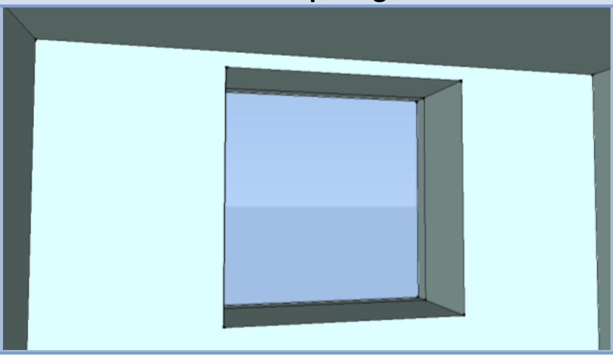
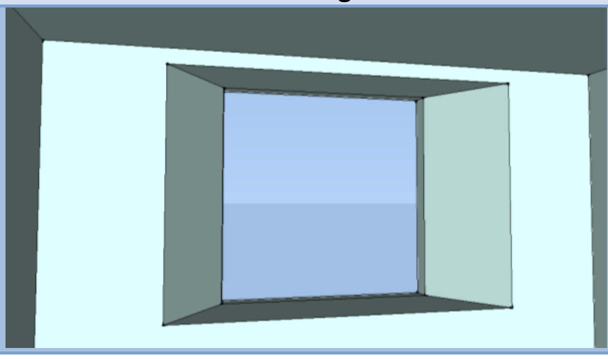
Material	Reflectance
White paint	0.84
Wooden floor	0.84
External ground	0.20

The Scanglas triple layer glazing used in the reference house has a light transmittance of 71%, and will be used here as well.

Tapered reveals

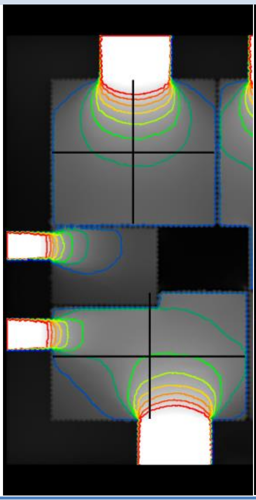
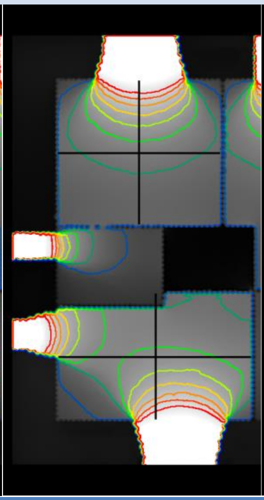
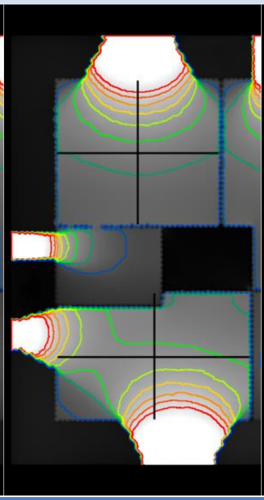
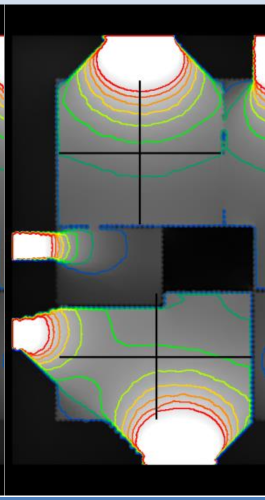
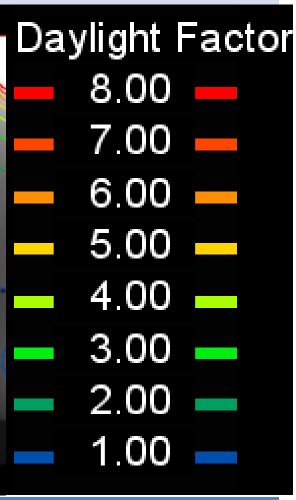
One way lower the heating demand of a house is to increase the insulation thickness, which results in the use of thicker external walls. The external walls of the reference house have a thickness of 560 mm, which is already thick, but perhaps even thicker walls could be utilized to reach very low energy consumption. This will also have a negative impact on the daylight conditions in the house. If the wall thickness is increased, there is also an inherent increase in the risk that the window might resemble a tunnel, depending on the window size. In addition, a thicker wall is more likely to obstruct the view out and it will also reduce the intake of daylight to some degree. One way to alleviate this problem can be to use tapered reveals, see table 17.

Table 17 – Visual comparison between regular and tapered reveals, for a 800 mm wall

No tapering	30° angle
	

As can be seen from table 17, by utilizing tapered reveals, the tunnel effect of the window is somewhat reduced. Neither the lower or upper parts of the wall have been tapered, which is because in the top there is little space for it and it perhaps would not help out much. In the bottom, it would be convenient for the occupants to be able to place potted plants in the window sill, so the walls were not tapered there either. Overall it appears more open and allows for a better view out, which is why it can be interesting to also see how this affects the actual daylight distribution in the room for different angles. In order to perform these preliminary tests, two representative rooms, room 1 and 9 from the reference house are used in order to easier compare the results.

Table 18 – Comparison of daylight intake for different reveal angles, on a 1000 mm wall

Reveal angle				
0°	**15°**	**30°**	**45°**	**Nomenclature**
				

As can be seen on table 18, an angle of 15° has a significant impact of the spreading of daylight in the room. At a 30° angle, the 2% contour line reaches from wall to wall across the middle.

It can be seen that the tapered reveals have a positive impact on the daylight distribution to the sides. Therefore they are useful to meet the second and third daylight criteria (see chapter 4) of 2% across the middle of the room and 1% elsewhere. They have less of an impact on the actual depth of the daylight and the first criterion of 3% in the center of the room.

With regards to the choice of reveal angle, it can be seen that the improvement from 30° to 45° is somewhat diminished compared to the large improvement from 15 to 30°. Therefore, and also in order to avoid unnecessary removal of wall insulation, it is decided that 30° is a sufficient angle.

Overhang

Another interesting building geometry to test is the use of overhang. The original purpose of having an overhang is to protect the façade from the weather. In addition, large overhangs will also prevent overheating. However, this might also reduce the daylight availability. Consequently here it is tested if it is worth to reduce the overhang size in order to increase the daylight intake.

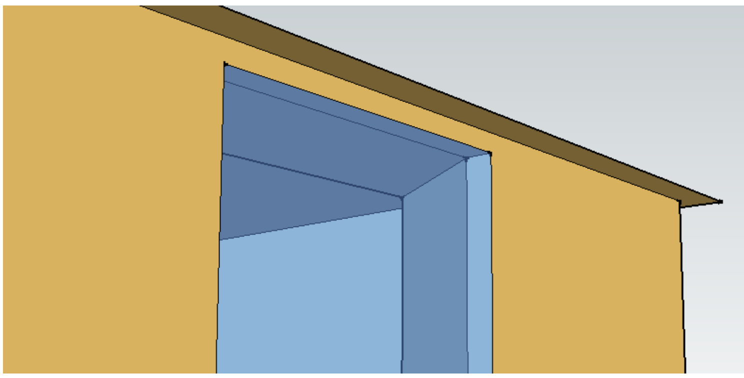
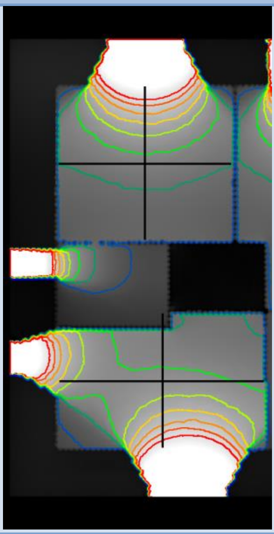
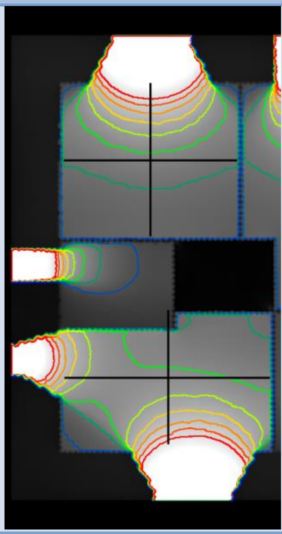
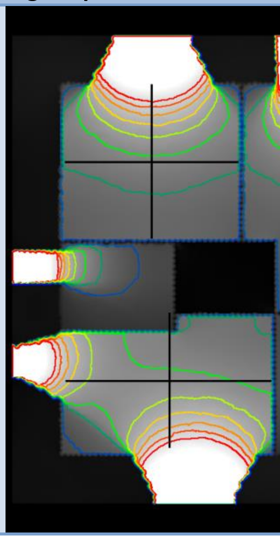
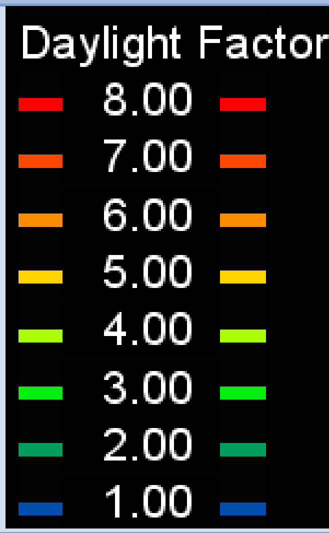


Figure 11 – the 200 mm overhang from the reference house, placed 100 mm above the windows

The original overhang, which can be seen on figure 11, is modeled along with a reduced overhang of 120 mm, and a 120 mm overhang placed higher above the window.

Table 19 – Comparison of daylight results from different overhangs

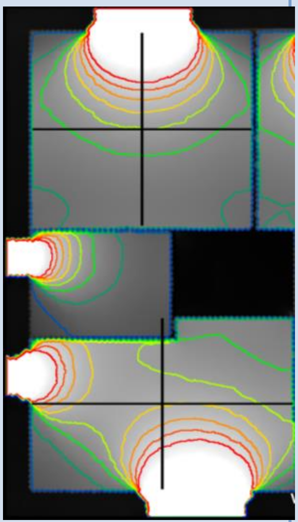
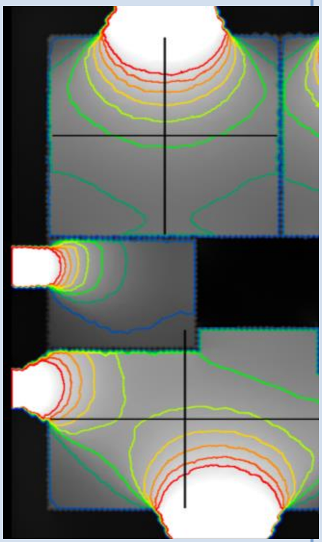
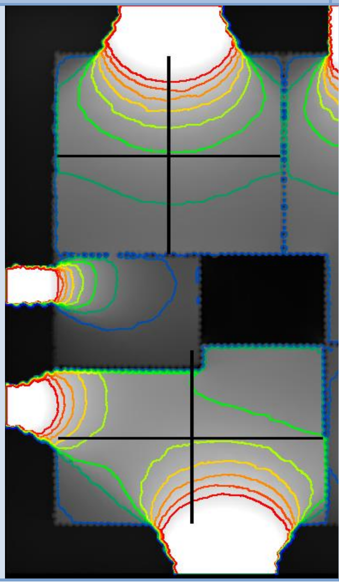
Overhang			
Original overhang	**Reduced overhang to 120 mm**	**Reduced overhang to 120 mm and placed at a higher position**	**Nomenclature**
			

From table 19 it can be seen that the reduction overhand size has little impact on the daylight conditions in the rooms. This can be due to the fact that the original overhang is already somewhat small and it is decided not to decrease the size further.

Wall thickness

One of the more important design parameters in a building is the wall thickness, which can have a significant influence on both the daylight conditions and the heating demand of a building. Since it could be interesting to develop a house with a lower heating demand than the reference house in order to perhaps better accommodate electric off-peak heating, is interesting to test different wall thicknesses and their influences on the daylight. Results of the investigations are illustrated in table 20.

Table 20 – Comparison between daylight intakes of different wall thicknesses

<table>
<tr><th colspan="4">Wall thickness</th></tr>
<tr><th>400 mm</th><th>600 mm</th><th>800 mm</th><th>Nomenclature</th></tr>
<tr><td></td><td></td><td></td><td>
</td></tr>
</table>

It can be seen that although the tapered reveals help reduce some of the negative effects of a thick wall and help achieve a better distribution of daylight across the room width, the thickness still has a significant influence on penetration of daylight across the room depth; accordingly it mostly impacts the first daylight criterion 3% in the middle.

It can be seen on table 20 in the upper room that with the current window size of 1.6 x 1.6 m and light transmittance of 71%, the 400 mm wall achieves a center daylight factor of 4% while the 800 mm wall reaches 3 %, thus still complying with the first daylight criterion.

Window Width

Another interesting parameter is the window width. Three different window widths have been simulated for windows of 1.6 m in height in both the upper and lower room, see table 21.

Table 21 – Comparison between window widths

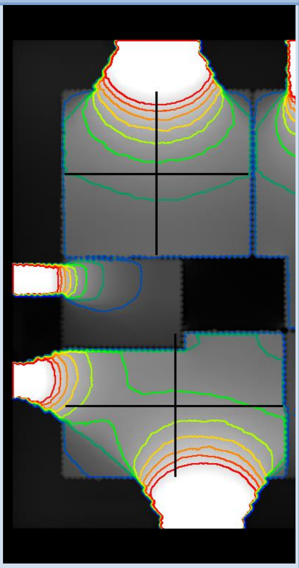
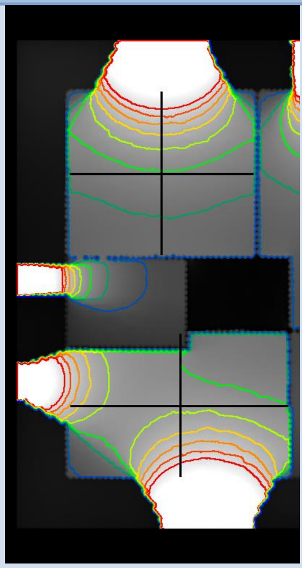
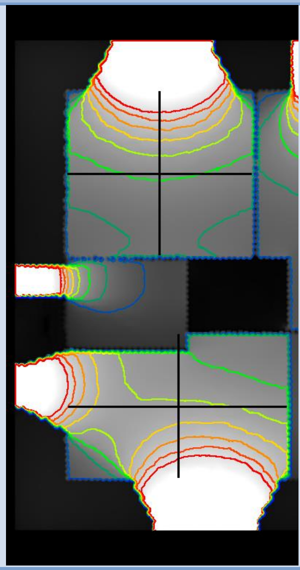
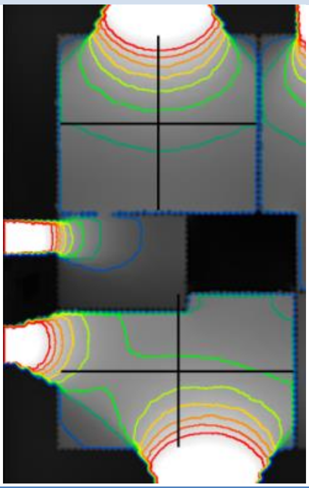
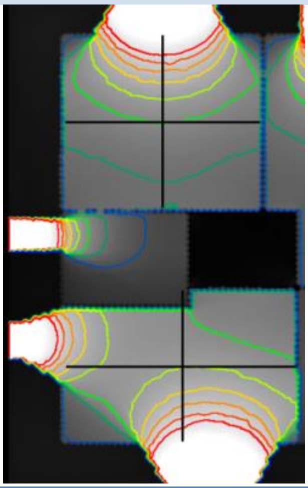
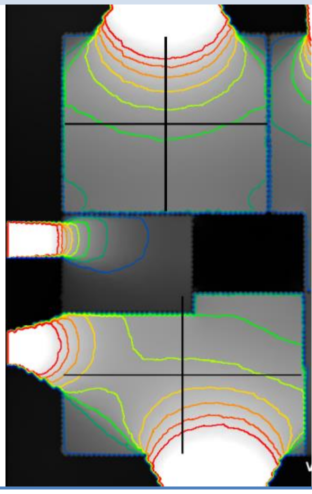
Window width			
1600 mm	**1800 mm**	**2000 mm**	**Nomenclature**
			

Table 21 shows that, the higher widths have a positive impact on the daylight distribution across the room width. It also has an impact on the penetration of daylight across the room depth, as seen in the case where a window width of 2000 mm is used and the 2% contour line reaches all the way to the back of the room. Overall, it can be said that the increasing of the window width can be seen as a useful way to improve daylight.

Window height

Another way to improve the daylight could be to increase the window height. This has been done for three different window heights by adding the height to the top of the window.

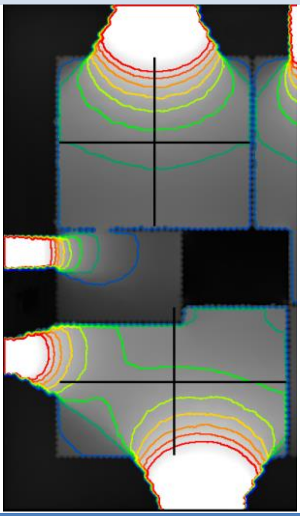
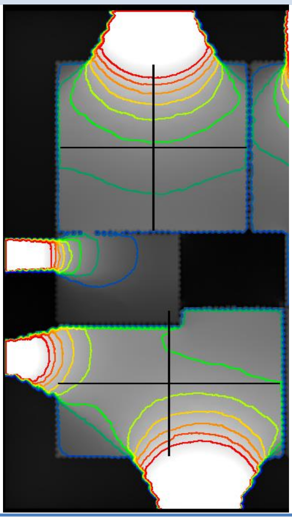
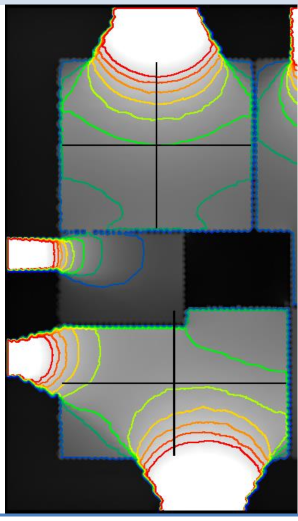
Table 22 – Comparison between different window heights, with the height added to the top of the window

Window height – added to the top of the window			
1600 mm	1800 mm	2000 mm	Nomenclature
			

It can be seen that the window height has a good influence on the distribution of daylight across both the room width and depth.

The same three window heights have been tested again – by adding the additional window area to the bottom of the window instead of at the top.

Table 23 – Comparison between different window heights, with the height added to the bottom of the window

Window height – added to the bottom of the window			
1600 mm	1800 mm	2000 mm	Nomenclature
			

It can be seen that the improvement in this scenario is less significant, with the 2000 mm case achieving only roughly the same as the 1800 mm case from table 22. This is not unsurprising; as the daylight factor is measured in a height of 850 mm and the default windows are placed 800 mm above the ground, hence a decrease of height to e.g. 600 mm is not going to increase the daylight as much as adding the same height to the top of the window. This corresponds well with the design guide, which states that it can be a good idea to reduce the amount of glass area with a low height and place windows higher in the façade instead, in order to achieve better daylight conditions.

Impact on heating demand

It is also interesting to know how the size of a window impacts the annual heating demand as well as the heating demand on the coldest day. To determine this, two identical generic 20 m^2 rooms with triple layer glazing were simulated in WinDesign, one with a south façade and the other with a north façade, each with both a 1.6 x 1.2 m window and a broader 1.6 x 1.6 m window.

Table 24 – Difference in the annual heating demand between a north and south room for two different window sizes

Heating demand [kWh/m² year]	1.6 x 1.2 m	1.6 x 1.6 m	Difference
South	1.47	1.53	4.1%
North	5.34	6.17	15.5%

It is seen that in regard to the annual heating demand, there is a difference in the relative impact of using a smaller window between a north and a south room. With a 15.5% difference between the window sizes for the north rooms, it can be indicated that the north facades are perhaps slightly more sensitive to window reductions than the south facades, with regards to the annual heating demand. The same comparison is carried out for the highest daily heating demand, occurring on a cold winter day, which determines the potential strain on the electric grid with electric night heating.

Heating demand – coldest day [Wh]	1.6 x 1.2 m	1.6 x 1.6 m	Difference
South	1610	1740	8.1%
North	2269	2532	11.6%

As is seen in table 25, the difference between north and south in regard to the maximum daily heating demand is less significant than for the annual heating demand, which could be due to the decrease in potential solar gains on a cold winter day.

It can be said that while the benefit of reducing the window size for a south room can seem insignificant in regard to annual heating demand, the corresponding decrease in maximum daily heating demand is perhaps greater. The difference between the benefit towards annual and daily heating demand in regard to window reduction is less significant for a north room, but altogether the benefit is larger than for the south room. This could be interesting in relation to achieving optimal daylight conditions without increasing the heating demand on a cold winter day.

