AALBORG UNIVERSITY
STUDENT REPORT

DEVELOPMENT OF A DECISION-MAKING TOOL

For energy efficient renovation of single-family houses from 1961 – 1978

TREE

Tool for **R**enovating **E**nergy **E**fficiently

Master thesis M.Sc. Building Energy Design

Aalborg University

13th of January 2017

Alma Dagbjört Ívarsdóttir

Rasmus Christiansen

Kristoffer Marseen Primsø

This page is intentionally left blank

AALBORG UNIVERSITY
STUDENT REPORT

Building Energy Design
Study Board of Civil Engineering
Sofiendalsvej 9-11
DK 9200 Aalborg SV
Denmark
Phone: +45 9940 8484
E-mail: civil@civil.aau.dk

TITLE:

Development of a Decision-making tool for energy efficient renovation of single-family houses from 1961 – 1978

PROJECT PERIOD:

September 2016 – January 2017

4th semester master thesis / Kandidatspeciale 30 ECTS

AUTHORS:

Alma Dagbjört Ívarsdóttir 20150019

Kristoffer Marseen Primsø 20148234

Rasmus Christiansen 20148233

SUPERVISOR: TINE STEEN LARSEN

EDITION: 1

NUMBER OF PAGES: 146

APPENDIX PAGES: 30

NB: this report includes an Excel based tool

Front page picture: (NK Design 2017)

SYNOPSIS

The Danish government has aimed to become independent of fossil fuels by 2050. Reducing the energy consumption in the existing buildings stock is crucial to achieve this. Single-family houses account for nearly 45% of the current building stock, and houses from 1961-1978 were found to show the greatest energy saving potential.

Motivating single-family homeowners to perform energy renovation is therefore one of the main goal in the years to come. This thesis revolves around the creation and development of a decision-making tool called TREE; Tool for Renovating Energy Efficiently.

The tool should motivate and inspire single-family homeowners to perform energy renovation while improving their indoor environment.

This page intentionally left blank

Preface

This report was produced as a Master Thesis in Building Energy Design (Cand.Scient.Techn) at Aalborg University, January 2017. This project was written during the period from September 2016 to January 2017.

The aim of the report is to develop a decision-making tool to motivate and inspire single-family homeowners to perform energy renovation through various motivational factors. Barriers and motivational factors behind energy renovations in single-family houses were also investigated. This was done in order to implement the motivational factors in the tool and possibly break down barriers, to increase the homeowners' incentive to conduct energy renovations. The report is directly aimed at homeowners of single-family housing from 1961-1979. Energy renovations is a small piece of a bigger puzzle, concerning environmental issues that the world is faced with.

We would like to direct a gratitude to our supervisor Tine Steen Larsen (AAU), for all the guidance and support throughout the semester.

Reading guide

This project is divided into two parts, main report, and appendix. The main report presents methods, calculations, assumptions, and results and are presented with continuous references to the appendix. The appendix presents theoretical descriptions along with additional calculations. Note that the excel based tool developed in this project has been uploaded to Aalborg university, digital exam, but is also attached on a DVD on the back side of the report. The tool should be reviewed as a part of this report.

All references in this report are collected in a bibliography at the end of the report. The Harvard method was used for source citation, so a source in the text refers to [Surname, Year].

Summary

This thesis revolves around the creation of a decision-making tool, able to inspire and motivate homeowners to perform energy renovations. The Danish government has aimed to become independent of fossil fuels by 2050. In order to achieve this goal, reducing the energy consumption in existing buildings stock is crucial as they account for 40 % of Denmark´s total energy consumption. The existing building stock in Denmark was found to presents a huge energy saving potential as more than 70 % of the current building stock was built before 1979 and is in need of undergoing extensive energy renovation. With single-family houses accounting nearly 45 % of the Danish building stock, great energy saving potential was found to lie in these houses. The greatest energy saving potential and need was found to be in houses from 1961-1979 therefore the project focused on these years.

Motivating single-family homeowners to embark into private energy renovations was found to be complicated. The strongest motivational factor among homeowners was concluded to be economic gains achieved through energy savings, while economy was also the largest barrier. Another critical motivational factor for homeowners was found to be the improved indoor climate and comfort from energy renovations. It was concluded that in order to motivate homeowners into conducting energy renovations, illustrating the positive non-energy benefits, such as improved comfort and indoor climate in combination with energy savings, could potentially be a motivational factor to increase the number of energy renovations.

TREE (Tool for Renovating Energy Efficiently) was created to inspire and motivate homeowners to perform energy renovations by combining these factors. The tool was developed in MS Excel workbook, as Excel has the capabilities to perform the calculations needed for the analysis while being commonly used and easily accessible, increasing the potential user group. The first step was done by creating a questionnaire that allows the homeowner to reflect upon the current comfort and discomfort experienced in the house, to get an overview of potentially problematic areas of the house. Thereafter, a thorough investigation was conducted into common building styles, components, and installations from these years, that created the main data base for the tool. This database what then used to perform the Monthly Average calculations to estimate the current conditions of the house. From there, measures and renovation recommendations related to energy savings and non-energy benefits were made based on investigations done through calculations and detailed analysis. Simple visualizations of the result, through graphs and illustrations were then created to give the homeowner a clear view of potential energy savings and the non-energy benefits accompanied.

Resume

Denne afhandling handler om udviklingen af et beslutningsværktøj, i stand til at inspirere og motivere husejere til at udføre energibesparende renoveringer. Den danske regering har sat sig som mål at blive uafhængig af fossile brændsler i år 2050. For at nå dette mål, skal energiforbruget i den eksisterende bygningsmasse reduceres markant, da de tegner sig for 40 % af Danmarks samlede energiforbrug. Den eksisterende bygningsmasse i Danmark viste sig at have et enormt energibesparelsespotentiale da mere end 70 % af den nuværende bygningsmasse blev bygget før 1979 og generelt trænger til omfattende renovering. Eftersom parcelhuse tegner sig for næsten 45 % af den danske bygningsmasse, er energibesparelsespotentialet i denne bygningskategori enormt. Det største energibesparelsespotentiale blev fundet i huse fra 1961-1979 som projektet derfor fokuserer på.

Det viste sig at være kompliceret at motivere parcelhusejere til at udføre private energirenoveringer. Den økonomiske gevinst ved energibesparende renovering viste sig at være den stærkeste motivationsfaktor blandt boligejere, men samtidig også den største barriere. En anden vigtig motivationsfaktor for husejere viste sig at være det forbedrede indeklima som energirenoveringer også medfører.

Det blev konkluderet, at man for at motivere husejerne yderligere, bør tydeliggøre de fordele, såsom forbedret komfort og indeklima, for husejerne for dermed at øge de motiverende faktorer og dermed antallet af energirenoveringer.

TREE (Tool for Renovating Energy Efficiently) blev udviklet med det formål at inspirere og motivere husejere til at udføre energirenoveringer ved at kombinere de føromtalte faktorer. Værktøjet er udviklet i MS Excel, da Excel har kapaciteten til at udføre de nødvendige beregninger, samtidig med at Excel er et almindeligt anvendt og let tilgængeligt redskab hvormed den potentielle brugergruppe øges. Det første skridt var at skabe et spørgeskema, der gør det muligt for boligejer at reflektere over den nuværende komfort og eventuelle ubehag, for at få et overblik over potentielle problematiske områder af huset. Derefter blev en grundig undersøgelse foretaget af byggestil, komponenter og installationer fra disse år, der skabte den vigtigste database for værktøjet. Denne database blev derefter brugt til at udføre det månedlige gennemsnitsberegninger[1] til at estimere de nuværende forhold i huset. Derfra blev foranstaltninger og renoveringer anbefalet i relation til energibesparelser og ikke-energimæssige fordele[2] baseret på undersøgelser udført gennem beregninger og detaljeret kontrol. Simple visualiseringer af det endelige resultat vha. grafer og illustrationer, blev derefter skabt for at give boligejeren et klart billede af de potentielle energibesparelser og de medfølgende ikke-energimæssige fordele.

[1] Monthly Average Calculations
[2] Non-energy benefits

This page is intentionally left blank

Table of Contents

Abbreviations

AAU	Aalborg University
ACH	Air Changes per Hour
BBR	Bygnings- og Boligregistret (Building and Housing Register)
Be15	Bygningers energibehov 2015 (Energy frame calculation software)
BR15	Building Regulation 2015
BSim	Building Simulation (Simulation software)
CO_2	Carbon Dioxide
COP	Coefficient of performance
DF	Daylight factor
DHW	Domestic Hot Water
DRY	Design Reference Year
DS	Danish Standard
EN	European Standard
EPS	Expanded Polystyrene
FAQ	Frequently Asked Questions
Ff	Share of glass in a window
Fs	Shadow factor
HVAC	Heating, Ventilation and Air-Conditioning
IEQ	Indoor Environmental Quality
kKh	Kilokelvin hour
kWh	Kilowatt hour
LED	Light-Emitting Diode
MAC	Monthly Average Calculations
PCB	Polychlorinated Biphenyls
PIR	Polyisocyanurate panel

PV Cell	Photovoltaic Cell
SBi	Statens Byggeforskningsinstitut
SPF	Seasonal Performance Factor
TREE	Tool for Renovating Energy Efficiently
VIP	Vacuum Insulating Panels

1 Introduction

This chapter presents the Danish government building energy and environmental related aims and ambitions. To achieve these goals, main strategies have recently been presented and will therefore be discussed here.

1.1 The Danish energy policy

The ambition of The Danish government is to be independent of fossil fuels by 2050, covering the total Danish energy demand by renewable energy sources such as the wind, the sun, biomass and geothermal energy. This is a huge transition with great reward. Energy independence will increase the security of supply and make the Danish economy more robust; less vulnerable to fluctuating prices of oil, coal, and gas. Furthermore, switching to renewable energy sources is a significant contribution towards meeting EU's ambitions of reduced greenhouse gas emissions from the EU by 80-95 % in 2050 compared to 1990. In order to achieve the 2050 goal, it is essential that the current energy used in existing buildings is reduced by 50% (Energistyrelsen 2016b).

At this point, the current governmental agreement is from 2012 and continues to 2020. The agreement was made by a wide majority in the Parliament. The parties of the agreement have committed themselves to discuss additional initiatives for the period after 2020, before the end of 2018 (Danish Energy Policy 2012).

Main strategies

There are two main strategies in terms of converting the Danish energy system. One is to increase the share of renewable energy, and the other is to ensure increased energy efficiency. Renewable energy covers wind, biomass, and biogas as the primary sources in Denmark. Geothermal and solar energy is secondary but their share is increasing.

The goal of increased energy efficiency is to reduce the primary energy consumption in Denmark. This applies to all parts of the energy supply, from producer to consumer, e.g. using waste heat at the power plant as district heating and increasing the efficiency by the individual consumers (households, private industry, public institutions etc.) by for example building and renovating in an energy efficient way (Energistyrelsen 2016b).

This is enforced by constantly monitoring and developing the Danish Building Regulations. As of 1st July 2016, the building regulation was updated from BR10 to BR15 where two renovation classes were added. Renovation classes can be used to document if a building meets the demands for the energy frame, as it is done with new buildings (Kragh 2016).

2 Problem description

This chapter will present the problem which formed the basis of the research conducted in this master thesis. Investigations and analysis into current problem will be presented. Furthermore, problem formulation, delimitations, aims and methodology.

2.1 Problem analysis

The construction industry in Europe is responsible for 42% of the energy consumption, around 35% of greenhouse gas emissions and more than 50% of all extracted materials (Birgisdottir et al. 2013). This strongly indicates a huge potential and that something needs to be done in this industry in order to reduce energy consumption and greenhouse gas emissions. The European building stock is currently being renewed at the rate of only 1 – 1,5% per year, meaning that the greatest potential of improvement is found in the existing building stock where energy consumption can be reduced by for example increased energy efficiency (BPIE 2011). The strategy for energy renovation in Denmark needs to be carried out so the existing building is renovated as they wear out. The need will only increase as the existing building components will wear out over the next 30-50 years, meaning that a large part of the current building stock will need to undergo energy renovation by 2050, as illustrated in Figure 2.1 (The Ministry of Climate 2014).

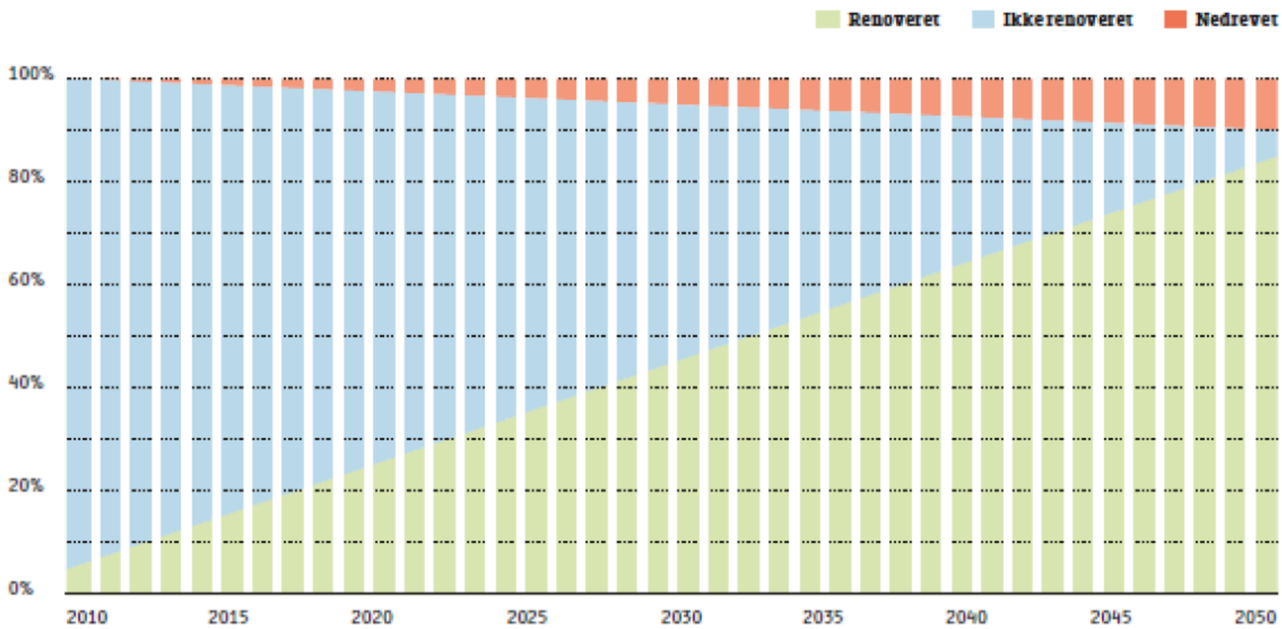


Figure 2.1 Main part of the buildings should be renovated by 2050 (The Ministry of Climate 2014)

There is urgent and increasingly need for energy renovations. It is crucial to investigate what would increase the willingness of homeowners, to conduct private energy renovations, in order to increase the rate at which the existing building stock is being renewed at.

2.1.1 Barriers and motivational factors of energy renovations

With an increasing awareness on energy savings from both public and political side, it would seem straightforward to get homeowners to invest in energy renovations of their house. However, homeowners are faced with many barriers before the renovation process even begins. Lack of knowledge and general interest in renovation, energy consumption, possibilities available, potential benefits and added value of the house, work like overwhelming barriers for the homeowners in many cases. Furthermore, unrealistic calculations of savings potential and lack of good examples contribute to the uncertainty about the actual benefits of an energy renovation. When the savings are smaller than expected, it has a negative effect on the length of the payback time of a renovation, and usually, payback times are already stretching over a relatively long period considering the amount of years a homeowner would stay in the same house (Mortensen 2015).

In Denmark, where most housings are connected to district heating, a large part of the heating bill is a fixed amount of the subscription fee. On average, the fixed amount of the heating bill is 33 % and for more than 100.000 homeowners, the fixed part of the bill is more than 50 %. The higher the fixed amount of the heating bill, the lower the financial incentive to invest in energy-saving measures will be. Looking solely at the economy, with the aforementioned facts in mind, it is understandable that most homeowners hesitate with energy renovations, but as soon as the investment has an impact on social status and comfort parameters, the story changes. There is no payback time on a renovated kitchen or a new bathroom. Nevertheless, these rooms are highly prioritized when it comes to renovation, due to increased living comfort, functionality and "show-off" value (Mortensen 2015). From this, it can be concluded that it is possible to motivate homeowners to do renovations without an economic gain in mind since there are other parameters at play.

In the paper: *"Economy controls energy retrofits of Danish single-family houses. Comfort, indoor environment and architecture increase the budget."* (Mortensen et al. 2014), the authors analyzed potential motivational factors having conducted a survey where almost 900 Danish homeowners participated. There was a general consensus that homeowners should have an economic incentive in order for them to perform energy renovations. Among many questions in the survey, one question stood out: "What do you generally think about retrofits conducted to save energy?"

The respondents were allowed to pick as many answers as they seemed fit. Top three answers were all positive towards a renovation:

- 72 %: *"It gives a lower energy consumption"*
- 44 %: *"It gives an increase in the property value"*
- 37 %: *"It gives a better indoor environment"*

However, more than a quarter of the respondents thinks that energy saving renovations are expensive and doubts that the potential savings are as high as one can expect, supporting the arguments about barriers, stated earlier in this chapter. When asked how important five house-related parameters are, shown in Figure 2.2, ranked in relation to each other, 48 % rank a good indoor environment as the 'Most important', compared to only 18 % answering that low energy consumption is most important.

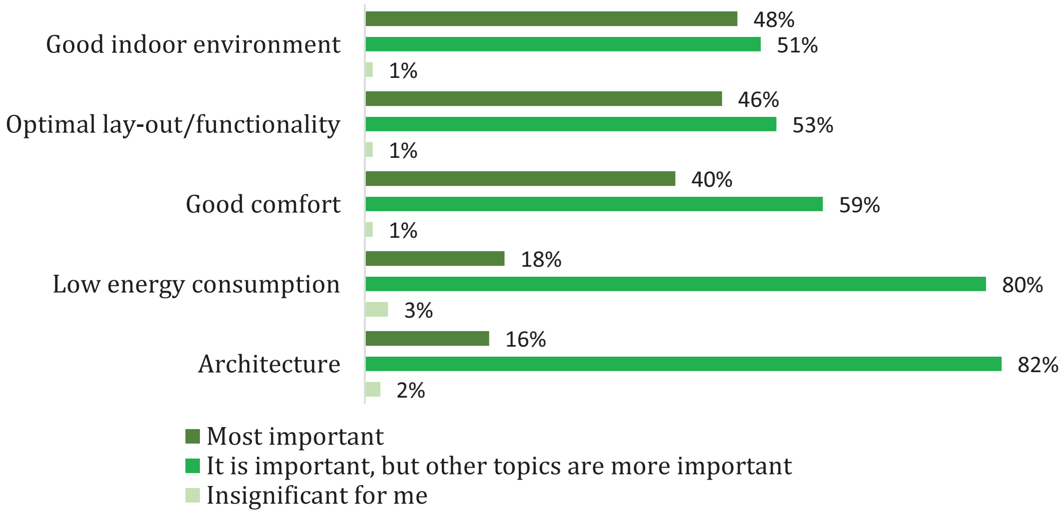


Figure 2.2 Five parameters evaluated individually according to their importance (Mortensen et al. 2014)

This adds to the understanding, that motivational factors for homeowners concerning energy renovation are highly dependent on the possible improvements to comfort parameters and the increased quality and functionality of the house.

As illustrated in Figure 2.2, when the 5 parameters are ranked in relation to each other as the 'Most important', low energy consumption is ranked as the second least important parameter of the five, only slightly higher than architecture. Part of the explanation could be, that a large part of the respondents believes that their energy consumption is lower or even much lower than the average of similar households. When the homeowner is convinced he is using less energy compared to similar households, the homeowner has little incentive to reduce his consumption (Mortensen 2015).

This is supported by an investigation made by the *Danish Energy Agency, Home and Realkredit Danmark*, Figure 2.3, showing that more than 50% of homeowners in Denmark, believe that their energy consumption corresponds to an energy mark of A or B, when in reality only 10% of the homes are marked with A or B. Only 15% believe that their consumption corresponds to mark E, F or G, when in reality this applies to more than 40%. Informing the homeowners about the current state of their home regarding their energy consumption seems to be crucial in order for them to realize the full potential of an energy renovation, and thereby increasing their incentive to renovate.

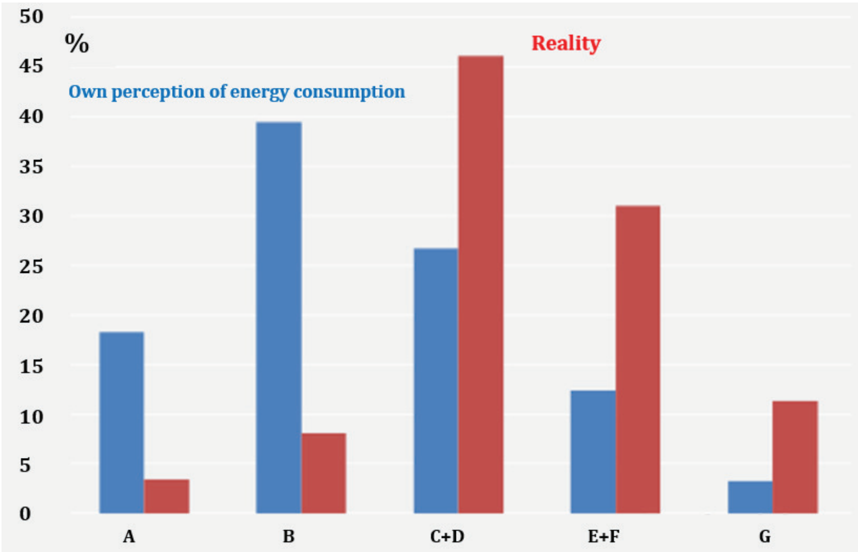


Figure 2.3 A large part of the Danish population lacks knowledge of the current conditions of their home, and thereby the potential of savings embedded in an energy renovation (Realkredit Danmark 2013).

A recent survey, Boligejeranalyse 2016, conducted by Bolius where around 3000 Danish homeowners participated., supports the fact that economy is a strong, if not the strongest motivational factor to energy renovate and highlights the great importance of improved comfort and indoor climate. Survey users were asked to mark 2-3 of the most important

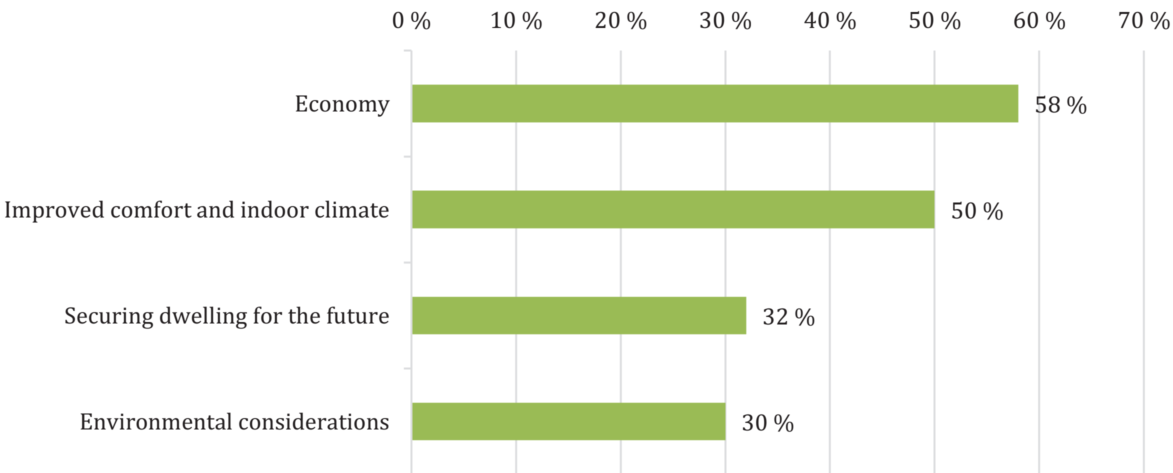


Figure 2.4 Which factors motivates an energy renovation (Boligejeranalyse 2016)

factors, where 58 % answered economy and 50 % answered improved comfort and indoor climate, as illustrated in Figure 2.4.

The same survey pointed out that economy was, by far, the biggest barrier keeping homeowners away from energy improvements illustrated in Figure 2.5.

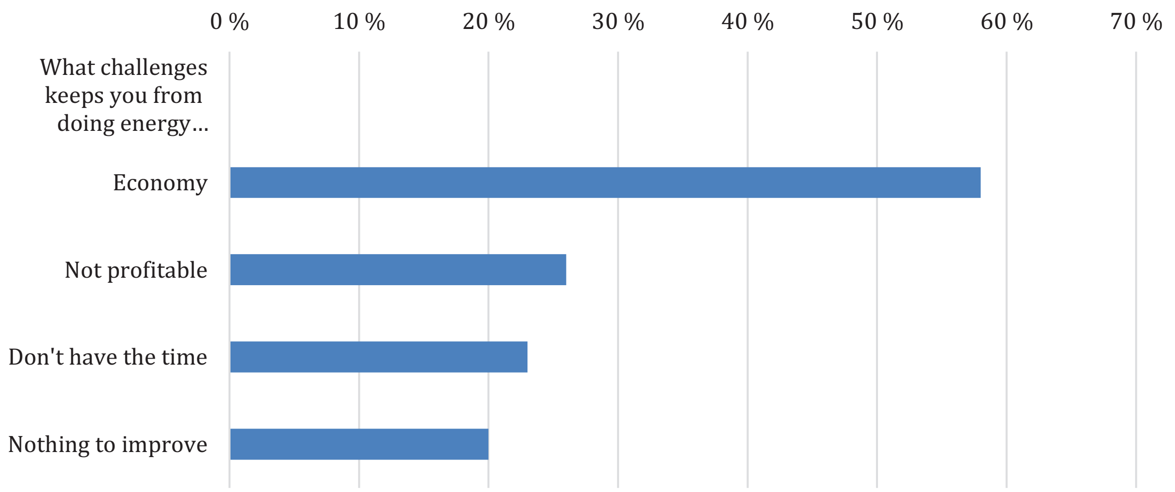


Figure 2.5 What challenges keeps you from doing energy improvement of your household? (Boligejeranalyse 2016)

From this chapter, it can be concluded that homeowners can be motivated by economic gains and potential improvements in parameters like comfort, indoor environment, and functionality, optimally in combination as stated by A. Mortensen (Mortensen 2015), p. 107:

> *"The most rewarding approach is predicted to be a combination of the themes and information about the potential improvements each of them can offer. This will also increase the total budget for the renovation project since the results indicate that the homeowners will pay more to get the improvements which in many cases is a natural gain when renovating."*

These potential improvements or side effects of an energy renovation are called non-energy benefits. Non-energy benefits will be the used term throughout this project and the benefits are described in details in chapter 3.1.4 Non-energy benefits. This analysis indicates a potential to increase the number of energy renovations by illustrating the positive non-energy benefits, such as improved comfort and indoor climate in combination with energy savings, in order to motivate homeowners to venture into major energy renovation.

2.1.2 Investigation of the current Danish building stock

This chapter will focus on a clarification of the energy savings potential in the current Danish building stock.

Through the recent century, construction of housing has undergone a significant development in terms of improved detailing and heightened focus on insulation, reducing energy loss through the building envelope, and thereby the energy consumption of the housing. Therefore, it is important to examine the composition of the current Danish building stock in order to define focus areas of the building stock with the largest potential energy savings. As the research on this area has already been done by Kim B. Wittchen in his publication (Wittchen 2009), the chapter will focus on a brief summary of the execution of the research and its findings.

First, building traditions are defined and split into 6 construction periods based on Danish building traditions. Based on knowledge of typical shift in the Danish building traditions and changes to the requirements for the structural elements in the older building codes, the existing building stock is split into the following construction periods: 1850-1930, 1931-1950, 1951-1960, 1961-1972, 1973-1978 and 1979-1998. Secondly, buildings are categorized in 5 different building types; farmhouse[3], single-family house, townhouse[4], apartment building and housing for commerce and services. Figure 2.6 shows that U-values of external walls have improved significantly through the years due to enhanced construction detailing and materials.

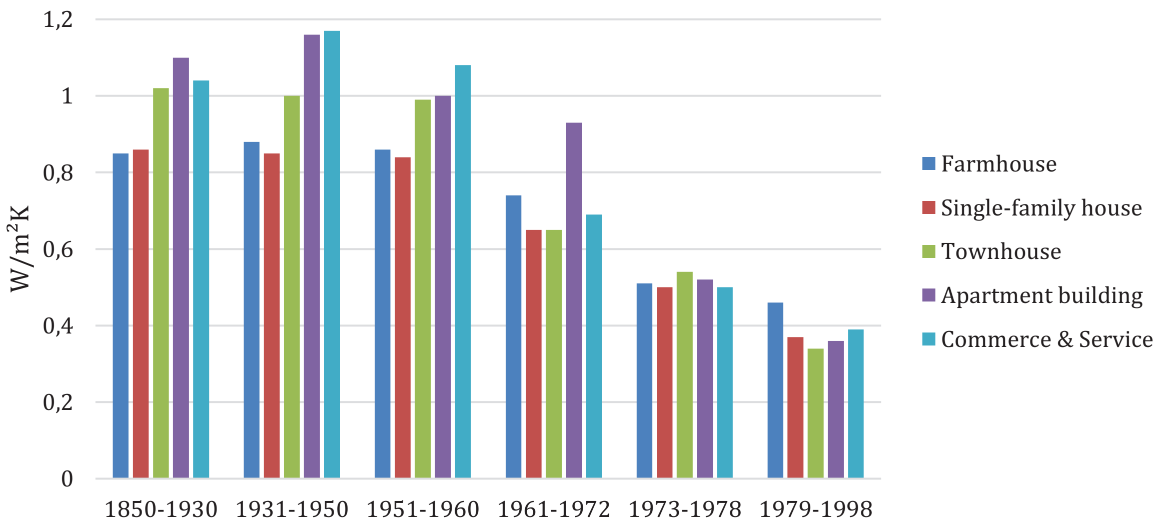


Figure 2.6 Area-weighed U-values for external walls. Values were also registered for roof, floor and windows. (Wittchen 2009)

Values for the roof, floor, and windows were also evaluated for each type, in each category, in order to define the relative energy savings potential. The U-values have been registered by

[3] Stuehus
[4] Række/kædehus

energy consultants as of 2006 when the Danish Energy Agency made energy markings a requirement.

Table 2.1 shows the part of the Danish building stock with an energy mark and thereby used as source data by 2009 when Wittchen's report was published. This data was then extrapolated to representative values of Danish buildings within the aforementioned five building types.
To calculate the absolute amount of potential energy savings, the amount of each type of building, given in m² floor area, constructed in the different periods was defined. Wittchen's findings are presented in the following.

Building type	BBR-code	Energy Marks	Marked area	Total area	Energy Marked
		[Qty.]	[m²]	[m²]	[%]
Farmhouse	110	2.379	449.599	25.824.000	1,74
Single-family house	120	77.959	10.294.284	160.571.000	6,41
Townhouse	130	16.480	2.759.277	35.025.000	7,88
Apartment building	140	5.483	6.559.423	82.855.000	7,92
Commerce & Service	320	1.396	2.544.124	56.823.000	4,48

Table 2.1 Source data: energy marked buildings as of October 2008 (Wittchen 2009)

Buildings constructed according to the Building Regulations in 1998 and later are not included in the calculation of the potential of energy savings in existing buildings. This is because the potential of these buildings is limited, while the investment required to influence the energy efficiency is expected to be relatively high in terms of improving the building envelope (Wittchen 2009).