7. Design 1

Now that the preliminary daylight examination has been carried out, the next step is to use these considerations in the attempt to design a house with a lower heating demand than the reference house. This design will be referred to as Design 1.

The wall thickness tests showed that while decreasing the wall thickness did have a positive impact on the daylight intake; it was possible with the default window size and glazing to satisfy all three daylight requirements with an 800 mm wall. It is therefore chosen for Design 1 to proceed with a wall thickness of 800 mm, since this should be an effective way of reducing the heating demand, hence reducing the strain on caused to the electric grid by electric night heating, and perhaps provide an increase to the overall viability of off-peak heating. Still, 800 mm is a very thick wall and it might not be desirable, but for now Design 1 will proceed with 800 mm.

In addition, Design 1 will introduce a new glazing type, along with a slightly more optimized window layout, as well as a general increase in insulation thicknesses. Therefore, Design 1 will be a more bulky house in general compared to the reference house, and if the results are found to be favorable in regard to the off-peak heating, a slimmer design can be considered later.

Glazing

The glazing used in the reference house and the preliminary examinations of daylight has been a triple layer glazing from Scanglas called Climatop Ultra N, with 90% argon filling. It is a well performing glazing with no obvious replacement, but the glazing is a highly important part of the building envelope, so it could be interesting to improve the glazing in order to perhaps achieve a lower heating demand.

Therefore, the report Mapping of innovation in building components [2] is utilized, where different glazings are compared for potential use in low energy buildings conforming to the 2020 requirements of 20 $\frac{kWh}{m^2 year}$. There are different types of laboratory products such as aerogel windows, but given the fact that the potential of these is somewhat speculative yet, they are perhaps not as interesting.

One type that looks interesting is a triple layer low-iron glazing with anti-reflective coating, and the properties can be seen in comparison with the current glazing on table 26.

Table 26 – Properties of the anti-reflective glazing and the glazing from Scanglas from the reference house

	Energy glazing 90% argon Triple layer	AR-coated low-iron glazing Triple layer
U_g [W/m²K]	0.6	0.5
g [%]	50	59
LT [%]	71	81

As can be seen on Table 26, the anti-reflective coated glazing is somewhat of an improvement: the U-value is lower, resulting in a lower heat loss, higher g-value allows for a higher utilization of solar gains, although also increases the risk of overheating, and the higher light transmittance allows for a higher daylight intake.

Building Envelope

In Design 1, the priority is to reach a lower heating demand, with a lessened regard for aesthetics or economy, and therefore the building envelope in this design will be somewhat bulky. The Preliminary Examination of Daylight showed that a wall thickness of 800 mm was perhaps feasible from a daylight standpoint with the use of tapered reveals of 30°. The new AR-coated glazing with a 10% higher light transmittance should help in this regard.

The roof insulation thickness in the reference house is 1 m, which is here increased to 1.5 m. This should be possible without much consequence except for of the aesthetic impression from the outside. The insulation thickness in the floor is increased from 750 mm to 1500 mm, which has no impact on the aesthetics but the problem in this regard is that the higher insulation thickness will perhaps increase the long time deformation, which might increase the risk of cracks, depending on the building joints and the compressive strength of the insulation. An overview of the changes can be seen on table 27.

Table 27 – Comparison between the U-value of the roof, wall and floor of the reference house and Design 1

	Reference house				Design 1			
Roof	**Roof**				**Roof**			
		Thickness	λ	R		Thickness	λ	R
		m	W/(m K)	m^2K/W		m	W/(m K)	m^2K/W
				0.04				0.04
	Roof space	-	-	0.30	Roof space	-	-	0.30
	Insulation	**1.000**	**0.040**	**25.00**	**Insulation**	**1.500**	**0.037**	**40.54**
	Wooden parts	0.025	-	0.16	Wooden parts	0.025	-	0.16
	Plasterboard	0.026	0.250	0.10	Plasterboard	0.026	0.250	0.10
				0.1				0.1
	Total	1.051		25.70	Total	1.551		41.24
			U-value	**0.039**			**U-value**	**0.024**
Wall	**Wall**				**Wall**			
		Thickness	λ	R		Thickness	λ	R
		m	W/(m K)	m^2K/W		m	W/(m K)	m^2K/W
				0.04				0.04
	Plaster	0.010	0.460	0.02	Plaster	0.010	0.460	0.02
	Light Concrete	0.050	0.170	0.29	Light Concrete	0.050	0.170	0.29
	Insulation	**0.400**	**0.032**	**12.50**	**Insulation**	**0.640**	**0.032**	**20.00**
	Light Concrete	0.100	0.170	0.59	Light Concrete	0.100	0.170	0.59
				0.13				0.13
	Total	0.560		13.57	Total	0.800		21.07
			U-value	**0.074**			**U-value**	**0.047**
Floor	**Floor**				**Floor**			
		Thickness	λ	R		Thickness	λ	R
		m	W/(m K)	m2K/W		m	W/(m K)	m^2K/W
				1.5				1.5
	Concrete	0.100	1.300	0.08	Concrete	0.100	1.300	0.08
	Insulation	**0.750**	**0.036**	**20.83**	**Insulation**	**1.500**	**0.036**	**41.67**
	Singles 32/64	0.150	0.880	0.17	Singles 32/64	0.150	0.880	0.17
				0.17				0.17
	Total	1.000		22.75	Total	1.750		43.58
			U-value	**0.044**			**U-value**	**0.023**

As can be seen on table 27, these thick insulation thicknesses yield low U-values, which should reduce the heating demand, even if the design is perhaps not entirely realistic.

In addition to the thicker envelope, the line loss from the foundation is reduced to 0.05 W/mK, which according to [2] can be seen as realistic in the year 2020, with the use of an improved foundation solution.

Optimizing the windows

The reference house in this report is based on a 2020 design which means it has already been optimized somewhat but there is still room for improvement, especially due to the higher light transmittance of the new AR-coated glazing, hence the aim is to reduce window sizes to a point where they more closely conform to the three daylight requirements. That way, a high quality of daylight is ensured, with no excess glass to cause overheating. This is done by taking into account the consideration of the Preliminary examination of the daylight chapter as well as some of the advice from [4], in order to adjusting window placement, window sizes and removing unnecessary windows.

In the following, only the window width is changed. This is due to the discoveries in the preliminary daylight investigations regarding the window heights, where it was found that having a low window is not as beneficial as having a high window; hence in order to achieve optimal daylight, all windows are placed high in the façade and not below a height of 0.8 m. Another consideration in this regard is the fact that that individual optimization of the height would perhaps create an asymmetric appearance of the façade.

On all the daylight factor result figures, black lines have been added manually, to indicate the center point as well as a center line across in order to help quickly decipher whether the daylight factor is 3% in the center and 2% across. It would perhaps have been slightly more precise if the center daylight factor could be automatically extracted directly from Visualizer but that would prove problematic in rooms that are not rectangular, such as in room 2, which is both kitchen and living room. Here it is chosen to have two center points; one for the kitchen part and one for the living room part.

The parameters used for this optimization in Visualizer are the same as in the Preliminary examination of daylight chapter, which are among the default values found in the Visualizer program.

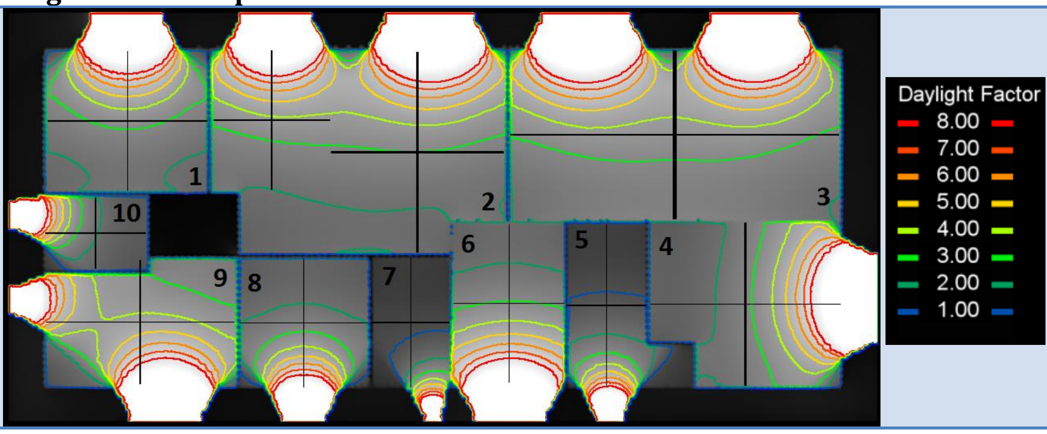
Table 28 – Surface properties used in the Visualizer simulations

Material	Reflectance [-]
White paint	0.84
Wooden floor	0.84
External ground	0.20

The new house model with 800 mm exterior walls is assessed in Visualizer, anti-reflective coated glazing with 81% light transmittance. The aim is then to optimize the window placement in primary rooms in order for them to more closely match the three daylight requirements.

Table 29 – Results of daylight simulation with the a wall thickness of 800 mm, the same window placement as the reference house, the AR-glazing and tapered reveals

800 mm exterior walls – New AR-coated glazing 81% LT Glass-to-floor ratio
Original window placement



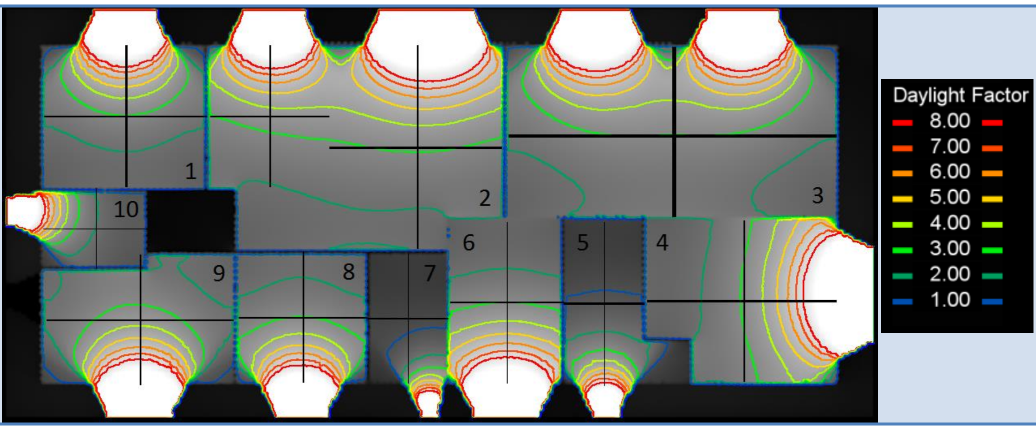
Room	Ratio
1	18%
2	17%
3	19%
4	18%
5	9%
6	23%
7	10%
8	15%
9	24%
10	17%
Avg - primary	**19.8%**

It is seen on table 29, that the current window design is slightly unbalanced, mostly in regard to the first daylight requirement of 3% in the center. Room 6 fits fine but the other rooms could use some adjustment in order to more closely match the three daylight requirements. For example in room 9, the center daylight factor is around 4.5%, which means the side window is perhaps unnecessary.

The window sizes are optimized through iteration of placement and size of the windows until the daylight conditions in the rooms more closely fit the three daylight requirements of 3% in the center, 2% across center and 1% all over.

Table 30 – Daylight results for the whole house with the same setup, but with optimized window placement

Optimized window placement — Glass-to-floor ratio



Room	Ratio
1	16%
2	17%
3	15%
4	20%
5	9%
6	21%
7	10%
8	18%
9	17%
10	17%
Avg - primary	17.6%

As can be seen, the 3% contour lines are now much closer to the center. The most problematic in this regard were the deep rooms 2 and 4, which required an increase in window size. The windows in room 3 were moved slightly together and reduced in size, moving the 2% line across the room closer to the center. Room 8, which is a utility room, had an increase in window size despite strictly speaking not being a primary room, so that one now conforms to the requirements as well. Room 9 had the small window removed and the remaining window was centered and reduced. It can be seen that in room 9, unlike the other rooms, the limiting factor was the 2% daylight factor across the room, which was due to the width of the room.

By optimizing the window sizes the, a lower glass % was achieved in primary rooms while still conforming to the three daylight criteria, even though the exterior wall thickness was increased to 800 mm. The AR-coated windows with 81% light transmittance helped in this regard. This should be able to reduce the overheating hours and perhaps reduce the heating demand on a cold winter day, thus resulting in less strain of the electric grid due to electric off-peak heating.

Design 1 results

Now that the insulation thicknesses have been increased, the new glazing has been implemented and the window sizes have been optimized, the next step is to calculate the results similarly to the reference house.

Annual heating demand

First the annual heating demand in calculated in WinDesign along with the corresponding number of overheating hours.

Table 31 – Comparison of results for heating demand and overheating between the reference house and Design 1

Number	Orientation	Design 1 - thick insulation, 800 mm walls, optimized windows with AR-coated glazing: Heating demand [kWh/m² year]	Ti > 26 °C [h]	Reference house: Heating demand [kWh/m² year]	Ti > 26 °C [h]
1 – Room	South	0.9	91	6.6	72
2 – Living room/kitchen	South	1.2	96	1.7	63
3 – Living room	South	0.4	69	3.0	63
4 - Bedroom	West	6.4	79	16.5	40
5 – Bath	North	0.7	0	6.6	0
6 – Room	North	3.0	46	9.2	24
7 – Hallway	North	19.6	0	28.9	0
8 – Utility	North	1.7	55	6.4	2
9 – Room	North	5.6	0	17.9	25
10 - Bath	East	1.7	298	7.3	211
Total – weighted		**2.9**		**8.1**	

As can be seen on table 31, the annual heating demand in Design 1 has been lowered to 2.9 from $8.1\frac{kWh}{m^2 year}$, which can be seen as a not insignificant decrease.

Heating demand – cold winter day

Again the days with the highest daily heating demands are found.

Table 32 – The ten days with the highest daily heating demand for the whole house

Daily heating demand – Entire house: Rank	[kWh]	Month	Day
1	10.8	12	25
2	10.5	12	21
3	10.5	12	22
4	9.8	12	23
5	9.7	1	6
6	9.6	12	24
7	9.5	1	7
8	9.1	1	8
9	8.8	12	26
10	7.5	1	21

It is seen that like with the reference house, the worst days in terms of heating demand is typically the December days. To supply enough heat for the worst day of December 25th during six hours in the night would require a heating power of $\frac{10.8\ kWh}{6h} = 1.8\ kW$, which can be seen as an improvement over the 4.1 kW required to heat the reference house. By the same simple assumptions as with the reference house regarding the acceptable added off-peak load to the national electricity supply, should be able to supply $\frac{1800\ MW}{1.8\ \frac{kW}{dwelling}} = 1{,}004{,}000\ dwellings$, hence it can be said that the strain on the grid is perhaps not significant.

Concrete temperature rise

The estimated concrete temperature rise is also found for each room, corresponding to the temperature rise the occupants should experience more than five days each year with a 10 cm slab of concrete.

Table 33 – The temperature rise in the concrete, comparison between Design 2 and the reference house

			Temperature rise [K]	
	Orientation	Room type	Design 1	Reference house
Room 1	South	Room	0.5	1.5
Room 2	South	Living room/kitchen	0.5	0.5
Room 3	South	Living room	0	0.5
Room 4	West	Bedroom	1	2
Room 5	North	Bath	0	1
Room 6	North	Room	0.5	1
Room 7	North	Hallway	2	2.5
Room 8	North	Utility	0	1
Room 9	North	Room	0.5	2
Room 10	East	Bath	0.5	1

It is seen that due to the lower heating demand of Design 1, the necessary concrete temperature rises have also been decreased. It is seen that especially the previously slightly problematic room 9 is now only subject to a 0.5 K temperature rise in the room, which can be contributed to the removal of the small window in this room during the window optimization.

From the results in general it can be seen that while the reference house was perhaps not unaccommodating towards electric off-peak heating, a more efficient house has been found with Design 1, in which the strain on the electric grid has been reduced along with the temperature increases the occupants are subject to.

8. Design 2

From Design 1, a potential was found towards improving the reference house to be more accommodating towards electric off-peak heating. The only problem was that that it perhaps happened at the expense of reasonable house design, with very thick insulation thicknesses and an 800 mm exterior wall. Therefore the next approach is to attempt to reach a heating demand similar to that of Design 1 but with a slightly more realistic and reasonable approach, which will then be referred to as Design 2.

Different possible design changes will be proposed and evaluated individually, and in the end a design will be chosen consisting of those of the changes that are deemed to be most useful. In this process, the method of balancing the insulation thicknesses and quality according to Cost of Conserved Energy will also be utilized in order to achieve a design which is also balanced from an economic perspective. The result should hopefully be a design with slimmer, more realistic proportions and which is more economically balanced, without a significant increase in heating demand from Design 1.

Slimmer design

First shown are those of the changes that will have a negative impact on the heating demand in the attempt to achieve more reasonable proportions of the envelope. These can also be put in contract to the positive effect of the design changes, which will be conducted afterwards.

Reducing exterior wall thickness to 600 mm

By reducing the exterior walls from 800 mm to 600 mm, it would provide for less bulky, better looking exterior walls with a better view out due to the reduced “tunnel effect”. It would also make it easier to convince building contractors and architects that it is a reasonable and viable design, but having 200 mm less insulation increases the heating demand, as can be seen on table 34.

Table 34 – Comparison between heating demands with a decrease in wall thickness

Wall thickness	Design 1	800 mm -> 600 mm	Increase
Heating demand [kWh/m² year]	2.88	3.78	0.90

This is a loss which can perhaps be compensated for, for example by increasing insulation quality or using a more efficient wall structure, allowing for more insulation within the same wall thickness. Both of these options will be explored.

One advantage can be that it allows for a higher daylight intake and subsequently a slightly more efficient window design. By re-optimizing the window sizes after decreasing the wall thickness by 200 mm, it allows for a decrease in width of most of the windows. Thus, the glass-to-floor ratio is decreased from 17.6% to 15.7% allowing for perhaps slightly lower heat loss in some rooms, as well as a general reduction in overheating hours.

Reducing roof insulation thickness to 1 m

In Design 1 the roof thickness is 1.5 m, which is somewhat excessive, so therefore it could be ideal if the roof thickness could be reduced to a more reasonable measure, but there is not any immediate reason to reduce the roof thickness, other than to avoid a thick building envelope.

Table 35 – Heating demand due to decreased roof thickness

Roof thickness	Design 1	1.5 m -> 1.0 m	Increase
Heating demand [kWh/m² year]	2.88	3.07	0.19

As can be seen on table 35, by reducing the roof thickness to 1 m, the heating demand is increased by $0.19\,\frac{kWh}{m^2 year}$.

Floor insulation

Unlike with the roof, where the only reason to reduce the thickness was to avoid a bulky envelope, there are some physical reasons why a thick floor insulation is not feasible, as unfortunately the allowable insulation thickness is severely limited by the compressive strength of the insulation material. Otherwise it would be reasonable to think that very thick floor insulation could be ideal, since it is underground and cannot be seen.

Therefore it can be said that the current floor insulation thickness of 1.5 m is unrealistic and needs to be reduced. The proposed thickness is 600 mm, which can be seen as a more realistic thickness to use in a single family house, if the insulation has a compressive strength of 80 kPa. To use more would perhaps require the expensive insulation types with compressive strengths of 150 or 250 kPa. From [19] it is recommended to use a compressive strength of 80 kPa with insulation thicknesses of 300 mm or above. Still it can be said that 600 mm is perhaps in the excess of what is practical with 80 kPa insulation and perhaps small cracks could occur, depending on the joints of the house, but overall it can be seen as an acceptable compromise.

Table 36 – Heating demand due to decreased floor insulation thickness

Floor insulation thickness	Design 1	1.5 m -> 0.6 m	Increase
Heating demand [kWh/m² year]	2.88	3.85	0.97

As can be seen on table 36, the decrease in floor insulation to 0.6 m causes an overall increase in heating demand of 0.97 $\frac{kWh}{m^2 year}$.

That applied limitation of 600 mm only applies to the thickness of the insulation itself, so there is no gain by using a slim floor design in general. Therefore, there is no reason to replace the thick layer of regular concrete, since it is needed to for the floor heating and also has the gainful effects of a high thermal mass.

Design improvements

It can be seen the increased in heating demand from slimming the envelope down to more realistic proportions is not insignificant, so perhaps some of the following potential design changes can reduce the heating demand through a more efficient design.

More effective exterior wall design

It could be interesting to implement a more efficient design of the exterior wall, allowing for a higher insulation thickness without an increase in wall thickness, which is also interesting because a slimmer wall benefits proportionally more to such a change. Two designs are proposed; a light design and a heavy design:

Light design

The proposed light wall design consisting of 2 x 13 mm plaster, wooden skeleton frame and an air cavity of 25 mm can be seen with the following type of wooden plywood I-beams.

Figure 12 – Example of plywood I-beams from Hunton for use in wall structures [6]

The skeleton frame allow for a higher overall insulation thickness at the expense of a slightly higher thermal conductivity of the insulation layer due to the beams taking up some of the space for insulation.

Table 37 – Comparison of the wall U-value between the new light design and the lightweight concrete wall used in Design 1

Light design	Thickness	λ	R	
	[m]	[W/(m K)]	[m^2K/W]	
			0.13	
Facade cover	0.022	0.460	0.00	
Ventilated cavity	0.025	0.170	0.00	
Insulation (λ32) + plywood	**0.727**	**0.034**	22.03	
Gypsum	0.026	0.170	0.15	
			0.13	
Total	0.800		22.44	Lightweight concrete wall from Design 1
		U-value	**0.045**	**0.047**

As can be seen on table 37, the surface resistance is 0.13 m^2K/W for both the interior and exterior side. This is carried out according to DS418 [25], which states that as a result of the ventilated cavity with an opening larger than 15 cm^2 for every 1 m of wall, the exterior surface insulation should be increased to 0.13, but the ability of the façade cover to insulate is nullified.

With a thickness of 73 mm, this design is somewhat slimmer than the current concrete design, which has a thickness of 160 mm. This allows an extra 87 mm of insulation but the downside is that since it is skeleton wall, the insulation is penetrated by wooden I-beams with a body of plywood, effectively increasing the thermal conductivity of the insulation layer from 0.032 to 0.034 $\frac{W}{mK}$. This is found by from an assumed plywood thermal conductivity of 0.13 $\frac{W}{mK}$ by weighing the thermal resistances according to the relative proportions in the wall, assuming one I-beam for every 600-650 mm length of the wall, and therefore the direct gain due to the increased insulation thickness is diminished. It is a light design, so utilizing plaster on the interior side of the wall instead of lightweight concrete will reduce the external wall thermal mass from 21 to 7 $\frac{Wh}{m^2K}$.

Table 38 – comparison of heating demand between the old concrete wall and the new wooden skeleton wall

Light wall design	Design 1	Light skeleton wall	Decrease
Heating demand [kWh/m² year]	2.88	2.61	0.27

As can be seen on table 38, with a 600 mm exterior wall, the extra insulation caused by the more efficient design reduces the overall heating demand by 0.27 $\frac{kWh}{m^2 year}$

Heavy design

Another option is to use high performance concrete with for example thicknesses of 20 mm and 30 mm, allowing for a thickness of 50 mm, which is slightly slimmer than the light wood skeleton design. The advantage is that the insulation layer is not penetrated by wood, which allows it to retain the thermal conductivity of 0.32 $\frac{W}{mK}$. It is also heavier than the skeleton wall but not much. It is much more expensive and therefore perhaps not suitable for single family houses. The use of high performance concrete will yield a 27 mm increase in insulation thickness, a slightly improved thermal conductivity and the slight increase in thermal mass over the light design.

Table 39 – Comparison of U-values for high strength concrete wall and lightweight concrete wall

High strength concrete	Thickness	λ	R	
	[m]	[W/(m K)]	[m2K/W]	
			0.04	
Plaster	0.010	0.460	0.02	
High strength concrete	0.030	0.170	0.18	
Insulation	**0.740**	**0.032**	**23.13**	
High strength concrete	0.020	0.170	0.12	
			0.13	
Total	0.800		17.36	Lightweight concrete wall from Design 1
		U-value	**0.042**	**0.047**

It can be seen that this design allows for a slightly higher insulation thickness compared to the light wooden design and more importantly, the insulation is not penetrated by a wooden I-beam and therefore a better U-value of 0.042 W/m^{2}K is reached.

Table 40 – Comparison between heating demand for the high performance concrete wall and the lightweight concrete wall

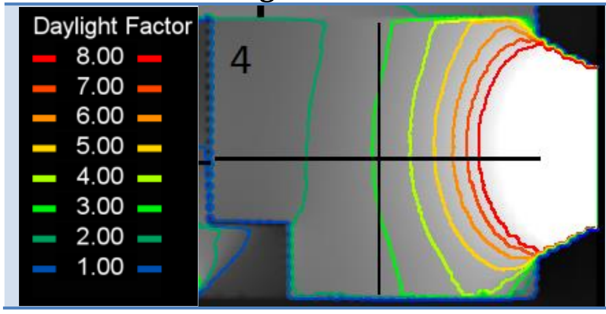
	Design 1	High performance concrete	Decrease
Heating demand [kWh/m² year]	2.88	2.54	0.34

It can be seen that using high performance concrete yields a slightly lower heating demand compared to the light wooden design, but it is unlikely that it will be worth the higher expense. Overall, the wooden design is the more attractive of the two proposed wall designs.

New Room Design

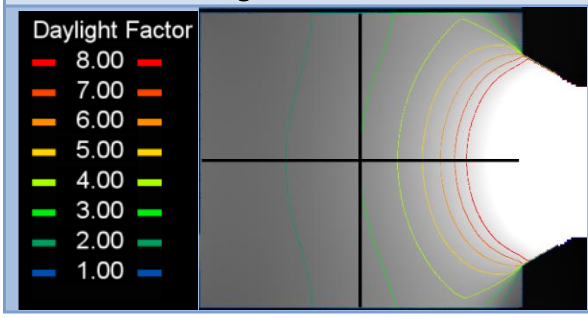
Another way to try and bring down the heating demand is by making slight changes to the room design, if for example one room has unfortunate proportions in regards to daylight intake, such as room 4.

Table 41 – Daylight and window size in room 4

Room 4 from Design 1	Window width
	2.2 m

As is seen from table 41, due to the angle in the wall, the wall is somewhat far away from the window compared to the size of the room, resulting in a large window of 2.2 m in width in order to conform to the requirement of 3% daylight in the center. It is proposed to remove the edge in the corner and adjusting the placement of the wall accordingly, thus reducing the depth of room 4 without actually changing the total area of either that or the neighboring bathroom.

Table 42 – Daylight and window width in room 4 after adjusting the wall

Room 4 from Design 1	Window width
	1.9 m

As is seen, the room depth was reduced from 4425 mm to 4050 mm without changing room areas, reducing the necessary window width to 1.9 m.

Table 43 – Comparison of heating demand and overheating hours before and after adjusting the wall and window size in room 4

New room design

	Heating demand			Overheating $T_i > 26$		
	Design 1	New room design	Decrease	Design 1	New room design	Decrease
Room 4 – west bedroom	6.4	5.8	0.6	79	52	27
Whole house	2.88	2.81	0.07	-	-	

It is seen from table 43 that reducing the window size in room 4 did reduce the heating demand in the room slightly as well as reducing the amount of overheating hours, but the impact on the building as a whole was not significant.

New Window Design

The windows in the primary rooms have been optimized to conform to the three daylight requirements, but the windows in the secondary rooms have not been altered. Therefore it could be interesting to reduce the window sizes in these secondary rooms. It might be an efficient way to reduce the heating demand, since most of them are facing north.

In small bathrooms it can be said that the window are sometimes covered with curtains or fitted with translucent glazing, so having a somewhat large window can perhaps be seen as unnecessary. In addition, these rooms are not occupied as frequently as primary rooms, so the potential discomfort due to smaller windows is reduced.

To start off, a reduction of window sizes to 0.5 m x 0.5 m is proposed.

Table 44 – proposed reduction in window sizes

Room	Current size		Proposed size	
	Size [m]	Area [m^2]	Size [m]	Area [m^2]
5 – Master bathroom	1.6 x 0.6	**1.0**	0.5 x 0.5	**0.25**
7 – Hallway	2.0 x 0.4	**0.8**	0.5 x 0.5	**0.25**
8 – Utility	1.6 x 1.2	**1.9**	0.5 x 0.5	**0.25**
10 – Secondary bathroom	1.6 x 0.6	**1.0**	0.5 x 0.5	**0.25**

As can be seen, the new window size represents a significant decrease in window size.

Table 45 – Heating demand in the four rooms and the whole house before and after reduction in window sizes

Heating demand [kWh/m² year]			
	Before	After	
5 – Master bathroom	0.7	0	
7 – Hallway	19.6	13.2	
8 – Utility	1.7	0	
10 – Secondary bathroom	1.7	0	Difference
Total - house	2.88	2.44	0.44

It is seen on table 45, the reduced window sizes result in a heating demand decrease of 0.44 $\frac{kWh}{m^2 year}$ for the house. The heating demand for room 5, 8 and 10 is reduced to 0, which suggests that the change was somewhat effective, even if perhaps the majority of the reduction in heating demand in this case stems from room 7.

New Window Design – with 1.5 % daylight factor

While effective, there is one significant problem with the smaller windows, which is that the windows have perhaps been changed into peepholes, which can be seen as unacceptable by many occupants. In an attempt to rectify this fact, a compromise is proposed: to achieve a center daylight factor of 1.5 % in room 5, which is the master bathroom and room 8, which is the utility room. It can be said that even though these are secondary rooms, the master bathroom and the utility rooms are perhaps places where occupants can frequently spend time and thus still have a certain expectation regarding the daylight conditions; hence small windows are perhaps not acceptable in these rooms. Therefore, the windows in the master bedroom and utility room are sought to be only slightly reduced in size, in order to achieve the center daylight factor of 1.5 %.

This leaves only small windows in the secondary bathroom and the hallway, and the idea is that it is more acceptable in these rooms since they might be covered up by the occupants. After optimizing the two windows for 1.5 %, the proposed window sizes are as follows:

Table 46 – Proposed new window sizes with 1.5% daylight factor in room 5 and 8

Room	Current size		Proposed size	
	Size [m]	Area [m²]	Size [m]	Area [m²]
5 – Master bathroom	1.6 x 0.6	**1.0**	1.6 x 0.7	**1.1**
7 – Hallway	2.0 x 0.4	**0.8**	0.5 x 0.5	**0.25**
8 – Utility	1.6 x 1.2	**1.9**	1.6 x 0.6	**1.0**
10 – Bath	1.6 x 0.6	**1.0**	0.5 x 0.5	**0.25**

As seen from table 46, the size of the window was increased slightly, in order to accommodate the center daylight factor of 1.5 %, but the utility room window was reduced in size.

Table 47 – Comparison of heating demands with the new windows sizes

Heating demand [kWh/m² year]			
	Before	After	
5 – Master bathroom	0.7	0.9	
7 – Hallway	19.6	13.2	
8 – Utility	1.7	0.4	
10 – Secondary bathroom	1.7	0	Difference
Total - house	2.88	2.52	0.36

It is observed that the measures regarding the new window design with the 1.5 % daylight factor in room 5 and 8 result in an overall reduction in heating demand of 0.36 $\frac{kWh}{m^2 year}$. It can be said that the small windows in the bathroom and hallway is a somewhat effective measure at reducing the heating demand, and while it might be displeasing to some occupants, it is perhaps not an unacceptable compromise.

Doors

When analyzing the room-based calculations from Design 1, it becomes evident that two rooms have a higher heating demand than the rest, as can be seen on table 48.

Table 48 – Heating demand for each room as it was for Design 1

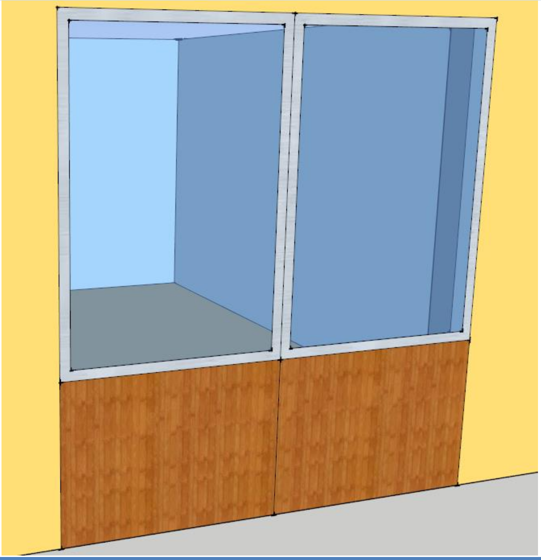
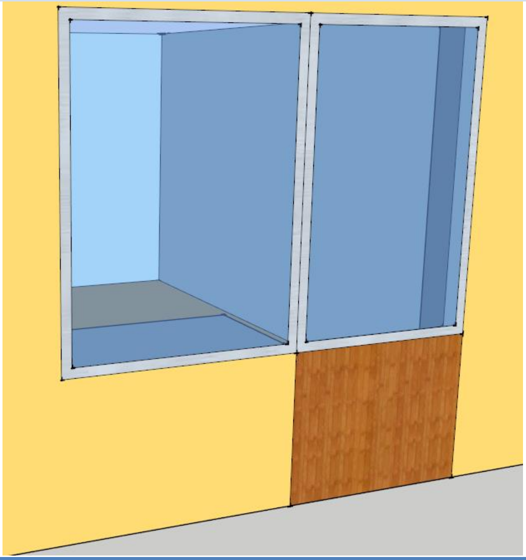
		Design 1	
Room type	**Orientation**	Heating demand [kWh/m^2 year]	Weighted heating demand [kWh/m^2 year]
1 – Room	South	0.9	0.09
2 – Living room/kitchen	South	1.2	0.24
3 – Living room	South	0.4	0.08
4 - Bedroom	West	6.4	0.77
5 – Bath	North	0.7	0.04
6 – Room	North	3.0	0.20
7 – Hallway	North	19.6	0.73
8 – Utility	North	1.7	0.11
9 – Room	North	5.6	0.57
10 - Bath	East	1.7	0.05
Total – weighted		**2.88**	

It is seen on table 48 that both rooms 4 and 7 have a higher heating demand than the rest of the rooms, the common denominator being the fact that they both contain exterior doors and are not faced south. The south faced doors in room 2 and 3 are already integrated with the glazing and thus do not appear to contribute meaningfully toward the heating demand, but the exterior doors in the west bedroom and north hallway appear to be a source of heat loss, despite the fact that they are modern, well-insulated doors with a U-value of 0.6, since their U-values are inferior to that of the exterior wall. The door U-value is on par with the glazing, which has a U-value of 0.5, but without the gainful transparent properties, hence there is perhaps room for improvement, as the doors are, along with the frames, the weakest part of the building envelope. Two solutions are proposed: a new door design and VIP doors.

New door design

The idea of the new door design is to minimize the amount of door area in the building, and a proposed way to achieve this can be seen below.

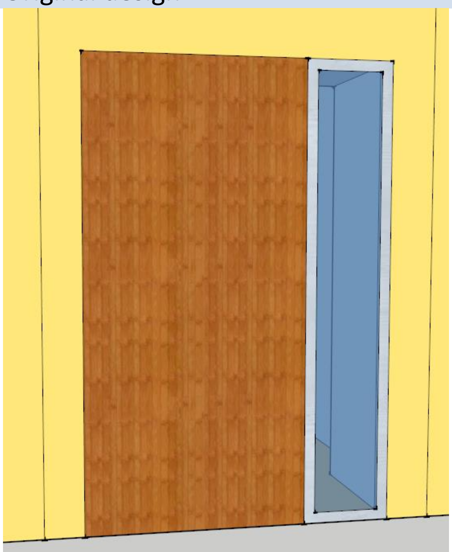
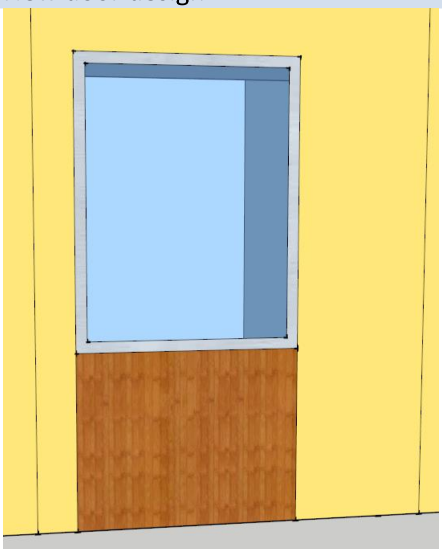
Table 49 – Proposed new door design for room 4 by replacing the double doors with a single door

Room 4 – west facing bedroom	
Original design	New door design
	

As can be seen on table 49, excess door area can be removed by redesigning double door to become a single door while still preserving the glazing by having a window beside the door instead. Thus the width of the door part is reduced by 1.2 m. The disadvantage is that a single door instead of a double door can be seen as a decrease in general comfort by the occupants.

A similar change is proposed in room 7, which is illustrated below.

Table 50 – Proposed new door design for room 7 by integrating the window into the door

Room 7 – north facing hallway	
Original design	New door design
	

As can be seen on table 50, in the original design from the reference house, the window is beside the door and in addition, it has a very elongated shape, resulting in a larger frame area relative to e.g. a square window. In the proposed new design, the window is incorporated into the door, reducing the overall window + door area of the room by 29%. This reduces the amount of redundant door area to only a height of 0.8 m and allows for a more regular shape of the window part with a relative frame area of only 17 % compared to the 29% in the original design.

Table 51 – Heating demand before and after the new door design

New door design

Heating demand	Design 1	New door design	Decrease
Room 4 – west bedroom	6.4	5.2	1.2
Room 7 – north hallway	19.6	8.5	11.1
Whole house	**2.88**	**2.32**	**0.56**

As can be seen on table 51, the new door design allows for a not insignificant decrease in heating demand for the two rooms, resulting in a decrease of 0.56 $\frac{kWh}{m^2 year}$in heating demand for the whole house.

VIP doors

Another proposed solution to bring down the heating demand of the two rooms is by the use of Vacuum Insulated Panels (VIP). Doors are thin by design, so increasing the insulation thickness is perhaps not a viable option; hence vacuum insulated panels in the doors can be seen as an effective way to reduce the heat loss of the doors. At 0.005 W/mK, these thin panels have an extra-ordinarily low thermal conductivity but they are expensive, so they are usually utilized only there absolute necessary, for example when re-insulating existing old buildings. One disadvantage is that they leak over time, which can necessitate replacement later on. Installing them just where the envelope is weakest – the doors – is perhaps an effective design. That way, the panels could also be more easily replaced later on, for example with a hatch in the door. The door is assumed to have 5 cm of the panels.

Table 52 – U-value for VIP door

Door with vacuum insulated panels

	Thickness	λ	R
	[m]	[W/(m K)]	[m^2K/W]
			0.04
Wood	0.010	0.170	0.06
VIP	**0.050**	**0.008**	6.25
Wood	0.010	0.170	0.06
			0.13
Total	0.070		6.54
		U-value	**0.15**

As can be seen on table 52, the thermal conductivity λ is assumed to be 0.008 W/mK, which is slightly higher than the table value. This is to take into account the leaking of the panels over time, reducing their ability to insulate.

Table 53 – Heating demand comparison with and without VIP doors

VIP doors

Heating demand	Design 1	VIP doors	Decrease
Room 2 – Kitchen/living room	1.2	1.2	0
Room 3 – Living room	0.4	0.4	0
Room 4 – west bedroom	6.4	5.2	1.2
Room 7 – north hallway	19.6	10.4	9.2
Whole house	**2.88**	**2.39**	**0.49**

It is seen on table 53 that installing the VIP panels in the doors is, like the previously shown new door design, an effective way to reduce the heating demand in these room, yielding an overall decrease of 0.49 $\frac{kWh}{m^2 year}$ for the whole house, but only in the north and west rooms.

New door design + VIP doors

Both the VIP door design and the new door design are effective and therefore it can be seen as interesting to try and combine them, since they are not mutually exclusive, however they do diminish each other to some extent. By using the new door design, the need for the vacuum insulated panels is diminished since the door area is decreased, which also makes it cheaper to install the panels in the remaining door area.

Table 54 - Heating demand comparison, combined VIP doors and new door design

New door design + VIP doors

Heating demand	Design 1	VIP doors + new door design	Decrease
Room 4 – west bedroom	6.4	4.6	1.8
Room 7 – north hallway	19.6	5.9	13.7
Whole house	2.88	2.15	0.73

As can be seen on table 54, when using the two proposed designs together, even though they somewhat diminish each other, the result is still an overall decrease in heating demand of 0.73 $\frac{kWh}{m^2 year}$ for the entire house, hence it can be seen as a beneficial design change.

Proposed design

From the above tests, the following design changes are chosen to be implemented in Design 2:

- Light wooden exterior wall – more insulation with same wall thickness
- New room design – adjusted wall in room 4
- New window design – small windows in hallway and secondary bathroom, 1.5% daylight factor in master bathroom and utility
- New door design – reduced door areas, integration with window and VIP

Overall it could be seen that the heating demand could be reduced somewhat – mostly by optimizing doors, but a slight reduction was also found by reducing the window areas in certain north facing secondary rooms.

Cost of Conserved Energy

Now that the desired design changed have been found and along with a new exterior wall, the next step is to analyze the house with CCE-calculation (Cost of Conserved Energy) in order to achieve a design which is balanced from an economic perspective in relation to insulation quality and thickness.

This is done by calculating the marginal energy saving price for the exterior wall, the floor and the roof, which tells something about how good of an investment it is to implement one more cm of a given insulation in an envelope component. The idea is then to choose a solution which is balanced between each of the components in terms of insulation thickness and quality, within the given boundaries. That way, any imbalances that might occur between the costs of the floor, roof and wall could be avoided and the result should be a solution that is perhaps balanced from an economic standpoint. Depending upon the boundaries, it can perhaps be necessary to accept a higher cost of conserved energy for e.g. the exterior wall in order to reach an acceptable U-value.