As highlighted in Table 2.2 and illustrated in Figure 2.8, the largest part of the five categories are single-family houses built in 1961-1972, but also a considerable amount in 1973 – 1978, where the detailing and materials used were similar to the 1960s.

Area in million m²	Farmhouse	Single-family house	Townhouse	Apartment building	Commerce & service
1850-1930	18,74	27,72	4,27	24,84	11,09
1931-1950	2,45	13,72	2,16	14,92	3,35
1951-1960	0,84	12,98	2,5	8,02	2,79
1961-1972	0,91	**58,24**	5,3	14,35	11,41
1973-1978	0,72	**24,66**	4,35	4,57	6,67
1979-1998	1,08	19,95	15,06	8,08	16,88
Total	24,74	157,27	33,64	74,78	52,19

Table 2.2 Mio. m² covered by the five building categories (Wittchen 2009).

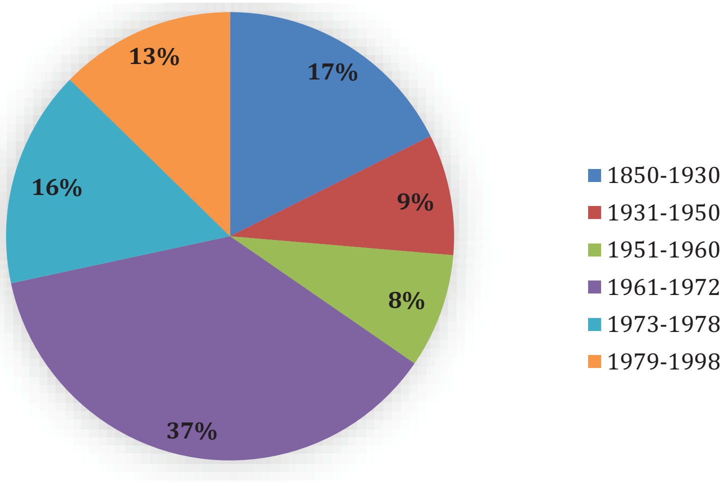


Figure 2.8 Area distribution of the six building periods from 1850-1998.

Combining the areas with U-values of the different building components from the periods provides us with the total, calculated energy consumption given for each type of housing within the six different building periods, shown in Figure 2.7. This is a strong indicator of the energy savings potential. However, as the average U-value of the construction components increased through time, it can be expected to see higher potentials the longer we go back in time, as long as the area is disregarded. However, the area should not be disregarded as this represents the number of potential housing, and thereby clients with interest in the solutions of this project. As it can be seen, single-family houses from 1961-1972 represent a significant amount of the total energy consumption. As there was very little, if any, development in construction detailing and materials through the 1970s, renovation solutions targeting 1961 – 1978 would pose the

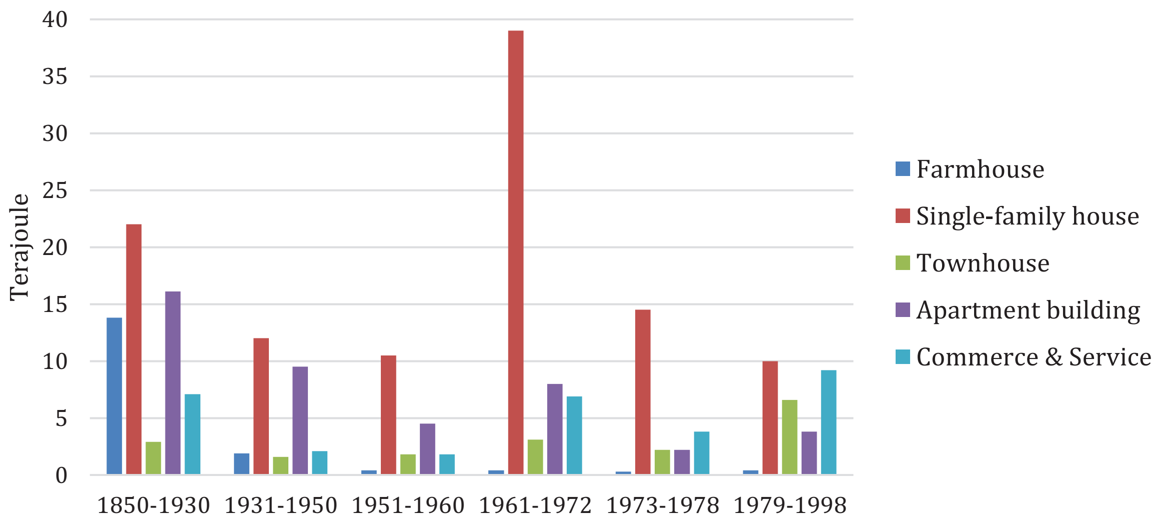


Figure 2.7 A combination of the performance (U-value) and the amount of area built in Denmark within each type of housing and period, provides an overview of the total energy consumption of those areas (Wittchen 2009).

greatest potential when it comes to energy savings, and therefore focus will be on these years in this project.

2.1.3 Identifying groups of homeowners

In order to inspire and convince homeowners to perform energy renovations of their homes, it is essential to identify this target group to accommodate their needs and wishes. This chapter is based on an investigation made by DTU BYG where 90 questionnaires were sent to homeowners of single-family housings constructed between 1960-1970. The target group represents different levels of income and from both sides of Storebælt. Additionally, nine interviews were performed to uncover their opinions in details (Almlund et al. 2002).

Homeowners have different preferences depending on where they are in their lives. In general, homeowners focus on design and functionality. They listen to arguments when it comes to quality, durability, cost savings, health, comfort and easy maintenance. They express a general concern in the lack of trustworthy guidance and want it to be more personal according to their specific situation (Almlund et al. 2002).

The investigation identifies three different homeowner groups, presented in the following section.

The new homeowners

Their income is fairly high compared to the two other groups, but as they bought the house recently and have children living at home, they do not have much money available for energy renovations. However, this group can see clear benefits of energy renovations as they are aware that energy prices are on a constant rise, but seem to lack knowledge and know-how. This group expects to stay in the house for many years, conducting renovations as the years go by and their economy allows it. Keywords for this group are low maintenance, quality, functionality and a healthy environment (Almlund et al. 2002).

The wealthy fifty-year-olds

The wealthy fifty-year-olds have paid most of their mortgage and their children have moved out. This results in a healthy economy and usually spending the most money on the renovation of the groups defined. However, money is spent on replacing the bathroom or kitchen rather than energy efficient renovations. Increasing the "show-off" value of the house is more important than investing in energy efficient renovations that hardly pay itself back before they move out of the house. They are also frightened by the potential inconvenience a renovation project can cause (Almlund et al. 2002).

The elderly original homeowners

Most of the elderly homeowners have lived in the house since it was constructed. They have a close relationship to the house, the materials, and its appearance, leaving little incentive to do refurbishments. This group spends the least amount of money on renovations and the housing is usually not maintained to the required degree. The group tends to link resource saving products with a decrease in comfort (Almlund et al. 2002).

THE MAIN TARGET GROUP

Based on the results of the investigation, it was chosen to focus on the new homeowners and the wealthy fifty-year-olds. Both groups are carrying out renovations and spending money on the house. The new homeowners need guidance in establishing renovation plan that can be carried out which illustrates the clear benefits, when time and economy allows it, while the wealthy fifty-year-olds need to be inspired to do energy renovations by, for example, presenting them their current situation and thereby the potential savings along with the potential non-energy benefits

2.1.4 Non-energy benefits from energy renovations

As mentioned earlier, there are benefits connected with energy renovations that are not related to energy savings alone. The non-energy benefits are mainly related to the indoor environment, comfort, floorplan layout, robustness, prolonged lifespan, architecture and increase of sale value.

Adding additional insulation, changing old doors and windows or replacing an old vapor barrier improves the airtightness of the building envelope. This will as well decrease potential discomfort from drought, downdraft, temperature variations on surfaces, moisture and noise from the outside, improving the overall indoor comfort When it comes to architecture, there are also possibilities of improvement concerning comfort parameters. Adding windows/skylights, increasing the size of the windows, painting with light and reflecting colours, changing materials or increasing room height are all parameters that can be changed to induce more daylight into the house and increase the visual comfort (Mortensen 2015).

Improved energy efficiency, and thereby reduced energy consumption can have a positive effect on the energy mark of a house. As energy prices are constantly rising and the fact that every house that is for sale in Denmark needs to have an energy mark assessment made by law, the awareness of energy marks and their significance for a potential buyer are increasing. This is reflected in the price/m^2 of the housing.

The robustness of the house will increase as energy effectiveness increases, making the house less vulnerable to increasing energy prices or potential carbon emission/energy-related taxes. Also, replacing old constructions improves the health of the construction and prolongs the lifespan of the house. Aforementioned measures will improve the value of the house and increase the sale value when time comes (Mortensen 2015).

2.2 Problem formulation

Knowing that buildings consume 40 % of the total energy consumption in Denmark, there is a huge potential for energy reductions in this area (Energi- Forsynings- og Klimaministeriet 2014). Single-family housing is one of the most common types of housing in Denmark accounting for 1.2 million out of a total 2.6 million dwellings in Denmark (Statistics Denmark 2016). Improving the energy efficiency in these type of dwellings is, therefore, essential in order to achieve the goals of the Danish energy policy by 2050.

Even with the increased focus on the existing building stock in Denmark and Europe, the greatest attention in current regulations and available tools are on achieving energy efficiency in new constructions. There is knowledge, know-how, and arguments for doing energy renovations, but the aforementioned barriers between the homeowner and this information seem to be insurmountable.

While standards and building regulations gradually adapt to more energy efficient renovation procedures, the customer needs to be convinced of investing in more energy efficient methods and solutions. The homeowner needs to be inspired with the intention of changing their mindset and behaviour, increasing willingness to choose energy efficient solutions and potentially adopt more sustainable choices in their everyday life.

Having defined three different user groups it is clear that each user group needs to be approached individually as motivational factors and available finances vary accordingly. In order to inspire and motivate the homeowner, the current state of the house should be defined and presented, consequently ruling out potential misconceptions about the homeowners' self-consumption.

This project concerns the development of a decision-making tool to inspire and motivate homeowners to perform energy renovations by including potential non-energy benefits improvements related to the indoor environment. Increased knowledge and a supportive tool will allow the industry to tackle the barriers that homeowners are faced with in renovation projects. Decisions are based on the numerous desires, needs, and values of a homeowner while incorporating the important aspects of energy efficiency.

2.3 Delimitation

Research initiated by The Danish Energy Agency and conducted by Kim B. Wittchen in 2009, presented potential of energy savings according to the year of construction. Wittchen divided the Danish building stock into 6 categories. The highest potential was given in the periods 1850 – 1930 and 1961 – 1972.

Between 1961 and 1978, around 448.000 single-family houses[5] were built in Denmark. This is a significant amount in only seventeen years, as a matter of fact, buildings from this period

[5] parcelhuse

count for 17% of the total current building stock (Statistics Denmark 2016). As building regulations changed very little concerning construction detailing, buildings from this period are very similar, subsequently making the target group larger by designing renovation solutions that would fit any case from that period. Therefore, the tool is aimed for renovations of buildings in this 17-year period.

2.4 Aims

According to the low rate at which the building stock is renewed in the EU and Denmark, the potential for energy savings in the existing building stock is enormous. Due to the lack of support and decision-making tools which are able to assist in breaking down barriers that homeowners are facing, it was chosen to create and develop a decision-making tool for energy renovation that will combine energy savings and non-energy benefits related to indoor environment and comfort. The tool will present the user with energy efficient measures and renovations that can be carried out in order to improve comfort and indoor environment with the purpose of increased energy efficiency and thereby potential economic gains.

Non-energy benefits related to indoor environment and comfort are one of the main motivational factors in inspiring homeowners to make energy efficient renovations. The aim is therefore to create a tool that can guide the homeowner towards energy renovation, by defining the possible areas of optimization to improve their level of comfort and increased energy efficiency.

2.5 Methodology

References used in this project are primarily based on secondary data method, both quantitative and qualitative methods and then literature research.

Quantitative methods, in terms of statistical data, have been used to clarify the potential energy savings in the current Danish building stock, and ultimately defining the target group of single-family housing in this project. User surveys were used to define the motivational factors and barriers of the Danish homeowners living in the target single-family homes, and finally, qualitative interviews were used to specify the motivational factors and barriers within each of the three defined homeowner groups.

For the development of the tool, various type of literature was reviewed, ranging from academic literature, online sources, producer and supplier information and research articles. Building regulations, requirements, and standards were as well analyzed and used in the development of the tool.

3 Literature review

This chapter will present review of literature as it relates to the current investigation. An overview of the potential energy improvements, along with current BR15 regulations is first presented. Furthermore, economy aspects, non-energy benefits and occupant behaviour are presented. Ending up presenting energy renovations tools that are currently available on the market.

3.1 Energy efficient renovation

3.1.1 Decreasing energy consumption

The Danish government aims to become independent from fossil fuels by 2050, relying solely on renewable energy sources. Figure 3.1 illustrates energy consumption of different areas as of 2009. As shown, the consumption of energy in households are significant. The plan is to lower the overall energy consumption for households by improving the efficiency of the energy using systems while also implementing new building regulations for energy use in buildings. This can be accomplished by making energy efficient renovations of the existing building stock, introducing renewable energy sources and replacing old, inefficient utilities.

The Danish Government has made short term goals, one being to lower the use of fossil fuels by 33 % in 2020, but since the overall consumption will only decrease by 6 % from this, it is essential to implement renewable energy sources as well (Government 2011).

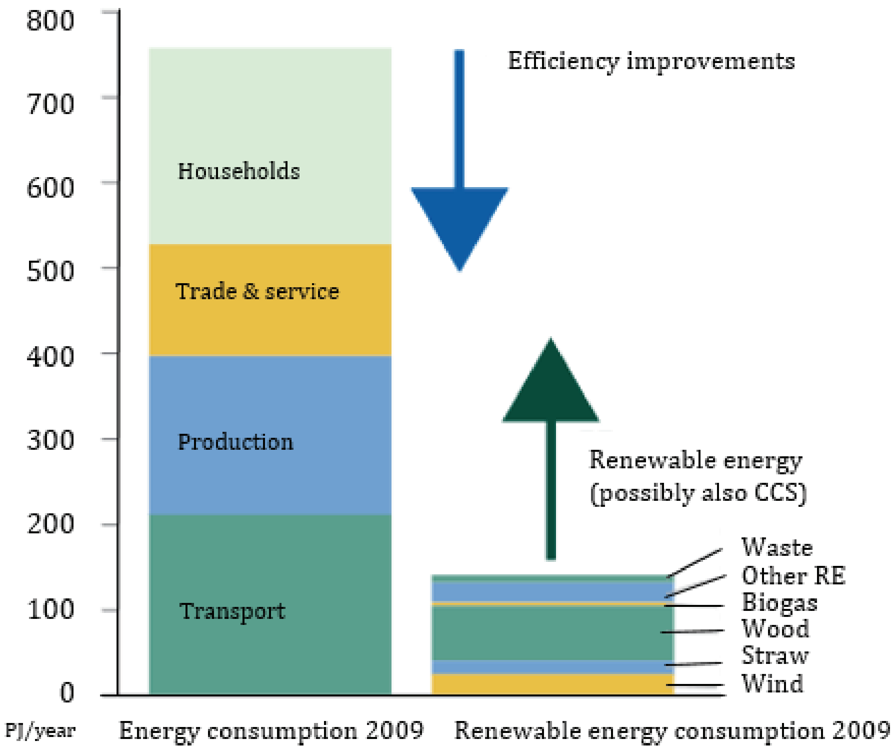


Figure 3.1 Energy consumption and renewable energy (Government 2011).

The goal for the existing building stock is to lower its energy consumption by 35 % before 2050. Improving the energy efficiency can be expensive as a standalone solution, making it difficult to convince the client to perform one, therefore, it is suggested that energy efficient renovations are done together with other renovations such as the need of a new roof, replacing old components or informing the client about potential non-energy benefits of the energy renovation (Energistyrelsen 2014).

Making energy efficient improvements does not only lower the energy demand but usually also increases the comfort of the building. In 2014, the Danish Energy Agency renovated three different buildings constructed between 1900 – 1965. The improvements of the buildings were mainly performed to lower the energy demand, however, interviews with the homeowners indicated that comfort, in terms of draught and temperature gradients had improved (Energistyrelsen 2014). As illustrated earlier, optimized comfort parameters are of great value to most homeowners, but they are also difficult to quantify and value. Experience from living and working in the building prior to the renovation can reveal these kinds of improvements, so it is important to involve the homeowners in the process by e.g. interviews or questionnaires.

Buildings are responsible for more than 40 % of the energy consumption worldwide (Nielsen et al. 2016). The need for lowering the energy use in buildings is considered a high priority when discussing energy efficient procedures.

Energy Source

Although new and renovated buildings have a low energy demand, the energy needed for space heating, hot water and electricity are still significant. The first step of decreasing energy consumption is always to limit the use of energy by adding more insulation, sealing the building envelope or replacing windows, old construction components, and utilities. Secondly, renewable energy sources are recommended. Renewable energy in Denmark utilizes the Sun, the wind, and energy stored in the ground to create electricity or heating. Heat pumps use electricity to operate, but they produce more energy than they consume (COP > 1.0) therefore, they are classified as a renewable energy source.

The energy production from renewable energy sources can either be at the individual cadastral or in larger scale, on municipality level. When multiple households share a heat pump, instalment, maintenance and running cost are cheaper than when single households have their own decentralized system. However, as the Danish building regulations are developed through time, demands to energy efficiency are increased. Furthermore, BR15 introduces demands to the “conversions and other alterations” category, which is the category that is used when renovations are carried out, where renewables are required as part of the energy supply. This is further described in the following chapter.

3.1.2 Danish Building Regulations 2015

In this chapter, an overview of regulations relevant to improvements and renovations in the Danish Building Regulations 2015 is presented. Renovations are covered by the "Conversions and other alterations" category of the Danish Building Regulations 2015, as illustrated in Figure 3.2. These regulations will form the basis of the decision-making tool.

New buildings	Change of use	Extensions	Conversions and other alterations	Replacements of building elements and installations	Reparations and upkeep*
Energy requirements Chapter 7.2	Energy requirements Chapter 7.2	Energy requirements Chapter 7.3	Energy requirements (cost-effective) Chapter 7.4	Energy requirements Chapter 7.4	No energy requirements Chapter 7.4

Figure 3.2 Six different categories in the Danish Building Regulations 2015 (Danish Knowledge Centre for Energy Savings in Buildings 2016).

Firstly, this chapter describes legal requirements for thermal insulation, concerning cost-effective energy improvements and renovations (depicted in Figure 3.3) and how they should be achieved.

Conversions and other alterations to the building (cost-effectiveness) and replacement of building parts. Chapter 7.4.2	U value W/m² K	Approximate insulation thicknesses mm
External walls and basement walls in contact with the soil	~~0.20~~ → 0.18	200 (heavy) / 250 (light)
Suspended upper floors and partition walls (adjoining rooms/ spaces that are unheated or lightly heated*)	0.40	75
Ground slabs, basement floors in contact with the soil and suspended upper floors above open air or a ventilated crawl space	~~0.12~~ → 0.10	300
Ceiling and roof structures, including jamb walls, flat roofs and sloping walls directly adjoining the roof	~~0.15~~ → 0.12	300
Doors/gates	~~1.65~~ → 1.80	
Hatches to the outside or to rooms/spaces that are unheated or lightly heated*	~~1.65~~ → 1.40	
New secondary windows	~~1.65~~ → 1.40	
Renovated secondary windows	- → 1.65	
Skylight domes	~~1.65~~ → 1.40	
Requirements for linear loss for joints between building elements	**Ψ value** W/m K	
Foundations	0.12	
Joints between external walls, windows, external doors, glazed external walls, gates and hatches	0.03	
Joints between roof construction and roof lights or skylight domes	0.10	

Lifetimes that can be used to calculate cost-effectiveness	Years
Retro-fitted insulation to building elements	40
Windows with secondary windows and coupled frames	30
Heating systems, radiators and underfloor heating and ventilation ducts and fittings including insulation	30
Heat appliances, etc., for example boilers, heat pumps, solar heating systems, ventilation units	20
Lighting fittings	15
Automation for heating and climatic control equipment	15
Joint sealing works	10

Figure 3.3 BR15's requirements for thermal insulation concerning costeffective energy improvements and lifetimes of different improvements used in the calculation (Danish Knowledge Centre for Energy Savings in

Cost effectiveness indicates how rewarding an energy saving measure is, and it is calculated by equation (1). If the cost-effectiveness is greater than or equal to 1,33, the investment is considered cost-effective for the building owner. This corresponds to a payback time of ¾ of its expected lifetime (Danish Knowledge Centre for Energy Savings in Buildings 2016).

$$\frac{\text{Lifetime in years } \cdot \text{annual savings in DKK}}{\text{Extra investment}} \geq 1{,}33 \tag{1}$$

As an alternative to satisfying the U-values and linear losses of BR15, you can choose to use the energy performance framework for existing buildings – also called renovation classes as shown in Figure 3.4.

Energy performance framework for existing buildings			
Dwellings, student accommodations, hotels, etc.			**Energy label**
Renovation class 1	$52.5 + \frac{1{,}650}{\text{heated floor area}}$	kWh/m² per year	A
Renovation class 2	$110 + \frac{3{,}200}{\text{heated floor area}}$	kWh/m² per year	C

Figure 3.4 Energy performance framework for existing building (Danish Knowledge Centre for Energy Savings in Buildings 2016).

This is implemented to allow for greater flexibility (Danish Knowledge Centre for Energy Savings in Buildings 2016):

> *"instead of having requirements for achieving heat savings by re-insulating per building element and with accompanying cost-effectiveness calculations, the energy performance framework gives the freedom to carry out other energy saving measures that in total bring the building's energy demand down to a future-proof level."* (Danish Knowledge Centre for Energy Savings in Buildings 2016).

Besides fulfilling the performance framework, the energy demand should also be reduced by at least 30 kWh/m^2 per year. Furthermore, it is required that part of the total energy supply for the building is renewable. This is achieved when the building is either supplied by district heating or has an additional contribution from wind power, PVs, solar thermal energy or heat pumps. Buildings solely relying on oil, natural gas or electric heating is, therefore, subject to this requirement (Kragh 2016).

Renovation Class 1 shall also meet the requirements for indoor climate described in BR15 chapter 6.2 Thermal indoor climate, 6.3.1 Ventilation and 6.5 Artificial lighting as seen in Appendix A: BR15: Conversions and other alterations (Danish Knowledge Centre for Energy Savings in Buildings 2016).

3.1.3 Economic aspect

In this chapter, the homeowners' investments related to energy renovations are presented. As earlier described, the economy is the largest barrier and an important motivational factor for homeowners.

The energy renovation potential is huge in an old house. A large part of people buying an old house has their mind set on shaping it, according to their own style and wishes. But it can be expensive to perform renovations, therefore, it is important to ensure that the architect, craftsman or designer understands all the ideas and thoughts from the owners, at the same time ensuring maximum comfort and a high level of energy efficiency. As the regular homeowner has very little insight into comfort parameters, TREE guides him through different choices of energy saving measures and renovation while taking potential comfort improvements into account.

Figure 3.5 indicates that a large part of homeowners is willing to spend money on maintenance as an ongoing process (Boligejeranalyse 2016). It also indicates that it is very different how much money people spend over the years. Some homes are up to date when it comes to building envelope and interior, and only need basic maintenance, while others need much more in-depth renovation. It is important to have a plan and an overview of the total cost of the renovation and the operational cost when the extensive renovation is conducted. This ensures that the owner knows the costs for instalment and operation.

The lifespan of materials varies; therefore, it is important to investigate different solutions. Another important factor, that comes with planning, is the ratio between construction cost and running cost. Adding the proper amount of insulation, using passive solutions and renewable energy sources, will lower the consumption and thereby the monthly running cost.

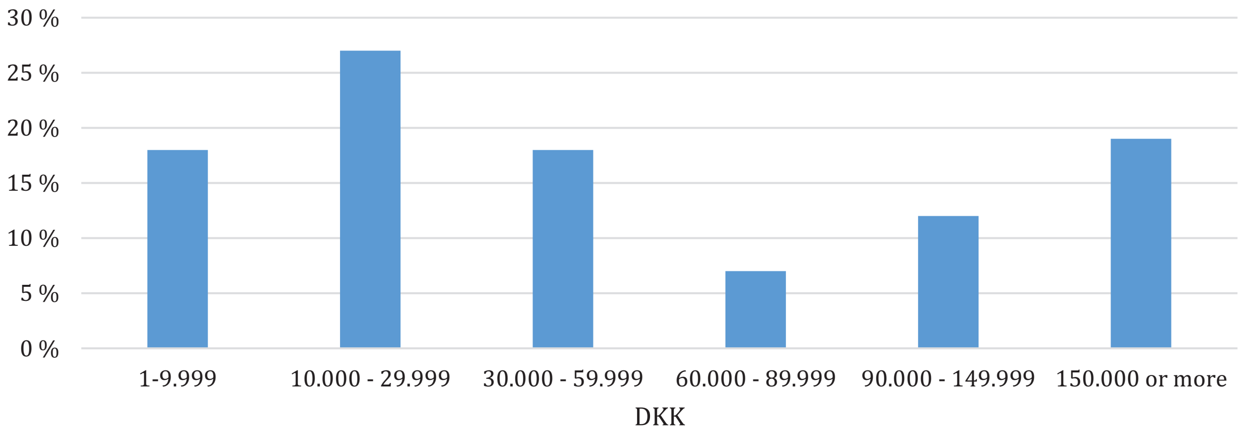


Figure 3.5 How much money have you spent on repairs of major maintenance work in the past year? (958 answers) (Boligejeranalyse 2016)

When doing maintenance of the house it is important to guide the owner to think in a broad context to ensure that the cost of instalment vs. running cost, in terms of energy consumption, is considered. As an example, changing the construction for energy improvements, like adding more insulation in the external walls, is not always profitable as a standalone instalment. Therefore, it could prove useful to plan energy efficient renovations together with other renovations/refurbishments of the housing.

The Danish Technological Institute has researched possible savings by adding new technology or modifying the current construction. Table 3.1 depicts a few examples of what can be done and their savings (Teknologisk Insistut 2016). All these examples are suggestions, but should always be followed up with further investigations - for instance, adding more insulation on the internal side could create a risk of moisture in the construction etc.

Component	Improvements	Yearly Savings
36 cm or 48 cm brick wall with no insulation.	Insulation 50-75 mm – internal side.	73 kWh/m^2
Manually controlled pump	Automatic controlled pump	280 kWh/pcs.
60 W Lightbulb	10 W A+ light bulb	32 kWh/pcs.

Table 3.1 Examples of savings by energy improvements in their lifespan (Teknologisk Insistut 2016)

3.1.4 Non-energy benefits

This chapter will present a theoretical overview of the benefits achieved when performing energy efficient renovation, that is not related to energy or emission savings.

Renovating a building with the main goal of decreasing the energy efficiency usually triggers benefits to the occupants, such as improved air quality and comfort, reduces problems related to the building physics, increases quality in the living space or lessens exposure to energy price fluctuation etc. These benefits are often called non-energy benefits. All these benefits are beneficial to the occupants, resulting for instance in a healthier indoor environment and added value to the renovated building (Ferreira & Almeida 2015). However, these factors are often forgotten or ignored, when energy efficient renovation is planned. Cost plays a huge role in any renovation planning since many of the energy efficient renovation measures are often expensive and have a long payback time. Therefore, it is crucial that the non-energy benefits gained from each measure are presented to inspire and convince the homeowner. This can encourage the occupant to invest in each measure, even though they have a high cost and long payback time. Therefore, further investigation into non-energy benefits is performed in this chapter to determine which benefits could inspire the occupant to perform an energy renovation.

USE OF TERMS

There is a general discussion about what term to use, describing these benefits. The most obvious arguments are quite simple. People working within the indoor environment field do not like that the indoor environment parameters is considered to be a co-related or a secondary parameter and would argue that improving these parameters could simply be the highest priority of a homeowner, rather than reducing the energy consumption (Knudsen & Jensen 2015). In that sense, the non-energy benefits would be the primary motivational factor and the energy efficiency would become the potential non-energy benefit or ancillary benefit.

Others would argue that these parameters are interrelated so strongly with energy that describing them as non-energy benefits would seem incorrect. However, a term of the potential benefits that come with a refurbishment or energy renovation and does not concern the optimization or monetization of energy, is needed regardless of the strong bond in-between. As this report emphasizes the importance of the benefits to the point where they are not co-related, but are the main priority for the homeowner, it seems most appropriate to use the term *non-energy benefits* which will be used henceforth.

NON-ENERGY BENEFITS DEFINITION

Non-energy benefits are so-called side-effects that arise from energy related renovation measures beside reduction of energy, CO_2 emissions, and cost. These benefits can have significant value for the building and their occupants but are often disregarded due to e.g. lack of knowledge, willingness, and additional cost/work. However, these benefits should inspire occupants to undertake renovation measures that might not be the most cost and energy beneficial but will increase e.g. their living conditions with a healthier indoor environment. Figure 3.6 Illustrates a definition of the relations between benefits and energy savings in a renovation case.

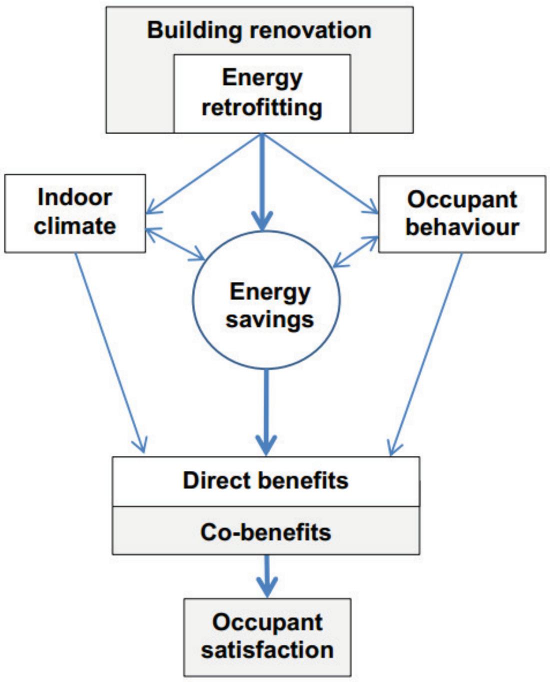


Figure 3.6 Possible interactions between energy retrofitting, energy savings, indoor climate and occupant behaviour and the direct benefits and non-energy benefits for the occupants (Knudsen & Jensen 2015).

In this figure, direct benefits are lowered energy consumption and CO_2 emissions, while non-energy benefits (non-energy benefits) cover better indoor climate and comfort, improved building aesthetics, a lower energy bill and robustness to fluctuation in energy prices (Knudsen & Jensen 2015).

All parameters are more or less connected. The behaviour of occupants can cause large variations in the energy consumption by for example turning the radiators on and off during the day or uneven settings on the radiators of the house. The indoor climate can also trigger behaviour that influences the consumption in both directions e.g. by opening the windows in winter, to air out while the radiators are still on, desiring higher indoor temperature or kids playing with the thermostats etc. (Knudsen & Jensen 2015). Occupant behaviour is further described in chapter 3.1.5.