The full formula, along with the following assumptions is found from [19].

$$CCE = \frac{\frac{n}{n^t} \cdot a(n,r) \cdot I_{initiative} + VO_{annual}}{f_1 \Delta E_{annual} - f_2 \Delta E_{operation,\ annual}}$$

Under the assumption that the maintenance cost for the exterior walls, floor and roof are independent upon the insulation thickness and quality, the formula can be simplified to the following.

$$CCE = \frac{\frac{n}{n_t} \cdot a(n,r) \cdot I_{measure}}{\Delta E_{annual}}$$

Where

- CCE = Cost of Conserved Energy
- n = the economic lifetime, typically 30 years in Denmark [years]
- n_t= the technical lifetime. Set to 100 years for insulation materials – the time during which the product is expected to perform properly [years]
- a(n,r) = annuity the capital recovery rate [-]
- $\Delta I_{measure}$ = Price change due to the measure, consisting of insulation price and additional related costs of e.g. excavation [kr]]
- ΔE_{annual} = the annual conserved energy as a result of the implemented measure [kWh/year]

and

$$a(n,r) = \frac{r}{1-(1+r)^{-n}}$$

Where

- r = the real interest rate, assumed to be 2.5%, since the value has typically fluctuated between 2% and 3% [%]
- n = the economic lifetime, typically 30 years in Denmark [years]

For the floor, roof and wall, the value of E_{annual} becomes.

$$E_{annual} = D_H \cdot U_{component}$$

Where

- D_H = The amount of degree hours in the heating season – a reduced value is used for components facing the ground [kKh]

Thus the marginal energy price can be calculated for the roof, floor and wall. First each component will be evaluated individually with relevant insulation types and corresponding prices found from [19], before a combined solution with a balanced CCE is proposed.

Floor

First the floor is examined, the limitation of which is that it is chosen for the floor insulation not to exceed 600 mm with compressive insulation strength of 80 kPa, in order to reduce the risk of cracks, but the use of insulation with higher strength is investigated. With the floor, $I_{measure}$ consists of both the insulation price as well as the excavation price. The price of excavation is found from [19]:

$$Excavation\ price = \frac{9802 \cdot depth + 1187}{A_{dwelling}}\ [kr]$$

The compared insulating materials from Sundolitt are as seen on table 55. Number specifies the short term compressive strength, e.g. 80 kPa.

Table 55 – Price and thermal conductivity of different floor insulation materials

Material	Thermal conductivity [W/mK]	Price [kr/m³]
S80	0.038	740
S150	0.036	1223
C80	0.031	1020

From these prices and thermal conductivities, the CCE can be calculated for different thicknesses of insulation. The CCE table will be presented in order to attempt to give an impression of the relative performance of each insulation type, by listing the prices corresponding to the estimated maximum thickness, which is 600 mm for the floor:

Table 56 – Cost of conserved energy and U-value for the insulation materials with a thickness of 600 mm

600 mm	Cost of conserved energy [kr/kWh]	U [W/m²K]
S80	4.04	0.054
S150	6.72	0.052
C80	6.32	0.045

As can be seen on table 56, with a floor insulation of 600 mm, the Sondolitt S80 yields the lowest CCE. In general the prices can perhaps be seen as somewhat high, so 600 mm of insulation is perhaps unnecessary.

Roof

Unlike the floor and wall, the roof has not got any significant additional price that increases with the thickness of the insulation, so only the insulation price itself is taken into account. The investigated insulation types is Murfilt mineral wool from Isover and Kooltherm phenolic foam from Kingspan.

Table 57 – Price and thermal conductivity of the different wall insulation materials

Material	Thermal conductivity [W/mK]	Price [kr/m³]
Murfilt 37	0.037	233
Murfilt 34	0.034	280
Murfilt 32	0.032	400
Kooltherm K8	0.021	1875

As can be seen, the prices are generally much lower for these materials than for the floor insulation, since there are no requirements regarding compressive strength. Therefore the cost of conserved energy should be lower, meaning it will be more attractive to implement a thick insulation layer, but as previously established, it could perhaps be attractive to keep the total roof thickness down to 1000 mm due to aesthetic considerations, which amounts to 950 mm of insulation. The CCE results for this thickness are shown in table 58.

Table 58 Cost of conserved energy and U-value for the insulation materials with a thickness of 950 mm

950 mm	Cost of conserved energy [kr/kWh]	U [W/m²K]
Murfilt 37	1.26	0.038
Murfilt 34	1.64	0.035
Murfilt 32	2.48	0.033
Kooltherm K8	17.43	0.022

As can be seen, the CCE prices are also lower than for the roof, partly due to the absence of additional costs. The Kooltherm phenolic foam does not appear to be a viable option for the roof due to the price.

Wall

The wall has more limitations attached to it than the roof and floor, both due to the established limitation of a maximum total thickness of 600 mm, and because it has the highest additional expenses due to the need for additional excavation, concrete, foundation and roof:

- Excavation $\frac{18174 \cdot d_{wall} + 1382}{A_{facade}}$
- Concrete $\frac{1736 \cdot (54.5m \cdot 0.7\ m \cdot d_{wall}) + 2389}{A_{facade}}$
- Foundation $\frac{3165 \cdot (54.5m \cdot d_{wall}) - 35015}{A_{facade}}$
- Roof $\frac{162 \cdot A_{roof} + 2272}{A_{facade}}$

For the wall, the same insulation materials as from the roof are investigated. The CCE prices are found for 527 mm of insulation, corresponding to a total wall thickness of 600 mm with the new light wooden exterior wall.

Table 59 – Cost of conserved energy and U-value for the different wall insulation materials

527 mm	Cost of conserved energy [kr/kWh]	U [W/m²K]
Murfilt 37	4.26	0.072
Murfilt 34	4.66	0.066
Murfilt 32	5.27	0.063
Kooltherm K8	11.64	0.044

As is seen from table 59, the CCE prices for the wall are somewhat high, even for the cheap Murfilt 37 mineral wool, which can be contributed to the additional construction costs of excavation, concrete etc. One way to reduce this additional cost could be to utilize a different foundation structure, for example the type L.2 from [7]

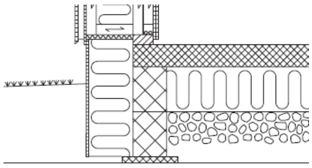


Figure 13 – example of a foundation solution that could reduce the excavation expenses [7]

It is seen from figure 13 that with this solution, the foundation itself does not extend out as far as the exterior wall, and therefore it is assumed that there are no additional expenses of excavation, concrete or foundation related to adding e.g. 1 cm of additional wall insulation, but the insulation itself does extend farther down, resulting in an approximated 20% increase in insulation volume, hence an additional 20% expenses toward insulation. The CCE prices are calculated for the new foundation in table 60.

Table 60 – Cost of conserved energy and U-value for insulation materials with a less expensive foundation solution

527 mm	Cost of conserved energy [kr/kWh]	U [W/m²K]
Murfilt 37	0.46	0.072
Murfilt 34	0.58	0.066
Murfilt 32	0.97	0.063
Kooltherm K8	5.27	0.044

As is seen, with a different foundation, the CCE prices were reduced. The Kooltherm phenolic foam is perhaps still too expensive for a 600 mm wall, but with a smaller wall thickness it could potentially be a viable solution.

Proposed solution

Now that the CCE prices for the wall, floor and roof have been established, the next step is to find a solution which balances the three according to CCE, ensuring that the expense towards one of the parts is not greater than to the others.

Table 61 – List of the proposed insulation types and thicknesses

	Insulation type	Insulation thickness [mm]	Total thickness [mm]	$\lambda_{insulation}$ [W/mK]	U [W/m²K]	CCE [kr/kWh]
Floor	Sundolitt S80	530	780	0.038	0.059	3.26
Roof	Isover murfit 32	1090	1140	0.032	0.029	3.25
Wall	Kingspan Kooltherm K8	410	480	0.021	0.056	3.29

As can be seen, a solution was found in which the components match up closely in terms of Cost of Conserved Energy. It is seen that the Kingspan phenolic foam was found to correspond well with the rest of the components in terms of CCE with the use of a smaller insulation thickness, and this can be contributed to both the more efficient foundation. As a result, the total wall thickness will be 483 mm instead of the expected 600 mm, which is positive since it allows for a higher daylight intake, a less bulky exterior and a slightly reduced transmission area.

It can be said that with a thinner wall, it would perhaps be possible to reduce the window sizes very slightly in some rooms, but the concern is that at 15.3% glass to floor ratio for primary rooms, the windows are already small and it is not desirable to reduce them further. Thus the occupants can enjoy a slightly higher daylight factor, as can be seen on figure 14.

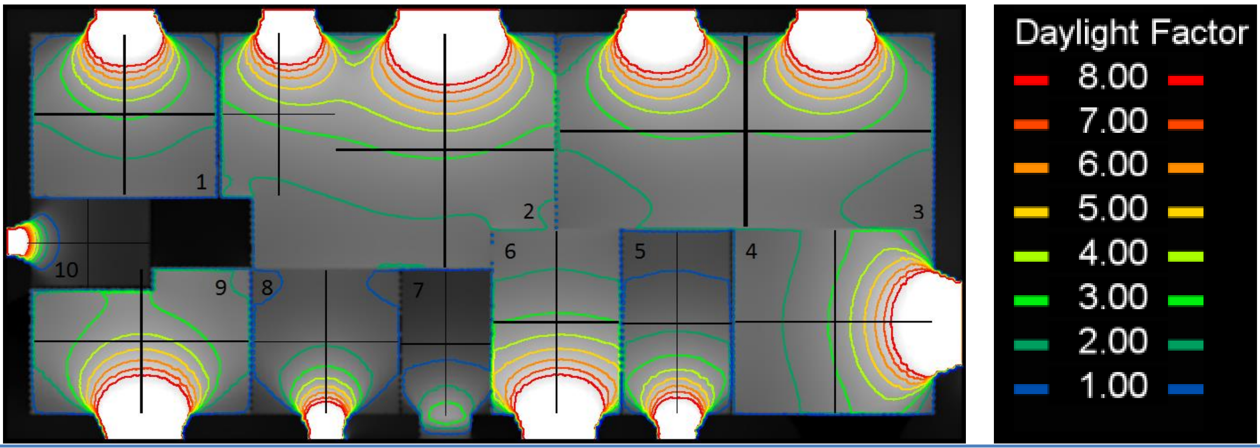


Figure 14 – Daylight conditions in the house

It is seen that the daylight factor increases slightly, to approximately 3.2% for most rooms.

A suitable solution was found with the use of CCE. It can be discussed whether the common CCE price was set too low or too high, but it was positive that the prices were able to match up. Even if 3.25 kr/kWh can seem high, it can be said that it is the marginal price, hence the price of the last cm and not the price as a whole.

Thermal mass

Now that a new exterior wall has been established, the thermal mass can be found.

Table 62 – Thermal mass for Design 2

Thermal mass	Volumetric heat capacity	Thickness	Area	Thermal mass
	[MJ/m³K]	[m]	[m²]	**[Wh/m²K]**
Concrete - floor	2.4	0.100	163.3	67
Plaster - roof	0.9	0.026	163.3	7
Plaster - wall	0.9	0.026	178.7	7
Aerated concrete - inner walls	0.7	0.100	125.2	15
			Total	**95**

It can be said that with the lighter exterior wall instead of the thermal mass is reduced slightly, by 14 Wh/m²K. It can be said that while thermal mass is useful for reducing overheating and it does reduce the heating demand slightly, it is perhaps not as useful in general as real insulation. Since thermal mass acts as a heat buffer, it is perhaps most useful when the direction of the heat flow changes during the course of a day, which does not occur often in Denmark, and never on a cold winter day, hence the increased insulation of the new wall will be more effective at reducing the heating demand on a cold winter day, thus reducing the strain applied to the electricity grid.

Results

Now that Design 2 has been established, with a slightly optimized window and door design, a more efficient exterior wall and thinner insulation in general, the results are found from simulation.

Annual heating demand

First the heating demand is established from WinDesign simulations.

Table 63 – Annual heating demand and overheating hours for Design 2

Results			Heating demand	Overheating hours
Room	Orientation	Room type	[kWh/m^2 year]	T_i > 26 °C
Room 1	South	Room	2.3	52
Room 2	South	Living room/kitchen	0.6	36
Room 3	South	Living room	0.6	28
Room 4	West	Bedroom	7.5	33
Room 5	North	Bath	3.7	0
Room 6	North	Room	5.4	15
Room 7	North	Hallway	10.1	0
Room 8	North	Utility	2.8	0
Room 9	North	Room	9.7	0
Room 10	East	Bath	1.8	0
		Total - weighed	**3.51**	

It is seen that the heating demand for Design 2, which is 3.51 $\frac{kWh}{m^2year}$, which is slightly higher than Design 1 at 2.88 $\frac{kWh}{m^2year}$, and somewhat lower than the reference house at 8.1$\frac{kWh}{m^2year}$. The amount of overheating hours has also decreased.

Maximum daily heating demand

The day with the maximum heating demand has been found.

Table 64 – Heating demand of the different rooms for the coldest day of December 21st

Maximum daily heating demand			Dec 21	
			Heating demand	
Room	Orientation	Room type	[kWh]	[Wh/m^2]
Room 1	South	Room	1.8	110
Room 2	South	Living room/kitchen	1.9	57
Room 3	South	Living room	2.4	67
Room 4	West	Bedroom	2.8	145
Room 5	North	Bath	0.8	83
Room 6	North	Room	1.2	109
Room 7	North	Hallway	0.8	127
Room 8	North	Utility	0.7	69
Room 9	North	Room	2.3	144
Room 10	East	Bath	0.3	59
		Total [kWh]	**15**	
		Power – 6h [kW]	**2.5**	

It is seen that the heating demand on the coldest winter day is 15 kWh, which requires a heating power of 2.5 kW to be supplied during the night – which is higher than the 1.8 kW from Design 1.

Concrete temperature rise

The concrete temperature rise has been found for Design 2.

Table 65 – Estimated concrete temperature rise for the different rooms

			Temperature rise [K]	
	Orientation	Room type	Design 2	Design 1
Room 1	South	Room	0.5	0.5
Room 2	South	Living room/kitchen	0.5	0.5
Room 3	South	Living room	0.5	0
Room 4	West	Bedroom	1	1
Room 5	North	Bath	0.5	0
Room 6	North	Room	0.5	0.5
Room 7	North	Hallway	1	2
Room 8	North	Utility	0.5	0
Room 9	North	Room	1	0.5
Room 10	East	Bath	0.5	0.5

As is seen on table 65, the concrete temperature rise is similar to that of Design 1. One exception is room 7, where the heating demand has been reduced due to the design changes of the door and window, resulting in a temperature rise similar to that of the rest of the rooms.

Design 2 evaluation

Overall it can be seen that the Design 2 results are not dissimilar to those of Design 1, with insulation thicknesses that can be seen as more reasonable and a thinner exterior wall of 480 mm instead of 800 mm. Therefore henceforth Design 1 will be disregarded, and when it comes to the later evaluations of the viability of electric off-peak heating, Design 2 will be compared to the reference house.

In general the reference house can represent a conventional low energy 2020 house and Design 2 can represent a design where more emphasis has been put towards heating demand, hence Design 2 will also be a slightly more expensive solution in general, with e.g. AR-coated glazing and VIP doors, as well as some compromises such as smaller windows, a west facing double door in room 4 reduced to a single door reduced to a single door, and small windows in room 5 and 7. In turn it can be said that Design 2 is perhaps more accommodating towards electric off-peak heating as the heating demand has been reduced and some of the negative aspects such as concrete temperature rise and possible strain of the electric grid has been reduced. The advantages and disadvantages of Design 2 and the reference will be explored further, but first some slightly more realistic simulation conditions will be established.

9. Improved WinDesign

Now the reference house and Design 2 has been established have been established, but before analyzing them in an economic context relating to the viability of off-peak heating, they are to be simulated in a slightly more realistic context. Part of that is to establish an improved version of WinDesign, the primary function of which is to implement variable internal load, and also to use slightly more pessimistic inputs, which will be introduced afterwards.

Winter and summer venting

One problem that can occur in WinDesign is that sometimes the results will yield a higher heating demand than necessary, when a high venting rate is used, which should not cause a higher heating demand. Ideally, when the venting is enabled at a certain set-point, e.g. a room temperature of 23 °C, it should only cool the room down to a certain point, e.g. the heating set-point of 20 °C. What happens instead is that due to the hourly calculation method, the venting is applied for a full hour, even though it may only need a few minutes to cool the room. Thus the venting continues even though the room temperature is 20 °C, which results in an additional heating demand.

This creates some irregular heating patterns with sudden spikes in hourly heating demand, and it most often happens either in the spring or autumn, where overheating can still occur but the outside air is cold enough to be able to cool the room from 23 °C to 20 °C in less than an hour.

It can be said that the problem in general is not great enough to warrant any worry over increased heating demand, but since the problem can become noticeable in some rooms, it is attempted to try and minimize this excess heating demand.

There are ways to do this without changing the program – for example by increasing the venting set-point from 23 °C to 24 °C or lowering the venting rate. These will diminish the problem but it is perhaps not ideal since both also yield more overheating hours.

A perhaps better way to deal with the problem is to alter the program to utilize different summer and winter venting rates. This way, a low venting rate can be used in the winter, where it is less needed, and a high venting rate can be used in the summer where it is most needed. To accompany this, is the ability to change the length of the summer period, and with some tuning of this period, it is possible to eliminate some occurrences of this excess heating demand. Thus venting rates calculated from SBi-213 [11] can be used, which were between 3.9 and 4.2 h-1 for the south rooms, instead of inputting a lower value of e.g. 3 h^{-1} in the attempt to reduce the additional arbitrary heating demand. Therefore, this change will mostly result in a reduction of overheating hours.

Variable internal load

Until now the internal load has been assumed to be 3 W/m^2, which was deemed more realistic for a house in the year 2035 with more efficient appliances. By itself it is a more demanding value than e.g. 5 W/m^2 in regard to heating demand, but the fact that it is static is perhaps somewhat optimistic, since in reality the internal heat load varies greatly during the day according the current use of a given room. For example, the living room might have a high internal load in the evening while the bedroom might have a low internal load during the day.

Therefore, WinDesign was changed to allow the user to specify different internal loads depending on the time of day, the type of room and whether it is weekend or not. In order to determine realistic values, Table G.8 of ISO 13790 [8] was utilized, and since it is designed for an internal load of 5 W/m^2, all values are being adjusted with the same factor in order to reach an average of 3 W/m^2 for the house as a whole.

Table 66 - The internal heat load schedule for two room types as described in [8], scaled to reach a sum of 3 W/m^2

Internal load	Hours	Living room and kitchen [W/m^2]	Other areas [W/m^2]
Monday to Friday	07 to 17	4.3	0.5
	17 to 23	10.9	0.5
	23 to 7	1.1	3.3
	Average	4.9	1.4
Saturday and Sunday	07 to 17	4.3	1.1
	17 to 23	10.9	2.2
	23 to 7	1.1	3.3
	Average	4.9	2.1
Average		4.9	1.6
Area-weighted average		**3.0**	

As seen on table 66, using the ISO 13790 standard as a guide, the internal load varies from 0.5 W/m^2 in an unused bedroom to 10.9 W/m^2 for a kitchen or living room in use, hence this model can put more stress on the simulations than with an evenly distributed internal load, both with regard to heating demand and overheating hours. For example the internal load might not be very high when it is most needed, or it might be higher than desired on a hot summer day.

Overall, it should make it harder to obtain desirable results from the simulations, but it can be discussed whether the above schedule is representable for a real dwelling, with only two represented rooms. Therefore the model is expanded to represent four rooms instead.

Table 67 – Internal load schedule expanded to include four room types

Internal load	Hours	Living room + kitchen [W/m^2]	Bedroom [W/m^2]	Regular room [W/m^2]	Bath + hallway [W/m^2]
Monday to Friday	07 to 17	2.5	1.0	1.0	1.0
	17 to 23	8.0	1.0	6.5	2.0
	23 to 7	1.5	5.0	5.0	1.0
	Average	3.5	2.3	3.7	1.3
Saturday and Sunday	07 to 17	3.0	1.0	4.5	1.0
	17 to 23	8.0	3.0	3.0	2.0
	23 to 7	1.5	5.0	5.0	1.0
	Average	3.8	2.8	4.3	1.3
	Average	3.6	2.5	3.9	1.3
Area-weighted average		**3.0**			

On table 67, the model the internal loads can be seen for different times of the day across the different rooms. The bathrooms can now be simulated with a minimum of heat load, since occupants spend less time there compared to other rooms. Another difference is the differentiation between bedroom and regular room, allowing the regular room to be used as a children's bedroom, with activity in the afternoon also. The following results include the variable internal load as well as the summer and winter venting.