Research conducted by Ferreira & Almeida (2015) indicated, however, that these non-energy benefits can be identified and divided depending on the eye of the beholder. Based on analysis of significant literature and several case studies, a white paper *"Benefits from energy related building renovation beyond costs, energy, and emissions"* from the 6th International Building Physics Conference 2015, defines the high relevance of non-energy benefits achieved from renovations and how they differentiate according to the perspective of the target group. The authors worked with two perspectives, the private (user/owner/promoters) and the macroeconomic (society/policy makers) perspective, described in the following subchapters (Ferreira & Almeida 2015).

PRIVATE PERSPECTIVE

Looking at a renovation from a private perspective, a homeowner would aim for the highest possible added value to his home, with the least cost or the greatest reduction in running costs. In order to accommodate this, the typical market solutions have been based on the most cost optimal solutions e.g. the cost per saved kWh. However, in that equation, the real added value and non-energy benefits are disregarded or simply overlooked. Therefore, it is crucial to introduce and educate the homeowner of the potential non-energy benefits achieved when a specific renovation measure is chosen.

For example, as seen in chapter 4.2.2.4 Windows, the payback time for new windows on two of the reference houses spans from 17 to over 50 years depending on their heating source. Changing windows would seem to be a bad choice from a financial perspective. However, new and up-to-date windows add numerous potential non-energy benefits: introducing more daylight into the room if window opening is enlarged, varying the amount of passive solar heating through the window pane, reducing external noise, increasing thermal comfort by improving airtightness resulting in increased usable living space in some cases, increasing security or improving aesthetics. Only when the homeowner is fully aware of the potential non-energy benefits, he can achieve the highest amount of added value to his house. Table 3.2

summarizes the non-energy benefits of the private perspective, in three categories together with the possible renovation measure each benefit is affected by.

Category	Non-energy benefit	Description
Building quality	**Building physics**	Less condensation, heat loss, humidity and mould problems (furniture can be placed etc. close to the wall without risking damages (mould) and draught)
	Ease of use and control by user	Ease of use and control of the renovated building by the users (automatic thermostat controls, easier filter changes, faster hot water delivery, etc.)
	Aesthetics and architectural integration	Aesthetic improvement of the renovated building (often depending on the building identity) as one of the main reasons for building renovation
	Useful building areas	Increase of the useful area (taking advantage of 1st floor balconies by glazing or enlarging the existing ones, People and furniture can be situated e.g. close to the window without risking damages (mould and draught) or decrease of useful area (like the case of applying interior insulation)
	Safety (intrusion and accidents)	Replacement of building elements with new elements at the latest standards, providing fewer risks for accidents, fire or intrusion
Economic	**Reduced exposure to energy price fluctuations**	Reduced exposure to energy price fluctuations gives the user a feeling of control and increased certainty to be able to keep the needed level of comfort.
	Increased value	Increase the value of the building and potential rent value
User Wellbeing	**Thermal comfort**	Higher thermal comfort due to better room temperatures, higher radiant temperature, lesser temperature differences, air drafts and air humidity.
	Natural lighting and contact with the outside	More day lighting, involving visual contact with the outside living environment (improved mood, morale, lower fatigue, reduced eyestrain).
	Indoor Air quality	Better indoor air quality (fewer gasses, CO_2 emissions, particulates, microbial contaminants that can induce adverse health conditions) better health and higher comfort
	Internal and external noise	Higher noise insulation, but increased risk of higher annoyance due to internal noise after the reduction of external noise level
	Pride, prestige, reputation	Enhanced pride and prestige, an improved sense of environmental responsibility or enhanced peace of mind due to energy related measures
	Ease of installation and reduced annoyance	Ease of installation can be used as a parameter to find the package of measures that aggregates the maximum of benefits

Table 3.2 Typology of private benefits of cost-effective energy related renovation measures, partly:(Ferreira & Almeida 2015).

MACROECONOMIC PERSPECTIVE

From a macroeconomic perspective, non-energy benefits assist policy makers in developing energy related policies and understanding how decisions in one area may impact other areas. The table is divided into 3 categories: Environmental, economic and social, concerning reducing air pollution, waste reduction, productivity and increased employment, welfare, and reduced mortality among others. Table of macroeconomic benefits of cost-effective energy related renovation measures can be found in Appendix B: Macroeconomic benefits of cost effective energy related renovation measures (Ferreira & Almeida 2015). These benefits do not concern single-family homeowners and will therefore not be investigated further in this thesis.

3.1.5 Occupant behaviour

Occupant behaviour is strongly linked to indoor climate, energy consumption, direct benefits and non-energy benefits as described in chapter 4.2.4

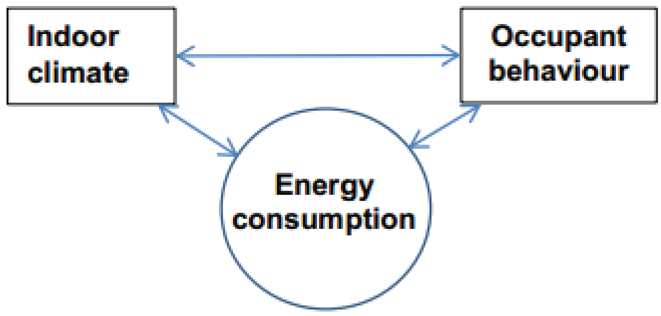


Figure 3.7 Possible interactions between indoor climate, energy consumption and occupant behaviour (Knudsen & Jensen 2015).

Occupant behaviour cannot be predicted and put into a formula, thus making it difficult to account for. However, investigations show that occupants react when they feel uncomfortable, and these reactions can lead to disruptive behaviour towards the most energy efficient use of the housing (opening windows, uneven thermostat settings throughout the housing, clogging of mechanical ventilation inlets etc.). In order to quantify occupant behaviour and their proneness to take action, results from statistical analyses are used to define standard behaviour patterns that contribute to more accurate calculations of the energy consumption in buildings (Knudsen & Jensen 2015).

In TREE, it is essential that the homeowner(s) is interviewed about his behaviour and the current state of the house in order to uncover potential issues. This is done to make sure that everything is taken into account when choosing energy saving measures and renovations. Also, making sure that the use of the building fits the knowledge level of the occupant or that the occupant can obtain the appropriate amount of knowledge through instructions, to ensure ease of use. The occupant's know-how plays a significant role in renovation situations, where new technology is installed. It is very common that building simulations tools overestimate the possible energy savings when dealing with new technologies. This phenomenon is known as the "rebound effect" proved possible by Guerra Santin: "Occupant behaviour in energy efficient dwellings: evidence of a rebound effect". The rebound effect is only relevant when dealing with energy efficient dwellings, which would require the target buildings of this project to undergo extensive renovation. When that is the case, the interaction between the occupants' behaviour and indoor climate is crucial in order to completely understand energy savings in the building (Knudsen & Jensen 2015).

3.2 Energy renovation tools

Energy efficient renovation of a building can be a complex process. It is difficult to determine what renovation measures to perform and what results to expect. Therefore, using a decision-making tool when energy renovating a building, can be of great assistance. In the recent years, increased focus on energy efficient renovation has caused the creation of new methodologies and decision-making tools throughout the field - developed for various building types, combining many aspects of the renovation process, such as technical, financial, energy and comfort. Many of the currently available tools have previously been reviewed and described by Lee et al. 2014 and Anne et al. 2016 (Hoon Lee et al. 2014)(Nielsen et al. 2016). However, most of these tools only identify potential renovation opportunities and measures for medium to large buildings, such as multi-storey apartment and office buildings, with an enormous focus on energy savings, environmental impact, and investment cost analysis. A minority of the tools available on the market, target smaller buildings, such as single-family houses. A literature review is presented in this chapter, with the aim of providing an overview of currently available decision-making tools for energy efficient renovation of smaller buildings, such as single-family houses, and their focus aspects.

3.2.1 An overview of currently available tools

Some of the few existing decision-making tools, without presenting a thorough overview, are illustrated in Table 3.3. As seen, most of the currently available decision supporting tools serve larger building projects. These tools are in general well-developed but are often considered as being quite complex. Focusing on smaller projects, such as a single-family house, with these complex tools can be time-consuming and rather complicated. The only decision-making programs found that would fit the single-family construction market, were REFLEX, Besparelsesberegner, and the SparEnergi guide. REFLEX goes into several aspects of the building renovation such as the economy, energy, environment, thermal comfort and indoor air quality. It also includes energy simulation and criteria calculation. These aspects can be very complex and require in detail knowledge that only some professionals in the field would possess, it has not been used in the Danish market. The Besparelsesberegner tool, created by the Danish Knowledge Center for energy savings is a very user-friendly, web based tool. It suggests potential renovation measures of the existing building in relation to energy performance in accordance with some information on energy savings. However, it does not cover potential environmental aspects, indoor environment or any parameters concerning non-energy benefits. SparEnergi is a web-based guide where users choose between a vast number of energy saving recommendations. SparEnergi mainly focuses on the economic benefits of an energy saving renovation.

Name of tool	Authors/developers	Target buildings	Target Audience	Aspects: Energy performance	Economy	Environment	Indoor environment	Other non-energy benefits
EPIQR	(Jaggs & Palmer 2000)	Apartment buildings	Building owners, designer, contractor	X			X(Indoor air quality)	
European Retrofit Advisor	(E2ReBuild 2014)	Apartment buildings	Building owners, designer, contractor	X	X	X		
TOBUS	(Flourentzou et al. 2002)	Office buildings	Building owners, designer, contractor	X	X		X	
REFLEX	(Pasanisi & Ojalvo 2007)	Single-family houses, townhouses, apartment buildings	Costumer, energy supplier	X	X	X	X(Thermal and atmospheric comfort)	
RENO-EVALUE	(Anker & Maslesa 2013)	Apartment buildings and offices	Building owners, seller, designer, contractor		X	X	X(Indoor climate and comfort)	X
Besparelsesberegner **(Renovation saving calculator)**	(Danish Knowledge Centre for & Energy Savings in Buildings 2015)	Single-family houses and townhouses	Building owners, designer, contractor	X	X			
SparEnergi **(webpage guide)**	(Energistyrelsen 2016c)	Single-family houses, apartment buildings	Building owners	X	X			
BSV-tool **(Decision-making tool for energy renovation)**	(Teknologisk Institut, 2016)	Apartment buildings, offices, institutions	Contractors, municipality, consultants,	X	X	X		

Table 3.3 Partial overview of existing decision-making tools for energy renovation. Partly cited from (Nielsen et al. 2016)

3.2.2 Tool improvements

SparEnergi was evaluated by the research and insights management company, Epinion, who found that users were very positive towards the design of the web page, ease of use, level and amount of information provided (Hamborg et al. 2016). However, SparEnergi has only had little success. The evaluation made by Epinion, from January 2016, states that SparEnergi is little known and not very present in the minds of people who knows about it. However, the investigation also showed that an increased amount of information about the financial savings can cause loss of credibility when the calculations are not spot on. This is expressed in the qualitative data and data from the focus group, where users express outrage when SparEnergi's information about the users' energy consumption does not correspond to reality. Adding this information is, therefore, a balancing act between making it easy for the user to relate to the economic gains without making it too specific so that individuals experience calculations as untrustworthy (Hamborg et al. 2016).

None of these decision-making tools present the potential overall non-energy benefits that follow with energy renovation projects as a consequence. These non-energy benefits are indoor environment improvements in terms of better overall comfort for occupants, increased indoor air quality, increased daylight, less draught etc. Developing a decision-making energy renovation tool for single-family houses in Denmark, which also presents the potential improved indoor environment and other non-energy benefits, gained by the renovation, would serve as motivational factors and increase the likeliness of homeowners renovating their single-family homes. Getting a tool like this out to the public in Denmark could increase the pace of renovation and assist in reaching the aforementioned goals of reducing CO_2 emissions.

4 Development of the energy renovation tool

This section outlines the development of the tool. Firstly, current conditions of houses and their installations from these year are investigated. Thereafter, potential energy saving measures and renovations are analysed. Questioner was then developed to investigate the occupant's perception on the current conditions of the indoor environment in their home.

4.1 Goals of the tool

Since the renewal of existing building stock is rising each year, there is an enormous potential for improving the energy savings and at the same time improving the indoor environment and comfort in single-family homes.

The aim is to develop a decision-making tool for energy efficient renovation of single-family houses by presenting renovation recommendations together with potential non-energy benefits as motivational factors for the homeowners.

Why is a decision-making tool needed?

- Decisions on which building components to renovate are often made on hunches instead of profound analysis.
- Clear criteria for choosing a renovation strategy/solutions are often missing.
- Renovation measures are, therefore, often not optimal. They may even be obtrusive to later renovation measures.
- Many single-family houses from 1961 - 1978 have an urgent need for an extensive renovation/reconstruction (E2ReBuild n.d.).

4.2 Investigation of current conditions and potential energy efficient renovation

4.2.1 Reference houses

This chapter aims to investigate and define the construction and building practice for single-family housing from 1961 – 1978. This investigation will be the basis of the extensive measures in the tool, indicating the current construction of the buildings and whether they have been renovated or not. To present the most typical constructions for this period, five reference houses were selected, listed in Table 4.1. Housing from this period is likely to have undergone renovations or modifications over the years. The investigation is based on the original drawings from the municipality, furthermore, potential renovations and improvements are also reviewed in this chapter. This information is then compared to other researches and legislations from 1961 – 1978. The materials from the municipality can be found in Appendix C: Reference Houses.

Reference House	**Year of construction** *[-]*	**Area** *[m²]*
Ref. A	1962	176
Ref. B	1966	117
Ref. C	1968	149
Ref. D	1975	123
Ref. E	1978	132

Table 4.1 List of reference houses selected by year of construction

It is important to have in mind, that due to the building customs at the time, the construction in reality can vary from the drawings and literature. The 1960s and 1970s are known for poor quality of construction and there are typically many design flaws, because it had to be built quickly and cheaply (Bolius 2014). However, for this chapter the focus is on creating a base for what can be expected depending on the year built or renovated and not as much on uncovering the construction errors.

4.2.2 Building envelope

4.2.2.1 Current condition

In this period, the thermal conductivity of insulation materials was typically 0,038 W/mK. The same value is used in similar studies: *Report R-165: Energy renovation of a typical Danish single-family house from the 1960-80's* from 2008 (DTU 2008). The U-values, in this chapter, are calculated by *Rockwool Energy* software and according to DS 418.

In the years 1961 – 1978, four different building regulations were in use. In Table 4.2 the required U-values for specific components, according to the different building regulations, are shown. The following chapters will as well investigate the reference houses to explore the actual U-values of their components.

Building Components	BR 61 *[W/m²K]*	BR 67 *[W/m²K]*	BR 72 *[W/m²K]*	BR 77 *[W/m²K]*
External wall > 100 kg/m²	1,10	1,10	1,00	0,40
External wall < 100 kg/m²	0,50	0,50	0,60	0,30
Wall facing unheated room	1,70	1,70	2,00	0,50
Ground floor	0,40	0,40	0,45	0,30
Floor facing ventilated crawl space	0,50	0,50	0,60	0,60
Ceiling-/Roof	0,40	0,40	0,45	0,20
Exterior Doors	-	-	-	2,00
Windows	-	-	2,90	2,90

Table 4.2 U-values from building regulations (Klimaministeriet 2016)

External Wall

Most houses from this time have bricks on the outer shell, whereas bricks as inner shell was associated with great expense, therefore, it was constructed with lightweight or aerated concrete. The gap between the inner and outer shell may have been insulated varyingly up to 75 mm according to sparenergi.dk. The most common insulation used was mineral wool, where others used aerated concrete with higher U-values than mineral wool. In some cases, houses have massive external walls composed of aerated concrete. (Energistyrelsen 2016c).

External Wall	Construction *[-]*	U-Value *[W/m²K]*
Ref. A	Double walled, from inside: 108mm brick. Air gap. 108mm brick. / Type 2: 10mm wooden board. Vapour barrier. 100mm insulation. 19mm wooden board.	1,63/0,33
Ref. B	Double walled, from inside: 108mm brick. 75mm insulation. 108mm brick.	0,40
Ref. C	Double walled, from inside: 75mm aerated concrete. 50mm insulation. 108mm brick.	0,50
Ref. D	Double walled, from inside: 17mm wooden board. Vapour barrier. 95mm wood per 600mm w/ 100mm insulation. Wind barrier. 50mm air gap. 108mm brick.	0,35
Ref. E	Double walled, from inside: 100mm lightweight concrete. 75mm insulation. 108mm brick.	0,37

Table 4.3 External wall construction of reference houses

As seen in Table 4.3, the variations in insulation thickness are between 0 – 100 mm, where previously the insulation thickness was described to be up to 75 mm. Reference house A and B are also constructed with the double brick facade, which was common practice up to the 1960s, but later phased out due to high construction cost. House A has wooden construction between windows, which is also a typical characteristic from that period. Only House D has a wooden construction as inner shell, whereas C and E follow the description with aerated and lightweight concrete based on the research conducted by The Danish Energy Agency.

Ceiling- and roof construction

Three types of roof construction were widely used. *Low slope,* where the slope of the roof is between 15° to 30°, high slope up to 45°, and finally a flat roof construction. A common build up for all of them was 100 mm of insulation, typically glass- or rock wool, and interior finish of plasterboard or wood. Between the plasterboard or wood and the insulation, the vapour barrier was placed often in plastic or aluminium foil. These vapour barriers are known to be assembled very poorly, which can create unwanted infiltration and cause moisture in the construction. Common to many of the houses are the large overhangs that protect the structures from the weather and provides shading for the windows. In addition, the roof construction starts right above the windows, for the builder to save bricks. If the roof has a high slope it typically has a 1st floor, but in the end of the '70s it became popular to have an integrated balcony in continuation of the 1st floor. (Energistyrelsen 2016c).

Roof/ceiling	**Construction** *[-]*	**U-Value** *[W/m²K]*
Ref. A	Flat roof, from inside: 19mm wooden board. Ventilated air gab w/ 150mm insulation. 25mm wooden board w/ roofing felt.	0,25
Ref. B	Low slope, from inside: Plasterboard. 25mm wood per 200mm. 100mm Insulation. Ventilated attic. Asbestos cement roof.	0,48
Ref. C	High slope, from inside: Plasterboard. 25mm wooden board (foam work). 100mm rock wool insulation. Attic. Asbestos cement roof.	0,33
Ref. D	Low slope, from inside: 15mm wooden board. Vapour barrier. 22mm wood per 580mm w/ 100mm insulation. Ventilated attic. Roof tiles.	0,37
Ref. E	High slope (1st floor including balcony), from inside: Plasterboard. Vapour barrier. 25mm wood per 400mm w/ 175mm insulation. Roof tiles.	0,23

Table 4.4 Roof construction of reference houses

The roof construction, described in Table 4.4, follows the common trend from the years 1961 – 1978. The insulation level varies from 100 mm to 175 mm, where the 100 mm is generally used. Vapour barrier is only mentioned in Ref. D and Ref. E, both built in the 1970's according to BR 72.

Throughout the years, a common renovation procedure in older houses has been to add more insulation to the attic. Most attics are unused and therefore an obvious place to make energy saving measures. The web guide sparenergi.dk has made a simplified overview of roof/ceiling construction depending on insulation thickness. The roof construction, that will also be used in TREE, varies from an insulation thickness of 25 mm – 400 mm with a U-value of 0,82 - 0,092 W/m^2K (Energistyrelsen 2016c). When comparing the *Sparenergi.dk* roof/ceiling construction (100 mm insulation) with a U-value of 0,35 W/m^2K to reference houses B, C, and D (also 100 mm insulation), where the U-value is calculated to be between 0,37 – 0,33 W/m^2K, it is estimated that these values from sparenergi.dk are validated.

Ground Floor

Houses from the '60s and '70s use 80 – 100 mm concrete as ground floor partition commonly finished with parquet flooring. Between the flooring and concrete there is a vapour barrier and often 50 – 75 mm insulation. If the parquet flooring was not suitable (in e.g. bathroom, kitchen, or laundry room) a tile flooring was used. Then the insulation was placed underneath the concrete with a typical thickness of 20 – 50 mm, either being mineral wool or polystyrene (Energistyrelsen 2016c).

Ground floor	**Construction** [-]	**U-Value** [W/m²K]
Ref. A	Wood floor, from inside: Parquet floor. Air gap. 100mm insulation. Wood. 600mm Crawl space.	0,32
Ref. B	Wood floor, from inside: Parquet floor. 50mm wood (impregnated) per 600mm w/ 70mm insulation. Tiles, from inside: Tiles. 120mm concrete. 200mm slag.	0,30/0,26
Ref. C	Wood floor, from inside: Wood. 50mm wood (foam work) (impregnated) w/ 50mm rock wool. 100mm concrete. PVC foil. 200mm sand.	0,33
Ref. D	Wood floor, from inside: 19mm melamine particleboard. Vapour barrier. 100mm wood per 440mm w/ 75mm insulation. Foil. 500mm crawl space. 80mm concrete.	0,47
Ref. E	Carpet, from inside: 160mm concrete. Foil. 75mm insulation.	0,27

Table 4.5 Ground floor construction of reference houses

As shown in Table 4.5, all the constructions are assembled differently. A positive common feature is that they all have insulation in the construction (except the tile floor in Ref. B). Ref. B has insulation placed directly on the soil, whereas Ref. A and Ref. D have a crawl space underneath the flooring. This creates a risk of moisture if it is not ventilated properly. Ref. B and Ref. C use impregnated wood in the construction, which in some cases could pose a health risk (Bolius 2015b).

Windows and doors

At the beginning of the 1960s windows with double glazing were introduced. The windows are large in size without mullions and the frame is made of wood. In the 1960s and '70s there were no regulations regarding the size of the windows, therefore, large facades facing the garden often consist of more glazing area than wall (Energistyrelsen 2016c). The U-value of a double glazing window, from this period, is estimated to be 2,4 W/m^{2}K (Klimaministeriet 2016).

Linear Losses

The investigation of the reference houses and building regulations indicates a lack of focus on linear losses. Linear losses are critical at joints around windows/doors and the connection between foundation, external wall and ground floor. The challenge in constructions from this time was the lack of insulation in the above-mentioned areas, which created unwanted thermal bridges. Aerated concrete (λ = 0.22 W/mK) was used at the top of the foundation, but none of the projects have specific descriptions or detailing solving the issue of thermal bridges.

Table 4.6 shows the values for linear losses around windows with 20 mm overlap, as used in the reference houses. The insulation thickness of the materials are estimated to be 00 – 20 mm corresponding to 0,04 – 0,11 W/mK (Dansk Standard 2011).

Insulation/ Construction	**Brick Concrete** *[W/mK]*	**Brick Brick** *[W/mK]*	**Brick LW Concrete** *[W/mK]*	**LW Concrete LW Concrete** *[W/mK]*
00 mm	0,13	0,11	0,09	0,06
10 mm	0,05	0,05	0,05	0,05
20 mm	0,04	0,04	0,04	0,04
30 mm	0,03	0,03	0,03	0,03
40 mm	0,02	0,02	0,02	0,02
50 mm	0,01	0,01	0,01	0,01

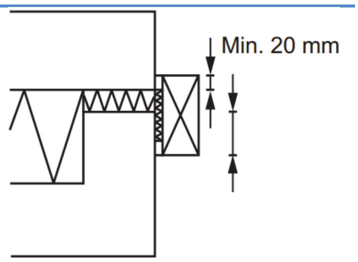


Table 4.6 Linear losses around windows with a minimum 20 mm overlap of the joints (Dansk Standard 2011). LW: Lightweight Concrete

In Building Regulations 1961 – 1977 (BR 61, BR 67, BR 72, BR 77) there were no restrictions regarding linear losses. Therefore, the value for linear losses around windows are estimated as worst-case scenario (0.06 – 0.13 W/mK) in Table 4.6 – Same procedure as in the DTU studies introduced earlier (DTU 2008).

The linear losses between foundations and external walls are shown in Table 4.7.

External wall *[-]*	**Linear loss** *[W/mK]*
Bricks / Light concrete / Light wall on concrete foundation	0,70
Bricks / Light concrete / Light wall on leca blocks	0,24
Bricks / Light concrete / Light wall on leca blocks w/ insulation	0,18
BR08 standards	0,15
Proper insulated wall	0,12

Table 4.7 Linear losses of foundation and external walls

4.2.2.2 Prior renovations

COMPONENTS

Since the houses are more than 30 years old, many of them have likely been renovated in some way over the years. It can be difficult to determine the new renovated construction; therefore, the tool will use the U-values from the building regulations (Table 4.8) depending on the year of renovation.

Building Components	**BR 82** *[W/m²K]*	**BR-S 85** *[W/m²K]*	**BR-S 98** *[W/m²K]*	**BR 08** *[W/m²K]*	**BR 10** *[W/m²K]*	**BR 15** *[W/m²K]*
External wall > 100 kg/m²	0,40	0,40	0,30	0,40	0,30	0,30
External wall < 100 kg/m²	0,30	0,30	0,20	0,40	0,30	0,30
Wall facing unheated room	0,50	0,50	0,40	0,50	0,40	0,40
Ground floor	0,30	0,30	0,20	0,30	0,20	0,20
Ground floor w/ floor heating	-	-	0,15	0,30	0,20	0,50
Floor facing ventilated crawl space	0,30	0,30	0,20	0,30	0,20	0,20
Exterior Doors	2,00	2,00	1,80	2,00	1,80	1,50
Windows	2,90	2,90	1,80	2,00	1,80	1,40

Table 4.8 U-values from Building Regulations 1982 – 2015 (Klimaministeriet 2016)

WINDOWS

Since the 1970s, new types and energy-enhancing windows have been released on the Danish market. The total U-value depends on the glass and the frame, therefore, Table 4.9 uses standard total U-values. These values are for each step of the development of new windows over the years. Still, there will be different variations of framework, e.g. casement windows, that influence the U-value.

Windows	**g** *[-]*	**Ff** *[-]*	**U-value** *[W/m²K]*
1 Layers	0,65	0,70	2,20
1 Layer + 1 Layer Energy Glass	0,65	0,70	1,80
2 Layer Energy Glass	0,65	0,70	1,42
2 Layer Energy Glass w/ Warm Edge	0,44	0,70	1,30
3 Layers Energy Glass (BR 15)	0,45	0,73	1,15
3 Layers Energy Glass (BR 2020)	0,38	0,74	0,80

Table 4.9 Properties of windows (Klimaministeriet 2016). g: solar radiation through the pane. Ff: percentage glass of total window area

4.2.2.3 Optimization of building envelope

In this chapter, an investigation of possible renovation solutions that can be performed to provide energy efficiency will be made. The aim is to examine the effect of different renovation solutions on the energy consumption and to see which areas would be most optimal to renovate first. From these investigations, the best available energy efficient measure will be collected to use for the TREE tool, which then can be used to estimate the most optimal energy efficient renovation for each individual case. The investigation will focus on building envelope components and energy frame of the previously mentioned reference houses with some additional construction components from 1961 - 1978 to extend the range of components covered by the tool.

RENOVATION SOLUTIONS

The heat loss from the building envelope can be significantly high in old buildings compared to new buildings. Hence, during a renovation process, the thermal performance of each component needs to be considered and how it can be improved in order to reduce the heat loss from the building and make it more airtight. This is a crucial step to ensure the optimal thermal comfort of the occupants and reduce the energy consumption (Wiseman & Summerson n.d.). Therefore, it is critical to document the current conditions of the building when using the tool. This will give an insight in the renovation needs and show where the most critical areas in need of renovation are in the building.

Over the years, the building regulations, regarding the thermal insulation of the building envelope, has tightened drastically as the understanding of possible energy optimizations (energy saving objectives) of buildings has grown. Additionally, the heat insulation materials and techniques have as well developed and been improved. It is important to consider combining multiple renovation measures when renovating with energy optimization in mind in order to achieve the best solution possible. For example, if additional thermal insulation is to be added to the external wall to improve the heat loss of the building, replacing the old windows will have significant effect on not only the improved heat loss but will also improve indoor environment by e.g. eliminating draught from windows, increasing airtightness, decreasing overheating etc. (Hakkinen et al. 2012). Combining possible renovation solutions together in the tool without eliminating further improvements will therefore be one of the focus areas in the tool.

THERMAL INSULATION

The most recognised and cost-effective method used when renovating the building envelope in an energy efficient way is by insulating it. By properly insulating the building envelope and improving the thermal design, the heat loss will be reduced significantly and the energy use will be cut (Dufour 2012).

Insulation solutions can be easily incorporated in new buildings, however, the solutions available for existing buildings are limited. The insulation solutions available also highly depend on the existing conditions of the structure e.g. airtightness, moisture problems and thermal performance, and as well on the available area for the insulation. Therefore, to represent the building envelope structure from the period of 1961-1978, the building envelopes of the reference houses are used in this chapter to investigate the different possible and most optimal insulation solutions, divided into external walls, ground floor, ceiling/roof and windows.

It is complex, costly and time consuming to renovate, and therefore, it is important to insulate the buildings up to at least the minimum standard set by the BR15, or even up to the high standards of Low energy class 2020. However, in this report, focus will only be put on achieving minimum standards of the BR15 and documenting the energy savings through the energy frame classes called Renovation class 1 and 2, as explained in Chapter 3.1.2.

SELECTION OF INSULATION MATERIAL

Insulation comes in many variations according to insulating properties and price. Energy savings can be achieved by using the right insulation material and provide a better comfort level at a reasonable amount of money. Investigation of commonly used insulation materials on the Danish market, was made to ensure their availability in order to use them in TREE. Furthermore, insulation materials were assessed to define the most suitable in reaching the BR15 standards, when considering thermal properties and cost. The thermal conductivity is the key performance parameter of the insulation material and has an influence on how well the material insulates. On the other hand, initial investment cost and uncertainty about the actual saving potential are some of the most influential factors for single-family homeowners when choosing renovation measures (Mortensen 2015). Therefore, the prices of each individual insulation materials are compared to its thermal conductivity - investigating the link between the initial investment and the potential energy savings when insulation measures are performed in the building envelope.

The most commonly used insulation materials in Denmark and their thermal conductivity are shown in Table 4.10 (Virén et al. 2011)(Videncenter for energibesparelser i bygninger 2012). It is important to choose the right type of insulation with the right thermal conductivity providing the required thermal resistance for the appropriate location in the building envelope and as well fits in the available space. The lower the thermal conductivity is, the more resistant the insulation is to heat flow. For example, polyisocyanurate foam (PIR) has almost twice as low thermal conductivity than foam glass batt insulation, and it can be a crucial factor when choosing insulation for an area with limited space (CMHC Corporation 2012).

Batts, plates and rolls type		**Loose-fill and granules type**	
Insulation material *[-]*	**Thermal condutivity** *[W/mK]*	**Insultation material** *[-]*	**Thermal conducutivity** *[W/mK]*
Glass wool	0,032 – 0,043	Cellulose fibre	0,040
Rock wool	0,030 - 0,040	Mineral fiber	0,028 – 0,037
Expanded polystyrene (EPS)	0,031 – 0,041	Light clinker	0,085 – 0,090
Polyisocyanurate foam (PIR)	0,022 - 0,035	Expanended perlite	0,042
Foam glass	0,038 – 0,055		
Gray EPS	0,031		
Vacuum insulating panels (VIP)	0,008		

Table 4.10 Characteristics of common insulation materials used in Denmark (Virén et al. 2011) (Videncenter for energibesparelser i bygninger 2012)

To establish a basis of this assessment, a reference unit was chosen in order to compare the price data obtained. The reference unit chosen, illustrated in Table 4.11, is a heavy external cavity wall from Reference house B. This is a very common type from this period. The calculation of the thickness and the price of each insulation material is made to achieve the recommended BR15 U-value of 0,18 W/m^{2}K.