Table 68 – Heating demand results with the new WinDesign with variable internal load and the old WinDesign

Heating demand – Design 2			New WinDesign		Original WinDesign	
			Heating demand	Overheating hours	Heating demand	Overheating hours
Room	Orientation	Room type	[kWh/m^2 year]	$T_i > 26$ °C	[kWh/m^2 year]	$T_i > 26$ °C
Room 1	South	Room	0.9	21	2.3	52
Room 2	South	Living room/kitchen	0.2	33	0.6	36
Room 3	South	Living room	0.3	23	0.6	28
Room 4	West	Bedroom	9	15	7.5	33
Room 5	North	Bath	10.6	0	3.7	0
Room 6	North	Room	7.2	8	5.4	15
Room 7	North	Hallway	22.4	0	10.1	0
Room 8	North	Utility	9.6	0	2.8	0
Room 9	North	Room	6.1	6	9.7	0
Room 10	East	Bath	8.3	0	1.8	0
		Total - weighed	**4.67**		**3.51**	

It is seen that the variable internal load has decreased the heating demand in living rooms due to the higher load, but the heating demand of some secondary rooms have increased significantly, such as in the hallway and the bathrooms. There are also fewer overheating hours, which can be contributed to the summer and winter venting addition in the new WinDesign. The annual heating demand has increased to $4.67 \frac{kWh}{m^2 year}$.

In general it can be seen that internal load is a somewhat significant factor for a house. The specifics of the numbers in the internal load schedule can be discussed but overall the model should be more representative of a real house.

10. More realistic inputs

Now that the new version of WinDesign has been established, the next step is to implement some less favorable inputs than previously used, with the aim of attaining results more representable for a real house.

Increased interior temperature – 22 °C

The heating set-point of 20 °C is perhaps slightly low, and occupants in general would perhaps prefer a slightly higher, more comfortable temperature such as 22 °C. The problem is that increasing the temperature set-point will result in an increased heat loss due to the increased temperature difference between the interior and the exterior.

At a glance an additional 2 °C of internal temperature does perhaps not seem noteworthy, but it can have a somewhat significant impact on the heating demand of a house. In order to reach an interior temperature of e.g. 20 °C, some of the heat is supplied by the internal load and the rest is supplied by the room heating. Assuming stationary conditions, if the internal load on a given day is able to raise the internal temperature to e.g. 15 °C, then the rest can be estimated to be supplied by space heating, corresponding to an increase in 5 °C. If the aim is 22 °C, then that increase from 15 °C is 7 °C, corresponding to an increase in 40% compared to the 5 °C, which has to be supplied by the space heating. It is a very simplified example, but it can be seen that a temperature increase to 22 °C is not an insignificant change, but perhaps as a realistic one. This should increase the annual heating demand more than the maximum daily heating demand, since the 2 °C increase is less significant if for example the exterior temperature is -12 °C on a cold winter day. In order to accommodate the increases temperature, the venting set-point in WinDesign has been increased from 23 °C to 24 °C.

Infiltration – 0.05 h-1

So far in the simulations, an infiltration of 0 has been applied due to the assumption that the house is very air tight. This is perhaps not a reasonable assumption, since infiltration also includes occasional air intake from e.g. door openings, so even with a very tight house, the infiltration would not be 0. According to SBi-213 [11], the infiltration is as follows:

- In use: $0.04 + 0.06 \cdot q50$ [l/s m^2]
- Not in use: $0.06 \cdot q50$ [l/s m^2]

Where q50 is the blower door test with a pressure difference of 50 Pa. Typical values for low energy houses is found from Komforthusene [9] where the values range between 0.16 and 0.35 l/(s m^2). If the value is assumed to be 0.16 l/(s m^2), then the resulting infiltration can be seen on table 69.

Table 69 – Infiltration values

Infiltration	[l/s m^2]	[h^{-1}]
In use	0.050	0.071
Not in use	0.010	0.014
Weighed – in use $^2/_3$ of the time	0.036	**0.052**

As can be seen on table 69, if the building is assumed in use 2/3 of the time, the additional air change due to infiltration becomes 0.052 h^{-1}. At a glance this can seem like an insignificant number and it is approximately a factor 10 lower than the mechanical ventilation, but it is important to remember that the infiltration does not benefit from the 91% heat recovery and thus the actual heat loss between the two can be seen as similar.

Results

Now that the more realistic inputs have been established, along with the improved version of WinDesign, the results will be presented for both the reference house and Design 2.

Table 70 – Heating demand results with the new WinDesign and the more realistic inputs, for Design 2 and reference house

Heating demand – Design 2			Design 2		Reference house	
			Heating demand	Overheating hours	Heating demand	Overheating hours
Room	Orientation	Room type	[kWh/m^2 year]	T_i > 26 °C	[kWh/m^2 year]	T_i > 26 °C
Room 1	South	Room	3.2	32	7.5	32
Room 2	South	Living room/kitchen	2.2	63	4.0	48
Room 3	South	Living room	2.5	44	5.4	54
Room 4	West	Bedroom	15.2	26	25.0	22
Room 5	North	Bath	16.9	0	22.0	0
Room 6	North	Room	14.1	13	18.6	11
Room 7	North	Hallway	31.9	1	43.1	22
Room 8	North	Utility	15.8	0	20.9	3
Room 9	North	Room	11.6	14	20.6	18
Room 10	East	Bath	14.1	0	20.5	209
		Total - weighed	**8.81**		**13.85**	

It is seen from table 70 that with more realistic inputs and the improved WinDesign, the heating demand is now 8.81 $\frac{kWh}{m^2 year}$ for Design 2 and 13.85 $\frac{kWh}{m^2 year}$. These numbers can then be seen as more representative of the annual heating demand of the houses, and will be used in the economic evaluation of the viability of electric off-peak heating.

Table 71 – Estimated temperature rise in the concrete slab with the new WinDesign and realistic inputs

			Temperature rise [K]	
	Orientation	Room type	Design 2	Reference house
Room 1	South	Room	1	1.5
Room 2	South	Living room/kitchen	0.5	0.5
Room 3	South	Living room	0.5	1
Room 4	West	Bedroom	1.5	2.5
Room 5	North	Bath	1.5	1.5
Room 6	North	Room	1.5	2
Room 7	North	Hallway	2	3.5
Room 8	North	Utility	1	1.5
Room 9	North	Room	1.5	2
Room 10	East	Bath	1	2

It can be seen from table 71 that the potential problem with temperature rise in the concrete is reduced in Design 2, due to the lower heating demand, but increased overall, especially in northern rooms.

Table 72 – Maximum heating demand on a cold winter day with the new WinDesign and realistic inputs

Maximum daily heating demand			Design 2		Reference house	
			21 dec		21 dec	
Room	Orientation	Room type	[kWh]	[Wh/m^2]	[kWh]	[Wh/m^2]
Room 1	South	Room	1.9	117	2.9	183
Room 2	South	Living room/kitchen	2.7	81	4.1	121
Room 3	South	Living room	3.3	91	5.4	149
Room 4	West	Bedroom	3.6	184	5.3	271
Room 5	North	Bath	1.5	158	1.7	186
Room 6	North	Room	1.7	153	2.2	196
Room 7	North	Hallway	1.4	221	2.3	370
Room 8	North	Utility	1.5	143	2.0	192
Room 9	North	Room	2.4	150	3.8	244
Room 10	East	Bath	0.7	132	1.2	230
		Total [kWh]	**21**		**31**	
		Power – 6h [kW]	**3.4**		**5.1**	

It is seen from table 72 that with the new inputs, the maximum daily heating demand is 21 kWh for Design 2 and 31 kWh for Reference house. Under the previous simple assumption regarding the 1800 MW difference in national consumption between the off-peak period and the rest of the day, the electric off-peak heating could potentially be conducted in 529,412 houses with Design 2 and 352,941 houses with the reference house. It is difficult to conclude further in this regard, but in general it can be said that the off-peak heating is perhaps unlikely to cause a problem for the grid unless it is utilized in a very large number of houses.

11. Hot Water Demand

As with the demand for space heating, it could also be interesting to investigate the possibilities of supplying the hot water demand with electricity, during the off-peak period between 00:00 and 06:00. Unlike with the space heating demand, the actual house and installations has only limited impact on the hot water consumption. The pipes and tank can be well insulated, but that only reduces the loss, which is not necessarily a large part of the total energy consumed for hot water demand. Some families might install water saving measures such as a water conserving showerhead, while others might take very long showers; hence the amount of hot water consumed is dependent upon behavioural patterns of the occupants and not the house itself, making the hot water demand somewhat unpredictable, and this can present some challenges regarding the size of the hot water tank for off-peak electric heating.

Annual hot water demand

The annual hot water demand is calculated according to EN15316-3-1 eq. 3 [10] where the daily volume of domestic hot water, $V_{W,f,day}$, is found.

$$V_{W,f,day} \frac{x \cdot \ln(f) - y}{f} = 0.68 \frac{l}{m^2\, day} \rightarrow 111 \frac{l}{day}$$

Where f is the floor area of 163 m^2 and x, y and z are given constants of 39.5 l/day, 90.2 l/day and 1.49 l/(m^2 day) respectively. The hot water volume of 111 l/s is consistent with the SBi-213 assumption of an annual consumption of 250 $\frac{l}{m^2\,year}$ = 111.6 $\frac{l}{day}$.

With an assumed hot water temperature of 55 °C, the necessary energy can be found from eq. 1 [10]:

$$Q_w = 4182 \cdot V_{w,day} \cdot \left(\theta_{W,del} - \theta_{W,0}\right) = 20.8\frac{MJ}{day} = 5.8\frac{kWh}{day} \rightarrow 2120\frac{kWh}{year}$$

Where $V_{w,day}$ is the daily hot water volume in m^3, $\theta_{W,del}$ is the hot water delivery temperature of 55 °C and $\theta_{W,0}$ is the cold supply temperature assumed to be 10 °C.

Thus the annual hot water demand is estimated to be 2120 kWh/year, and according to Dong Energy [21] the hot water consumption of a typical occupant is 850 kWh. Therefore this annual consumption is representative of the consumption of 2.5 typical occupants. The annual consumption can be used along with the annual heating demands to estimate the economic viability of electric heating in the off-peak night period. The daily hot water demand of 5.8 kWh can be supplied with an electric effect of 1kW during the six off-peak hours during the night; hence the total electric load during the cold winter night becomes 4.4 kW and 6.1 kW for Design 2 and the reference house, respectively.

Hot water tank dimensioning

Ordinarily, the size of a hot water tank is determined from an assumption that with a given charging power it should be able to provide a sufficient supply of hot water in a critical draw-off period that lasts a certain time, for example 65 minutes, and contains a number of different draw-offs for example 4 showers, 2 kitchen washes and 4 hand washes, as specified in DS439 [12]. Therefore a tank with a volume of e.g. 100 L or 160 L is found to be acceptable for a single family house under regular circumstances. If heating of the water is only permitted during the off-peak period during the night, then all the hot water consumed during the day has to be stored in the tank, which necessitates a larger tank.

Large tank – only night charging allowed

One way to try and diminish the problem of a large tank could be by utilizing a higher tank temperature, separated from the domestic hot water with a heat exchanger in order to reduce the volume of hot water in the tank needed to supply water at 55 °C. By for example charging to 88 °C, the necessary tank volume can be reduced by roughly 42 %. This could also eliminate the problem of lime build-up in the tank that occurs with temperatures above 55 °C, since the water in the tank is storage water and is not replaced as hot water is consumed.

From DS439 [12], typical hot water tapping types such as shower and hand wash have been found along with the corresponding hot water energy consumption. These have been used in an attempt to construct a dimensioning scenario which represents a day with a high water consumption for a house with a bath tub.

Table 73 – Possible domestic hot water consumption on a day with a large demand

Type	Tappings	Energy per tapping [kWh]
Bath tub	2	4.4
Shower	6	1.5
Kitchen wash	6	0.6
Hand wash	8	0.4
Small tapping	10	0.1
	Total	**25.0**

It can be seen that the above scenario is several times higher than the average daily demand of 5.8 kWh, which can partly be contributed to the use of a bath tub. Corresponding tank volumes have been found, for 55 °C and 88 °C, with an assumed ratio of 1.4 between total and effective tank volume.

Table 74 – Necessary tank sizes for a hot water demand of 25 kWh

Tank temperature	55 °C	88 °C
Effective tank volume [L]	504	291
Total tank volume [L]	706	407

As can be seen on table 74, with the scenario from table 73, even with a tank temperature of 88 °C, the tank volume becomes 407 L, which can perhaps be seen as somewhat excessive. The problem is that even with such a size of the tank, if no additional charging is allowed during the day, is it perhaps not unlikely that a day occurs where all the hot water is consumed, if for example a family has visiting guests who also need showers, hence even with a large tank and a high temperature, it is not a given that all needs can be covered. This is specifically a problem if no additional charging is allowed during the way, which would perhaps not occur with a more ordinarily sized tank, since it would be able to recharge between the different peak loads throughout the day.

In addition, there is the stationary heat loss of the tank to consider, which is greater for a large high temperature tank due to the relatively larger increase in temperature difference between ambient and tank temperature for a high temperature tank as well as the increased surface area.

Below, the stationary heat loss has been calculated from empirical formulas [26] for both a regular tank and a large high temperature tank, for two different insulation thicknesses.

Table 75 – Stationary heat loss for two tank types for different tank insulation thicknesses

24h tank loss [kWh]	Tank insulation	
Tank type	10 cm	20 cm
407L – 88 °C	1.3	0.8
150L – 55 °C	0.4	0.3

It can be seen on table 75 that compared to the calculated daily average consumption of 5.8 kWh, the heat losses are not insignificant for the large high temperature tank, although it can be reduced by use of thicker insulation. Due to this, as well as the large necessary tank volume and the fact that it uncertain whether it will be able to cover the demand on a demanding day, it does not seem attractive to only charge during the off-peak period in the night. Due to this, a compromise is investigated.

Reduced tank size – occasional additional charging allowed

In the case of space heating, one of the incentives to only heat during the off-peak hours at night with electricity is to reduce the strain on the electric grid. This can be seen as somewhat important for space heating since the peak loads of space heating are dependent upon the weather, hence if a large number of electrically heated houses need to heat during the same hours, it would perhaps create an unnecessary strain on the grid system.

The peak loads of the domestic hot water demand are more dependent upon occupant behavior, which means the few days in which the occupants of a given house consume large amounts of hot water can occur at any day of the year; hence the risk of stacked peak loads is less of a concern. With this in mind, a different approach is proposed: a tank which is large enough to cover the daily hot water demand on most days, for a family without a bathtub, where charging in the day is allowed in order to cover the demanding days.

From EN15316 Table A.2 [10], an example of an average daily tapping for a family is presented, with a daily hot water energy demand of 5.8 kWh, the same as previously calculated. It is assumed that a tank containing twice that amount would likely be able to cover the hot water demand on most days.

Table 76 – Necessary tank volume on a demanding day without a bath tub and with charging allowed during the day

Tank temperature	60 °C	88 °C
Capacity [kWh]	11.6	11.6
Stationary heat loss [kWh]	0.3	0.5
Effective tank volume [L]	200	128
Total tank volume [L]	279	179
Tank volume – rounded up [L]	300	200

As can be seen on Table 76, with an estimated necessary capacity of 11.6 kWh, the tank volume would need to be either 300 L or 200 L, depending on the temperature, and could feasibly be charged only during the six off-peak hours of the night, on most days.

If for example a hot water heater from Metro Therm of either 200 L or 300 L is utilized, the default heating element has an effect of 3 kW, which would be able to heat the water to 65 °C, and a larger heating element of 9 kW can be installed in order to heat the water to 88 °C. It can be said that the larger heating element could also be installed in the 60 °C 300 L tank, which could perhaps allow for a higher degree of tank discharge with no recharging during the day, without risking complete discharge of the tank.

12. Economic evaluation of electric heating in the off-peak period

The hot water demand has been estimated, along with the annual heating demand, and therefore the potential savings of off-peak heating can be estimated.

Current conditions

According to Our Future Energy [1] it is the ambition of the Danish government to promote initiatives regarding a more intelligent electric grid, part of which is to establish agreements with grid companies on the installation of intelligent electricity meters, and to incentivise dynamic tariffs. Today, half of all Danish consumers of electricity have an intelligent electric meter installed today, and it is the plan to install the last meters before the year 2020.

The possible savings regarding purchasing electricity at a lower off-peak price will be estimated, and the frame of reference will be the Nordpool spot prices. Nordpool is an exchange market where power is traded by companies in the Nordic and Baltic countries at hourly prices set according to supply and demand, which is why the prices will generally follow the market demand, resulting generally in lower prices in the off-peak and higher prices during peak hours. It is not possible for the individual consumer to purchase electricity at the Nordpool exchange, but different subscription models are available which support hourly prices corresponding to the Nordpool spot price.

Nordpool offers previous prices from nordpoolspot.com, and the spot prices from the heating season 2013 were used to determine the average hourly spot price of electricity, which can then be compared to the average spot price for the hours between 06:00 and 00:00 of 0.37 kr/kWh incl. VAT during the same period.

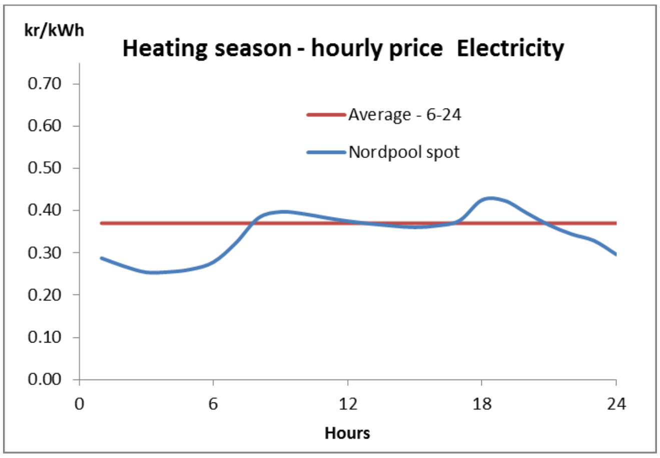


Figure 15 – The average hourly variation of the spot price during a day in the heating season, with the average value between 06:00 and 24:00 shown as the red line

As can be seen, the hourly price curve from Nordpool follows roughly the same pattern as the graph of the Danish national hourly electricity consumption in figure 3 (introduction), with peaks in the morning and evening, and a lower price during the night. In comparison, the static price is cheaper during the peaks but more expensive at night.

These numbers are used to estimate the potential savings of purchasing electricity at night at the Nordpool spot prices in the six off-peak hours during the night as opposed to purchasing it the rest of the day, where heating is more often needed for domestic hot water and space heating.

Table 77 – Average spot prices for the off-peak period from 00:00 to 06:00 and the rest of the day

	Prices [kr/kWh]
Spot 00:00-06:00	0.27
Spot 06:00-24:00	0.37
Difference	**27.8%**

As is seen on table 77, the difference in electricity price between off-peak spot price and the average price is 27.8%, but the actual price of electricity does not constitute a large part of the total price, since the total price includes the following added costs.

Table 78 – A list of the added costs that constitute the electricity price

Added costs	kr/kWh
Distribution	0.36
Public service obligation	0.19
Electricity tax	0.41
Total	0.96
Total incl. VAT	1.20

Therefore it can be said that the savings from purchasing electricity at night are somewhat diminished by the added costs of taxes and distribution. One positive aspect to this is that in 2013 the electricity tax was lowered for houses with electricity as the primary heating source. Thus for the first 4000 kWh, which is regarded as the average consumption of appliances, an electricity tax of 0.83 kr/kWh applies, and for all consumption above 4000 kWh, regarded as the electricity towards heating, a lower electricity tax of 0.41 kr/kWh applies.

Table 79 – The estimated average electricity prices for space heating at off-peak hours and the rest of the day

Electricity price incl. taxes	Prices [kr/kWh]
Spot 00:00-06:00	1.47
Spot 06:00-24:00	1.57
Difference	6.5%

As can be seen on table 79, the potential savings due night heating in the low-peak period is 6.5% with spot prices. With these prices, the following annual savings are found under the assumption that all heating towards domestic hot water and space heating is supplied by electricity during the six off-peak hours as opposed to the rest of the day.

Table 80 – Annual heating demands for domestic hot water and space heating with the corresponding estimated savings due to off-peak electricity consumption

	Reference house	Design 2
Domestic hot water	2120 kWh	2120 kWh
Space heating	2321 kWh	1439 kWh
Total heating	4441 kWh	3559 kWh
Price, 00:00-0600	6528 kr	5231 kr
Price, 06:00-24:00	6986 kr	5598 kr
Annual savings	457 kr	367 kr

As can be seen on table 80, the potential savings by purchasing the electricity at Nordpool spot prices during the off-peak period in the night is estimated to 457 kr for the reference house and 367 kr for Design 2.

These savings can perhaps be seen as somewhat modest, and one problem in this regard is also the heavy, static costs of taxation and distribution of the electricity, which constitute 80% of the total price, even after the 0.42 kr/kWh reduction in the electricity tax from electric heating; hence any gain from the actual buying price of electricity is diminished. It can therefore be said that a variable tax could be an interesting way to incentivise the consumption of electricity in off-peak periods, or perhaps in periods in which an excess of wind power is available regardless of the time of day. If the taxes and distribution tariffs varied according to the time of day with the same curve as the Nordpool prices, the potential savings could be seen on table 81.