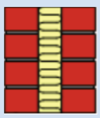
Reference *[House/Wall]*	**Construction** *[from inside to out]*		**U-value** *[W/m^{2}K]*
Ref. B	108 mm brick, 75 mm insulation, 108 mm brick		0,40

Table 4.11 Reference unit used for insulation price data comparison

For each insulation material, a certain type of external wall insulation product was chosen from a producer to obtain a price estimation. Note that the prices of insulation materials can vary with other manufactures and product types. All the products and related calculations can be seen in Appendix D: Insulation. By combining the thickness needed to insulate the Reference wall and the square meter price as shown in Figure 4.1, a good overview is created. As seen in the graph, two of the materials, VIP and PIR panels perform well with lower amount of thickness compared to the others due to their low thermal conduction. However, the price of the VIP panels is significantly higher, and therefore, it will not be used for the tool.

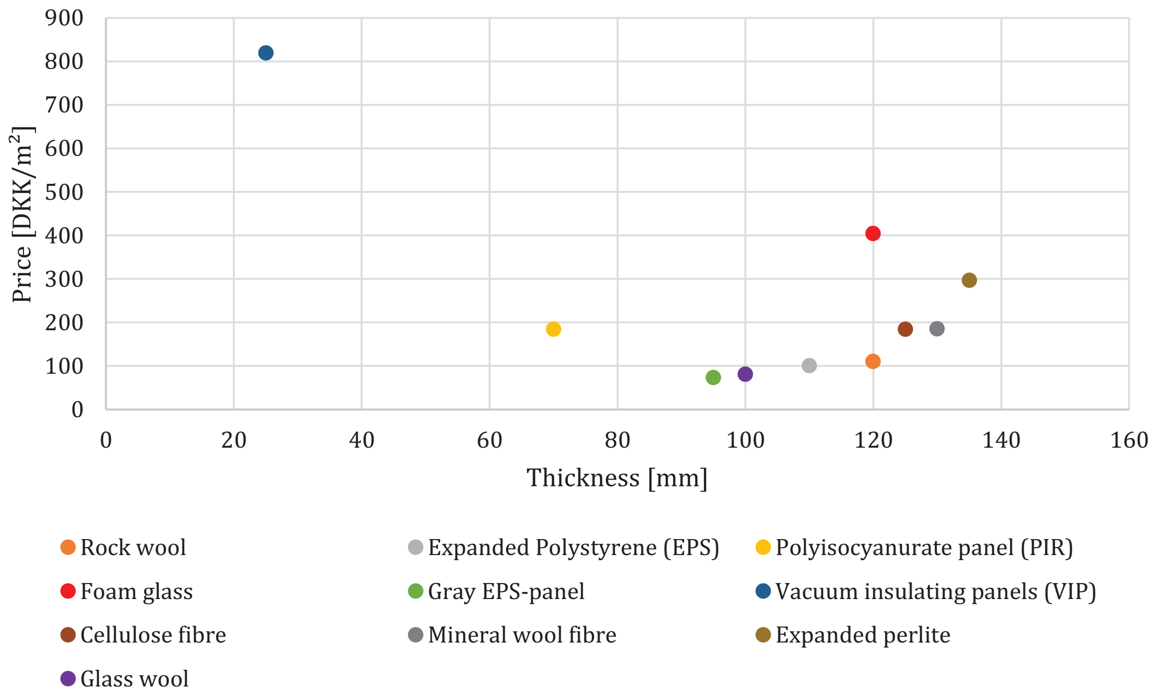


Figure 4.1 Price and thicknesses of certain insulation materials needed to achieve U-value of 0,18 W/m^{2}K

Expanded perlite, foam glass, mineral wool fibre and cellulose fibre has poor performance compared to the others and will not be used in the tool. The rest of the materials; rock wool, EPS-panels, glass wool and grey EPS-panels has great performance, both in price and thickness, but due to the similarity between the EPS-panels and grey-EPS panels, only the latter one was chosen. These three materials will then be used later for a further performance investigation when installed in the building envelope along with PIR panel. These insulation options will be available in the tool, so the type of insulation that provides the thermal resistance required, can be chosen depending on the available space and type of construction and its cost.

BUILDING ENVELOPE RENOVATION MEASURES WITH INSULATION

This section will focus on assessing the different application possibilities for the insulation materials assessed previously in the building envelope. Air sealing and insulating measures performed on the building envelope play a crucial role in improving the energy performance and comfort in the house. These measures can, however, often be performed on the interior or exterior structure of the building, but the efficiency and cost between these two placements can vary significantly. Therefore, it is important to determine if insulation measures should be taken on the inside or outside in each case. The choice is based on the following criteria:

1. The current condition and layout of the construction

2. The condition of the interior and exterior finishes and how easily they can be removed and restored
3. Specific property restrictions that may limit the thickening of the walls
4. If other renovation work will be performed at the same time
5. The level of energy savings wished to achieve (CMHC Corporation 2012)

As the information level about the actual conditions of the constructions in the houses when evaluated by the tool is limited, it is difficult to assess previously mentioned points number 1 and 2. However, there are specific signs that could be related to insulation problems that the occupant will be asked about in the questionnaire part of the tool, e.g. in the winter, if the walls and floors are cold on the inside, high heating cost or mould growth on the walls (CMHC Corporation 2016). These aspects should be assessed by a professional to rule out any critical problems, such as structural weakness or mould, before any renovation measures are performed.

Point number 3 is very case specific, therefore, an option will be in the tool to include certain measures if specific property restriction needs to be taken. Point 4 will be an important part of the tool, where focus will be put on combining renovation measures that can be done at the same time in the best way possible, and special focus will put on to never suggest a renovation measure that will restrict other measures in the future. The tool will evaluate point 5 in accordance to BR15, Renovation class 1 and 2, when it comes to the building envelope and have different renovation measures depending on the chosen renovation level. In the following chapter, an investigation of possible building envelope renovation measures concerning insulation materials is performed.

External wall

Normally, the most influential component in the building envelope is the external wall. The external wall covers the largest part of the building envelope and has critical impact on the heat losses of the building. Therefore, it is crucial to improve the performance of the wall to reduce the amount of heat loss from the building (Hakkinen et al. 2012).

Improving the thermal properties of the external wall is most commonly done by adding thermal insulation to it, which can be done in a number of different ways. The three main ways is to add external insulation, internal insulation, or insulation in the cavity of the wall. Choosing which of the three options would be most suitable for insulating the wall depends on the wall type. Also, it is important to consider the major differences in the ability to insulate the different types and the economy associated with such action. The external wall type can be either heavy- light- or cavity wall. For example, the most cost effective option would be to insulate the cavity wall (if the wall had an unfilled cavity). However, if the wall is solid, the best option would be to insulate the wall from the external or internal side (Wiseman & Summerson n.d.).

External insulation, illustrated in Figure 4.2, is typically the simplest solution when there is no empty cavity in the wall. It is a less invasive solution than internal wall insulation, as it does not reduce the internal space and can even improve the architectural appearance of the building. However, if the appearance of the building should be kept original, the external insulation is ruled out (Wiseman & Summerson n.d.).

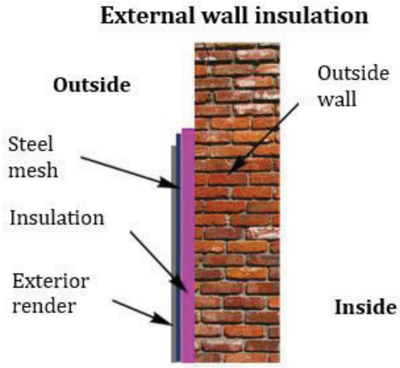


Figure 4.2 Possible external insulation solution (The Renewable Energy Hub 2012)

Internal thermal insulation is a good option when external insulation is not an option. This option is cheaper than external insulation, and could be installed on one wall at a time. However, even if it is a cheaper option and seems effective and easier to install, it could cause issues with thermal bridges at joints facing the outside e.g. between the walls, floors, ceilings and windows. Also, radiators and wall fittings would need to be repositioned (Thorpe 2016). Furthermore, adding thermal insulation and cladding, could cause condensation. The risk of condensation is not as high with externally mounted insulation compared to internal. By insulating externally, the temperature of the wall will increase, decreasing the risk of condensation. Internal insulation will decrease the temperature of the wall. This affects the dew point, drawing it towards the internal surface of the wall, with risk of moisture in the insulation layer. If the original wall was equipped with a vapor barrier, this would also cause problems and should be removed. Thus, it is important to install a new vapour barrier to prevent moisture problems, as shown in Figure 4.3 (Pullen 2015). Condensation in the construction can cause several serious problems like rot, mould and fungus, followed by general discomfort and pose a health risk to the occupant. It is important to investigate the risk of condensation in the construction to be able to prevent it.

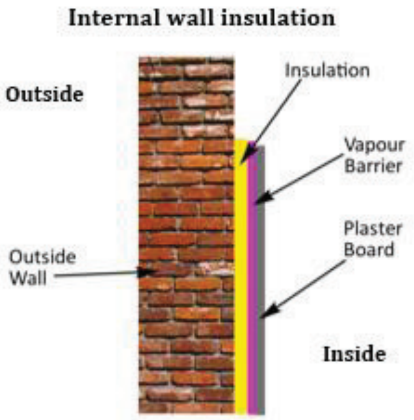


Figure 4.3 Possible external insulation solution (The Renewable Energy Hub 2012)

In conclusion, both methods prevent heat loss or heat gain by creating a barrier between the internal area of the building and the outside, which will result in reduced energy consumption. However, both solutions have distinct pros and cons as illustrated in Table 4.12 (Thorpe 2016).

	Internal insulation	External insulation
Pros	-Cheaper -Easier to accomplish one area at the time -Ideal if the interior is being renovated anyway	-Improves weather protection -Easier to take care of thermal bridges -More flexibility with insulation thicknesses -No internal disturbance to occupant -Optimal airtightness -Lower risk of moisture problems
Cons	-Loss of internal space -High risk of thermal bridging and condensation -Disturbing to residents when installing -Sockets and light switches need to be re-fitted -Door frames and other interior features could present a problem	-More expensive -Roof overhang, gutters and windows need to be re-fitted -House may have boundary restrictions

Table 4.12 Illustrating pros and cons of internal and external insulation (Thorpe 2016)

One critical downside of internal insulation is the loss of internal space. Even though the payback time, on average, is lower compared to external insulation, the loss of internal space will decrease the living space in the house, which could lead to decreased value of the housing. Also, trying to prevent a high loss of space when insulating internally, could result in restriction on the insulation thickness, which would have negative effect on the thermal efficiency (Thorpe 2016).

Another critical downside of internal insulation is the high risk of thermal bridging at joints, which will lead to higher heat loss and condensation risk. A good example is illustrated in Figure 4.4, where the difference between the temperature of the existing wall when re-insulated externally or internally is shown. Note that the arrows indicate the direction and magnitude of the heat flow. The small arrows indicate the thermal bridging by flowing in different directions, and the biggest arrows indicate where the thermal bridging is the worst. By insulating the wall externally, the existing wall keeps warm and no thermal bridging occurs. However, when insulating internally, the existing wall becomes cold and the joint between the external wall and internal wall forms a thermal bridge, which results in higher heat loss and risk of condensation (Peuhkuri & Rode 2010a).

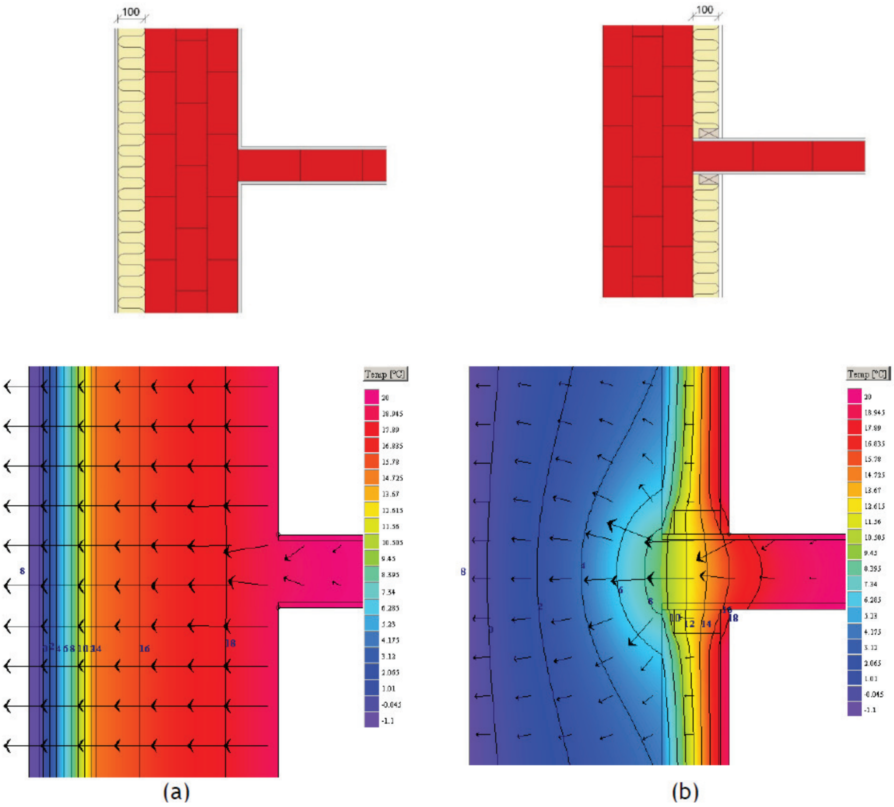


Figure 4.4 Horizontal section view: Heat flow difference between (a) 100 mm outside and (b) 100 mm internal re-insulation through a 300 mm solid brick wall and 100 mm internal wall. Thermal 2D calculation program used with a steady state condition [T_{inside}: 20 ° C, $T_{outside}$: -1,1 °C] (Peuhkuri & Rode 2010b)

The third solution is cavity wall insulation. This is an optimal solution for existing walls with an empty cavity. The insulation can be installed rather easily by drilling holes through the outer leaf, blowing in the cavity-fill insulation. It is essential to check if the cavity is open at the gable or eaves prior to insulating. This method is cheaper than the previously mentioned methods, and additionally it causes minimal disturbance and obtrusiveness when installing. The existing wall thickness is kept the same and the width of the cavity restricts the possible insulation thickness. In some cases, the width of the cavity will not be enough to achieve required U-value requirements according to BR15. The cavity width needs to be carefully checked before the insulation is installed to achieve the optimum energy savings. Thermal bridging problems can also occur where the insulation have not settled right and/or is soaked by condensation (Andersen 2014). External walls with empty cavities was uncommon in the period of 1961-1978. Due to the low quantities of empty cavity walls from this period, and the rare possibility of achieving thermal properties of BR15, it was chosen to focus on internal and external insulation in further investigations and in the tool.

HEAVY AND LIGHT EXTERNAL WALLS

Heavy external walls are usually made of bricks or concrete, where the inner leaf is normally loadbearing. However, if the whole wall is solid, it is all loadbearing. The heavy external wall should be insulated if the existing insulation thickness is less than 100 mm. Light external walls are typically built up from wooden frame structure that is either cladded with wooden boards, or with outer leaf of concrete or bricks with a ventilated cavity. It is recommended that the existing light walls should be further insulated when the original insulation thickness is 150 mm or less (Energistyrelsen 2016c).

The exact amount of insulation depends not only on the thermal properties of the insulation that is used, but also on the other materials presented in the element, such as bricks, concrete, wood, metal etc. However, the amount of space needed is also a crucial measure to have in mind. Therefore, an investigation was done in the Selection of insulation description chapter, into the different insulation types, their thermal properties and insulation thicknesses required to achieve the U-value requirement of 0,18 W/m^2K, stated in BR15

As can be seen in Table 4.13, the current reference houses were used to investigate insulation thicknesses and properties to reach the recommended BR15 U-value of 0,18 W/m^2K or lower, and to investigate the potential annual energy savings per area. To offer more variety in the tool, four Reference walls were used to include a variety of wall constructions from this period (Energistyrelsen 2016c). The heat transmission coefficients (U-value) were calculated for all the external walls according to calculation methods in DS 418.

For the first investigation, a rock wool insulation from the previous investigation in Figure 4.1 with the thermal conductivity of 0,037 W/mK was chosen, as it is a very commonly used insulation material in Denmark. As can be seen in Table 4.13, the insulation thickness needed to achieve the BR15 U-value has a great impact on the final width of the wall. As expected, the highest energy savings are then achieved in the uninsulated walls. Note that each wall is given an identification name that will be used in the tool and in further write ups, when referred to specific wall.

Ref. house	Heavy/Light wall construction *[from inside to out]]*	Current U-value *[W/m^{2}K]*	Thermal conductivity *[W/mK]*	Insulation thickness *[mm]*	Achieved U-value *[W/m^{2}K]*	Energy savings *[kWh/m^2 per year]*	Wall ID name
Ref. A.1	H: 108mm brick, 50mm air gap, 108mm brick	1,63	0,037	190	0,18	79,0	W01
Ref. A	L: 10mm wooden board, Vapour barrier, 100mm insulation, 19mm wooden board.	0,33	0,037	100	0,17	11,8	W07
Ref. B	H: 108mm brick, 75mm insulation, 108mm brick	0,409	0,037	120	0,18	16,0	W02
Ref. C	H: 75mm aerated concrete, 50mm insulation, 108mm brick	0,50	0,037	150	0,17	64,2	W03
Ref. D	L: 17mm wooden board. Vapour barrier, 95x95mm wood c/c 600mm, w/100mm insulation. Wind barrier. 50mm air gap. 108mm brick.	0,35	0,037	110	0,18	13,1	W08
Ref. E	H: 100mm light weighted concrete. 75mm insulation. 108mm brick.	0,37	0,037	100	0,18	9,0	W04
Heavy wall 1	H: 240 mm brick	1,77	0,037	180	0,17	86,0	W05
Heavy wall 2	H: 200 mm light weight concrete	2,97	0,037	190	0,18	97,0	W06
Light wall 1	L: 10mm wooden board. Vapour barrier. 75mm insulation. 19mm wooden board.	0,42	0,037	125	0,17	15,0	W09
Light wall 2	L: 12mm plaster board. Vapour barrier. 125mm insulation. 108mm brick.	0,26	0,037	80	0,17	5,4	W10

Table 4.13 Optimized insulation thickness in Reference houses external wall + four example walls (H: Heavy wall/ L: Light wall)

Having investigated the necessary insulation thickness with the thermal properties in Table 4.13, further investigation into the three other insulation materials chosen from the investigation in Figure 4.1. The thermal conductivity of each material can be seen in Table 4.14. This investigation is an example to illustrate the potential decrease in insulation thickness, when thermal conductivity is improved.

Insulation material *[-]*	Thermal conductivity *[W/mK]*
Glass wool	0,034
Grey EPS-panels	0,031
Polyisocyanurate panels (PIR)	0,022

Table 4.14 Thermal conductivity of chosen insulation materials

As shown in Table 4.15, when the thermal conductivity of the insulation material is improved, the width of insulation needed to achieve the recommended BR15 U-value demand is decreased, resulting in slightly thinner walls. However, the insulation materials differ a lot, not only in properties, but also in cost and appearances, which should be considered compared to the benefits gained. For example, the PIR-panels achieve the thinnest width, or around 42 % less width on average than rock wool, however, the PIR-panels are around 60 % more expensive, so the pros and cons need to be considered. Thus, PIR-panels would be optimal solution for areas, where limited amount of space is available. As mentioned before, the final width of the wall is very important, when it comes to the available space and window placement. The windows need to be replaced and moved outwards, aligned with the new facade, to reduce linear losses and achieve optimal daylight access into the building. Therefore, the lesser width of the insulation material installed, the smaller space it takes outwards. Note when choosing insulation material, it is as well important to investigate the material's fire class, moisture resistance and density.

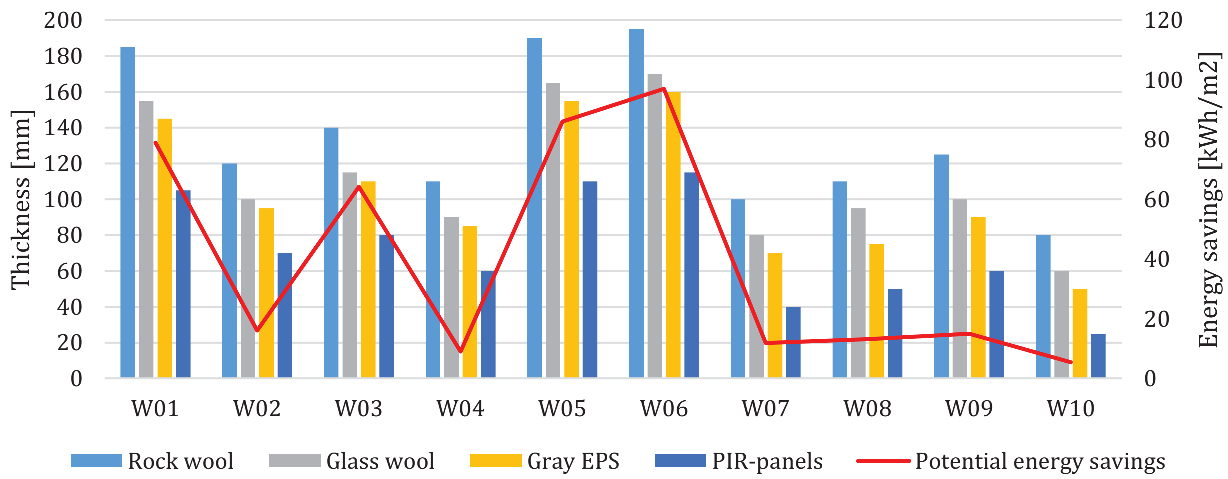


Table 4.15 Effect of lambda value on insulation thickness and potential energy savings for external walls, achieving heat transmission coefficient of 0,17 – 0,18 W/m²K

To investigate the influence of the improved external wall insulation level on the buildings' energy frame, Be15 models of four reference houses were used. In Figure 1.5, it can be seen that by improving the U-values of the external wall construction to the required value of 0,18 W/m²K, the energy savings vary from 8 % to up to 30 %. Ref. B, Ref. D, and Ref. E have similar savings, but Ref. C has a significant saving of 30 % which can be due to the low thermal resistance of the existing wall. Figure 4.5 shows as well the limit for Renovation class 1 and 2, and where both Ref. B and Ref. E fulfil Renovation class 2, without fulfilling the BR15 U-value requirements. These renovation classes can be used to satisfy the energy requirements as an alternative to satisfying the U-values and linear losses of BR15. However, to fulfil the renovation classes, the energy performance framework must be fulfilled, and the energy demand must be reduced by at least 30 kWh/m^2 per year. As seen from Figure 4.5, the energy demand for Ref. B and Ref. E is not reduced by 30 kWh/m^2 per year, therefore, not fulfilling Renovation class 1.

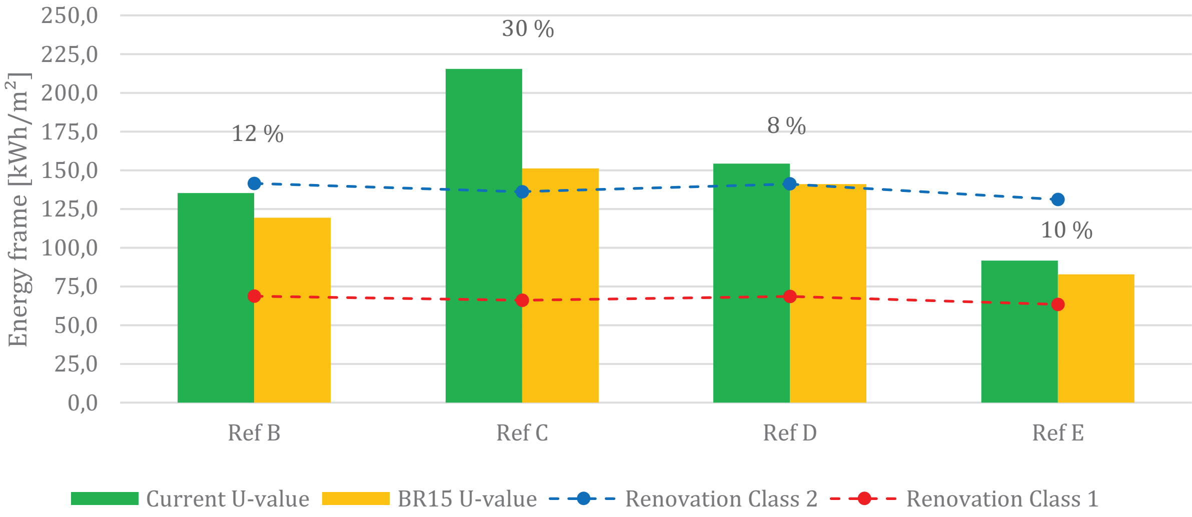


Figure 4.5 External wall, savings from current to BR15 values

It is to be expected when a renovation of the external walls is conducted, the linear losses around windows and doors a lowered. With the new standards of construction, compared to 1961 – 1978, the linear losses have been decreased, but according to BR15 they can maximum be 0,03 W/mK around windows (BR 2015). These values should be minimized both when renovating the external walls and/or when replacing the windows. In Figure 4.6 the energy savings are illustrated by lowering from the estimated linear loss in the Reference houses, seen in 4.2.1 Reference houses, to the recommended value of 0,03 W/mK. The savings are minor, between 1 % and 2 %, therefore, this is not the most crucial part considering energy savings. However, the comfort of reducing draught with decreased linear losses is not to be neglected. In TREE, there will be no separated optimization suggestion to reduce linear loss, due to, as earlier described, it is combined with optimization of external walls and replacement of windows and doors.

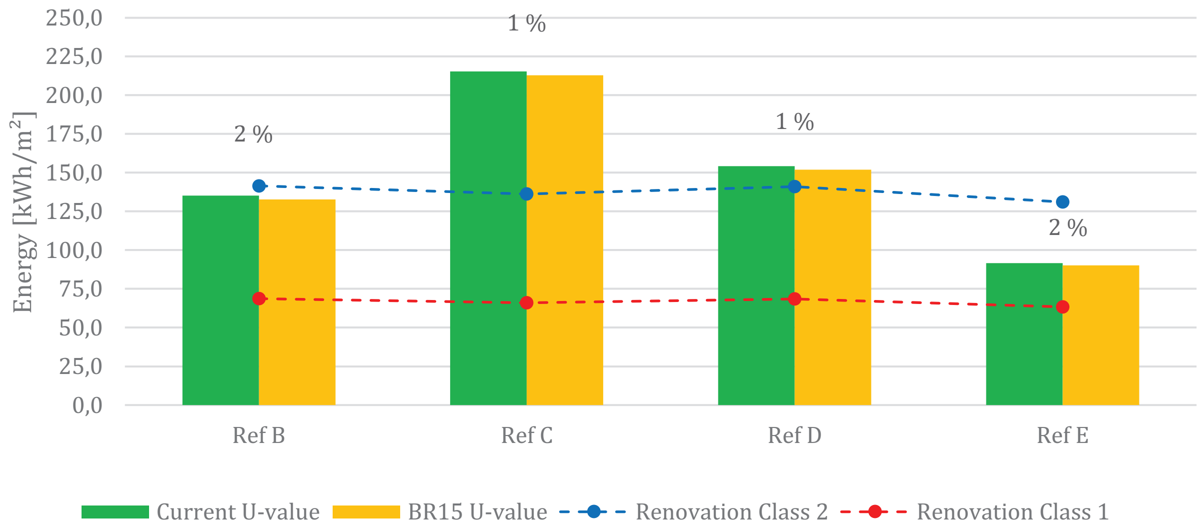


Figure 4.6 Linear loss around windows/doors, savings from current to BR15 values

All price calculations were done according to V&S price book and can be seen in Appendix J. The savings were calculated for each reference wall from Table 4.13, and these prices are then used in TREE. This tool is used to reduce the energy consumption, and technical solutions are not taken into consideration in the final optimization suggestion. The description between different types of insulation is to give inspiration to the user, but further technical solutions should be chosen by a professional. It is expected that the professional will do a moisture analysis to ensure that the solution selected does not create condensation in the construction.

Ground floor

The ground floor can be a tricky area to renovate and quite costly compared to the benefits gained. The heat loss through the ground floor is in general low compared to e.g. walls and roof due to the ground temperature normally being warmer than the outside air around the other components. Therefore, it would perhaps be an area to consider for thermal improvements after the walls and roof have been improved, which has shown to contribute more to the building's overall thermal performance (GreenSpec 2016b). Nevertheless, reducing heat loss (transmission loss) by thermally insulating the ground floor will reduce the energy consumption. Furthermore, reducing energy consumption is not the only benefit gained, but e.g. the thermal bridging can as well be eliminated at floor/wall joints, indoor comfort level can be increased with warmer floors and risk of condensation can be reduced (RIBA CPD 2012). Making the ground floor air tight to prevent the radon gas from seeping into the home is also a critical improvement to conduct.

The most common method of improving the thermal properties of the ground floor is to add thermal insulation. The insulation can be installed in different ways, depending on the current build-up of the floor construction and its thermal properties. Major differences lie between the solutions, specially the obstructiveness and cost. The most common type of ground floor slabs from this period were concrete floor slab and suspended timber floor.

The simplest and least obtrusive way to thermally improve concrete ground floor is to add the insulation on top of the existing floor construction and finish with a new flooring. However, this method has few critical problems which can restrict the insulation thickness, e.g. the floor level is raised reducing the ceiling height, radiators and doorframes need to be re-fitted and steps to staircases changed. Another method to consider is to install the insulation below the ground slab, but this method is way more obstructive and costly. The existing floor is removed and sometimes soil needs to be excavated to have space required for the insulation thickness. The insulation thickness is therefore less restricted, however, rooms take longer to heat in comparison to the first solution, due to the decreased heating respond time of the thick concrete slab (GreenSpec 2016b).

When insulating a suspended timber floor, various type of insulation materials can be fitted between the joist. This is an efficient solution to reduce the heat loss and improve airtightness which is usually high in timber flooring. This method can be done rather quickly with low obstructive measures and the additional load on the structure is minimal (GreenSpec 2016b). However, it needs to be considered that the ventilated crawl space can reduce the effectiveness of the insulation.

All over in Denmark there is radon, however, the level vary according to geography (Boligejer 2016). Radon level can be reduced either by ventilation underneath the ground floor construction or by having suction from the capillary layer. The suction method, whether it is active or passive, is considered the most optimal solution to reduce the level of radon. Both the passive and active solutions depend on the air pressure underneath the ground floor, however, the active has installed mechanic ventilator and the test results show this to be the most effective (Byg-Erfa 2015). Reducing the level of radon is one of the non-energy benefits of renovating the ground floor.

To investigate the influence of the improved ground floor insulation level on the building's energy frame, Be15 models of four reference houses were used. In Figure 1.7, it can be seen that by improving the U-values of the ground floor construction to the required value of 0,10 W/m^{2}K, the energy savings are from 7 % to up to 14 %. The ground floor construction varies in each reference house, as can be seen in Table 4.16, therefore, the severity of the renovation measures and energy savings varies. With 10 % in average on energy savings, the ground floor is the construction that has the least influence on the energy savings while being the most obstructive and expensive renovation measure to take. Therefore, it should be considered carefully if these measures should be taken. These measures could be considered if e.g. floor heating or new sewer system needs to be installed, or the radon level needs to be decreased. When combining these renovation measures together, the price for reducing heat loss in the ground floor will be less. Ref. D has larger savings than the others, and this is because of the vented crawl space. If the floor is not air tight, then the natural ventilation will lead to draught in the floor construction, which will result in a low comfort level and high heat loss.

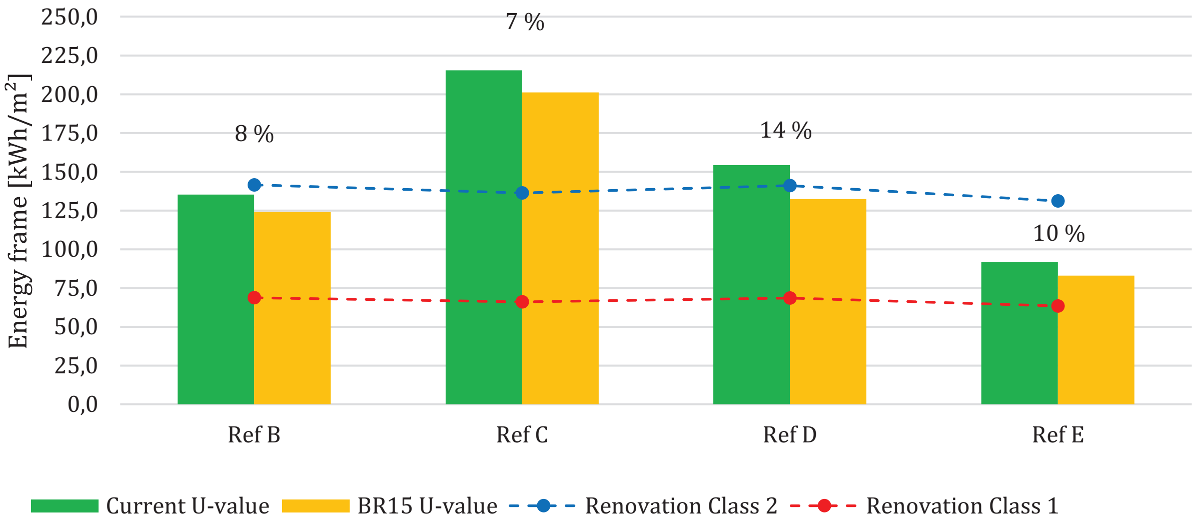


Figure 4.7 Ground floor, savings from current to BR15 values

Reference house A and D both have a crawl space where it is important to maintain a ventilation level to prevent moisture and mould (Energistyrelsen 2016c). The rest of the reference houses are without a crawl space. Therefore, in Table 4.16 there are two different solutions. In Ref. A and Ref. D floor construction, the current wooden construction is replaced and new insulation (ƛ 0,037 W/mK) installed, while all the other floor constructions have new insulation (ƛ 0,036 W/mK) installed on the entire ground floor and with a new concrete finish. Note that each floor is given an identification name that will be used in the tool and in further write ups when referring to specific floor construction.

Ref. house	Construction *[from inside to out]*	Current U-value *[W/m²K]*	Thermal conductivity *[W/mK]*	Insulation thickness *[mm]*	Achieved U-value *[W/m²K]*	Energy savings *[kWh/m² per year]*	Ground floor ID name
Ref. A	Parquet floor, Air gap, 100mm insulation, 50mm wood per 500mm, 600mm Crawl space.	0,32	0,037	320	0,10	12,4	G01
Ref. B	Wood floor, from inside: Parquet floor. 50mm wood (impregnated) per 600mm w/ 70mm insulation.	0,30	0,037	300	0,10	11,2	G03
Ref. B1.	Tiles, from inside: Tiles. 120mm concrete. 200mm slag.	0,26	0,037	220	0,10	7,9	G04
Ref. C	Wood floor, from inside: Wood floor, 50mm wood (foam work) (impregnated) w/ 50mm rock wool. 100mm concrete. PVC foil. 200mm sand.	0,33	0,037	300	0,10	14,2	G05
Ref. D	Wood floor, from inside: 19mm melamine particleboard. Vapour barrier. 100mm wood per 440mm w/ 75mm insulation. Foil. 500mm crawl space. 80mm concrete.	0,47	0,037	350	0,10	21,8	G02
Ref. E	Carpet, from inside: 160mm concrete. Foil. 75mm insulation.	0,27	0,037	250	0,10	8,8	G06

Table 4.16 Ground floor construction

Having investigated the necessary insulation thickness with the thermal properties in Table 4.16, further investigation of the three other insulation materials chosen from the investigation in Figure 4.1 was conducted and added in the tool.

All price calculations were done according to V&S price book and can be seen in Appendix J. The savings were calculated for each reference wall from Table 4.13, and these prices are then used in TREE.

Another benefit, when renovating the ground floor and the external wall, is reducing the linear loss at the foundation. In Figure 4.8, only the linear loss around the external wall is taken into consideration. This is because the length is longer, therefore, the loss is higher and because the linear loss at inner walls is estimated to be much lower than external wall. As an example, in Ref. E the linear loss at the external wall is estimated to be 0,32 W/mK, where the linear loss at the inner walls is 0,09 W/mK (See Appendix E: Be15: Reference Houses). The average savings are 3 % or 4,8 kWh/m², which will be used in TREE as an assumption, when renovating the ground floor.

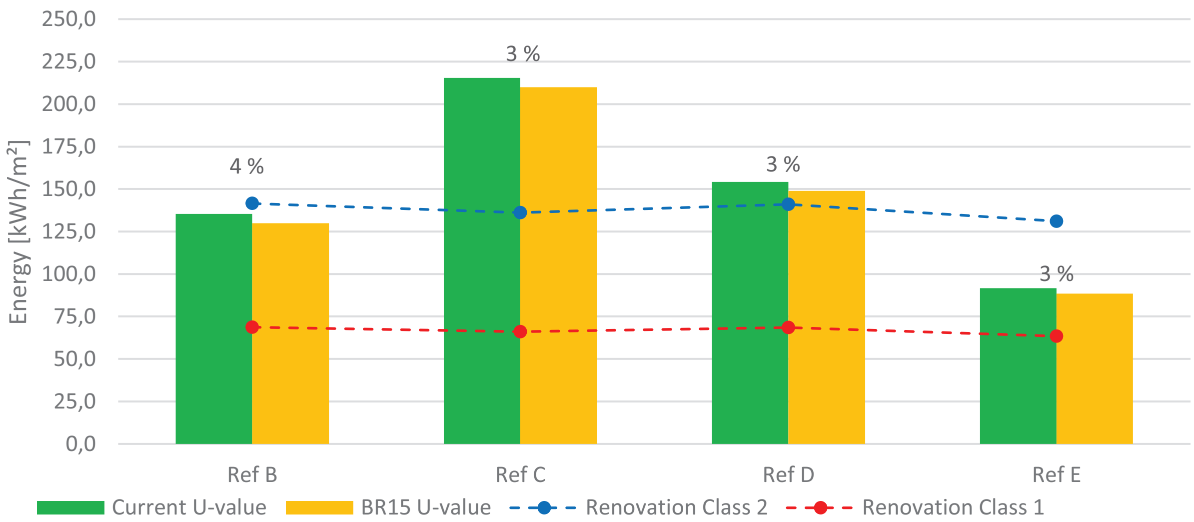


Figure 4.8 Line losses around foundation, savings from current to BR15 values

Roof/Ceiling

Heat rises, and therefore, there can be a major heat loss through the roof if it is not insulated properly. Thus, insulating the roof structure is one of the most efficient methods of improving the thermal performance of an existing building (GreenSpec 2016a). The roof can be insulated in different ways, which will depend on the roof type, whether it is flat or pitched, the structure and the condition of the existing roof.

When renovating a pitched roof, the insulation can be mounted either at the ceiling or rafter level. If the roof is insulated between the rafters, it will keep the roof and loft area warm, and is called *warm roof*. However, if insulation is installed at the ceiling level, the roof and loft area will be cold, and is called *cold roof*. The choice between these solutions should depend on the usage of the loft area and the condition of the structure (Pullen 2014). If the area is only used for e.g. storage, it may be a waste of material and energy installing rafter insulation, because the area will become a heated space resulting in waste of energy. However, if it is used actively as a room, this solution would be beneficial. It is though faster and less expensive to install loft insulation if possible. An important factor to keep in mind when installing insulation, is to consider how the moisture and ventilation dynamics acts within the roof space, to avoid the risk of condensation (GreenSpec 2016a).

The flat roof constructions are as well divided into cold and warm roof. In warm flat roofs, the insulation is placed above the roof deck, which keeps it warm. The insulation is, however, placed below the roof deck in cold flat roofs. This solution will need a ventilation gap between these components, increasing the risk of condensation. The most common insulation measure, when renovating a flat roof, is to place an overlay of insulation on the current roof construction with new membrane and roof covering. This solution will prevent thermal bridging, while keeping the thermal mass of the structure on the warm side. Another solution would be to mount the insulation under the ceiling, which could seem easier, however, this solution could cause increased risk of condensation and lower the ceiling height, which is not an option in some cases(GreenSpec 2016c).

To investigate the influence of the improved roof insulation level on the building's energy frame, Be15 models of four Reference houses were used. In Figure 4.9, it can be seen that by improving the U-values of the roof construction to the required value of 0,12 W/m^{2}K, the energy savings are from 6 % to up to 15 %. In all cases, the insulation was placed horizontally at the ceiling level. This makes the renovation more simple as more insulation can be placed above the current one. However, note that the first step is to always check the condition of the existing insulation and to ensure that it is dense without airholes. Furthermore, the attic walkway may be raised and it is important to ensure the necessary ventilation of the attic (BYG-ERFA 2005).

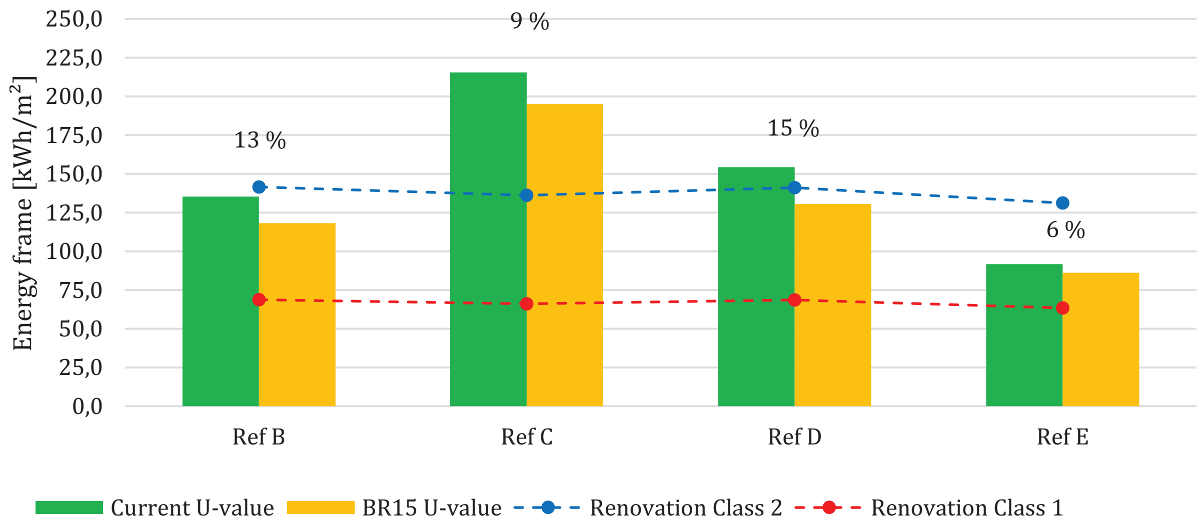


Figure 4.9 Roof, savings from current to BR15 values

In Table 4.17 the potential savings from added insulation layer to the building envelope at the roof or ceiling level are shown. The insulation is either installed on top of the current insulation layer or all old insulation would be replaced by a new layer, as shown in Table 4.17. In all the cases the existing insulation is used after the renovation, thereby, only extra insulation has been added to lower the U-value to 0,12 W/m²K. It might be that the roofing needs to be replaced due to age, but this will not be dealt with in TREE. It would be recommended to do roofing replacement, ceiling, or wall renovation at the same time as the insulation is being added.

Refer-ence	**Construction** *[from inside to out]*	**Current U-value** *[W/m²K]*	**Thermal conductivity** *[W/mK]*	**Insulation thickness** *[mm]*	**Achieved U-value** *[W/m²K]*	**Energy savings** *[kWh/m² per year]*	**Roof ID name**
Ref. A	Flat roof: 19mm wooden board. Ventilated air gab w/ 150mm insulation. 25mm wooden board w/ roofing felt.	0,25	0,039 / 0,037	100 / 300	0,12	6,5	R01
Ref. B	Low slope: Plasterboard. 25mm wood per 200mm. 100mm Insulation. Ventilated attic. Asbestos cement roof.	0,48	0,039 / 0,037	100 / 225	0,12	17,1	R02
Ref. C	High slope: Plasterboard. 25mm wooden board (foam work). 100mm rock wool insulation. Attic. Asbestos cement roof.	0,33	0,039 / 0,037	100 / 200	0,12	20,4	R03
Ref. D	Low slope: 15mm wooden board. Vapour barrier. 22mm wood per 580mm w/ 100mm insulation. Ventilated attic. Roof tiles.	0,37	0,039 / 0,037	100 / 200	0,12	23,6	R05
Ref. E	High slope (1st floor including balcony): Plasterboard. Vapour barrier. 25mm wood per 400mm w/ 175mm insulation. Roof tiles.	0,23	0,039 / 0,037	100 / 200	0,12	5,5	R04

Ref. Roof	High slope: 12.5mm plasterboard, vapour barrier, 25x25mm wood c/c 400mm, roof tiles.	1.90	0.036	250	0.12	144	R06

Table 4.17 Optimized insulation thickness in reference houses in the roof construction. Added insulation on top of current layer (left side)/completely new insulation layer (right side)

Having investigated the necessary insulation thicknesses with the thermal properties in Table 4.17, further investigations of the three other insulation materials chosen, in Figure 4.1, were done and added to the tool.

All price calculations were done according to V&S price book and can be seen in Appendix J. The savings were calculated for each reference wall from Table 4.13, and these prices are then used in TREE. Another improvement that can be made while renovating the building envelope at the roof is ensuring that the vapor barrier is intact and if not then fix it. As earlier described in this chapter, the risk of mould and fungus occurs when condensation is happening in the construction. A main issue is electricity plugs penetrating the vapor barrier, or ducts for ventilation. If the ducts are not insulated, warm air is moving in the construction and condensation most likely occurs in the construction (BYG-ERFA 2015).

AIR TIGHTNESS

By improving the constructions as described in this chapter, it is assumed, that the air tightness level is also improved. In the chapter 4.2.4 Questionnaire - Non-energy benefits, further investigation is made into the non-energy related benefits that are gained by renovating the building envelope. In the beginning of this chapter, external walls and roof were described as the most important parts of lowering the energy consumption (Hakkinen et al. 2012). By renovating these components up to the standards, it can be concluded that the airtightness of the building improves significantly. As seen in Figure 4.10, improving the airtightness has a great impact on the energy consumption. These values are with some uncertainty, as the correct infiltration level has not been measured but estimated as described previously in chapter 4.2.2.1. All the Reference houses have been estimated with high level of infiltration so the reduction to normal level gives the average results of 17 % of the heating consumption.

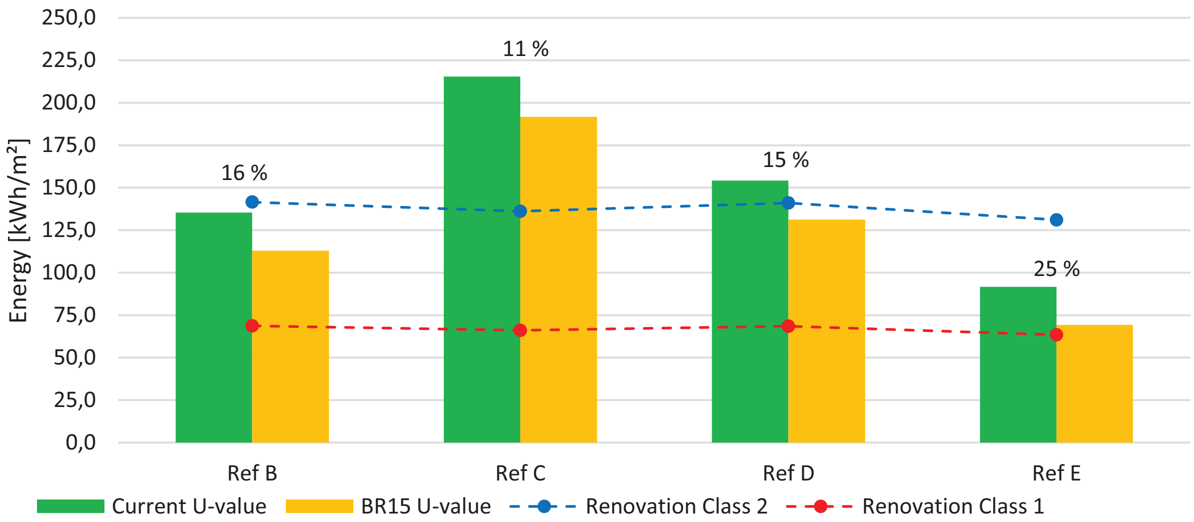


Figure 4.10 Infiltration, savings from current to BR15 values

PRIORITISATION OF INSULATION INSTALMENT

When renovating in stages/gradually (step by step) with, in some cases, limited budgets, it is important to know which area is the most beneficial to insulate first to achieve good energy savings. Therefore, a short investigation was made, where each building component was improved up to BR15 requirements, as described in this chapter. For this investigation, reference house B was used again as an example. Reference house B was chosen, because it has in average similar parameters as the other reference houses.

As described previously, the roof and external wall tend to have the highest heat loss, depending on the thermal resistance of the structure. As seen in Table 4.18, when the thermal resistance was improved in these components, the highest energy saving potential is illustrated. This demonstrates, that high energy savings can be achieved by insulating both of these components. Therefore, when renovation considerations are made, focus should be put into renovating the roof and external wall first, and then ground floor. The external wall should be prioritized over the roof if non-energy related benefits should be taken into account as well, those benefits will be explained further in chapter 4.2.4. Note, that the prioritisation will depend on current conditions and thermal parameters of each construction in every case and should always be evaluated by a professional. The same goes for the potential energy savings which will vary depending on the construction. As expected, the highest energy saving potential is achieved when all components are improved up to BR15 requirements. However, the potential payback time needs to be considered as well when deciding where to renovate.

Insulation renovation actions to achieve energy savings			Potential energy savings *[kWh/m² per year]*
Roof/ceiling	**External wall**	**Ground floor**	
U-value improvement *[W/m²K]* 0,33 to 0,12	**U-value improvement *[W/m²K]* 0,40 to 0,18**	**U-value improvement *[W/m²K]* 0,30 to 0,10**	
x			17,4
	x		16,3
		x	11,5
x	x		33,2
	x	x	27,4
x		x	32,1
x	x	x	44,2

Table 4.18 Potential energy savings when renovating building components up to BR15 requirements

4.2.2.4 Windows

Windows are a key parameter regarding both energy consumption and indoor comfort. This chapter will shortly describe the development that windows has gone through since the 1960s, and present two examples of a window replacement in two reference houses for calculating heat loss and heat gain (E_w) and their payback time. The calculations are made with both the standardized E_{ref} calculation where the orientation percentages are fixed, and a calculation with the actual orientation percentages from the reference house. Lastly, a description of different properties of window glass is introduced, and what measures can be taken to increase or reduce the amount of solar radiation entering the house.

In the passive solutions chapter, 4.2.5 Passive solutions, an investigation of how the treatment of indoor surfaces is carried out. It describes how the colour of paint, can influence the daylight factor of a room.

From the beginning of the 1960s, windows with double glazing, also known as thermal glazed windows[6], were introduced to replace one-layered panes. Windows became larger in size, without mullions and the frame was made of wood. In the 1960s and '70s there were no regulations regarding the size of the windows, therefore, large facades facing the garden often consisted of higher glazing area compared to the wall area. The glazing had worse insulating properties than the external wall itself, thereby increasing the heat loss from the house to its surroundings (Energistyrelsen 2016c). The U-value of the pane was significantly reduced from 6,0 to 2,4 W/m²K (Klimaministeriet 2016). At the end of the 1980s, energy panes with argon instead of air were developed. As argon has a higher density than air, the air circulation between the panes was reduced and the heat loss through the panes was reduced. Double glazed energy panes have a U-value of 1,1 W/m²K and three layers have 0,6 W/m²K (Energitjenesten 2016b). Figure 4.11 roughly summarizes the different panes. The pane itself

[6] Termorude

is only an indication of the total U-value of the window. The material and detailing of the framework also has an impact.

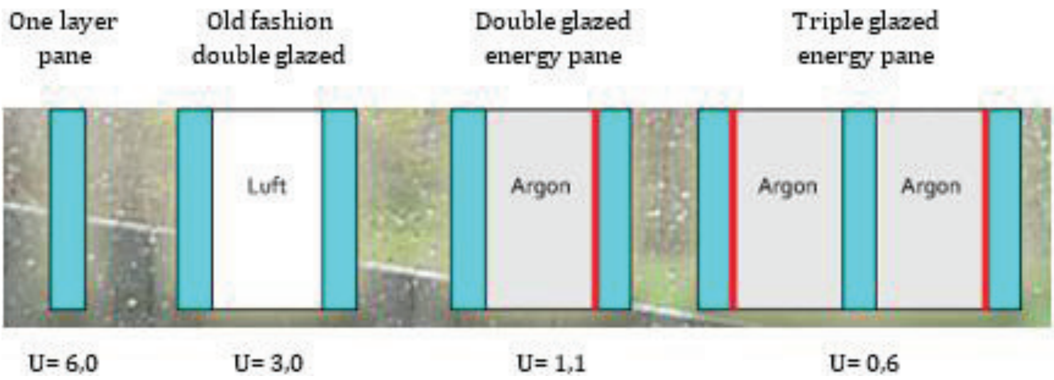


Figure 4.11 U-values of different window panes. Total U-value of the window changes according to the frame used and the potential use of mullions (Energitjenesten, 2016)

Today, some windows contribute positively to the total energy balance of a house. This means that the energy contribution from the Sun, through the window, is larger than the heat loss in the heating season. The energy contribution is described by the E_W value. Heat gains and losses are determined using Danish climate data from DRY and window properties, calculating the amount of solar radiation through the window pane (g-value) and heat loss (U-value) together with indoor temperature which is set to 20 °C in reference calculations (E_{ref}). The E_{ref} was made in order to compare and legislate on windows according to the energy balance of a one-leaf window in a standard European size of 1,23 · 1,48 m, with fixed orientation values (26 % towards North, 41 % south and 33 % East/West) and a shadow factor F_s of 0,7 (Energitjenesten 2016b).

The g-value describes the amount of solar radiation that penetrates through the window. A g-value of 0,60 means that 60 % of the solar radiation will penetrate through the window. As no solar radiation, will penetrate through the window frame, the total g-value of the window depends on the ratio between the windowpane and the total window area. This is called the Ff-value. Higher Ff-value equals more pane area compared to the window size and, thereby, more daylight and higher contribution from solar radiation. The last important factor is the LT-value (light transmittance value) describing the amount of light that penetrates through the window. As with the g-factor, an LT-value of 0,8 means that 80 % of the daylight that strikes the window pane will penetrate to the room (Energivinduer.dk n.d.).

As of 1st July 2016, the BR15 demands that renovated or replaced windows achieve energy mark B, which is an E_{ref} value of > -17 kWh/m² a year. It is expected that BR2020 will disallow any loss (E_{ref}: > 0 kWh/m²) through the window.

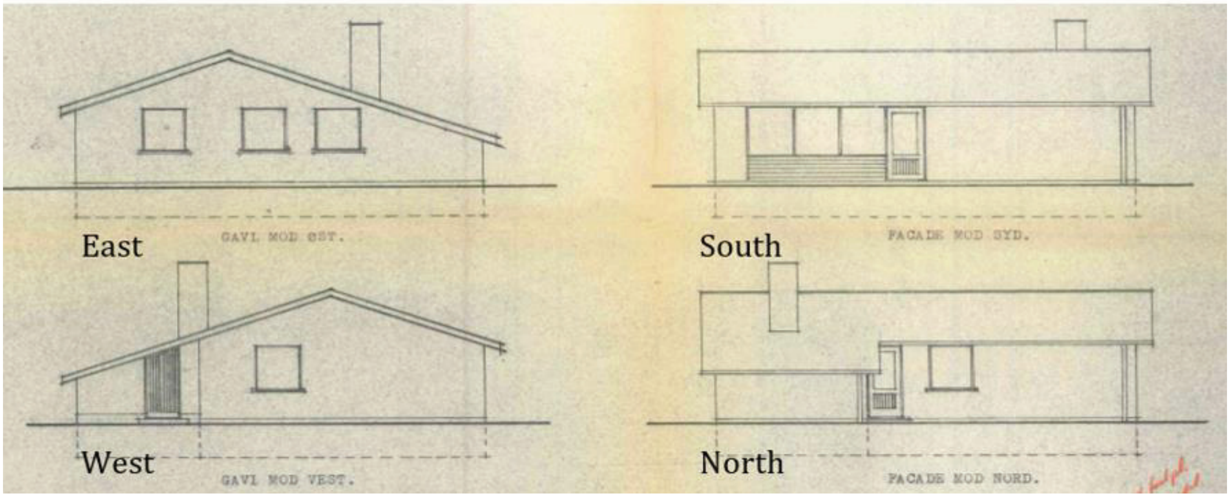


Figure 4.12 Facades of reference house B

Reference house B has 4 façades with a total of 8 windows and 3 doors (Figure 4.12). Southern window section is 4,81 m · 1,4 m and doors according to drawings. To simplify, doors and windows are presumed to have the same Ff-value of 70 %. All three doors are assumed to be alike, even though the western looks different on the drawing. U-values, g-values and Ff-values are found in *Energihåndbogen 2016 p. 125* (Klimaministeriet 2016):

Windows:
121 · 127 cm (~1,54 m^2)
U-value: 2,8 W/m^{2}K
g-value: 0,75
Ff-value: 0,7

Doors:
970 · 210 cm (~2,04 m^2)
U-value: 2,8 W/m^{2}K
g-value: 0,75
Ff-value: 0,7

Total pane area of each facade:

East: 1,54 m^2 · 3 pcs. = 4,62 m^2 · 0,7 = **3,23 m^2**

South: 4,81m · 1,4m = 6,73 m^2 · 0,7 = **4,71 m^2**

West: 1,54 m^2 + 2,04 m^2 = 3,58 m^2 · 0,7 = **2,51 m^2**

North: 1,54 m^2 + 2,04 m^2 = 3,58 m^2 · 0,7 = **2,51 m^2**

Solar radiation differentiates according to orientation of the façade, location of the house and the amount of degree hours in the heating season (from DRY). The energy contribution *E,* from the windows can be calculated using the values in Table 4.19:

Orientering	Korrigeret solindfald I_{kor} [kWh/m^2]	Gradtimer G [kKh]
Nord	104,5	90,36
Syd	431,4	90,36
Øst/vest	232,1	90,36

Table 4.19 Simplified evaluation of solar radiation (BYG DTU, 2009)

$$E = Ikor \cdot \mathbf{g} - \mathbf{G} \cdot \mathbf{U} \tag{2}$$

Reference house B is calculated with its actual orientation of the windows and the same assumption regarding the shadow factor Fs (0,7), in order to investigate the potential deviation from the standardized calculation:

$$Eref\ B = Ikor \cdot \mathbf{pane\ area} \cdot \mathbf{Fs} \cdot \mathbf{g} - \mathbf{90,36\ kKh} \cdot \mathbf{U} \cdot \mathbf{total\ window\ area} \tag{3}$$

East: 232,1 kWh/m^2 · 3,23 m^2· 0,7 · 0,75 – 90,36 kKh · 2,8 W/m^{2}K · 4,62 m^2 = -775,3

South: 431,4 kWh/m^2 · 4,71 m^2 · 0,7 · 0,75 – 90,36 kKh · 2,8 W/m^{2}K · 6,73 m^2 = -635,9

West: 232,1 kWh/m^2 · 2,51 m^2 · 0,7 · 0,75 – 90,36 kKh · 2,8 W/m^{2}K · 3,58 m^2 = -599,9

North: 104,5 kWh/m^2 · 2,51 m^2 · 0,7 · 0,75 – 90,36 kKh · 2,8 W/m^{2}K · 3,58 m^2 = -768,1

-775,3 - 635,9 - 599,9 - 768,1 = -2.779,2 kWh / year.

Reference house B has a total energy contribution through its windows of -2.779 kWh pr. Year.

Using the standard calculation (2) with the fixed orientation percentages, the loss is assumed to be lower due to the fact that the standard calculation accounts for a higher amount of the windows to face South (41 % vs. 36 %), where the solar gain is higher.

196,4 kWh/m^2 · 0,75 · 12,96 m^2 – 90,36 kKh · 2,8 W/m^{2}K · 18,51 m^2 = -2.774,17 kWh pr. year.

The deviation is less than 5 kWh over a year corresponding to less than 0,2 %. This corresponds to a sensitivity analysis made by DTU, investigating the influence of the orientation distribution of the windows. A 7 % change in the amount of window panes facing South would change the energy contribution by 10 kWh/m^2 corresponding to a change in energy mark. The sensitivity increases with a higher g-value (BYG DTU 2009).

Even though one energy mark is a big difference, the calculation can be used as a relative comparison of different windows, and therefore, can be used in the decision-making tool.

An investigation was made on two reference houses. One from 1975 and one from 1965:

1975	Original	Energy mark A	Energy mark B
E_w	**-1.903 kWh**	**-53 kWh**	**-260 kWh**
Savings in kWh		1.849 kWh	1.643 kWh
Price of replacement:			
Materials (windows/doors)		39.288 DKK	34.464 DKK
Man hours		8.500 DKK	8.500 DKK
Total		**47.788 DKK**	**42.964 DKK**
Savings according to heating source:			
District heating 1 kWh = 0,50 DKK		925 DKK	822 DKK
Natural gas 1 kWh = 0,80 DKK		1.476 DKK	1.314 DKK
Oil 1 kWh = 1,00 DKK		1.849 DKK	1.643 DKK
Payback time according to heating source:			
District heating		**52 years**	**52 years**
Natural gas		**32 years**	**33 years**
Oil		**26 years**	**26 years**
1965	**Original**	**Energy mark A**	**Energy mark B**
E_w	**-2.780 kWh**	**-43 kWh**	**-350 kWh**
Savings in kWh		2.737 kWh	2.430 kWh
Price of replacement:			
Windows		36.247 DKK	31.667 DKK
Man hours		11.200 DKK	11.200 DKK
Total		**47.447 DKK**	**42.867 DKK**
Savings according to heating source:			
District heating 1 kWh = 0,50 DKK		1.369 DKK	1.215 DKK
Natural gas 1 kWh = 0,80 DKK		2.190 DKK	1.944 DKK
Oil 1 kWh = 1,00 DKK		2.737 DKK	2.430 DKK
Payback time according to heating source:			
District heating		**35 years**	**35 years**
Natural gas		**22 years**	**22 years**
Oil		**17 years**	**18 years**

Table 4.20 Investigation of the difference of payback time on two windows marked with energy mark A and B.