Table 81 – Potential savings if the distribution and taxes followed the same curve as the spot price

	Reference house	Design 2
Total heating	4441 kWh	3559 kWh
Price, 00:00-0600	3919 kr	3140 kr
Price, 06:00-24:00	5428 kr	4350 kr
Annual savings – Dong	1510	1210
Difference	27.8%	27.8%

It can be seen that with variable taxes and distribution costs, the potential for savings becomes greater; hence the consumer would have an actual economic incentive to speculate in the electric consumption of the house and perhaps invest in intelligent appliances which could take advantage of the variable price. It can be said that it would be very unrealistic for the whole tax and distribution part of the electricity price to fluctuate in a similar way as the spot price, and this would likely add an unreasonable cost to companies and families unable to adjust to the prices. But as long as the taxes constitute a vast majority of the price, the potential savings are diminished, and therefore it could perhaps be beneficial for the grid as a whole if the taxes somehow dis-incentivized the consuming of electricity in peak periods or periods of low availability of electricity, and added an additional incentive to consume electricity when it is readily available. This would perhaps also have a positive impact on the overall price of electricity in the future, where a smoothing of the daily peaks in consumption could perhaps limit the need for backup generators or additional wind turbines.

The increase of wind power

Regardless of variable tax, with the implementation of intelligent electric meters and more advantageous tariffs, there are indications that the potential for savings will be greater in the future, due to a larger portion of the electricity being produces by wind turbines and coal plants have been phased out along with other non-renewable sources.

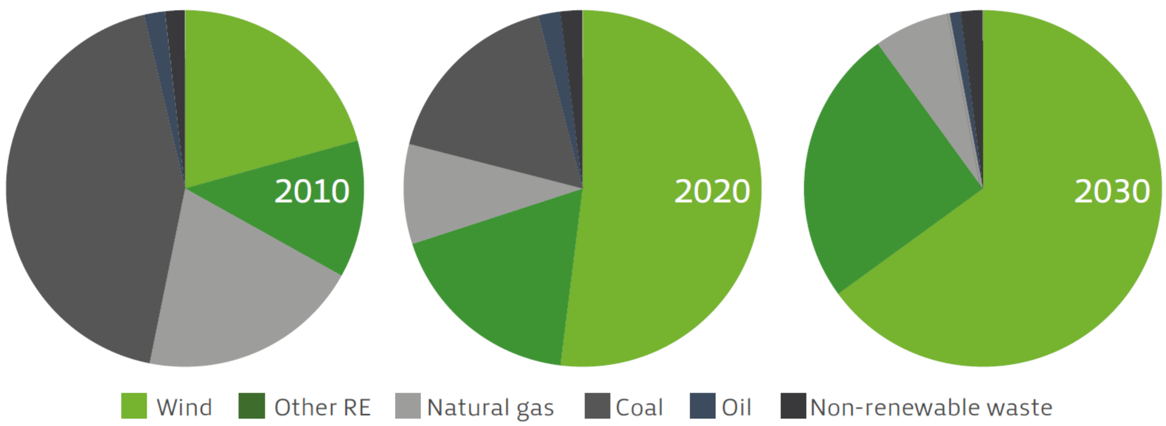


Figure 16 - Electricity production by energy source [1]

As can be seen on figure 16, according to the climate plan from the Danish government, by the year 2020, wind turbines will constitute 50% of the Danish electricity supply, increasing further to approximately 65% in 2030. In contrast, the ambition is for coal, which a cheape but highly polluting source, to be phased out completely in 2030. Due to this, as the transition towards sustainable energy with a majority of wind energy occurs, the price could perhaps change in several ways. Since coal is a cheap source of energy, the production price is likely to rise, which means the total price of electricity could amount to a larger percentage of the total price than today; hence given the same spot price curve, the 27.8% difference between spot prices at night and day price should become more significant to the overall price.

With coal power the electricity output can be better controlled and lowered according to demand, for example during the night, and while the wind is slightly stronger during the day, the turbines are not immediately controllable, and will continue to produce electricity throughout the night depending on the wind feed. This means that as wind power becomes more prevalent, a natural surplus of electricity could occur at night, which could result in a lower hourly price at night, relative to the rest of the day.

Another consequence of the fact that the wind turbines are not immediately controllable is a general necessity of overproduction in order to ensure the necessary level of production in periods of low wind, which could increase the electricity price, perhaps resulting in a proportionally larger production price in relation to taxes, which increases the potential for off-peak savings.

In addition to the overall increase in production price, there is also the possibility that the peak prices will increase, for example due to the possibility that activating the more expensive backup turbines might be necessary in order to cope with demand during low wind periods, in which case it will perhaps be more attractive to avoid consuming electricity during the peak periods in the future. This corresponds well with the expectation from Smart grid strategy [28], that spot prices will fluctuate more in the future.

It can be seen that there are multiple opportunities for off-peak night heating and general speculation in the energy price to become more attractive as wind turbines cover a larger part of the national electric supply, but in order to help finance the expansion of renewable energy, according to Our Future Energy [1], the plan is to increase both the PSO part of the taxes and grid tariffs in general. Therefore it can be said that there is a possibility that the positive aspects of increased wind turbine power supply could be outweighed by increased static taxes. Overall it can be said that in relation to electric off-peak night heating, the annual savings are unlikely to be meaningful compared to heating as needed during the entire day.

13. Economic viability of direct electric heating

Since the night heating with direct electricity can be seen as acceptable in relation to the grid strain, concrete temperature rise and hot water tank size, and a slight potential for savings has been found due to the lower hourly prices at night, the next step is to find out whether it can be seen as an economically viable method of heating, as opposed to supplying the heat with a heat pump.

The advantage of a heat pump is that it has a coefficient of performance (COP) in the excess of 4, which enables it to supply the same heat as a direct resistance heating element while only consuming a fraction of the electricity.

The disadvantage is that a heat pump represents a somewhat significant investment. From [13] and [14], the following estimated prices have been found for both the installation of an air-to-water heat pump and a geothermal heat pump.

Table 82 – Price examples of the total costs regarding investment in a heat pump [13][14]

Geothermal heat pump	Estimated price [kr]
Heat pump Vølund Fighter 1245 6kW, integrated hot water tank, Bufferunit, ground loop, brine.	88,750
Installation	18,750
Electrical work	6,000
Burying of ground loop	12,500
Total	126,000

Air-to-water heat pump	Estimated price [kr]
Nibe Split Interior module ACVM 270 Exterior module AMS 10	88,750
Installation	16,250
Electrical work	9,000
Total	114,000

It can be seen that at 126,000 kr and 114,000 kr, both systems present a somewhat significant investment.

One difference between geothermal heat pump and an air-to-water heat pump is the lifetime, which is slightly shorter for an air-to-water installation. This is partly due to the Danish weather, where the temperature often shifts between frost and thaw, in addition to the salty air, which puts an additional strain on the air-to-water heat pump. This puts the estimated lifetime at 15 years, as opposed to around 20 years for a geothermal heat pump. The lifetime is an important factor in the economic consideration of investing in a heat pump.

Another important factor is the coefficient of performance (COP), which determines the savings each year. The Danish Energy Agency [15] has listed a number of heat pumps with the best performance in the Danish climate along with their corresponding Seasonal COP, which is a measure for the average COP throughout the heating season. This is generally higher for geothermal heat pumps, which for the listed pumps range from 4.36 to 5.46. For the air-to-water heat pumps the SCOP is generally slightly lower at between 3.20 and 3.90. This is due to the fact that the geothermal heat pump is less dependent upon the exterior temperature, since the loop is buried in the ground.

Therefore the geothermal heat pump is the most immediately attractive of the two heat pump types, provided there is a garden available for the burying the ground loop. Since a heat pump has a high coefficient of performance, it can be said that there is perhaps little reason to engage in the off-peak heating.

The question is then whether or not it is economically feasible to invest in a heat pump given the low demand for heating in the houses. In order to try and determine that, a simple economic payback calculation is carried out.

The investment costs of the electric system are estimated to 8,169 kr for a 300 L electric water heater from Metrotherm, since the heat pump solutions include a hot water tank. An additional 10,000 kr is added, to account for other additional costs, such as a control system, to account for that being included with the heat pumps.

The electricity price is assumed to be 0.37 kr/kWh for the heat pump, resulting in a total price of resulting in a total price of 1.57 kr/kWh, including the reduction in the electricity tax of 0.43 kr/kWh for space heating. The annual price increase is estimated to be 4%, corresponding to the average increase in prices from Dong Energy between 1990 and 2010 [16]. The electricity towards direct electric heating is assumed to be 0.10 kr/kWh cheaper, corresponding to the potential savings from supplying the heat in the low-peak period at spot prices.

The annual maintenance costs of the heat pump is estimated to be 2000 kr, which corresponding to one legally required maintenance inspection every year.

Among the list of heat pumps suitable for the Danish climate from the Danish energy agency [15], a geothermal heat pump called GEO3 from Nilan has been found with a low effect of 3 kW to suit the general low heating demand of the houses, and a high seasonal coefficient of performance of 5.17. The price is for the heat pump itself is 15,000 higher for the Nilan GEO3, than for the Vølund Fighter 1245, used in the price example above, which brings the total investment to 141,400 kr.

With these assumptions, the economic viability of the heat pump investment is evaluated with a simple economic calculation that can be seen in table 83.

Table 83 – Estimated expenses over a period of 20 years for a heat pump and direct electricity

Geothermal heat pump	Reference house		Design 2	
	Heat pump	Direct electricity	Heat pump	Direct electricity
Initial costs [kr]	141,464	18,169	141,464	18,169
COP [-]	5.17	1	5.17	1
Annual consumption [kWh]	859	4,441	688	3,559
Initial electricity price [kr/kWh]	1.57	1.47	1.57	1.47
Electricity price 20 years [kr/kWh]	3.31	3.21	3.31	3.21
Initial annual electricity cost [kr]	1,351	6542	1083	5,242
Annual maintenance [kr]	2,000	0	2000	0
Initial annual expense [kr]	3,351	6542	3083	5,242
20 year expense [kr]	**221,700**	**225,282**	**213,706**	**177,474**

As can be seen on table 83, the difference in expenses after 20 years, between the heat pump and direct electricity, are close for the reference house and 36,000 kr for Design 2. The cumulative costs througout the years can be seen below.

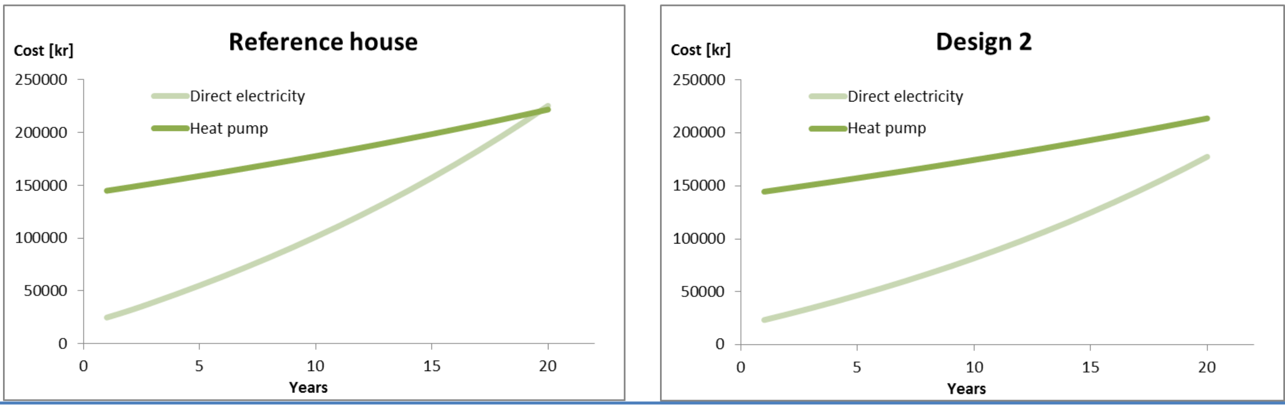


Figure 17 –Estimated expense curves for heat pump and direct electricity over a period of 20 years

It can be seen that that the investment has narrowly paid off after 20 years for the reference house, and has not paid off for Design 2. In either case, it can be said that it is perhaps not attractive to invest in a heat pump to supply heat, due to the low heating demand of the houses. One of the problems in this regard is the additional expense of the legally required annual maintenance, which is higher than the expenses towards electricity, hence it somewhat limits the annual savings. In contrast, it is perhaps also a prerequisite for a long lifetime of the heat pump, and for the high seasonal COP of 5.17, and it can be seen that the although the annual savings for the heat pump increase throughout the years due to the estimated 4% annual increase in electricity price throughout the years, it is perhaps not enough to make up for the initial investment.

It can be said that an investment in an installation that only narrowly pays off in the last year of the estimated lifetime of said installation is perhaps not a sensible investment. In addition, although there is an annual maintenance, there is no guarantee that the heat pump lasts 20 years. According to [17], a geothermal heat pump has an estimated lifetime between 14 and 20 years, hence ideally the heat pump should not have paid itself off later than e.g. 12 years, in order for the person investing in the heat pump to see it as a somewhat worthwhile to spend more than 100,000 on a heat pump. From this assumption that the heat pump should have a 12 year payback time in order for it to not be seen as an uninteresting investment, the following allowable prices have been calculated, for seasonal COPs of 5.17, representing the highly effective heat pump capable of handling the Danish weather, as well as 4.0 and 3.5, representing a slightly less efficient heat pump that is perhaps also slightly cheaper.

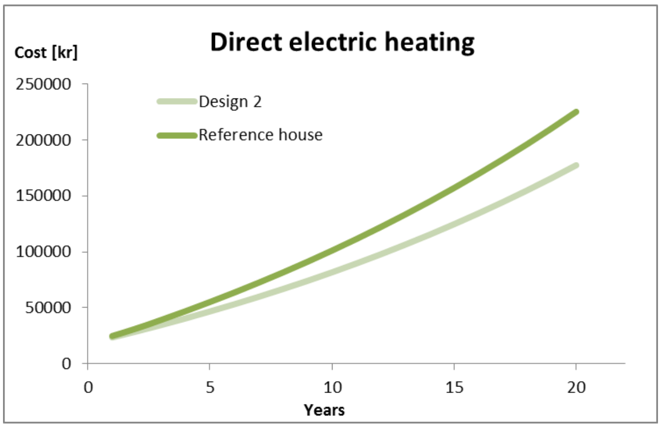
Table 84 – The estimated allowable costs of the heat pump if it is to be seen as a not uninteresting investment

12 year payback time	Reference house
Seasonal COP [-]	Heat pump allowable cost [kr]
5.17	78,000
4.0	72,000
3.5	68,000

It can be seen from table 84 that the cheaper heat pump with a lower seasonal COP also results in lower savings. Regardless of the efficiency of the heat pump, the prices above do not permit the purchase and installation of a heat pump with the necessary equipment such as ground loop and buffer tank, even if perhaps some of the additional expenses could be reduced due to the fact that the system is to be installed into a new house. Therefore it can be said that a heat pump is unlikely to be a worthwhile investment from an economic standpoint, for both the reference house and Design 2.

Product prices

From the heat pump calculations, it could be seen that the expense towards electric heating was somewhat different between Design 2 and the reference house.



Direct electric heating	Reference house	Design 2	Difference
20 year expense [kr]	225,282	177,474	47,808

Figure 18 – Comparison between the expenses after 20 years due to direct electric heating

As can be seen on figure 18, the estimated difference in the electric bill between Design 2 and the reference house after 20 years is 47,808 kr, which is due to the fact that Design 2 has a lower demand for space heating of 1439 kWh compared to that of the reference house. The reference house has a space heating demand of 2321 kWh and both designs have an assumed hot water demand of 2120 kWh.

To put this into perspective, it could be interesting to know to estimate the additional costs of Design 2 compared to the reference house. First the CCE prices are examined for the two designs, as seen in table 85.

Table 85 – CCE prices for the wall, floor and roof of the reference house and Design 2

Design 2	Insulation type	Insulation thickness [mm]	Total thickness [mm]	$\lambda_{insulation}$ [W/mK]	U [W/m²K]	CCE [kr/kWh]
Floor	Sundolitt S80	530	780	0.038	0.059	**3.26**
Roof	Isover murfilt 32	1090	1140	0.032	0.029	**3.25**
Wall	Kingspan Kooltherm K8	410	480	0.021	0.056	**3.29**
Reference house						
Floor	Sundolitt S150	750	1000	0.036	0.044	**14.32**
Roof	Paper wool	1000	1050	0.040	0.039	**1.14**
Wall	Isover murfilt 32	400	560	0.032	0.074	**3.24**

As can be seen on table 85, the CCE prices can be seen as somewhat uneven for the reference house, with a CCE of 14.32 kr/kWh for the floor and 1.14 kr/kWh for the roof; hence the floor design is an expensive solution.

Next the designs are compared by calculating the costs of those of the building components that differ between the two designs, such as insulation and excavation. These costs have been calculated from prices found in [19] as well as the program CCE-calc.

Table 86 – Costs of insulation and other materials for the reference house and Design 2

Reference house	Area	thickness	volume	Volumetric price	Cost
Insulation	[m^2]	[m]	[m^3]	[kr/m^3]	[kr]
Wall – Isover murfilt 32	97.5	0.40	39	400	15,597
Roof – Paper wool	167.6	1.00	168	205	34,366
Floor - Sundolitt S150	134.8	0.75	101	1,223	123,663
	Area			**Area price**	**Cost**
Components, etc.	[m^2]			[kr/m^2]	[kr]
Lightweight concrete wall	97.5			772	75,230
Roof	167.6			289	48,484
Excavation, concrete, foundation	167.6			1,209	202,731
				Total	**500,071**

Design 2	Area	thickness	volume	Volumetric price	Cost
Insulation	[m^2]	[m]	[m^3]	[kr/m^3]	[kr]
Wall - Kingspan Kooltherm K8	131.5	0.410	54	1,875	101,098
Roof - Isover murfilt 32	163.3	1.089	178	400	71,145
Floor - Sundolitt S80	134.8	0.530	71	740	52,876
VIP doors	4.4	0.05	0.22	48,491	10,547
	Area			**Area price**	**Cost**
Components, etc.	[m^2]			[kr/m^2]	[kr]
Wooden wall	107.6			710	76,437
Roof	163.3			322	52,608
Excavation, concrete, foundation	153.0			1,084	165,782
				Total	**530,494**

As can be seen on table 86, the total additional cost between the reference house and Design 2 is 30,424 kr. From the costs of insulation it can be seen that Design 2 utilizes more expensive solutions both for the wall and the roof but that the 750 mm of S150 insulation in the reference house is much more expensive than 530 mm of S80 insulation for the floor in Design 2. The prices of the vacuum insulating panels in the doors of Design 2 have been estimated to 48,491 kr/m^3 from [18] with a price of $595 for a 60" x 70" (2.7 m^2) panel with a thickness of 30 mm, yielding a total cost of 10,547 kr. The component costs are similar, but the expenses towards excavation, concrete and foundation are lower for Design 2 due to the foundation which results in an estimated reduced area towards these expenses corresponding to 200 m less around the periphery. Accordingly, the insulation area of the wall for Design 2 has been increased to account for the different foundation design.

One parameter that is not included in the above calculation is the window prices, since this is unknown for the AR-coated windows. Glass with anti-reflective coating is not currently used for windows in buildings, but according to [2], should it become a standard product, it can be expected that it should not necessarily become much more expensive than other glazing types. Therefore it can be speculated that the window costs of the reference house and Design 2 could be similar, given the smaller window area but slightly more expensive windows of Design 2.

Overall the additional cost of Design 2 is 30,424, which can perhaps be seen as reasonable given the fact that the demand for space heating has been reduced to 1439 kWh from 2321 kWh. With the same assumptions as previously, of a 4% annual increase in the overall electricity price, the payback time is 15 years with electric heating.

Solar heating

Given the fact that the investment into a heat pump was not found to be profitable compared to direct electricity heating, it could perhaps be interesting to invest in a solar collector instead, as a way to cover a part of the heating demand for the domestic hot water and reduce the electric expenses in general.

From [27] a low flow system has been found with a 4 m^2 collector and a 280 L mantle tank. It has a total price of 34394 incl. VAT for the collector, tank, collector loop, expansion system, installation, fluid, etc, and a net utilized solar energy of 1212 kWh/year. Since it includes a tank, the price for a 300 L tank will be assumed as the initial costs for the direct heating in the comparison.

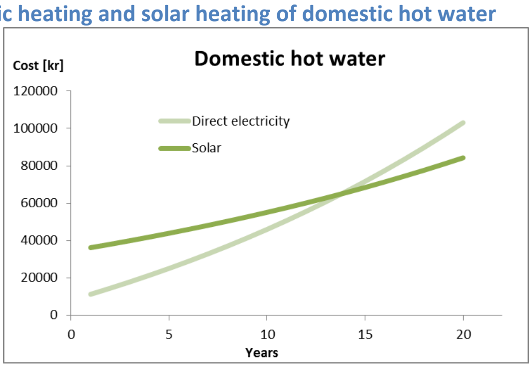
For the solar heating system, the electric auxiliary heating needs to operate with the solar collector, so an electricity price of 1.57 kr/kWh is assumed for the solar heating system. As with the heat pump calculation, a 4% electric price is assumed, and for the system with only electric heating, a 0.10 kr/kWh lower off-peak price is used.