Looking at the two different price calculations, it is clear that the incentive for replacing windows needs to be more than just a financial perspective as payback times spans between 17 and 52 years depending on the heat source used. As described in (the non-energy benefits) chapter 2.1.4, there is a lot of non-energy benefits connected with replacing windows:

- Changing properties of the window panes in order to find the best solution concerning light transmittance, passive solar heating, noise from outside, security and safety.
- Changing or expanding the window hole to increase the amount of daylight to the room.
- Various aesthetic improvements according to the individual desires of a homeowner.

It is essential to take the non-energy benefits into account, in order to add the highest amount of value to the house, as in terms of soft values for the homeowner. This is further described in the above-mentioned chapter, describing non-energy benefits. Figure 4.13 depicts four different examples of windowpanes with different functions, from a large, reputable company in Denmark; Rationel. SAFETY panes with hardened glass to reduce risk of breakage if anyone crashes into it. SOLAR that reduces the passive solar heating from the Sun, through the pane. SECURE which is fitted with laminated glass, making the window harder to break through, and lastly the SOUND pane that reduces noise considerably (Rationel 2016).

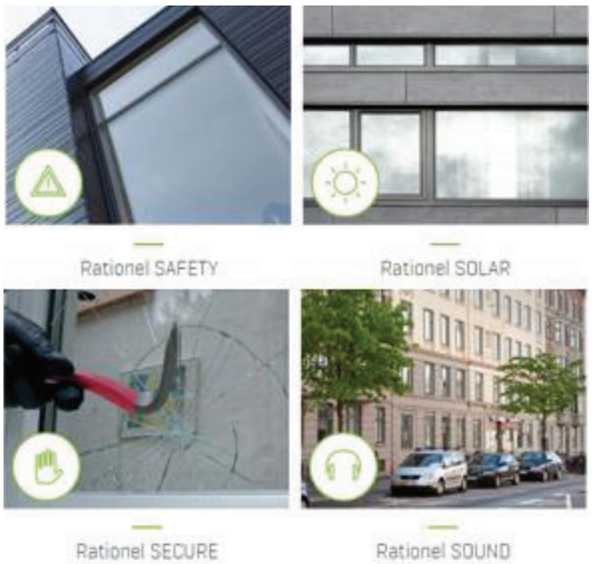


Figure 4.13 Four different examples of window panes with different properties (Rationel, 2016)

To conclude on this chapter, it is essential that the different solutions presented are used to make a tailored fit for the individual house. Improving the building envelope and replacing old windows with the best windows available (when it comes to E_{ref}), might cause overheating. Depending on the grade of improvement done to the building envelope, it could be considered to use SOLAR glass in the southern oriented windows or wait and see how the renovation will perform and then implement vertical fins or another form of external shading if overheating occurs.

4.2.3 HVAC

This chapter describes common heating and ventilation systems used in single-family houses in the period of 1961 – 1978. Common optimization possibilities are described for each system case in order to implement this in TREE.

General

Generally speaking, it is essential that the HVAC systems are dimensioned correctly and calibrated for optimal IEQ and energy efficiency. Afterwards, individual user needs should be taken into account e.g. preferred temperature, the need of maintenance, and level of control.

According to *Statistics Denmark,* the heating sources in 2016 in single-family homes builtbetween1960 – 1979 are as shown in Table 4.21. This reveals that almost 50 % has their own heat source, whereas only 2 % has a renewable source (Statistics Denmark 2016). Even though heat pumps uses electricity to produce heat, they are considered a renewable source in the EU if they produce more than they consume (REHVA 2011). For the same reasons, heat pumps will in this project be considered as a renewable source. They are using the energy from the Sun, e.g. the soil heated up or outdoor temperature, and the electricity consumed by the heat pump can be produced by PV-cells.

Source	Quantity	Percentage
District Heating	217.850	49,90 %
Boiler, oil	53.309	11,97 %
Boiler, natural gas	125.841	28,24 %
Boiler, neither oil or natural gas	9.246	2,08 %
Heat pump	9.580	2,15 %
Electricity	28.142	6,32 %
Others	1.359	0,31 %
Unknown	208	0,05 %

Table 4.21 Distribution of heat sources from 2016 in single-family houses built between 1960 -1979 (Statistics Denmark 2016)

In Denmark, district heating can be, or will be, produced by renewable sources or biomass. In 2050 it will be 100 % of the district heating that will come from renewable sources or biomass (Energistyrelsen 2016b). Replacing boilers and heating sources powered by electricity will have the largest positive significance on the environment. The solution can be changing to district heating, if available, or installing a renewable source for instance a heat pump. If that is not possible, a combined solution, where the old boiler is kept for use in peak hours and a renewable source is added, could reduce installation and running costs.

Energy demand

In the tool, the user will be asked to fill out the annual energy consumption for heating. To avoid the user getting stuck while using the tool, the estimation equation from SBi will have an estimated consumption for the user to fill in (SBi 2005). The equation for single-family homes, is as follows:

$$4816\ \text{kWh} + 104\ \text{kWh/m}^2 \qquad (4)$$

The equation is made by the SBi with multiple reference houses (SBi 2005). There are many things that should be taken into consideration when creating an equation for single-family homes, for instance, amount of occupants, their age, and heating systems.

4.2.3.1 Heating systems

BOILER

Single-family housing from this period was often built with central heating supplied from a boiler, connected to radiators for each heated room in the household. The boiler was originally fuelled by oil, but with the introduction of natural gas in Denmark in the 1980s, they were steadily converted to gas boilers throughout the country (Dansk Gasteknisk Center a/s 2016). As indicated in Table 4.21, more than 42 % of single-family houses use a boiler as a heat source.

Boilers produced before 2000 do not use the energy from the condensation and should be replaced with a condensing boiler or district heating. According to BR15 (8.5.1.4(2)), a boiler requires a CE-marked efficiency, which is only possible to achieve with a condensing boiler (Energitjenesten 2016a). The boiler should be insulated in order to reduce the heat loss to the surroundings. Lastly, it should be considered to change to district heating if it is available and/or adding a renewable source (Energistyrelsen 2016d).

As of 2013, it has been forbidden to install oil- and gas boilers in new housing if district heating is available in the area. By 1st July 2016, it became illegal to install or replace an oil boiler in existing housing, in areas where district heating or natural gas are available (Trafik- og Byggestyrelsen 2016). The oil boiler is only legal when: "*…there are no suitable alternatives available*" according to BR15.

Boilers, especially oil fired, are the least sustainable solution when it comes to carbon emissions. Another aspect is safety in terms of leakage. Carbon monoxide (CO) is a poisonous substance which is produced when organic, carbon-based fuels like gas or oil are not completely burned due to lack of air e.g. if chimneys, flues or vents are obstructed. Carbon monoxide gas is a so-called silent killer, as it has no colour, taste or smell. Therefore, it is recommended to install carbon monoxide alarms that can warn occupants day and night in case of a leakage (Boiler Guide 2016).

In order to reduce the amount of boilers in single-family homes, the tool suggests replacing with either district heating or a renewable solution. The tool does not take into consideration the age of the current boiler or its efficiency. The important thing is that the owner, at some point, replaces the boiler with another source or reduces the use by installing additional source (called a combined heat source). Therefore, the tool suggests a new source, however, by adapting the other renovation solutions in the tool, the annual consumption will be reduced and thereby the demand for the boiler. Replacing the boiler will eliminate potential health risks and the owner will be more robust to increasing energy prices.

The *Danish Technological Institute* has investigated the average annual kWh savings by changing from the current source to district heating as shown in Figure 4.14 (Teknologisk Insistut 2016). From Figure 4.14 it is shown that the potential savings on replacing a boiler with district heating highly depend on the age of the boiler. The new condensing boilers are more efficient than the old ones, however, the reduced CO_2 emissions are not evaluated and should also be taken into account.

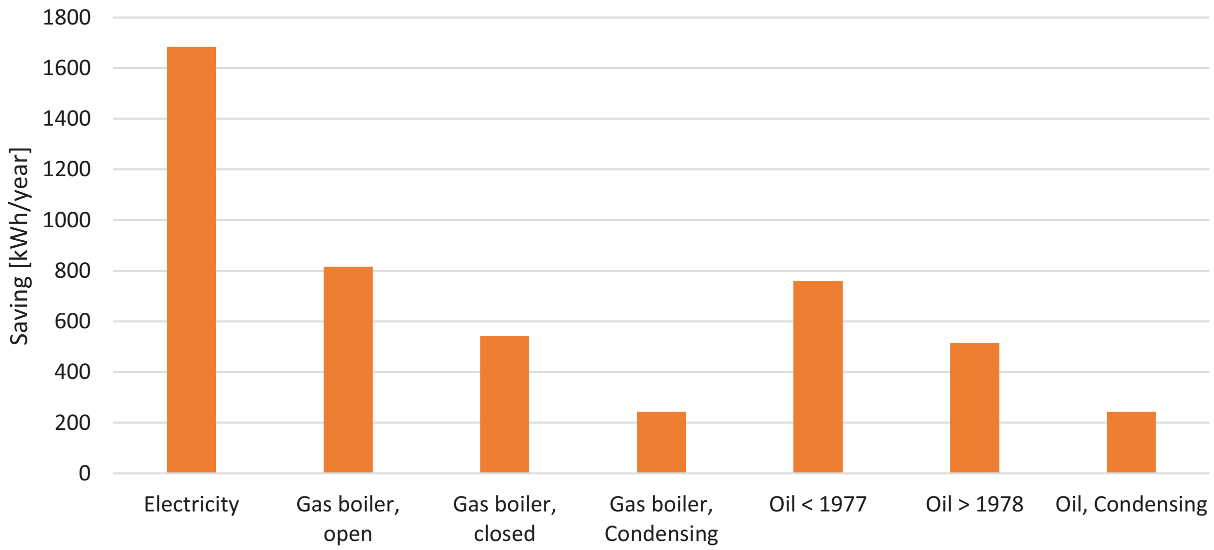


Figure 4.14 Estimated savings from changing to district heating (Teknologisk Insistut 2016)

The values, except electricity, in Figure 4.14 will be used in TREE to calculate the possible savings by replacing a boiler with district heating. The electricity will not be taken into consideration as the installment of a waterborne system is too extensive.

The values are estimations and will vary depending on the type of boiler. It would require too much information from the user to do exact savings calculations. This is inconsistent with keeping the tool simple to use as to why the estimated calculation was chosen.

BIOFUEL

Biofuel is the production of energy with e.g. wood, straw, biogas or organic waste. It is mostly common in areas not covered by district heating or natural gas. It is typically more affordable than oil and gas. It can be combined with solar heating, so that the Sun is utilized in the summer period where then the biofuel plant should be completely turned off (Energistyrelsen 2016a).

A biofuel plant develops smoke, which can disturb neighbours. A biofuel plant requires more work than other heating sources as it needs to be filled and cleaned regularly. The plant and the fuel need to be placed in a fireproof area and take up more space than other solutions.

Even though a biofuel boiler requires more maintenance than other sources and may create a smoke issue, it will still be suggested in the tool. It is important to have an alternative to areas where neither district heating or natural gas is available. This alternative, along with heat pumps, could be biofuel as it requires a minimum of installment.

Running cost

In the tool, it will be possible for the user to change the prices of the different heat sources, thereby, making the calculations more accurate for the actual cost in the local area.

In Table 4.22 prices for energy, from October 2015, are shown, which will be used for price calculations. Note that these prices vary over the year. The prices will be used for calculating the potential savings for different improvements. In the tool, these prices will be default prices and can be changed by the user to fit the area where the house is located.

Source	**Price incl. VAT – toll** *[DKK/kWh]*
Oil	1,00
Oil, condensing	0,90
Nature gas	0,80
Wood pellets 7% RH, *blown in*	0,43
Wood pellets 7% RH, bags	0,63
District heating	0,56
Electricity	2,27

Table 4.22 Energy prices as of October 2015 (Byggeri & Teknik I/S 2015)

District heating

In these years, some single-family houses were constructed in an area covered by district heating and connected to it by law. It was not common practice to insulate piping and heat exchangers in this period, even though it should be done to avoid unnecessary heat loss. Secondly, if the district heating unit is from 1990 or older, it could be worth replacing it with a newer and more efficient model (Energistyrelsen 2016d).

Heat pumps

A heat pump utilizes the energy stored in the ground, water or air. The three main types used in Denmark are geothermal heat pumps (brine/water) that extract the heat from the ground, air-to-water that extract heat from the surrounding ambient air while the secondary side is waterborne. The third one is air-to-air which extracts the heat from the surrounding air to warm up air on the secondary side (Bonin n.d.). The geothermal heat pump is one of the most efficient ones, but also more expensive and space consuming as it requires a terrain area for the piping to be installed. A horizontal system utilizes the energy stored in the ground from the Sun, whereas placing the piping vertically utilizes the energy from inside the earth. The horizontal system requires the most land area for piping, but is cheaper to install than the vertical system (Energistyrelsen 2016d).

The air-to-air heat pump is a great addition to a few houses that has electricity as a main heat source, however, it will not be suggested for houses that have waterborne systems installed. The issue with air-to-air heat pump is that it is heating the air in only one room, from where ventilation must circulate the air. This limits the efficiency, therefore, the recommendation in houses with waterborne systems will be to replace the main source with a geothermal or air-to-water heat pump.

The geothermal heat pump requires, as described, a major installment issue with the surrounding soil being dug up, however, the decision to be made and calculation of the quality of the soil should be made by a professional, therefore, not handled by the tool. The tool is to create inspiration on how to reduce CO_2 and energy consumption and not to provide final solutions. The advantage of installing a geothermal heat pump compared to an air-to-water heat pump is the reduction of the noise issue. As described in Appendix F: Heating, the air-to-water heat pump may create noise issues for the surroundings, therefore, both types of heat pumps will be suggested in the tool.

Heat pumps are regulated according to their coefficient of performance (COP), that describes the heat pumps efficiency. COP is the relationship between the power [kW] that is drawn out of the heat pump as cooling or heat, and the power [kW] supplied to the compressor. A COP of 2.0 means that 2.0 kW of cooling or heating power is supplied for each kW of power consumed by the pump's compressor (Grundfos 2016).

To understand if the installment of a heat pump in a building with existing heating system would be feasible, an investigation was done to see the possible kWh savings. The estimated kWh savings by replacing a boiler or electricity heater with a heat pump is shown in Figure 4.15. All heat pumps comply with the requirements in BR15 (Teknologisk Insistut 2016). As previously described one of the most efficient heat pump is the geothermal, but the installation of an air-to-water heat pump is easier and less expensive, however, with the efficiency more dependent on the seasonal variation.

As shown in Figure 4.15, the savings highly depend on the current boiler and its age. Of all the different types in Figure 4.15, the geothermal heat pump is the one creating the greatest potential savings. This is due to the higher average temperature on the ground during the year than the surrounding air, which the air-to-water is using.

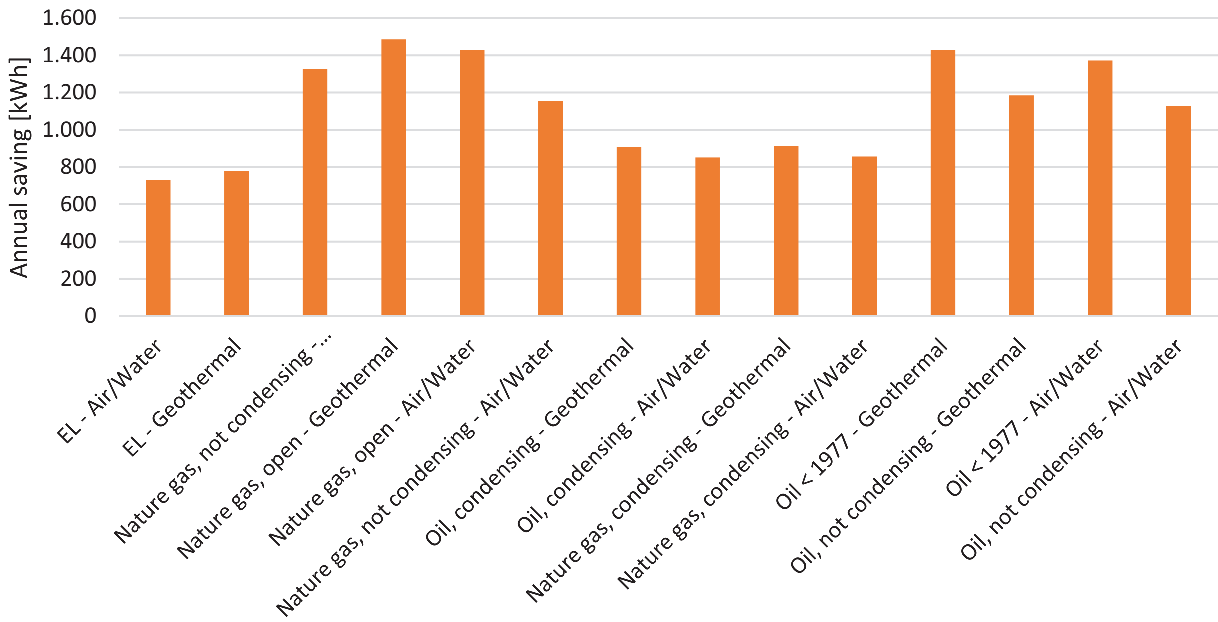


Figure 4.15 Estimated savings in converting into a heat pump (Teknologisk Insistut 2016)

The efficiency of the heat pump depends on the temperature on the secondary side of the system. The higher the temperature needed on the secondary side, the more electricity it requires for the compressor to compress, thereby raising the temperature. Therefore, lowering the temperature of the supply and return is recommended. Lowering the temperature can make the system incapable of providing the demanded amount of energy. However, no matter the heat source you have, the first step should always be to reduce the demand. This will result in the current radiators being oversized making room for lowering the temperature. This is described in the Appendix F: Heating.

Recommendation in TREE

There are multiple things to take into consideration when changing the heat source. Heat sources available can be regulated by law depending on area, e.g. if there is district heating available, legislation might demand that it should be chosen. Figure 4.16 shows five different options compared with cost. The calculation in Figure 4.16 is made with an average heating consumption (15.300 kWh) for a renovated 140 m^2 house (Energistyrelsen 2016c). The running cost for the heat pumps are calculated to be 5.068 kWh (Air/Water, COP 4.3, A7/W35[7]) and 5.394 kWh (Geothermal, COP 4.04, G0/W35) (varmepumpe-guiden.dk 2016), therefore, the temperatures in the heating system should be reduced to obtain this efficiency. This corresponds to the argument that before installing or replacing a heat source the heating consumption should be reduced. However, for a more accurate annual electricity consumption, the SPF could have been used for the calculation, however, SPF numbers were not available

[7] Temperature on primary side (7°C)/ Temperature on secondary side (35°C)

from the manufacturer. All energy prices are calculated with an increment of 2 % per year, as this is the estimated increase in energy prices (Danish Energy Agency / Energi Styrelsen 2015).

In Figure 4.16 district heating and biofuel are the cheapest ones over a 15-years period, especially the biofuel relates to a lot of maintenance, both weekly from the user and yearly from a professional. The cost of biofuel, as described in Table 4.22, varies depending on volume bought. For the calculation in Figure 4.16 a start price of DKK 0,63 per kWh is used (Byggeri & Teknik I/S 2015).

It can be concluded that heat pumps are the most expensive ones overall, but along with district heating, they require only a minimum of maintenance. The running costs are the electricity they use, which in this calculation are bought from the grid. The electricity could come from installing PVs on the roof (see 4.2.3.4: Electricity), which would then reduce the running cost of the heat pump and the owner would avoid the uncertainty connected to increasing electricity prices. A smart control system could make the heat pump produce heat while the electricity is produced by the PVs, storing the energy in a storage tank or in the thermal mass of the house.

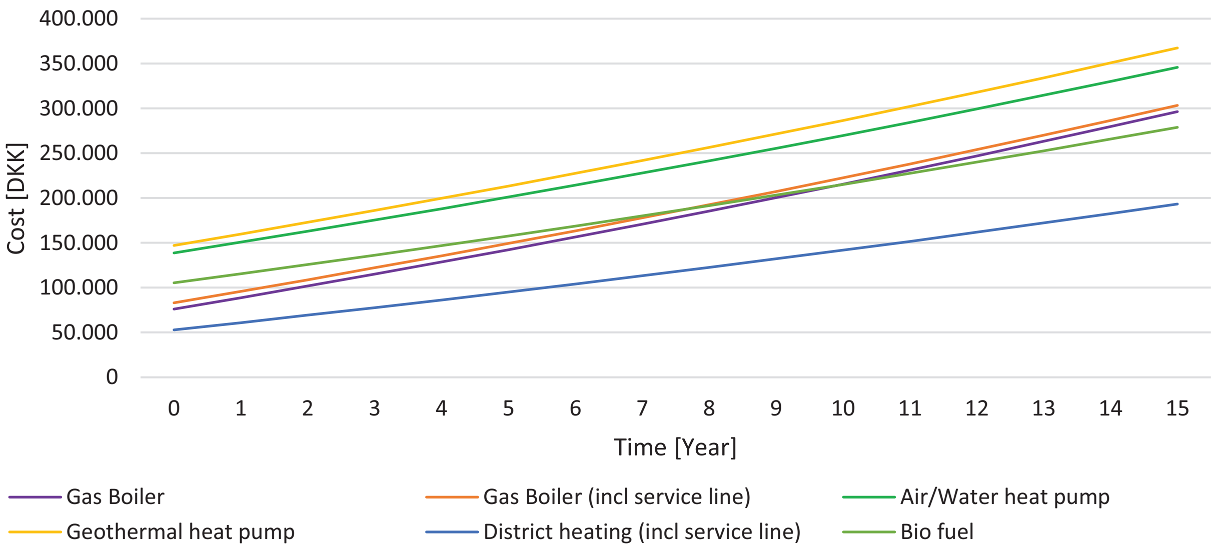


Figure 4.16 Instalment and running cost for heating source (V&S Price book) (Energistyrelsen 2016c)

In Table 4.23 the prices used in Figure 4.16 and in TREE, are shown. The prices include a system for production of DHW, which is either with a heat exchanger or hot water tank.

Source *[-]*	**Instalment cost** **(Appendix J: V&S Price book)** *[DKK]*
Gas boiler	76.111
Gas boiler (incl. service line)	83.089
Heat pump – Air-to-Water	138.728
Heat pump – Geothermal	147.034
District heating (incl. service line)	52.888
Boiler Biofuel	105.399

Table 4.23 Cost of replacing a boiler and installment by a professional incl. VAT (V&S Price books)

Heat source in TREE

As described, the decision about a new heat source does not only regard economy. Therefore, a professional should help to select the right source. In TREE the six solutions, as shown in Figure 4.16 , will be provided (if they do not conflict with current source) with cost and payback time.

This information will help calculate the savings for a new heat source. As mentioned earlier, reducing the energy demand should always be the first step, therefore, the provided optimization will be based on the calculations after the user has installed the energy improving suggestions e.g. lowering the U-value of the constructions.

In this example, the client has an annual energy consumption of 15.882 kWh. By following the suggested energy saving improvements, the estimated savings will be 20 % of the current heating consumption.

House	Oil boiler (from user/ or table)	=	15.882	kWh/year
Cost	(from user / or table)	=	15.882	DKK/year
Calculated savings	15.882 – 20 %	=	3.176	kWh/year
Gas boiler, 15 years	76.111 DKK + ((3.176 kWh · 15 years) · 0,80 DKK/kWh)	=	**114.223**	**DKK**
Payback (oil vs gas)	76.111DKK / ((1,00 DKK – 0,80 DKK) · 12.705 kWh)	=	**30.0**	**Years**

The same calculations will be made for all types shown in Table 4.23

Electric heating

Lastly, few houses from this period were built with electric heating. These were typically houses located in rural areas, outside of areas with a connection to district heating such as vacation houses and farm housing. However, if the house had electric heating prior to the regulation, or if it is too expensive to install central heating due to the technical characteristics of the house. Central heating will require a waterborne system to be installed (Bolius 2015a).

As of 2000, 6 % of Danish housing (corresponding to 150.000) was using electricity as the main heating source. Electricity is an expensive heating source and as a consequence, housing with electric heating has a lower selling price in Denmark (Bolius 2012) (Energistyrelsen 2004).

Electric heating suggestion in TREE

Installing a new waterborne heating system will be a very extensive and costly solution, therefore, the suggestion will be to add an air-to-air heat pump. The electricity used both to the heating system and the heat pump should be provided from PVs in order to lower the electricity consumption.

The estimated price for installing an air-to-air heat pump is 15.000 DKK with annual savings of 28 % on the electricity consumption (varmepumpe-guiden.dk 2016). Be aware that the price for electricity is 0,63 DKK/kWh less for all kWh above 4.000 kWh (SKAT 2016). This requires the owner to prove that electricity is the main source of heating.

The calculation in TREE

Yearly Electricity consumption	(from user)	=	10.000	kWh/year
Cost	(from user)	=	1,89	DKK/kWh
Instalment		=	15.000	DKK
Savings	10000 · 28 %	=	**2.800**	**DKK**
Payback	15000 / 2800	=	**5,4**	**Years**

SOLAR HEATING

A renewable way of producing DHW and/or additional space heating is by using solar collectors that use the energy emitted from the Sun. A solar collector absorbs solar radiation, converts it into useful heat and transfers it into the system by the heat transfer fluid. There are many different types and design concepts of collectors available on the market, but the three most common types are Flat-plate collector, Evacuated tube collector and Concentrated collector. More detailed information about each type can be found in Appendix G: Solar Collectors.

As mentioned before, solar collectors can also be used as a supplement for space heating, however, in this chapter the focus will be on producing for DHW since it is the most commonly used system in Denmark. By prioritizing the solar collectors for DHW production, a smaller system is needed. The need for solar collectors is then dependent on the DHW consumption, which varies from household to household.

According to SBi 213, a single-family house uses 250 l/m^2 DHW per year, however, typically no more than 60 m^3/year. In Table 4.24 the estimated DHW usage for the reference houses according to SBi 213 is shown. The rule of thumb is 4 – 6 m^2 solar collectors to supply a family of four with DHW. The optimal location for solar collectors is to face them South with an angle of 30 - 60° (Energistyrelsen 2016c). Inside the house, a hot water tank with a volume of 200 – 300 liters is placed, insulated and connected to either electricity or a boiler if the solar collectors do not fully cover the heating demand on its own (Energistyrelsen 2016c).

	Area *[m^2]*	**DHW** *[m^3/year]*
Ref. A	176.0	44.0
Ref. B	101.7	25.4
Ref. C	122.0	30.5
Ref. D	103.0	25.8
Ref. E	152.0	38.0

Table 4.24 Estimated annual DHW according to SBi 213

In Figure 4.17 a test simulation, conducted in Polysun, is performed to evaluate the recommended area of solar collectors from www.sparenergi.dk. The simulations are performed with Reference house A and B, located in Copenhagen and with flat-plate collectors facing South with an angle of 45°. Reference house A was chosen because it had the highest consumption of all the houses and Reference house B with the lowest. To simplify the test, a 300 liters storage tank is used for all simulations. The volume of the tank must be dimensioned according to the correct household consumption and area of the solar collectors. The recommendations from Polysun ranged from 150 – 600 liters tank. Simulations with the different sizes of solar collectors are performed twice. First, with the highest consumption (Ref A) and the second time with the lowest consumption (Ref B) as shown in Figure 4.17. It can be concluded that even with an area of 8 m^2 and the lowest consumption (Ref B), only August is covered 100 %. However, from March – October more than 90 % of the DHW is covered by the solar panels. This proves the importance of knowing the correct consumption before purchasing a solar heating system and, if possible, reduce the consumption by installing water saving equipment beforehand.

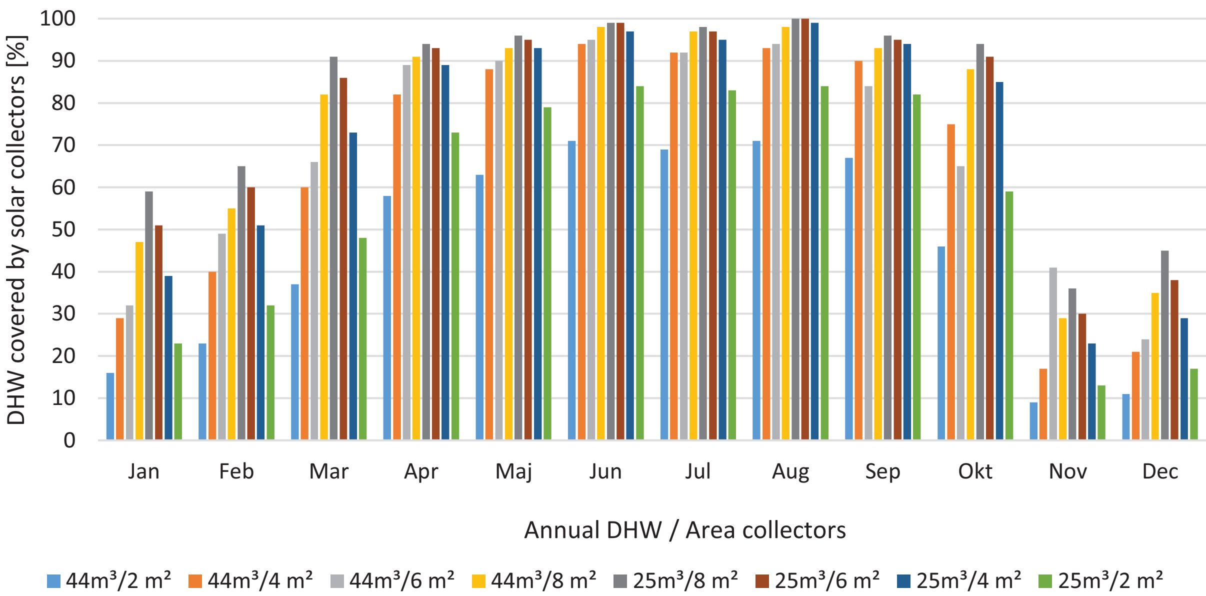


Figure 4.17 Solar collector calculation for DHW. Ref A 44 m^3 / Ref B 25 $m^3$with solar collector area.

Looking at Figure 4.17, it can be concluded that an area of 4 m^2 and 6 m^2 does not make a great difference. This can be explained by the water tank used as storage and with a volume of 300 L. This size is the optimal for the solar heating between 4 m^2 and 6 m^2, therefore, they can almost cover the same percentage of the consumption.

The results from Figure 4.17 do not fit with the rule of thumb saying that 6 m^2 should cover the total demand for hot water. This can be due to orientation, where South has more solar radiation than West and East. Looking at the highest consumption (44 m^3/year) and the smallest area of collectors (2 m^2), it is still able to produce more than 50 % of the DHW in half of the year, indicating that solar collectors are recommended and that the potential savings are significant. Table 4.25 describes the actual savings.

The possible savings of installing solar collectors has been calculated by *Technologic Institute* except for the savings for district heating. The saving for district heating has been made as following:

Area	(average from ref houses)	=	130,8	m^2
DHW consumption	(SBi 213)	=	250	L/m^2
Energy covered by solar heating	(average from Figure 4.17)	=	67,7	%
Energy producing DHW	(energy use from Be15)	=	13,1	kWh/m^2
Savings	$13{,}1\ kWh/m^2 \cdot 67{,}7\ \%$	=	**8,86**	**kWh/m^2**

Heat source *[-]*	**Annual Savings** *[kWh/m^2]*
Condensing boiler	30.4
Not condensing boiler	57.8
Electric heating	30.4
District Heating	8.9

Table 4.25 Savings by installing solar collectors for DHW (Teknologisk Insistut 2016)

In TREE the calculations are as follows:

In this example, the user has answered that the heating source is an oil boiler and the house is 130 m^2.

Area	(from user)	=	130	m^2
Annual savings	$30{,}4\ kWh/m^2 \cdot 130\ m^2$	=	3.952	kWh
Cost, heating	(oil boiler, values from user or standard value)	=	0,90	DKK/kWh
Annual savings	3.952 kWh · 0,90 DKK/kWh	=	**3.557**	**DKK**
Payback time	59.757,50 DKK[8] / 3.557 DKK	=	**16,8**	**Years**

However, it will be stated in TREE that the first step should be to change the heat source, which would affect the calculation. Therefore, it should be possible in TREE to see the savings based on changing the heat source as it will give a more accurate result. The needed area is 6 m^2 for the solar panels which could conflict with the PV cells (see chapter 4.2.3.4: Electricity) since they will both be placed on the roof, therefore, installing a heat pump instead would be recommended.

[8] (V&S Prisdata 2016) see Appendix J: V&S Price book

In order to reduce heat loss from the pipes, they should be insulated. This concerns pipes that are located outside the building envelope and in unheated rooms. The heat loss from the pipes varies depending on the size and the material they are made of. A simplified calculation is shown in Table 4.26 where the savings are estimated if the pipes are better insulated. The savings in DKK depend on the heat source because of the price of heating. All the pipes, used both for DHW and heating, should be insulated. For DHW the cold water should also be insulated since it keeps the water cold and prevents condensation.

The savings in Table 4.26 are for pipes outside the building envelope, however, it is recommended to insulate pipes inside heated areas for comfort reasons e.g. more accurate user control of the heating in the individual rooms. If the temperatures get up to 70 °C in the heating system, it can also create a risk for burns, when people are unaware of the hot pipes. This risk will also be reduced by insulating the pipes.

Insulation level before *[mm]*	**Insulation level after** *[mm]*	**Savings** *[kWh/m]*	**Investments**[9] *[DKK/m]*
< 10	10 – 20	10,9	308,36
< 10	> 20	11,7	372,53
10 – 20	> 20	0,8	372,53

Table 4.26 Pipe insulation (outdoor) (Teknologisk Insistut 2016). Annual savings in DKK dependent on heat source (Byggeri & Teknik I/S 2015)

A calculation to investigate what the suggestion in TREE should be:

No insulation to 20 mm	5,0m · 308,36	=	1541,80	DKK
Annual savings	5,0m · 10,9 kWh · 0,51 DKK/kWh	=	**27,80**	**DKK**
Payback	1.541,80 DKK / 27,80 DKK	=	**55,5**	**Years**
No insulation to 30 mm	5,0m · 372,53	=	1.862,65	DKK
Annual savings	5,0m · 11,7 kWh · 0,52 DKK/kWh	=	**29,84**	**DKK**
Payback	1.862,65 DKK / 29,84	=	**62,4**	**Years**
10 mm to 30 mm insulation	5,0m · 372,53	=	1862,65	DKK
Annual savings	5,0m · 0,8 kWh · 0,52 DKK/kWh	=	**2,04**	**DKK**
Payback	1.862,65 DKK / 2,04 DKK	=	**913,0**	**Years**

With a payback time of 55,5 – 913 years, it can be difficult to convince the client to install insulation on the piping outside. However, in the cost from V&S Price book, 88 % is for the man hours (see Appendix J: V&S Price book). If the client installs it himself, the calculation results in

[9] (V&S Prisdata 2016) Price is calculated for installing 5.0 meters

a payback time of 6,7 – 7,5 – 109,6 years. Thereby, the recommendation in TREE will focus on pipes without any insulation and self-installation. Adding insulation on piping in heated rooms is very case specific and mostly concern comfort parameters. If a room is very warm compared to the rest of the house, it could help insulating any piping going through that room.

Control of heating system

Every radiator or floor heating system should have its own control unit, preferably a thermostat measuring the operative temperature in the room. These thermostats will help provide a good thermal comfort, as they can keep the room temperature at the same minimum, and ensures a minimal use of heating. However, there are different kinds of control and optimization possibilities available.

To ensure that the heating system is optimally functioning in the rooms, it is important that nothing is blocking the radiators. Placing furniture, curtains, or radiator covers limits the efficiency of the radiator. The next step is to check that the radiator is cold at the bottom. When the radiator is heating up a room it should be warm at the top and cold on the bottom which indicates an effective cooling is in the heating system (Energistyrelsen 2016c). If the radiator is warm in the bottom the supply temperature can be lowered or a return valve can be installed on the radiator which can control the return temperature of the fluid Appendix F: Heating. Finally, one mixing shunt can be installed in the heating system, reusing the return fluid if the temperature is sufficiently high.

Questions for the user in TREE:

Is there anything blocking the radiators, e.g. covers or furniture?

If yes, then the recommendation text will be to remove it to ensure a good air flow around the radiator.

The most common thermostat in Denmark is a manual control with six different settings shown in Table 4.27. It is recommended to have the same settings on, all day, at each radiator, however, during longer leave or when venting out they should be lowered. Lowering the temperature in the room with 1 °C can save up to 5 % on the energy consumption (Danfoss 2015).

Settings	*	1	2	3	4	5
Temperature [°C]	9,5	14	17	20	23	25

Table 4.27 Danfoss thermostat, supply (Danfoss 2015)

New systems, such as *Danfoss Link*, are automatic. The system can control all the heating systems in the house including floor heating and it is controlled by an app on the phone or a control panel in the home. Some of the benefits are, that you can easily set when you are at work or on vacation. The system learns the time it takes for it to heat up, thereby, the temperature can be at a certain set point when you enter the home.

Danfoss has calculations saying that on average it saves 13 – 22 % of the energy consumption, however, there are also cases where savings have been up to 35 % (Danfoss 2015). All this is depending on the use of the house and how the radiators were controlled before.

It can be difficult to calculate or test the results from Danfoss, therefore, the 13 % will be used in the tool. This is the minimum savings in numerous test cases made by Danfoss and considered reliable input in TREE. The savings will also depend on the user's ability to use it correctly, however, that is up to the professional who installs it to ensure the owner has the appropriate knowledge of the system.

In TREE, the user will be asked about the number of radiators and how they are controlled as shown in Table 4.28

Options	**Suggestions**	**Savings**	**Investment** *[QNT/DKK]*
Manual control on supply	Change to automatic control	13 %	796[10]
Automatic control on supply	-	-	-

Table 4.28 Input in TREES

The calculation is as follows:

The user has answered that there are 8 radiators with manual control. The heating source is district heating with an annual use of 18.882 kWh for the cost of 9.818 DKK.

Heating consumption	(from user)	=	18.882	kWh
Heating, cost	(from user) 18.882 kWh / 9.818 DKK	=	0,52	DKK/kWh
Number of radiators	(from user)	=	8	qnt
Investment	8 qty. · 796 DKK	=	6.370	DKK
Annual savings	18.882 kWh · 13 %	=	**2.455**	**DKK**
Payback	6.370 DKK / 2.455 DKK	=	**2,6**	**Years**

4.2.3.2 Domestic hot water (DHW)

Today, hot water for the household is produced by a centralized system, district heating or solar collectors. Old hot water tanks were large (150 - 250 L) tanks placed horizontally, uninsulated and required a lot of energy to heat up the water. Modern tanks are reduced in size (60 - 110L), insulated and placed vertically in order to reduce the amount of energy needed to heat up the water. The hot water piping should be insulated according to building regulations/DS 452. If a circulation pump is installed on the system, it could be optimized by making it time controlled according to the needs of the household (Energistyrelsen 2016e). Some houses produce hot

[10] (V&S Prisdata 2016) (10 qnt 6370 DKK) + 25 % for automatic (Danfoss)

water through a heat exchanger, therefore, do not have a hot water tank. These should be checked if they are insulated well enough.

The temperature in the hot water tank should be kept at around 55°C. At this temperature, legionella bacteria are killed. Higher temperature requires more energy and causes calcium secretes from the water which reduces the lifetime of the hot water tank (Energistyrelsen 2016e).

In order to ensure that the client knows what the current temperature in the hot water tank is, a question regarding this will be applied to the tool. Another way to deal with this issue could be to apply the current temperature in the tool and then calculate the potential savings or additional heating consumption. This is disregarded since it requires a lot of information from the client concerning the properties of the tank, for instance type, insulation level, and volume.

However, in TREE, some standard values to calculate the heat loss (see Appendix F: Heating) will be provided for the user. Based on the answers, possible optimization options are provided. The heat loss is calculated from *Energihåndbogen 9.17.1* and the estimated savings are calculated with Be15. For example, insulating a 100 L hot water tank with 50 mm of insulation will save 25,5 kWh/m^2 per year on the heating consumption (Klimaministeriet 2016).

The same calculations can be made for having too high or too low temperature in the hot water tank. The optimal temperature in the tank is 55 °C and by changing the values in Be15 the estimated savings can be conducted. For example, lowering the temperature in the hot water from 60 °C to 55 °C will save 2,1 kWh/m^2 per year. This also, as earlier described, has health and maintenance benefits. All these tests are simplified by assuming that the tank is placed inside the heated area. All the calculations can be found in Appendix F: Heating.

There are different possibilities of making the domestic water supply more sustainable. This could be solar collectors for hot water, collecting and using rainwater for the toilet, washing machine and gardening purposes, or just adding water-saving equipment on the faucet or in the shower.

Pumps – DHW and heating

Depending on the heating and DHW system there can be a circulation pump. These pumps are used to circulate the fluid in the heating system for radiators, floor heating, heating the DHW, or if solar heating panels are installed. Many homes may also have a circulation pump on the DHW to ensure hot water within 10 seconds at the tap (Energistyrelsen 2016c).

Replacing an inefficient pump, whether it is on DHW or the heating system, may lead to energy savings. Older pumps, in single-family homes, that use more than 40 W or have 3 different settings, should be replaced as they are not energy efficient. Modern pumps are automatically controlled by the pressure in the system, therefore, use less energy than old pumps with constant speed (Energistyrelsen 2016c).

Table 4.29 shows the possible savings by replacing the circulation pump to a new one, however, this saving is highly dependent on when the heating system is in use e.g. whether it is used during the summer or not.

	Saving *[kWh/year]*	**Investment**[11] *[DKK]*
New pump, DHW	406	5.262,50
New pump, heating	406	5.262,50

Table 4.29 Circulation pump (SEAS-NVE 2016)

In TREE the user will be asked if there is a pump in the heating system and the DHW. The optimization is shown in Table 4.30.

Answer	**Optimization**
No pump	-
Manual pump	Install an automatic pump
Automatic pump, A-mark	-

Table 4.30 TREE input, circulation pump

[11] (V&S Prisdata 2016) See Appendix J: V&S Price book.

4.2.3.3 Ventilation

Housings from this period were built with natural ventilation through windows and/or valves in the facades. Contaminated air from the toilet, kitchen and utility room was led out through vertical vents, mechanical or natural driven, in the source rooms.

In TREE the options for selecting current ventilation will be as shown in Table 4.32 and will also include mechanical ventilation. Even though the houses were usually built with natural ventilation, the possibility to have it installed later is present.

Type	Fo *[-]*	qm *[L/s·m²]*	nvgv *[-]*	Ti *[°C]*	EL *[-]*	qn *L/s·m²*	qi,n *[L/s·m²]*	SEL *[kJ/m°]*	qm,s *[L/s·m²]*	qn,s *[L/s·m²]*
Natural ventilation, normal	1					0,3				2,4
Mechanical ventilation < 1995 (no HR)	1	0,3				0,13			0,3	2,4
Mechanical ventilation < 1995	1	0,3	0,55	18	1	0,13		2,5	0,3	2,4
Mechanical ventilation 1995 - 2006	1	0,3	0,60	18	1	0,13		2,0	0,3	2,4
Mechanical ventilation 2007 - 2010	1	0,3	0,65	18	1	0,13		1,8	0,3	2,4
Mechanical ventilation 2011 - 2015	1	0,3	0,70	18	1	0,13		1,8	0,3	2,4

Table 4.31 Ventilation for TREE, *Energihåndbogen 9.4.7* (Klimaministeriet 2016)

In addition to selecting the ventilation type, the user will be asked about the level of infiltration. They can select from Table 4.32

	Added to qn or qm *[L/s·m²]*
Normal	+ 0,0
Leaky	+ 0,1
Very leaky	+ 0,2

Table 4.32 Infiltration in TREE, Energihåndbogen 9.7.1 (Klimaministeriet 2016)

The infiltration can be difficult to measure for an unprofessional user, and has been simplified to normal, leaky, and very leaky. These terms are still very relative. The optimal solution would be to ask the owner to have a blower door test conducted. This, however, will be expensive and slow down the process, therefore, it has been decided to use the recommendations from *Energihåndbogen*.

Installing a mechanical ventilation system can ensure a good indoor air quality, keep moisture away from the construction and reduce the heat loss from venting out (Energistyrelsen 2016c). In Table 4.33 the estimated savings on the heating consumption from installing a mechanical ventilation system with heat recovery in the entire house is shown. However, installing a mechanical ventilation system in a single-family home is not without any issues. The ducts providing the fresh air or exhaust take up a lot of space and can be hard to install in an existing house. The ducts are often placed in the attic or ceiling, which is only possible if there is not a high ceiling.

A smart way to get around the issue with the installment of a centralized mechanical ventilation system is to install a decentralized system. Decentralized ventilation in a single-family home means that the mechanic vent is placed in the wall or window, extracting air from the room for a certain amount of time. Then the system turns from exhaust to supply and fresh air is provided into the room. The system still has heat recovery, which can, theoretically, be up to 90 % with an SEL of 0.997 KJ/m^3 (Duka 2016).

In TREE the savings will be from a test from the reference houses conducted in Be15 with the values from Table 4.31. The cost is described in Table 4.33 where the calculated savings for decentralized ventilation is set to 10 % of centralized. This is since decentral can be installed in one room only or in multiple (10 % for each installed). In TREE the user will be asked how many decentralized units they will install.

	Saving *[per unit]*	**Investment** *[DKK/unit]*
Mechanical ventilation w/ heat recovery, central	See Appendix F: Heating	65.000
Mechanical ventilation w/ heat recovery, decentral	10% of central	3.000

Table 4.33 Estimated saving by installing mechanical ventilation (Teknologisk Insistut 2016) (BOLIUS 2008)

SUMMARY

In Table 4.34 a summary of all the savings proposals in this chapter can be seen. They are ranked according to the price for saving 1.0 kWh, the full calculation can be found in Appendix F: Heating.

Improvement *[-]*	**Price per saved kWh** *[DKK]*
Lowering temperature 1 °C	0,00
Pipe, insulation from < 10 mm - 10-20 mm	0,23
Pipe, insulation from < 10 mm - > 20 mm	0,25
DHW Solar heating (Not condensing boiler)	0,49
Manual control - automatic control	0,55
New pump	0,86
DHW Solar heating (Condensing boiler)	0,94
DHW Solar heating (Electric heating)	0,94
Natural ventilation - central mechanical ventilation	1,16
Natural ventilation - decentral mechanical ventilation	0,04
DHW Solar heating (District heating)	3,20
Pipe, insulation from 10-20 mm - > 20 mm	3,73
Nature Gas boiler, open - District heating	4,32
Oil < 1977 - District heating	4,65
Nature gas, open – Air-to-Water	6,47
Nature Gas boiler, closed - District heating	6,49
Nature gas, open - Geothermal	6,60
Oil < 1977 - Air-to-Water	6,74
Oil > 1978 - District heating	6,84
Oil < 1977 - Geothermal	6,87
Nature gas, not condensing - Geothermal	7,39
Nature gas, not condensing - Air-to-Water	8,00
Oil, not condensing - Air-to-Water	8,20
Oil, not condensing - Geothermal	8,28
Nature gas, condensing - Geothermal	10,75
Nature gas, condensing – Air-to-Water	10,80
Oil, condensing - Geothermal	10,81
Oil, condensing – Air-to-Water	10,87
EL to geothermal	12,61
Nature Gas boiler, Condensing - District heating	14,49
Oil, Condensing - District heating	14,49

Table 4.34 Summary of savings in HVAC chapter range according to price per saved kWh with a lifespan of 15 years.

4.2.3.4 Electricity

This chapter focuses of the potential savings in the electrical installations. As it can be seen in Figure 4.18 this counts for only 13 % on average, therefore, there is a potential for a greater saving by looking at appliances connected to the plugs. The decision has been made to focus only on lighting and production in this chapter, as these are normally taken into account for buildings other than single-family homes. However, there is a potential, as will be described, for saving electricity, as well as reducing heat radiation from lightbulbs by replacing them with LED. To simplify, the appliances are placed in the appendix as they still have a great potential of reducing energy consumption

In Figure 4.18, the distribution of the electricity consumption in an average single-family home is shown. The 4 % for heating is not electric heating, but the electricity used for the heat pump (Energistyrelsen 2016c). As seen in Figure 4.18, the largest consumption goes to electrical appliances, such as TVs, computers, and washing machines. This can be lowered by not using stand-by power on the electrical appliances and by washing at lower temperatures (Further information can be seen Appendix I: Electricity).

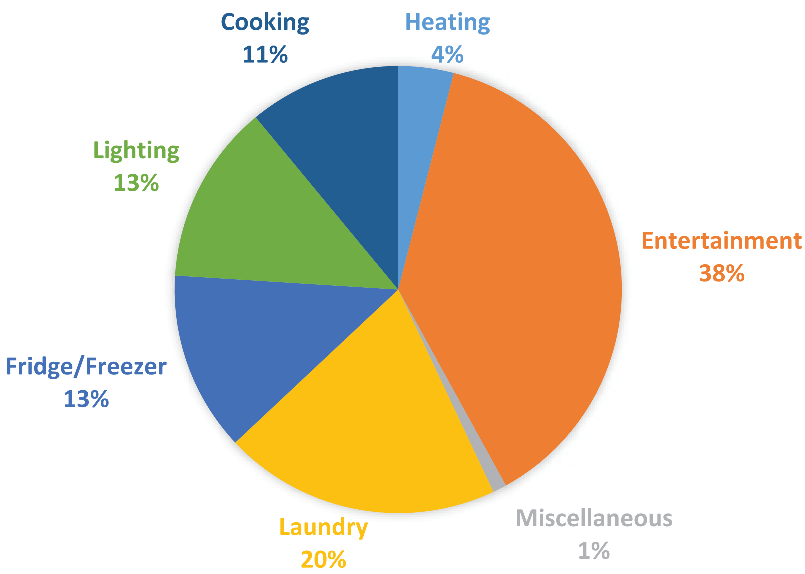


Figure 4.18 Distribution of electricity use (Energistyrelsen 2016c)

Figure 4.18 shows the average percentage of the electricity consumption in a single-family home to illustrate how the electricity consumption is divided. The type and quantity of appliances, of course, have a great influence on the distribution of the electricity consumption. If the owner already is following the advices in this chapter, or for appliances in Appendix I: Electricity, then the distribution will look different. But if the lighting or appliances are the type that uses more power, e.g. if they are of older technology, the total actual consumption is assumed to be larger. With that in mind, it cannot be ruled out that there are cases where an owner has incandescent bulbs and the appliances are energy saving, and in these cases Figure 4.18 will show values that varies from the actual conditions.

The average electricity consumption can be calculated as follows (SBi 2005):

$$530 \text{ kWh} + 12\text{kWh/m}^2 \cdot \text{gross area} + 690 \text{ kWh/occupants} = \text{kWh/year} \quad (5)$$

This equation will also be used in the tool if the user has no knowledge about the consumption for the last year. It is important that the user does not get stuck while using the tool, and with this equation the only information needed is the gross area and the number of occupants. The equation has been developed by SBi and made numerous reference cases. Things that have influence on the electricity consumption, besides the area and number of occupants, are the age of the occupants, for example, if it is an old couple or family with children, and the number of occupancy hours. All these have been taken into consideration when creating the equation, and therefore, the equation is assumed valid for the tool.

The electricity can come either from the connection to the grid, where the prices vary day by day, or from a private and/or local renewable energy source. The average price for electricity in the third quarter of 2016 was 2,29 DKK/kWh (incl. VAT and connection) calculated with an average use of 4.000 kWh (Energitilsynet 2016). The price of electricity varies depending on where in Denmark the user lives and which company is providing the electricity. In the tool, a price of 2,29 kWh, will be used as a reference, however, the user will also have the opportunity to change the price.

Solar cells

The electricity in a single-family home can be produced by a renewable source, such as PV-cells. The PV-cell converts the energy from the sun radiation directly into electricity by photovoltaic effect. The electricity production from the cell increases as solar radiation falling on the cell increases (Knier, 2002).

The cells can be placed either on the roof or on the ground, however, they should not be shaded at any time during the day as it will decrease the efficiency. The optimal orientation to achieve the highest efficiency is South with and angle of 35°. This is due to the high solar radiation on average from south and the ideal solar path angle through the year. There are three major kinds of PV-cells, polycrystalline, monocrystalline, and thin-film. Monocrystalline is known to be the most efficient on the market but the thin-film technology is a cheaper solution. (Pomianowski 2016).

Consumption from PV-cells

It can be difficult to determine to correct amount of electricity produced by the PV-cells as it depends on multiple different factors. As described previously, the orientation and angle has a great influence on the outcome. However, the amount of solar radiation is obviously also a factor to take into consideration. To make a simple estimation of the possible outcome, the tool uses the following equations.

The possible kWp is being determine by this equation (Pomianowski 2016)

$$\text{Total area of modules} \cdot \text{Module efficiency} / 100 = \text{kWpeak} \tag{6}$$

The module efficiency will be fixed, and 12 % is used (monocrystalline, standard (Pomianowski 2016)). In the tool the area comes from the client and the 80 % is assumed to be the module and the last 20 % the frame.

The total output is, as described earlier, dependent on the angle and orientation. Therefore, Table 4.35 has the solar radiation intensity depending on the location and the slope of the PV-cells (Pomianowski 2016).

	East -90	**-75**	**-60**	**SE -45**	**-30**	**South 0**	**30**	**SW 45**	**60**	**75**	**West 90**
0°	999	999	999	999	999	999	999	999	999	999	999
15°	988	1017	1044	1067	1084	1097	1090	1062	1038	1011	981
30°	958	1012	1060	1100	1130	1152	1124	1092	1050	1001	947
45°	914	963	1045	1096	1134	1163	1128	1087	1033	971	901
60°	853	928	997	1052	1092	1124	1087	1042	983	916	839
75°	772	845	912	967	1005	1033	998	957	901	933	759
90°	671	738	795	841	873	892	867	833	785	726	662

Table 4.35 Solar radiation intensity [kWh/year] (Pomianowski 2016)

By multiplying the kWp with the solar radiation the estimated total outcome can be calculated, and this value can be used as how much electricity the home will gain from this renewable system. This is because there will be no storage of electricity, therefore, the consumption of the electricity must forego at the same time it is being produced. It can be rather difficult to estimate how much of the produced electricity the household will use, so the following equation from Energihåndbogen 9.19.9 will be used in the tool for the estimation:

$$\frac{\text{kWh} \cdot \text{system factor}}{\text{annual electricity consumption}} = \text{selfconsumption factor (SF)} \qquad (7)$$

The factor will then be used in Table 4.36 to convert to percentage of self-consumption. The conversion from SF to percentage will be used for estimating the self-consumption from produced electricity.

SF	**0,1**	**0,2**	**0,3**	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	**0,9**	**1,0**	**1,1**	**1,2**	**1,5**	**2,0**	**3,0**	**4,0**	**5,0**
%	69	67	60	53	47	42	38	35	32	30	28	26	22	18	13	10	8

Table 4.36 Conversion between SF and percentage of self-consumption (Klimaministeriet 2016)

Input in the Tool

Table 4.37 shows the prices from V&S Price books, Appendix J: V&S Price book, for two different systems. The prices will be used in the tool depending on the size of the system. The module area described in Table 4.37 is the size of the system included in the price.

Module area *[m²]*	**PVs** *[kWp]*	**Investment** *[DKK incl. VAT]*
25	4.0	71.041
42	6.5	86.926

Table 4.37 Price for PV-cells (V&S Prisdata 2016)

In the tool the calculation will be conducted as the following example.

The user stated available roof area of 40 m^2, orientated Southeast with a slope of 30°.

Available roof area	40 m^2 · 80 %	=	32	m^2
Size of system	32m^2 · 12% / 100	=	3,84	kWp
Electricity produced	1100 kWh/year · 0,7 / 4000 kWh/year	=	0,19	SF
Self-consumption	1100 kWh · 0,19 SF	=	218	kWh/year
Yearly savings	218 kWh · 2,27 DKK/kWh	=	**480,67**	**DKK/year**
Payback time	71.041 DKK / 480.67 DKK/year	=	**147,8**	**years**

The tool will not take into consideration any subsidies from the government or the fact that you can get money when delivering electricity to the grid. Therefore, the calculations of the payback time in the tool will be the *worst-case* scenario. In the example, the payback time is longer than the expected lifetime of the system, therefore, the benefit is less reliant to the fluctuations in electricity prices. The electricity prices are also expected to increase in time, which is not taken into consideration. In general the electricity is estimated to increase with 2 % every year (SBi 2013). Finally, by applying smart systems, that can use electricity while it is produced, would help increasing the self-consumption. This could be washing machines or dishwasher, that can be operating during the day instead of in the evening.

Artificial Lighting

The artificial lighting is currently one of the main electrical consumers in the building, covering around 13 % of the total electricity consumption. This is an important area to have in mind to lower the electricity consumption by e.g. increasing the use of daylight in the building and as well implementing LED (Light Emitting Diode) lighting. BR15 has no legislations concerning lighting in single-family homes, however, BR15 recommends using lightbulbs with an efficiency of general lighting over 50 lm/W in offices. This is to ensure that the lightbulbs used are energy efficient (BR 2015). Reviewing some of the lightbulb producers on the Danish market reveals that there are numerous options when it comes to energy efficient lightbulbs, such as 94 – 150 lm/W (2 W – 5 W) lightbulb from Phillips, and 50 – 81 lm/W (1.1 W – 22 W) lightbulb from Ikea[12]. Therefore, it can be concluded that it is possible for homeowners to buy lightbulbs that are energy efficient according to BR15.

LED-lighting

As a guidance for the conversion from old light sources into LED, Table 4.38 can be used (Lysexperten 2016). There are no legislation regarding the Lux (lumen · area = Lux) level

[12] Values are from the producer's websites, both Phillips and Ikea. November 29, 2016

needed in residential homes, therefore, it is up to the individual to decide the needed Watt to have sufficient light. The artificial light should only be used when daylight is not enough, for instance, during night time. Increasing the daylight level and installing sensors measuring the level of natural light, and reducing the artificial light can be possibilities to save energy.

Incandescent lightbulb *[W]*	**Savings** <- ->	**LED** *[W]*	**Savings** <- ->	**Energy saving bulb** *[W]*
100	90 %	10	64 %	28
75	89 %	8	68 %	25
60	90 %	6	54 %	13
40	90 %	4	56 %	9
25	92 %	2	71 %	7
Average	**90 %**	**-**	**63 %**	**-**

Table 4.38 Potential savings in artificial lighting (Lysexperten 2016)

Every LED bulb has different colour temperatures given in Kelvin. Between 2.600 – 3.000 Kelvin corresponds to the colour temperature *warm white* equivalent to an incandescent bulb. From 3.500 – 4.000 Kelvin is known as *white,* which is good for workspaces e.g. kitchens (Energistyrelsen 2013). Studies show that the warmer the light, the more sleepy people get (Energistyrelsen 2016c).

Ra-value of lightbulbs is the colour reproduction. The higher the Ra-value is, the more precise we see colours, e.g. the Sun has a Ra-value of 100, whereas most incandescent bulbs are 99. The last important thing to look for, when buying LED, is the lifespan. Today, LEDs should have a lifespan of at least 15.000 hours (Energistyrelsen 2016c). Unfortunately, the long lifespan also means that many lamps bought today have fixed LED lightbulbs, therefore, they cannot be replaced (Energistyrelsen 2013). Remember to check if the LED lightbulb is dimmable if that is necessary. The transformer for a halogen spotlight should have a low Watt range in order to work if changed to LED, since they use less Watt than old halogen spotlights.

INPUT FOR TOOL

The total savings of the artificial lighting will be calculated as 13 % of the total electricity consumption, hence Figure 4.18. For the calculation, the conversion in Table 4.39 will be used, where incandescent lightbulbs and energy saving bulbs are changed to LED.

Table 4.39 shows the optimizations possibilities for the artificial lighting in the tool. To simplify for the user, the ratio between the different types of bulbs in percentage is used.

Question in TREE Tool *[-]*	**Suggestion** *[-]*	**Savings** *[%]*	**Investment** *[DKK/Bulb]*
Incandescent lightbulbs only	Change to LED	90	74.58
Incandescent lightbulbs are 50 % + 50 % light saver bulbs	Change to LED	76	74.58
Light-saving bulbs only	Change to LED	63	74,58
Light-saving bulbs 50 % + LED 50 %	Change to LED	31	74,58
< 51 % LED	-	-	-

Table 4.39 Artificial lighting in the tool. Average prices from Phillips and Ikea. November 29, 2016

The calculation in the tool will be done based on the actual electricity consumption of each individual case. However, if the consumption is unknown the previously explained equation will be used.

Example of the calculation with an annual electricity consumption of 4.300 kWh. The family has answered 50 % incandescent lightbulbs and 50 % LED:

Consumption	*(from user)*	=	4.300	kWh
Cost of Electricity	*per kWh*	=	2,27	DKK
Artificial lighting	*13 % of 4.300 kWh/year*	=	559	kWh
Changing all to LED	*76 % of 559 kWh*	**=**	**424**	**kWh**
Savings in DKK	*424 kWh · 2,27 DKK*	**=**	**962**	**DKK/year**

4.2.4 Questionnaire - Non-energy benefits

This chapter will present the development of the questionnaire which will allow the user to reflect up on the current comfort and discomfort experienced in the house and get an overview of what could be potentially causing it.

USER WELLBEING - PRIVATE PERSPECTIVE

With people spending approximately 90% of their time indoors and on average 16,3 hours per day spent at home in Denmark, it is crucial to provide a healthy indoor environment for the user (Keiding et al. 2003).

The Indoor Environment Quality (IEQ) describes the conditions inside the building felt by humans, in both physical and psychical way. It includes thermal-, atmospheric-, visual- and acoustic comfort as shown in Figure 4.19 (Dréau 2015). Having these parameters in mind from the start, when renovating a building, helps to create a healthy and comfortable building for the occupants. Due to the importance of these parameters for the user's wellbeing and it being one of the main motivational factor for homeowners to perform energy renovation, a special focus will be put on investigating the occupant's perception on the current conditions of the indoor environmental quality in the tool. Ranking them without simulating or measuring these parameters is almost impossible as the parameters vary in importance and perspective of each individual human being, as thermal sensation is subjective. Therefore, these parameters will be investigated in the tool through a questionnaire answered by the occupant, but this will as well help identifying potential problems and optimization possibilities in the house.