For the solar system, an additional annual consumption of 65 kWh is added, corresponding to a low power pump operating a few hours each day. In addition, an annual maintenance cost of 300 kr is assumed, corresponding to maintenance for collector fluid change every five years.

With these assumptions, the simple economic calculation is carried out to compare the solar heating system with the direct heating.

Table 87 - Comparison of expenses over a period of 20 years for electric heating and solar heating of domestic hot water

	Solar heating	Direct electricity
Initial costs [kr]	34,394	8,169
Net utilized solar energy [kWh]	1,212	0
Annual electric consumption [kWh]	973	2,120
Electricity price start [kr/kWh]	1.57	1.47
Initial annual electricity cost [kr]	1,530	3,116
Annual maintenance [kr]	300	0
Initial annual expense [kr]	1,830	3,116
20 year expense [kr]	**84,273**	**103,063**
Payback time [years]	14	-



As can be seen on table 87, the payback time is 14 years for the solar heating system. With a lifetime that can exceed 30 years, it can be said that the investment can become profitable over time, which can make it somewhat attractive for one who is willing to accept the somewhat long payback time.

It can be said that a solar system in general does not correspond well with electric off-peak night heating, since the electric heating element is needed to operate at the same time as the collector, to keep the auxiliary volume above a certain temperature of e.g. 51 °C, but since it covers roughly 60% of the expenses toward domestic hot water, there is perhaps no need to.

14. Energy frame

The energy frame of the house has not been a focus of this report, but it could still be interesting to investigate the possibilities of complying with the 2020 energy frame of 20 $\frac{kWh}{m^2 year}$ for a low energy house heated with off-peak electricity. The energy frame includes heating for domestic hot water, the space heating demand, the cooling demand and the electricity for building operation such as ventilation and pumps. The electricity for building operation has been found from [20] for the reference house to be 2.9 $\frac{kWh}{m^2 year}$, with a mechanical ventilation system with a SFP-value of 800 J/m^3, and it is the same for Design 2 since the two houses supply with the same mechanical ventilation rate. The hot water demand is calculated from the previously determined demand to $\frac{2120\ kWh/year}{163\ m^2} = 13\frac{kWh}{m^2 year}$. The space heating demand is estimated to 8.1 $\frac{kWh}{m^2 year}$ for the reference house and 3.5 $\frac{kWh}{m^2 year}$ for Design 2 from the room based WinDesign values calculated previous to the realistic inputs and new WinDesign. This should yield values close to those calculated by the Be10 program, which would otherwise have been used to determine the heating demand. With these assumptions, the energy frame is estimated for the reference house and Design 2 with the primary energy factor of 1.8 for electricity.

Table 88 – Calculation of energy frame with an energy factor if 1.8

Reference house	Energy	Energy factor	Primary energy
	[kWh/(m^2 year)]	[-]	[kWh/(m^2 year)]
Electricity	2.9	1.8	5.2
Space heating	8.1	1.8	14.6
Domestic hot water	13.0	1.8	23.4
		Total	**43.2**

Design 2	Energy	Energy factor	Primary energy
	[kWh/(m^2 year)]	[-]	[kWh/(m^2 year)]
Electricity	2.9	1.8	5.2
Space heating	3.5	1.8	6.3
Domestic hot water	13.0	1.8	23.4
		Total	**34.9**

As can be seen on table 88, neither of the houses satisfies the requirements of 20 $\frac{kWh}{m^2 year}$ for the 2020 energy frame. This is expected due to the fact that the primary energy factor of 1.8 for electricity is used instead of the factor of 0.6 from district heating that the house was designed for.

The primary energy factor is a politically defined measure of the overall efficiency and environmental burden of a given heating method; hence the factor for electricity is higher, since the general efficiency of direct electric heating is lower than e.g. a heat pump or district heating. In this regard it can be said that the positive aspect behind off-peak electric night heating is that by design it does not contribute to the peaks in the daily national demand which can perhaps become problematic as wind turbines become more prevalent. Instead the electricity is consumed at a time of 00:00-06:00 where the demand is low - when the electricity is cheap and the availability is generally higher. It could also be useful to consume the electricity in off-peak periods with high wind feed, in order for the energy producers to avoid negative spot prices i.e. having to pay for the electricity they deliver. Due to these considerations it can be said that a primary factor for electricity of e.g. 1.0 is perhaps more appropriate for electricity consumed in the off-peak period. If this factor is assumed for the space heating and domestic hot water, a lower energy frame is reached.

Table 89 – Energy frame with an assumed off-peak electricity factor of 1.0

Reference house	Energy	Energy factor	Primary energy
	[kWh/(m^2 year)]	[-]	[kWh/(m^2 year)]
Electricity	2.9	1.8	5.2
Space heating	8.1	1.0	8.1
Domestic hot water	13	1.0	13.0
		Total	**26.3**

Design 2	Energy	Energy factor	Primary energy
	[kWh/(m^2 year)]	[-]	[kWh/(m^2 year)]
Electricity	2.9	1.8	5.2
Space heating	3.5	1.0	3.5
Domestic hot water	13	1.0	13.0
		Total	**21.7**

As can be seen from table 89, if the lower primary energy factor for off-peak heating could be allowed, Design 2 could become close to complying with the 2020 energy frame. If instead the domestic hot water is supplied with the same low flow mantle tank solar heating system used in the solar heating price calculations, then the solar heating could cover 1212 kWh i.e. 57% of the domestic hot water demand, but the electric auxiliary energy supply would have to consume during the day at a factor of 1.8.

Table 90 – Energy frame calculations with a solar heating system

Reference house	Energy	Energy factor	Primary energy
	[kWh/(m^2 year)]	[-]	[kWh/(m^2 year)]
Electricity	2.9	1.8	5.2
Space heating	8.1	1.0	8.1
Domestic hot water	5.6	1.8	10.1
		Total	**23.4**

Design 2	Energy	Energy factor	Primary energy
	[kWh/(m^2 year)]	[-]	[kWh/(m^2 year)]
Electricity	2.9	1.8	5.2
Space heating	3.5	1.0	3.5
Domestic hot water	5.6	1.8	10.1
		Total	**18.8**

As can be seen on table 90, if the solar heating system is implemented and the compensation is applied to the space heating, Design 2 house is able to comply with the energy frame of 20 $\frac{kWh}{m^2 year}$.

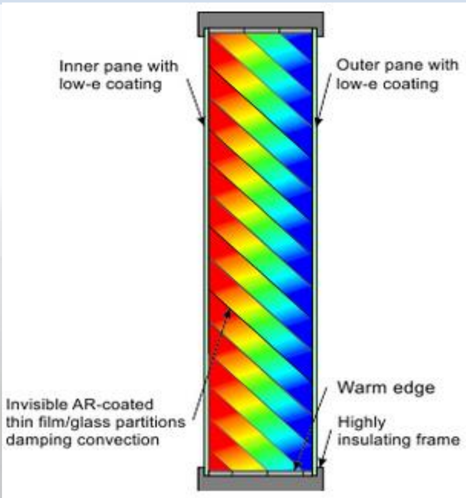
It can be said that the primary energy factor of 1.0 for off-peak electricity is speculative, but if it is implemented, there is a better chance for a low energy house with a lower space heating demand to be able to comply with the energy frame. One prerequisite for this could for example be if it could be shown that no electricity towards e.g. space heating would be consumed outside the off-peak period of 00:00-06:00. Regarding Design 2 and an allowed electricity factor 1.0 without solar heating, at 21.7 $\frac{kWh}{m^2 year}$ is close to complying with the energy frame, which means it would likely be able to achieve a lower value than 20 $\frac{kWh}{m^2 year}$ if for example a slightly more effective mechanical ventilation system was installed with a specific fan power of e.g. 400-500 J/m3, which can be seen as reasonable according to [2].

15. Future window possibilities

According to [2], the physical limits are soon met in relation to conventional window designs with triple layer energy glazing with low emission coatings and isolating gas fillings. It could therefore be interesting to investigate the future possibilities of different window designs in relation to the heating demand and the general viability of electric heating in the coming years.

A company called Superwindows has products in development that seek to vastly improve both glazing and frames.

Table 91 – Glazing and frame from Superwindows

INVIS160 tweed		SuperFrame	
 			
U_g [W/m^{2}K]	0.05	U_f [W/m^{2}K]	0.30

As can be seen from table 91, the U-value of the glazing is approximately a factor 10 lower than current triple layer glazing, hence it is similar to that of the rest of the building envelope. The U-value of the frame is low as well, compared to the value of 1.34 W/m^{2}K of the Hansen X-frame frames used in this report.

As can be seen, the glazing utilizes a structure of multi-layered thin panes in between two outer panes. The purpose of this is to eliminate the convection between the panes, since the convection loss can amount to a large part of the heat loss in regular double or triple layered glazing designs. As can be seen, by utilizing the small tapered air pockets, the hot air on the interior side cannot rise, and similarly the cold air on the exterior side cannot descend. Therefore the convection flow is greatly diminished, resulting in a much lower convection loss than regular glazing, and subsequently a very low U-value of 0.05 W/m^{2}K.

The frame utilizes a design consisting of two separate frame layers, which are separated by e.g. aerogel or vacuum insulated panels, so the actual material of the frame becomes less insignificant, as the two layers are separated by a highly insulating material. The structural integrity is attained by metal connectors when the window is open, but when it is closed, the two layers of the frame are only in contact through the insulation, hence no thermal bridges between the two frames.

The manufacturer claims the optical properties are similar to regular glazing but the specifics are somewhat uncertain, so for the following simulation, the values are assumed to be similar to those of the triple layer glazing from the reference house, with a g-value of 50% and a light transmittance of 71 %. The windows will be simulated in the Design 2 house with the window sizes adjusted according to the lower light transmittance.

Table 92 – Heating demand and overheating with the new windows

Heating demand – Design 2			Design 2 – SuperWindows		Design 2	
			Heating demand	Overheating hours	Heating demand	Overheating hours
Room	Orientation	Room type	[kWh/m^2 year]	T_i > 26 °C	[kWh/m^2 year]	T_i > 26 °C
Room 1	South	Room	1.0	33	3.2	32
Room 2	South	Living room/kitchen	1.3	70	2.2	63
Room 3	South	Living room	1.1	41	2.5	44
Room 4	West	Bedroom	8.8	26	15.2	26
Room 5	North	Bath	10.9	0	16.9	0
Room 6	North	Room	7.1	12	14.1	13
Room 7	North	Hallway	22.8	1	31.9	1
Room 8	North	Utility	10.9	0	15.8	0
Room 9	North	Room	5.6	12	11.6	14
Room 10	East	Bath	11.4	0	14.1	0
		Total - weighed	**5.20**		**8.81**	

As can be seen on table 92, installing the new windows into the Design 2 house reduce the heating demand by 41% compared to with the AR-windows.

Table 93 – Concrete temperature rise with the new windows

			Temperature rise [K]	
	Orientation	Room type	Design 2 – Superwindows	Design 2
Room 1	South	Room	0.5	1
Room 2	South	Living room/kitchen	0	0.5
Room 3	South	Living room	0	0.5
Room 4	West	Bedroom	1	1.5
Room 5	North	Bath	1	1.5
Room 6	North	Room	1	1.5
Room 7	North	Hallway	1.5	2
Room 8	North	Utility	1	1
Room 9	North	Room	1	1.5
Room 10	East	Bath	1	1

As can be seen on table 93, due to the lower heating demand, the subsequent temperature rise in the concrete due to the night heating is also reduced for most rooms.

Table 94 – Maximum heating demand with the new windows

Maximum daily heating demand			Design 2 – invis160 tweed		Design 2	
			Heating demand		Heating demand	
Room	Orientation	Room type	[kWh]	[Wh/m^2]	[kWh]	[Wh/m^2]
Room 1	South	Room	1.2	73	1.9	117
Room 2	South	Living room/kitchen	0.6	19	2.7	81
Room 3	South	Living room	1.6	44	3.3	91
Room 4	West	Bedroom	2.5	126	3.6	184
Room 5	North	Bath	1.0	111	1.5	158
Room 6	North	Room	0.9	81	1.7	153
Room 7	North	Hallway	1.0	165	1.4	221
Room 8	North	Utility	1.1	105	1.5	143
Room 9	North	Room	1.5	96	2.4	150
Room 10	East	Bath	0.6	110	0.7	132
		Total [kWh]	**11**		**21**	
		Power – 6h [kW]	**1.9**		**3.4**	

It can be seen from table 94 that the heating demand on a cold winter day is almost reduced to half compared to Design 2 with the new windows.

With the new glazing and frame, U-values in the excess of 0.16 W/m^{2}K for the whole window is possible, which yields transmission losses which are almost on par with those of the rest of the envelope. Therefore it can be said that for this window type, potentially very large north facing windows could be utilized without resulting in an additional heating demand.

The reduced heating demand amounts to an annual demand of 849 kWh towards space heating with the new windows, down from 1439 kWh with the AR-windows in Design 2. This amounts to estimated savings on the electric bill of 20,850 kr after 20 years.

In general it can be said that the circumstances surrounding these windows are uncertain, in regard to price, optical properties etc. One problem could be for example if the tapered inner panes are visible, perhaps from certain angles or that they distort the incoming daylight in a way that could be seen as aesthetically unpleasant and different from regular glazing. Since it is a product which is still in development, the price is unknown, and so is the economic viability of the windows. Even with all the uncertainty, it can be said that there is a great potential in the new glazing and frame design for use in low energy houses in general, should it someday become a standard product.

16. Lower night temperature

One of the problems with off-peak night heating is that the storage of heat in the concrete slab can perhaps be somewhat inflexible, and that storing enough heat for the whole day can cause increased temperatures.

Table 95 – Temperature rise for different thicknesses of concrete

Temperature rise [K]			Design 2			Reference house		
			Concrete slab thickness			Concrete slab thickness		
	Orientation	Room type	10 cm	15 cm	20 cm	10 cm	15 cm	20 cm
Room 1	South	Room	1	0.5	0.5	1.5	1	0.5
Room 2	South	Living room/kitchen	0.5	0	0	0.5	0.5	0
Room 3	South	Living room	0.5	0	0	1	0.5	0.5
Room 4	West	Bedroom	1.5	1	0.5	2.5	1.5	1
Room 5	North	Bath	1.5	1	0.5	1.5	1	0.5
Room 6	North	Room	1.5	1	0.5	2	1	0.5
Room 7	North	Hallway	2	1.5	1	3.5	2	1.5
Room 8	North	Utility	1	0.5	0.5	1.5	1	0.5
Room 9	North	Room	1.5	1	0.5	2	1.5	1
Room 10	East	Bath	1	0.5	0.5	2	1.5	1

As can be seen on table 95, the temperature rise is lower in Design 2, but in general the temperature rise can be reduced by utilizing a thicker concrete slab. As mentioned before, this can be seen as acceptable for most rooms, but it might not be acceptable in a bedroom where a lower temperature of e.g. 17 °C is desired but this can be solved by generally keeping a lower temperature in the bedroom. The problem is that keeping a lower temperature would not be acceptable in a kids or teenage bedroom, where occupants frequently occupy the room both during the day and the night, such a room 9.

This is where the inflexibility of the off-peak night heating could become a problem for some occupants compared to a regular heating method, where it is not a problem to reduce the interior temperature from 22 °C to 17 °C during the night. This would perhaps not be possible in a house with night heating, since the heating occurs exactly when the lower temperature is desired, and also is for some reason the temperature is forcibly lowered, for example with venting, the room would perhaps not be able to achieve the desired day temperature of e.g. 22 °C without re-heating during the day.

Therefore it could be interesting to implement a mechanism in these rooms to delay the heating, in order to be able to achieve a lower night temperature, while still being able to both supply heat during the off-peak night hours. One way to partially solve this this problem could be to supply the heat for the children's bedrooms through a storage heater – an electrically heated radiator capable of accumulating the energy throughout the night, which can be released as needed during the day. That way the occupants in these rooms could potentially enjoy an interior temperature of 20-22 °C during the day, stop the heat flow from the storage heater in the evening, sleep in the same room with a lower temperature, let the radiator accumulate heat during the off-peak hours and start the heat flow again the next day.

One problem with the storage heater could be that some unwanted heat will be discharged to the room during the night, depending on how much is needed for the next day and how well insulated it is. It can therefore be said that the overall flexibility would still be somewhat limited compared to e.g. a regular radiator, but installing such a storage heater could be a cheap and simple way to allow the occupants slightly more control over the night temperature in the children's bedrooms, while still utilizing the off-peak electricity for heating.

Another way to attempt to achieve a lower temperature at night in bedrooms could be to attempt to delay the heat with two layers of concrete in the ground slab and insulation between. If the bottom layer was heated as necessary, the heat could possibly be transferred to the top layer with a convection air flow, or perhaps with a loop of fluid connecting the two layers of concrete. The flow of fluid or air could perhaps both be natural or mechanical, driven by a small pump or fan. This way the flow to the upper layer could be controlled either by opening a valve or by turning on a small pump or fan, hence ideally it could work the same way as a storage heater – by accumulating heat in the night and discharging it as necessary. The advantage over the storage heater could perhaps be that the heat is better stored away and perhaps leaks less heat during the night, but this could potentially also cause a problem with potentially slow discharge, reducing the overall flexibility of the method. Storing the heat away could also lead to unnecessary heat loss, which would perhaps not be a problem for either the regular heated concrete slab or the storage heater.

In addition to that, the structure itself, with two concrete slabs separated by insulation and connected with e.g. a fluid loop and with a pump, would perhaps be complicated or expensive to assemble in comparison to buying a storage heater. Overall it can be said that the storage heater is a more attractive solution to achieve lower night temperatures.

17. Discussion

The overall indication is that electric off-peak heating can be seen as a viable heating method for a low energy house, both economically and from a thermal perspective in relation to temperature rise in the concrete. It can be said that the economic perspective is somewhat uncertain for such a heating method, and one negative aspect is that a house with electric heating is vulnerable towards changes in the electricity price, both short term and long term. If the electricity price rises disproportionally in the coming years, for example due to additional funding needed to ensure that the goals towards renewable energy are met, then it would be less attractive to supply a low energy house with electric heating at night. The potential off-peak savings on the electricity price is also uncertain, but it could be beneficial for electric off-peak heating as well as the national grid as a whole if a greater differentiation between the price of electricity in an off-peak period and in a peak period could be achieved, in order to incentivise a flexible consumption pattern more capable of adapting according to the availability of electricity in the future.

A large part of this is the heavy taxation of electricity, and although a reduced tax is applied to electric heating, it diminishes the benefit of purchasing at spot prices, and it could be beneficial for most parties if perhaps the tax, distribution and PSO part of the prices were more reflective of the market demands, with values lower during typical off-peak times of 00.00-06.00, and higher values during typical peak hours in the morning and evening. Even if the electricity price is more unpredictable than that, with change happening over the course of weeks and months, it could be beneficial for the grid and perhaps result in an overall lower electricity price if the daily consumption was more evenly distributed over the course of a day, and this becomes more important as the electricity supply transitions towards renewable sources and the more inflexible wind turbines. Therefore, a way to incentivize this in the coming years with intelligent electric meters could be if for example the electricity tax had different tariffs depending on the time of day where typical peaks and off-peaks occur.

One positive aspect in regard to the low cost of acquiring electric heating is that if perhaps after several years the electricity price is deemed to be rising too rapidly, it could be an option to invest in a for example a solar heating system later on.

In regard to Design 2 and the reference house, it can be said that the reference house is likely adequate for off-peak night heating. I can be said several ways of optimizing for heating demand were presented with the Design 2 house, resulting in both an improvement in regard to both the annual heating demand, which will benefit the occupants economically, the heating demand on a cold winter day, which can benefit the electric company and the grid system in general, and the temperature rise in the concrete slab, which can benefit the occupants with a more even temperature throughout the day. The lower window area in general could be seen as a detriment in spite of the fact that the daylight requirements are fulfilled. The average glass-to floor ratio is 15.3% average in primary rooms and some primary rooms do have lower ratios, which could be seen as a violation of the building code, which states that the daylight can generally be considered adequate when the glass-to-floor area is 15% with a light transmittance of 75%, but it can be said that it is does not account for rooms with tapered reveals where the window sizes and placement have been optimized with no low height glazing and the daylight factor calculated in Visualizer. Should the 15% glass-to-floor area become a strict room based requirement without the possibility of documenting the daylight intake by simulation, the window sizes in some rooms would have to be increased slightly by approximately 20 cm in width. This would increase the heating demand slightly from 8.8 to 9.1 $\frac{kWh}{m^2 year}$, and the overheating in for example room 2 would increase from 63 to 94. This is not a significant difference, so it can be said that would not be a problem to increase the glazing area, thereby also increasing the daylight intake in the rooms.

In general it can be said that while the reference house is likely adequate, the lower heating demand of Design 2 does present certain benefits, both regarding the comfort for the occupants with the lower concrete temperature increase and the strain on the grid system, but also economically. The heating demand on a cold winter day is 50% higher for the reference house compared to Design 2, which means the strain on the grid is lower for Design 2. The lower heating demand in general means the occupants will experience a lower temperature rise due to the storage of heat in the concrete slab amounting to a 0.5-1.0 K difference between Design 2 and reference house for most rooms. The prices of the anti-reflective coated glazing are somewhat uncertain since such glazing is not currently a standard product for use in building facades. The coating is currently used in lenses for cameras, telescopes and glasses but according to [2], should it become a standard product for windows, it would not necessarily become much more expensive than other window glazing, hence the prices between the houses are likely similar. The additional cost of Design 2 has been calculated to 30,424 kr, including the prices for insulation, excavation, wall materials etc. This expense could be paid back after 15 years due to the reduced spaced heating demand of 1439 kWh instead of 2321 kWh, and after 20 years the savings on the electricity bill would amount to 47,808 kr. The consequences of the strain on the electric grid is inconclusive, but it can be said that the strain has been reduced by 32% with Design 2, and that it could feasibly be installed in thousands Danish low energy houses without access to district heating.

As expected neither design was able to comply with the 2020 energy frame, which is due to the fact that the house was designed for use of district heating with a primary energy factor of 0.6. In general the space heating is less impactful for the energy frame compared to the hot water demand, which amounts to 13 $\frac{kWh}{m^2 year}$ before the energy factor, and is not dependent upon the house design, hence it can be said that without supplying the domestic hot water with heat from district heating, it can be problematic to comply with the energy frame. Since the primary energy factor is a politically defined measure of the overall efficiency and environmental burden of a given energy supply method, it can be said that a lower factor is perhaps appropriate for the off-peak electric heating, since it does not contribute to the peaks on the curve of the national electric consumption, and the fact that the electricity during the off-peak period is potentially superfluous depending on the wind feed.

If due to this a primary energy factor of e.g. 1.0 is allowed for off-peak electricity, then Design 2 would be close to complying with the 2020 energy frame with direct electric heating. In that regard a solar heating system could help reduce the energy frame to below 20 $\frac{kWh}{m^2 year}$. Another way to reduce the energy frame below 20 $\frac{kWh}{m^2 year}$ without solar heating could be with a ventilation system with a lower SFP of e.g. 400-500 J/m^3, which can be seen as realistic in 2020 according to [2]. It can be said that a primary energy factor of 1.0 for off-peak electric heating is speculative, but one thing that could perhaps help in this regard is that if the electricity supplier could be certain that no electricity for e.g. space heating would be consumed outside of the period of 00.00-06.00.

In general the value of consuming electricity in the off-peak period is somewhat uncertain. If the electricity is generally plentiful during the night in the near future due to 65% of the electricity being produced by somewhat uncontrollable wind turbines, and a general overproduction is needed to secure availability in peak periods, then it could be beneficial to consume this energy for space heating purposes rather than let it go to waste. It can be said that the primary reason a negative spot price was introduced by Nordpool was due to the prevalence of wind turbines in Denmark, which previously could become a problem for sellers of electricity to the Danish market [22] in periods of high wind feed. The value of electricity towards heating in the off-peak period is also dependent upon the value of alternative ways of consuming the excess electric energy, for example through the storage of the energy with synthetic fuel, or through the production of heat with large heat pumps for district heating.

In addition the value of consuming the electricity for direct off-peak heating is dependent upon how well the market adapts towards the more inflexible renewable electricity production in the future. In this regard it can be said that unless more differentiated tariffs are introduced between the peaks and off-peak periods, there is perhaps not a great incentive for private consumers to invest in more adaptable appliances and adapt to the renewable energy market. The economic viability of direct electric heating could also be influenced by the hot water demand. If the house has a large domestic hot water demand, for example due to four or five occupants, then the heat pump and the solar heating system would become more economically attractive.

18. Conclusion

In this project the aim was to determine the viability of off-peak electricity as a method of heating a low-energy house in a future where approximately 65% of the electricity is to be supplied by wind turbines. This was done by simulating a low energy house from an existing design [20] and evaluating it in regard to the annual heating demand as well as the heating demand on a cold winter day and the temperature rise in the concrete due to the storage of heat.

Based on the reference house, different ways to reduce the heating demand was investigated, resulting in Design 2, which is a design where optimal daylight conditions was achieved with the use of anti-reflective glazing, tapered reveals and optimized window placement. In addition, a more effective exterior wall design was used, allowing a higher insulation thickness relative to the wall thickness. Other optimizations were conducted in relation to the door and window design in certain rooms, and VIP panels were inserted into the doors. Then the insulation thicknesses were balanced through CCE calculation, resulting in an overall more balanced design and a thinner exterior wall.

After more realistic results were introduced along with a new version of WinDesign allowing variable internal loads, the heating demand was found to be 8.81 $\frac{kWh}{m^2 year}$ for Design 2 and 13.85 $\frac{kWh}{m^2 year}$ for the reference house. If these houses were to store the necessary heat in the concrete slab, the temperature increase in a 10 cm concrete slab would be between 0.5 and 1.5 K for most rooms with Design 2 and between 1 and 2.5 for most rooms in the reference house, which is likely to result in a similar interior temperature increase. With an interior temperature of 22 °C, this would mean up to 24.5 °C for some rooms, hence it is thermally acceptable, for most room types, but not for bedrooms where a lower temperature of e.g. 17 °C is desired in the night by some occupants. The inability for the occupants to properly change the room temperature necessitates some form of regulation of the stored heat in bedrooms, with for example a storage heater.

In regard to the hot water demand, it was found possible to store enough hot water in a 300L tank at 60 °C or a 200L tank at 88 °C for most days without charging during the day. This, as well as the acceptable concrete temperature increase, leads to the conclusion that both the reference house and Design 2 could feasibly be heated by direct electricity consumed in the off-peak period. The advantage of Design 2 due to the lower heating demand is that potential strain on the grid and the temperature rise due to the storage of heat is decreased. The potential for an economic advantage was also found with Design 2, despite the increased cost of materials amounting to 30,424 kr, due to the lower heating demand. This could be paid back after 15 years due to the reduced expenses to electric heating.

The economic aspect was also investigated in regard to the savings due to the off-peak consumption of electricity, and it found that the economic incentive to consume the electricity at the off-peak hour was not great, due to the fact that the spot price did not amount to a significant proportion of the total price. The investment into a heat pump was also investigated, and it was found that even with a heat pump with a high seasonal COP, specifically designed for the Danish climate, it was not attractive from an economic perspective to invest in a heat pump, due to the fact that the high investment cost was only paid back at the very end of its potential lifetime. One reason for this is the mandatory annual maintenance inspection, which accounts for a majority of the annual expenses to a heat pump for a low energy house. A solar heating system was also investigated for domestic hot water, and it was found that it could become a profitable investment after 14 years, which is acceptable due to the lifetime of a solar heating system in the excess of 35 years.

In addition, the energy frame was investigated, and it was found that compensation for the off-peak electricity is required for the heating method to be viable. With a primary energy factor of 1.0 for space heating domestic hot water, Design 2 was close to complying with the requirement, and it was possible to comply with the energy frame with a solar heating system instead, for domestic hot water.

19. Potential further investigations

One aspect that could be interesting to investigate is electric heating as a primary measure of heating instead of district heating. This could perhaps be relevant for certain European countries where the district heating is perhaps inadequate, ineffective or expensive. Therefore it could perhaps be a better investment from a national economic standpoint, to supply low energy houses with heating from electricity rather than to invest in distribution of district heating. The relevance of this could perhaps be increased as better components enter the market, for example the Superwindows, the use of which could have a significant impact on the heating demand, should they become reasonably priced. One problem in this regard is still the somewhat static domestic hot water demand, which would perhaps have to be reduced, for example with a solar heating system.

Another aspect that could be subject to further investigation is the thermal impact of the storage of heat in the concrete slab for use during a whole day, in different situations, how such a system would work best in practice and how it is best controlled. This report has assumed that the necessary heat is stored, so it could be interesting to determine the impact of for example a weather forecast that deviates from the actual weather. While this report does assume a variable internal load, it could also be interesting to investigate how different occupant behavior patterns and deviations from these could impact the thermal indoor environment and general viability of night storage of heat in a house. In this report the temperature increase in the concrete is calculated on room basis, so problems in this regard should be highlighted, but more detailed simulations of the thermal behavior in the concrete slab could be interesting, to determine is for example storage of heat in the concrete slab could lead to a disproportionate heat loss toward the ground, or perhaps inadequate heating if the floor is covered partly by a carpet. In this regard the usefulness of a storage heater could also be investigated, as a measure to allow more flexible interior temperatures in bedrooms while still supplying the heating in the off-peak period at night. The Design Reference Year does include naturally occurring temperature extremes in Denmark, but it could also be interesting to investigate the thermal performance in an extraordinary cold period or perhaps in a colder climate in general.

20. References

[1] The Danish government, “Our future energy” 2011

[2] Svendsen, S., et al. “Analyse 6. Komponentkrav, konkurrence og eksport. En kortlægning af innovation i byggekomponenter,” DTU byg, 2011

[3] Danish wind energy association, “Indpasning af vind-kraft i elsystemet,” Faktablad T3, 2009

[4] Svendsen, S. and Vanhoutteghem, L., ”Window Design in low energy class 2015 and 2020 dwellings,” DTU byg, 2011

[5] Ghaemi, S. and Brauner G, “User behaviour and patterns of electricity use for energy saving,” Technical University of Vienna, Institute of power systems and energy economics, 2009

[6] Hunton, “Teknisk håndbok for gulv, tak og vegg” hunton.dk. [Online][accessed: March 2014] http://dk.hunton.no/wp-content/uploads/sites/6/2013/05/Hunton_I-bjelken_teknisk_h%C3%A5ndbok_WEB1.pdf

[7] Tommerup, H. M et al., ”Udvikling af klimaskærmskonstruktioner. Rapport R-042”, DTU, 2000

[8] International Standard, ”ISO 13790 second edition. Energy performance of buildings – calculation of energy use for space heating and cooling,” 2008

[9] Komforthusene, [Online][accessed: March 2014], “http://www.komforthusene.dk/projektering/klimask%C3%A6rm/luftt%C3%A6thed”

[10] European Standard, ”EN 15316-3-1. Heating systems in buildings – method for calculation of system energy requirements and system efficiencies – Part 3-1: Domestic hot water systems, characterization of needs (tapping requirements,” 2007

[11] Aggerholm, S. and Grau, K. “SBi-anvisning 213. Bygningers energibehov”, SBi, 2007

[12] Danish Standard, “DS 439 4. udgave, Norm for vandindstallationer”, 2009

[13] Urhøj Smede ApS, ”Pris eksempel på jordvarmeanlæg,” www.urhoj.dk, [online] [accessed: March 2014], http://www.urhoj.dk/varme-systemer/jordvarme/pris-eksempel-paa-jordvarmeanlaeg.html

[14] Urhøj Smede ApS, ”Pris eksempel på luft/vand varmepumpe,” www.urhoj.dk, [online] [accessed: March 2014], http://www.urhoj.dk/varme-systemer/varmepumper/luft-vandvarmepumpe/pris-eksempel-paa-luft-vand.html

[15] Energistyrelsen, ”Varmepumpelisten,” [online] [accessed: March 2014], http://sparenergi.dk/forbruger/varme/varmepumper/varmepumpelisten

[16] Danfoss, “Solar solution brochure”, www.danfoss.com, [online] [accessed: March 2014], http://dk.varme.danfoss.com/PCMPDF/V 13473_Solar_Solution_brochure_19.pdf

[17] OK, “Jordvarme,” www.ok-varmepumper.dk [online] [accessed: March 2014], http://www.ok-varmepumper.dk/jordvarme/

[18] Glacier Bay Technology, “Barrier Ultra-R Superinsulation panels. Price list,” www.glacierbay.com, [online] [Accessed: March 2014], http://web.archive.org/web/20110811071256/http://www.glacierbay.com/barrier_price.asp

[19] Buhl, M, “Udvikling og analyse af højisolerede klimaskærmskonstruktioner,” DTU byg, 2012

[20] Grøn, M. and Roed, S., “Undersøgelse og udvikling af metode til økonomisk optimering af lavenergiboliger”, DTU byg, 2011

[21] Dong Energy, “Typisk vandforbrug,” www.dongenergy.dk [online] [accessed: March 2014], https://www.dongenergy.dk/privat/energitips/tjekditforbrug/gennemsnitsforbrug/vandforbrug/Pages/typiskvandforbrug.aspx

[22] Nordpool, ”Nord Pool Spot implements negative price floor in Elspot from October 2009” www.nordpoolspot.com, [online] [accessed: March 2014], http://www.nordpoolspot.com/Message-center-container/Exchange-list/Exchange-information/No162009-Nord-Pool-Spot-implements-negative-price-floor-in-Elspot-from-October-2009-/

[23] Szameitat, J. and Svendsen, S., ” Reducing the energy consumption in window-wall assemblies by combining wide unsealed windows and tapered reveals”, DTU

[24] Danish Standard, “DS/EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics,” 2007

[25] Danish Standard, “DS 418. Beregning af bygningers varmetab,” 2011

[26] Fan, J. ”11127-Lecture 07-DHW generation,” lecture slide 7, Sustainable heating and cooling in buildings, DTU, 2010

[27] Furbo, S. “February10”, lecture slide 4, Solar heating systems, DTU, 2012

[28] Climate, energy and building ministry, “Smart Grid-Strategi. Fremtidens intelligente energisystem,” 2013

21. Appendix

Appendix 1 - Project plan

This project plan was written a month into the assignment and is included as per the requirement of the DTU student handbook.

Motivation and objective

The climate goal for 2035 is for the heat and electricity supply in Denmark to be renewable. It is an ambitious goal if the majority of the electricity is to be produced by wind turbines. Therefore it could be interesting to examine a type house which is to be heated by electricity, and in that regard problems could arise of for example a large number of houses are heated by electricity, for example due to the increased peak loads in cold periods on the grid, which could require an unnecessary amount of wind turbines to cope with the demand, or unneeded use of traditional power plants or backup generators.

To accommodate the climate goal of 2035, it could be interesting to investigate the potential use of electric heating in a low energy house, with for example electric radiator or floor heating. To avoid strain on the electric grid and perhaps purchase the electricity at a cheaper price, it is important to investigate the possibilities of consuming the electricity for heating outside the peak periods, for example during the night where the national consumption is generally lowest. It could also be relevant to investigate the possibilities of a larger hot water tank with the purpose of only heating it in the off-peak periods, as well as the possibilities of conducting the heating with the use of a heat pump.

Method

The aim is to investigate a low energy reference house which complies with the energy frame 2020 in relation to the electric heating and investigate ways to reduce the heating demand. Thereby the focus is not on the actual energy frame but more the actual heating demand towards space heating. Several parameters will be investigated, such as the possible thickness of the exterior wall while still complying with daylight requirements, and in this regard the use of tapered reveals will be investigated. In this regard the use of good windows with for example low U-value, thin frame and a high light transmittance will also be investigated along with the corresponding overheating hours which will be investigated on room basis.

It could also be interesting to investigate possible ways to reduce the heating demand for a cold winter day, where the space heating demand will be highest. The use of vacuum insulating panels will also be investigated. Thereby the insulation level of e.g. the doors could become closer to that of e.g. the exterior wall. There is also a need for mechanical ventilation with a high degree of heat recovery.

These simulations are expected to be carried out in WinDesign, and when a satisfactory house design is found, the heating demand on the coldest winter day will be investigated, along with the possibility of consuming the electricity towards space heating and domestic hot water outside the peak periods of the electric grid. The possibility of supplying the space heating in the off-peak hours into a concrete slab will also be investigated, thereby heating in the off-peak hours for the use over a longer period of e.g. the rest of the day.

Appendix 2 - Auto-evaluation and learning goals

This section is included as per the requirement of the DTU student hand book.

A few of the learning goals will be picked out and commented on as they pertain to this report.

- can identify and reflect on technical scientific issues and understand the interaction between the various components that make up an issue

This learning goal has been applied in this project by analyzing the specific issue of supplying the heating for a low energy house in the off-peak hours into the concrete slab for use throughout the entire day. The different components and interactions of such an issue has been applied in the form of e.g. the subsequent temperature rise in the concrete, the possible strain on the electric grid, the possible savings by purchasing electricity at the lower off-peak price, the possibility of also utilizing off-peak heating for the domestic hot water, the relevance of investing in a heat pump and the possible disadvantages of storing heat for the whole day in the concrete slab.

- masters technical scientific methodologies, theories and tools, and has the capacity take a holistic view of and delimit a complex, open issue, see it in a broader academic and societal perspective and, on this basis, propose a variety of possible actions

This has been applied with the use of electric heating during the night and the possible impact of this in relation to a broader societal perspective regarding the climate goals and the future grid system powered in majority by wind turbines and the impact this could have on the available supply of electricity. Some changes are also proposed in relation to creating a greater differentiation between the price of electricity consumed during peak and off-peak hours, in order to incentivize the consumption of electricity in off-peak hours, which could be of benefit for the grid in general, and especially in the future where wind turbines become more prevalent.

- can, via analysis and modelling, develop relevant models, systems and processes for solving technological problems

This learning goal has been applied through the use of the program WinDesign, which has been used to determine the heating demand as well as the overheating hours. In addition, the raw hourly data hidden within the program was utilized to determine the maximum daily heating demand as well as the estimated temperature rise in the concrete. In addition, a method was developed in order to make the extraction of said data much less laborious. In addition, the WinDesign program was altered in order to allow for slightly more realistic results in regard to the heating demand, with the implementation of variable internal load, which, had a somewhat significant impact on the results.

Appendix 3 – Miscellaneous inputs and results

This section contains miscellaneous values

Values from the reference house:

Reference house	Gross area	UA	Window Area	Glass ratio	Venting h^{-1}	Ventilation h^{-1}
Room 1	16.7	3.8	2.6	0.18	5.4	0.87
Room 2	34.3	4.9	5.8	0.17	5.0	0.34
Room 3	37.2	6.8	6.4	0.19	5.6	0.31
Room 4	20.0	4.0	3.2	0.18	4.5	0.87
Room 5	9.5	1.8	1.0	0.09	3.2	0.00
Room 6	11.2	1.7	2.6	0.23	6.0	0.34
Room 7	6.3	1.0	0.8	0.10	4.0	0.00
Room 8	10.6	1.8	1.6	0.15	4.8	0.00
Room 9	16.4	3.8	3.5	0.24	6.0	0.88
Room 10	5.3	1.0	1.0	0.17	5.9	0.00
	167.6					

Values from Design 2:

Design 2	Gross area	UA	Window Area	Glass ratio	Venting h^{-1}	Ventilation h^{-1}
Room 1	16.1	2.7	1.9	0.13	4.1	0.87
Room 2	33.8	4.2	4.8	0.14	4.2	0.34
Room 3	36.2	5.3	4.5	0.13	3.9	0.31
Room 4	19.4	3.0	2.7	0.15	4.0	0.87
Room 5	9.3	1.4	1.1	0.11	3.8	0.01
Room 6	11.0	1.4	2.2	0.20	6.0	0.34
Room 7	6.2	0.8	0.3	0.03	1.5	0.00
Room 8	10.3	1.5	1.0	0.08	2.9	0.00
Room 9	15.8	2.7	2.4	0.17	5.2	0.88
Room 10	5.2	0.8	0.3	0.03	1.5	0.00
	163.3					

Values from the economic calculations:

	Heat pump			Direct electricity			Solar DHW	
Year	Price 4%	Expenses ref	Expenses D2	Price 4%	Expenses ref	Expenses D2	Solar	Electric
1	1.57	144815	144547	1.47	24711	23411	36224	11292
2	1.64	148220	147673	1.53	31514	28863	38055	14539
3	1.70	151682	150844	1.60	39069	34547	39946	17925
4	1.77	155202	154062	1.67	46927	40474	41902	21455
5	1.84	158782	157329	1.74	55099	46652	43923	25136
6	1.91	162426	160646	1.81	63599	53093	46014	28972
7	1.99	166136	164016	1.89	72438	59806	48176	32971
8	2.07	169914	167441	1.97	81630	66802	50412	37139
9	2.15	173763	170923	2.05	91191	74093	52726	41482
10	2.24	177686	174464	2.13	101133	81690	55121	46007
11	2.33	181687	178066	2.22	111474	89606	57599	50723
12	2.42	185767	181733	2.32	122228	97854	60164	55636
13	2.52	189930	185467	2.41	133412	106446	62820	60754
14	2.62	194180	189270	2.51	145044	115397	65570	66086
15	2.72	198520	193145	2.62	157140	124720	68419	71639
16	2.83	202953	197095	2.73	169721	134432	71369	77424
17	2.95	207484	201123	2.84	182805	144546	74425	83449
18	3.06	212116	205232	2.96	196412	155080	77592	89724
19	3.19	216853	209425	3.08	210564	166050	80873	96259
20	3.31	221700	213706	3.21	225282	177474	84273	103063