This should uncover the lack of comfort and potential flaws in the house that the homeowner has simply adapted to in his everyday life, without thinking of it as a place for optimization. This could be e.g. that the homeowner is not using the whole living space because of draught and cold surface temperatures. The homeowner might not think of the possibility of freeing more useable (comfortable) square metres by replacing an old window to decrease draught or adding external insulation to reduce radiation from a cold surface and making an uncomfortable zone in the house comfortable again. The questions in the questionnaire from this chapter will be presented in the end of each comfort chapter.

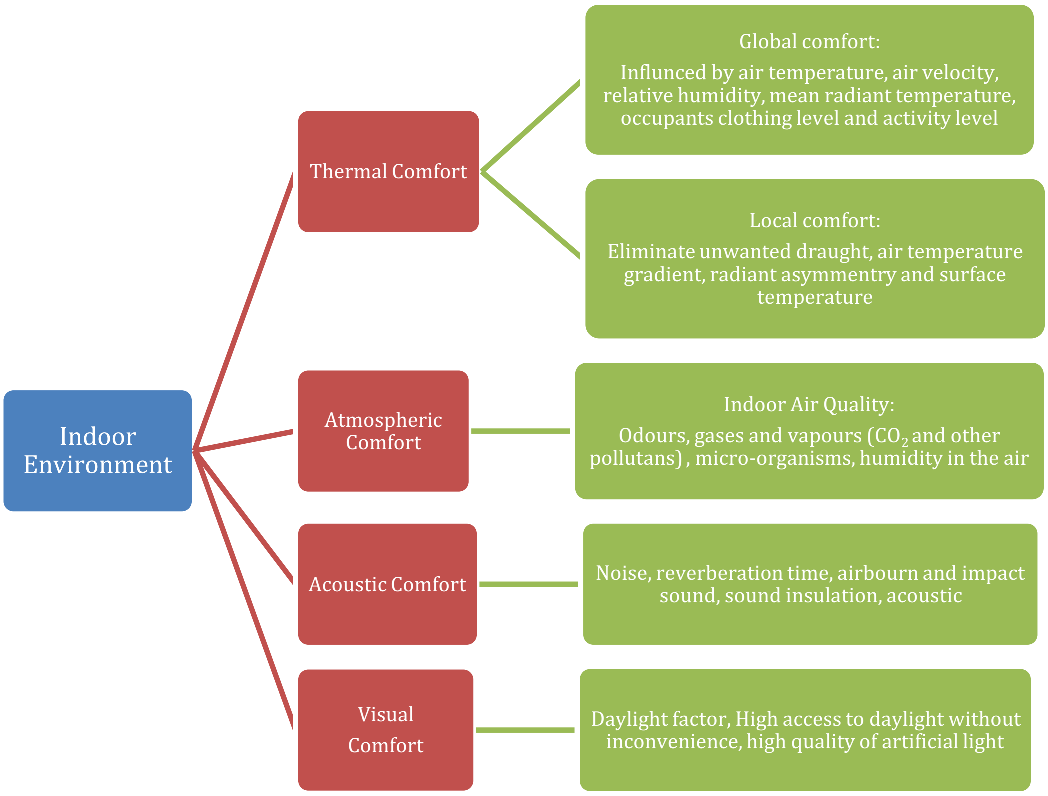


Figure 4.19 Comfort categories and parameters that have influence the indoor environment

The potentially achieved non-energy benefit will as well be introduced in each measure in the tool. This is done to create awareness and inspire occupants to create and achieve higher indoor environment quality in their homes while choosing energy efficient renovation measures.

THERMAL COMFORT

Thermal comfort is the occupants satisfaction with the surrounding thermal conditions and is crucial to consider when renovating (Autodesk 2013). By providing a good thermal comfort, comfortable living conditions can be achieved while the occupant feels comfortable globally and locally over his whole body. The global comfort achieves comfort for the body as a whole, while the local comfort does it by eliminating the unwanted cooling or heating of one particular part of the body (Dréau 2015). Parameters that influence these two comfort categories can be seen in Figure 4.19. The parameters that will be focused on in the tool questionnaire will be air- and surface temperature, draught and humidity. These questions are presented in Table 4.40 and will give a rough input into the current conditions of these parameters in the house

Questions:	Answer:	Indication of:	Possible measure:
Do you have problems with the temperature being too warm in the summer?	*Yes, very much / Yes, sometimes/ no, not at all / don´t know*	If yes: Indication of overheating in the house which can lead to uncomfortable thermal comfort	Add solar shading to decrease solar heating: blinds, shutters, overhang Improve windows: higher g-value
Do you have problems with the temperature being too cold in the winter?	*Yes, very much / Yes, sometimes/ no, not at all / don´t know*	If yes: Indication of badly insulated and leaky building envelope, leaky windows, insufficient heating system,	Insulate building envelope to decrease heat loss and improve airtightness, replace windows, improve heating system.
Do you experience cold external walls inside your home?	*Yes / no / don´t know*	If yes: Indication of badly insulated and leaky external walls with possible thermal bridges	Insulate external walls and decrease thermal bridges, increases living space
Do you experience cold feed in your home?	*Yes / no / don´t know*	If yes: Indication of badly insulated and leaky floor construction	Insulate floor construction
Do you experience draught from windows in your home?	*Yes, very much / Yes, sometimes/ no, not at all / don´t know*	If yes: Indication of leaky and insufficient windows with possible thermal bridging	Change out windows for new, decrease thermal bridges
How do you find the draught condition in your home?	*Good / average / bad*	If bad: Indication of leaky building envelope	Insulate building envelope and upgrade windows to make more airtight
Do you dry your clothes inside?	*Yes / no / don´t know*	If yes: Can lead to condensation and moisture problems, which can cause damp symptoms and mould.	Dry clothes outside or in well ventilated rooms
Do you have problem with mould growth and mildew?	*Yes / no / don´t know*	If yes: Can be cause of badly ventilated house, high air humidity and leaky building envelope	Clean away the mould if possible, increase ventilation in the house, insulate and make building envelope airtight
Do you have problem with condensation (humidity) on the inside of windows in the winter?	*Yes / no / don´t know*	If yes: Indication of high humidity level in the indoor air and lack of ventilation	Control the source of the humidity, increase ventilation and heating in the building, replace windows with double or triple glazing

Table 4.40 Questions related to thermal comfort, partly: (Knudsen & Jensen 2015)

People breath up to 15 kg of air per day, and as they spend around 90% of their time indoors, consequently the indoor air is breathed in mostly. Therefore, it is crucial to provide good indoor air quality (ActiveHouse 2015). As shown in Figure 4.20, air quality is as well one of the parameters of the indoor climate that people are least satisified with, according to a user survey conducted in Denmark, answered by 2340 persons living in old buildings (Dréau 2015).

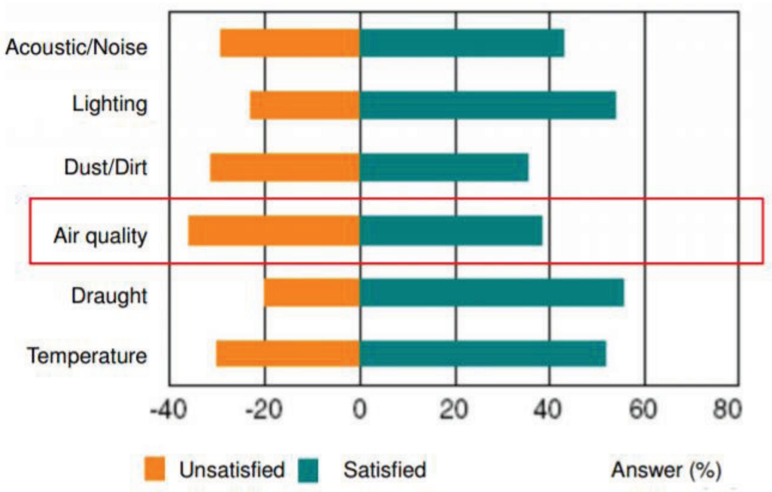


Figure 4.20 Degree of satisfaction with the indoor climate accourding to a user survey conducted in Denmark (Dréau 2015)

Indoor air quality refers to the quality of the air inside the building. It is influenced by the concentrations of pollutants and thermal conditions (temperature and relative humidity) that affect the health, comfort and performance of occupants, as shown in Figure 4.19. The indoor air can even be in some cases around 2 to 5 times more polluted than the outdoor air due to the everyday activities, products and materials in the building, therefore improving the indoor air when renovating is vital for the human wellbeing (GreenGuard 2016). It is also important to keep in mind that when the airtightness of the building envelope is improved when renovating, the existing infiltration level will be reduced. This will mean that other measures, such as increased natural and/or mechanical ventilation, need to be taken to provide acceptable good and healthy indoor air.

Nonetheless, the indoor air quality can be improved firstly by minimizing the indoor emissions, keep the indoor area dry and ventilate well. A so-called source control, limiting the pollutant from the source such as humans, their activities and building materials, is one of the best strategies to reduce indoor air pollution and limit chemical exposure. It is as well important to keep the humidity inside at a sensible level to limit the risk of mould and condensation, which can be done with good ventilation and source control. Rooms like bathrooms and kitchen, where humidity will raise in specific times, humidity needs to be removed by ventilation. Ventilation, either natural or mechanical, removes or dilutes pollution, making it an important part in achieving good indoor air quality. The most commonly used indoor air quality indicator is CO_2 level, measuring the CO_2 produced by human breathing and emitted by appliances such as gas cookers and boilers. Other indicators of the indoor air quality are humidity and volatile organic compounds (VOCs). The indoor levels of these indicators, most commonly the CO_2 levels, can be monitored by relevant sensors, meters or monitors which will indicate when there is need of ventilation, natural or mechanical, to provide adequate air quality. Ventilation can, however, increase the energy consumption and cost in a cold climate like Denmark. Good stability needs to be achieved, but too much ventilation can cause draughts, while too little will cause bad indoor air quality. Using natural ventilation can also be a good way to create good indoor air quality in the house by airing out with windows in the morning, afternoon and before bed, by using timers or sensors as a controller (Velux 2014).

The parameters that will be focused on in the tool questionnaire will be air quality, odours and humidity. These questions are presented in Table 4.41 and will give a rough input into the current conditions of these parameters in the houses.

Questions:	Answer:	Indication of:	Possible measure:
Do you have problems with stuffy/heavy air?	*Yes / no / don´t know*	Indication of badly ventilated building with high pollution level in the air	Ventilating mechanically or naturally
Do you have problem with unpleasant smells/odours?	*Yes / no / don´t know*	Indication of badly ventilated building, maybe specially kitchen and bathrooms, with unpleasant odours	Ventilating mechanically or naturally with focus on kitchen and bathrooms
Do you experience difficult breathing in your home or have some respiratory illness?	*Yes / no / don´t know*	If yes: Pollutant from building materials and products can cause discomfort and increase risk of asthma, allergies and pulmonary infections	Reduce material pollutant emissions by using low-emission building material, furnishing, paint, adhesives, grouts, sealants and caulking, increase ventilation
Do you have exhaust fan kitchen/bathrooms/laundry room?	*Yes, all/ Yes, in one /no, none / don´t know*	If no: Can lead to odour, condensation, and moisture problems, which can cause damp symptoms and mould. Decreases air quality	Ventilate all rooms, preferably with mechanical senor controlled ventilation (exhaust fan) to remove moisture to the outside
Do you dry your clothes inside?	*Yes / no / don´t know*	If yes: Can lead to condensation and moisture problems which can cause damp symptoms and mould.	Dry clothes outside or in well ventilated rooms
Do you open your windows often on the winter to air out?	*Yes, allot/ Yes, sometimes /no, never / don´t know*	If no: Can lead to stale air and could potentially lead to health issues, condensation and moisture problems which can cause damp symptoms and mould.	If naturally ventilated; Air out your home in the mornings, afternoon, and evenings for 5-10 min or install mechanical ventilation

Table 4.41 Questions related to indoor air quality, partly: (Knudsen & Jensen 2015)

ACOUSTIC COMFORT

Acoustic comfort is an important part of the indoor environmental quality as unwanted noise can have a negative effect on the health and mood of the occupants. However, it can be very subjective what the occupants perceive as noise or sound. Noise can be defined as unwanted sound, depending on the situation and perception, while sound is defined as what the occupant can hear without discomfort and annoyance. The unwanted noise can be generated from indoors and/or outdoors. The generated indoor sound is transmitted in two ways, by airborne sound and sound transmitted through the building itself. The airborne sound comes from human activities and mechanical noise that travels through air, walls, floors and ceilings. While the sound transmitted through the building can come from occupants in living spaces in neighbouring rooms, or through the ground and building, the parameters affecting the outdoor noise level can be e.g. from traffic or the weather. The possible outdoor noises will as well vary significantly depending on the building's location, where higher noise levels can be expected in the city centre compared to the country side (Velux 2014). Other parameters that influence the acoustic comfort can be seen in Figure 4.19.

First and foremost, it is critical to improve and create a good acoustic environment for all occupants if the opportunity is there when renovating. There are good opportunities to do that when renovating in an energy efficient way due to the potentially needed improvements of building envelope and installations. As the building envelope plays a key role in protecting the interior from the unwanted outdoor noise, possible noise reduction measures can be implemented while the energy efficient renovation measures are conducted. This can be done by using e.g. soundproofing insulation, gypsum plates, panels, joist caps and acoustic membrane. Installing new windows, double or triple glazed, will as well reduce the noise level from the unwanted outdoor sound. The noise level from installations and pipes can as well be improved by installing sound proofing insulation or wrap.

The parameters that will be focused on in the tool questionnaire will be the airborne sound from the outdoors, as it is the building envelope the renovation measures focus on in the tool to achieve better energy efficiency. Unwanted noise from installations will as well be part of the questionnaire. These questions are presented in Table 4.42 and will give a rough input into the current conditions of these parameters in the house.

Questions:	Answer:	Indication of:	Possible measure:
Do you have problems with outdoor noise such as traffic noise?	*Yes / no / don´t know*	If yes: Lack of sound insulation in building envelope and windows	Install double or triple glazed windows, insulate building envelope, use soundproofing insulation, gypsum plates, panels, joist caps and acoustic membrane
Do you have problems with noise from activities inside the house?	*Yes / no / don´t know*	If yes: Lack of sound insulated floor, internal walls and internal installations	Sound proof the internal area, dampen the floor sound with e.g. carpet or rugs, install sound absorbent gypsum plates on ceiling and internal walls
Do you have problems with noise from technical installations?	*Yes / no / don´t know*	If yes: Loose water pipes, air bubbles in pipes, worn out valves and pipes,	Install sound proofing insulation or wrap, replace old worn out pipes and valves
How do you find the level of noise in your house?	*Good / average / bad*	If bad: Leaky building with lack of sound proofing in building envelope and installations	Sound insulate the building envelope and installations, install new windows

Table 4.42 Questions related to acoustic comfort, partly: (Knudsen & Jensen 2015)

VISUAL COMFORT

When optimal visual comfort is achieved, the occupants will have enough light for their activities, the quality and balance of the light will be right and occupants will have good views to the outside. It will help to create a comfortable visual environment for the occupants, which will support their wellbeing and productivity. While badly lit environment or extremely lit will result in fatigue and tiredness (Cauwerts n.d.). Visual comfort can be achieved by daylight, which describes the controlled use of natural light in and around the building, and artificial lighting. However, daylight has a higher efficacy than artificial light to deliver the same light output. Daylight also achieves healthier lighting leading to e.g. better performance and productivity of the occupants, and therefore, sufficient amount of daylight needs to be provided to the indoor environment. Artificial lighting will, however, always be mandatory to provide lighting source when daylight is not available. Good combination of daylight and artificial light is therefore crucial to achieve good visual comfort. It is also important to consider the inconvenience that can result from too much daylight, such as glare discomfort, excessive reflections and overheating in the room. The discomfort, glare can cause to the occupants, can lead to more use of shading devices than normally necessary, which affects the full usage of the daylight potential in the room. This can also have a negative effect in relation to solar gains, by using the shading devices more the room would be exposed to less solar gains than initially expected, which could lead to higher heat consumption.

The parameters that will be focused on in the tool questionnaire will be the daylight access/amount, possible discomfort by glare, view to the outside and interior reflectiveness.

These questions are presented in Table 4.42 and will give a rough input into the current conditions of these parameters in the house.

Questions:	Answer:	Indication of:	Possible measure:
Do you think that the daylight level is sufficient enough in your home?	*Yes / no / don´t know*	If no: Insufficient window area and location, few windows compared to floor area, dark interior, too much use of blinds	Increase current window area when replacing window, install more windows in sufficient location and/or skylights, add glass external doors, open up the floor area, paint interior in light colour to increase reflectiveness
Do you experience discomfort by glare from sun and sky when you are inside your home?	*Yes / no / don´t know*	If yes: Lack of shading and insufficient glass in window	Install external or internal shading device with occupant control
Are you satisfied with the view to the outside in your home?	*Yes / no / don´t know*	If no: Insufficient window area and location	Increase current window area when replacing window, install more windows in sufficient location
Is your interior painted in light colours?	*Yes, all / Yes, some /no / don´t know*	If no: Can decrease the reflectiveness of daylight in the room	Paint surfaces with lighter colours

Table 4.43 Questions related to acoustic comfort, partly: (Knudsen & Jensen 2015)

4.2.5 Passive solutions

This report, in cooperation with the tool, aims to improve energy performance and introduce potential non-energy benefits at the same time. This chapter, investigates the possibility of implementing passive solutions in order to reach these aims. The tool will perform an analysis of the heating and cooling demand of the building. The possibilities of reducing both demands without increasing the energy demand, e.g. electricity for mechanical cooling, will be investigated.

The indoor environment and energy consumption of the building greatly depend on the construction and installations, as well as on the internal and external loads. Analysis of the macroclimate is an important step in the design phase of a new building, due to the impact of the external climate (external loads) on the building.

An analysis of the location of the building and its climate is critical in order to determine the potential of implementing natural ventilation or other passive solutions and their effectiveness. As described in chapter 4.2.2.4 Windows, orientation of windows are essential when it comes to heat gains from solar radiation (Heiselberg 2007b).

As this thesis focus on single-family homes from 1961 – 1978, changing the building layout can be complicated. The internal gains and losses of the building is important to consider. This is done in the following chapters.

NATURAL VENTILATION

Renovation of a single-family house may have the consequence of increased airtightness in the building. This requires additional ventilation in order to obtain a good and healthy indoor environment (Velux 2014). The increased need for ventilation can either be by natural or mechanical ventilation, but this chapter will only focus on the passive part: natural ventilation. The advantage of natural ventilation is a low or non-existent energy consumption. Disadvantages are that it depends on weather conditions. High wind speeds can cause draught and low ambient temperature causes heat loss. Manual control is needed to open and close windows and doors, meaning that the IAQ relies on occupants venting out.

The level of ventilation is dependent on the use of the room. Bedrooms are used the most in a 24-hour period, whereas, living rooms are larger, meaning that they have more area per person and when it comes to ventilation, it is often a comfort requirement rather than a health requirement. In living rooms two or three openable façade windows are often required to fulfil the demand of fresh air. The activities in kitchens generate humidity, smell, and small particles, and even though there should be a kitchen hood, airing out is an efficient supplement. In kitchens, two openable windows are preferred, and cold draughts are rarely a problem in kitchens due to the heat from ovens and stove. Bathrooms are not used much during a 24-hour period, however, the need for ventilation is high because of odour and raising humidity during showers. It is recommended that bathrooms have mechanical extraction, but having one or two openable windows is an advantage (Velux 2014).

The natural ventilation path depends on the occupants' behaviour and the building layout. The occupants' behaviour concerns placement of furniture, manual opening and closing of windows, and doors being closed, ajar, or open. Having skylights in kitchens and bathrooms (wet rooms) can function as extraction and ensure a higher air change rate (Velux 2014).

DAYLIGHT

In order to minimize energy consumption for artificial lighting, daylight plays an important role. Several studies have found that the need for artificial lighting in domestic buildings can be reduced by 16-20 % if daylight use is increased in the building, depending on the location and orientation. The size of the reduction depends on the lighting control systems, how well the room is day lit during occupied hours and the function of the room, e.g. if it is an living room or a bedroom (Velux 2014).

A common problem in buildings, in connection with windows, is the discomfort glare caused by daylight. The discomfort that glare causes, can lead to increased use of shading devices which affects the full usage of the daylight potential in the room. This can also have a negative effect in relation to solar gains, by using the shading devices more the room would be exposed to less solar gains then initially expected which could lead to a higher heat consumption.

Reflected light from the ground, neighbouring structures and/or internal surfaces is often a significant source of daylight, see Figure 4.21. The most critical factor to take into consideration for reflecting surfaces is the reflectance factor. For example; a white painted building will normally reflect about 80 % of the incident light, while grass only reflects about 10 % (Heiselberg 2007a).

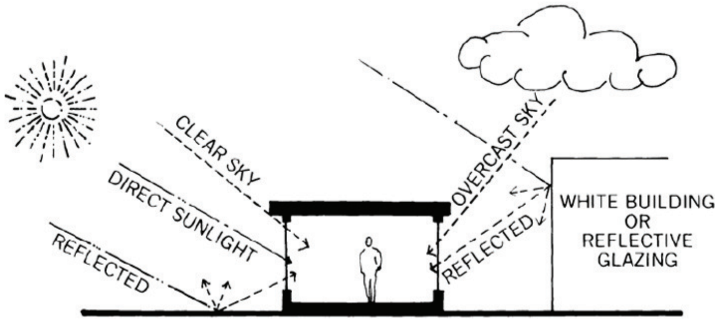


Figure 4.21 Different sources of daylight (Heiselberg 2007a)

The colour and reflectance of the room surfaces are as well an important part of the lighting system. Lighter surfaces reflect more than darker surfaces, and are more likely to obtain a satisfying environment for the occupants with more indirect or reflected light. In general, bright painted walls and ceiling surfaces inside of a room give a better daylight level due to the higher surface reflectance. In order to limit the risk of glare, the material of shading devices, used to control access of daylight into the room, should be in dark colours. The following investigation, made in SimLight in BSim studies the impact that different shades of paint can have on the DF in a room. The room is 4,0 m wide, 3,0 m high and 5,0 m deep. Has two identical windows of 1,03 m · 1,20 m with a Ff value of 82,7 %.

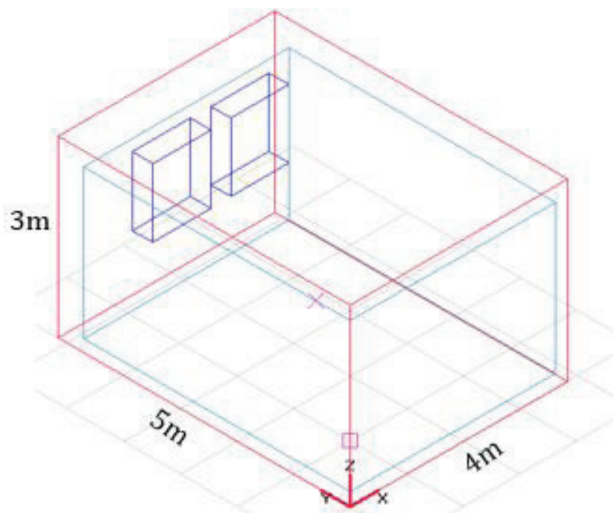


Figure 4.22 Room tested in SimLight. Reference point in the middle of the room by the X.

Two SimLight calculations with CIE-overcast sky were performed: one with light paint (white, mat) and another with dark paint (black, mat) on walls and ceiling. The floor was kept the same in both calculations (medium grey). As depicted by Table 4.44, the total DF was increased by 2,16 % from 5,46 % to 7,62 % and the percentage of the room, covered with a DF above 2 % was more than doubled from 24 % to 59 % (marked with a thick line in the coloured overview). This indicates that using light finish painting will increase the daylight factor, therefore, painting surfaces inside will be recommended in TREE, if the user is dissatisfied with the daylight level.

Light finish	**Dark finish**
Total Daylight Factor = 7,62 %	Total Daylight Factor = 5,46 %
Reflectance factor	**Reflectance factor**
Floor = 0,33 (Finish: Medium Grey)	Floor = 0,33 (Finish: Medium Grey)
Wall = 0,85 (Finish: White, mat)	Wall = 0,15 (Finish: Black, mat)
Ceiling = 0,85 (Finish: White, mat)	Ceiling = 0,15 (Finish: Black, mat)

Light finish:

2.51	2.02	6.17	6.82	4.1	7.06	7.62
1.96	3.54	5.21	5.97	6.19	6.26	6
2.27	2.7	3.51	4.11	4.41	4.4	4.14
2.01	2.34	2.71	2.98	3.25	3.09	2.95
1.87	2.04	2.2	2.37	2.51	2.43	2.36
1.71	1.85	1.94	2	2.08	2.09	2.03
1.61	1.7	1.75	1.81	1.84	1.83	1.76
1.57	1.62	1.65	1.69	1.71	1.7	1.7
1.54	1.59	1.62	1.65	1.67	1.68	1.65

Dark finish:

0.02	0.48	5.14	5.77	2.67	5.71	5.46
0.42	1.77	3.99	4.71	4.74	4.78	4.19
0.62	1.39	2.24	2.74	2.95	2.81	2.42
0.57	0.96	1.34	1.6	1.84	1.63	1.4
0.45	0.66	0.83	0.99	1.11	1.01	0.87
0.33	0.49	0.58	0.64	0.71	0.69	0.6
0.28	0.36	0.4	0.46	0.48	0.47	0.41
0.23	0.27	0.3	0.34	0.34	0.34	0.3
0.19	0.23	0.24	0.26	0.27	0.26	0.24

Percentage of the room with a DF >2 %: **59 %**	Percentage of the room with a DF >2 %: **24 %**

Table 4.44 SimLight simulations showing the effect of surface reflectance on the daylight factor.

Another indicator of the impact in the room is the lux level of the internally reflected light from Diffuse Sky Light and Externally Reflected sources. Diffuse sky light is reflected on the internal surfaces from the direct illumination (direct sunlight) and externally reflected illumination is

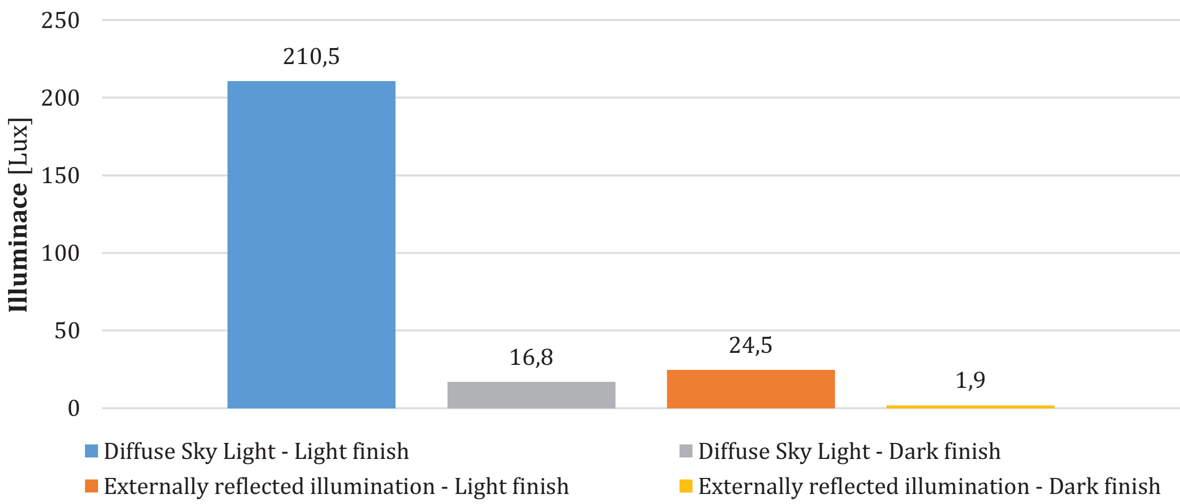


Figure 4.23 Internally reflected illumination from Diffuse sky light and external reflected light.

reflected into the room, from the ground or other nearby buildings. As shown below in Figure 4.23, the internally reflected illumination from the diffuse skylight is more than 12 times lower with a dark finish compared to the light finish. It is the same case for the illumination from the externally reflected sources, where the dark finish is almost 13 times lower than the light finish. This is a strong indicator, as discussed earlier, that the lighter finishes at the internal surfaces are a great and easy solution when aiming for a higher/better daylight factor level in the room.

Passive solar heating

The main purpose of windows in buildings is to provide daylight and view to the outside, but windows are also providing solar gain, which can be used for space heating in the building during the heating season. The purpose of using windows with high-energy performance is reduction of heating need in the building. The aim is to explore the gains during the heating season, but at the same time not to compromise the unpleased overheating at the summer time.

In general, windows play a crucial role in reducing the heating consumption to the lowest level possible. In chapter 4.2.2.4 Windows, the energy performance and their related payback times are investigated.

In order to implement solar heating into the building with passive solutions, it is necessary to get familiar with the term solar radiation, and how it is related to the building itself. Simple changes in the design of a window, orientation of the building or choice of materials can change the need for heating in a building significantly. Solar radiation can be a great source of natural heat that does not require any mechanical support.

As mentioned above, a proper orientation of the building plays a major role in accordance with solar heating. Some proposals have been made according to which orientation is the most preferable in different types of rooms. This should be taken into consideration in the tool, asking whether homeowners express discomfort in any rooms with the possibility of changing the use of the rooms or adapting by, for instance, changing window properties (further described in the window chapter 4.2.2.4 Windows.

- An east- or southeast facing window for kitchen and bedrooms to benefit from the earliest winter morning sunshine
- Southern orientation for daytime occupied areas
- East and West facades can be source of overheating in summer, due to the low altitude of the sun (Liu 2016b)

Passive solar heating consists of two to three components. An absorbing surface that converts the solar radiation into thermal energy, the space to be heated, and finally, an optional mass for heat storage. Heat storage requires the correct materials to be used in the construction. Table 4.45 explains the different levels used in the tool to differentiate between the different construction levels. A high thermal mass has the ability to absorb the energy from the solar radiation, thereby ensuring a steadier operative temperature in the room. It stores the energy during daytime and releases the heat as the temperature drops during the evening and in the night.

Level	Description	Wh/K·m^2
Extra light	Light walls, floors, ceilings of skeleton with slabs or boards, with no heavy parts	40
Medium light	Individual heavier elements such as concrete deck with a wooden floor or porous concrete	80
Medium heavy	More heavy elements such as concrete slab with tile and brick or tile and concrete	120
Extra heavy	Heavy walls, floors and ceilings of concrete, brick and tile	160

Table 4.45 Thermal mass properties used in the tool (SBi 2014).

Different materials and their properties can be found in Figure 4.24 and can be used as guidance when selecting materials for the renovation. PCM (Phase Change Material) has a significant higher storable property than the rest. PCM is a component that can be added to other materials and ensures that the heat is obtained while there is a large solar radiation and released when the temperature drops in the room (Liu 2016a). According to SBi, this can save up to 15 % of the energy consumption (SBi 2009). PCM combined with construction materials is still in the development phase in Denmark, but is expected to be a common thing within a few years. Therefore, this should be seen as inspiration and guidance to the possibilities for using passive solar radiation. Glass wool and water are not commonly used as finishing for walls, but they serve to illustrate the link between materials and how important selecting the right material can be.

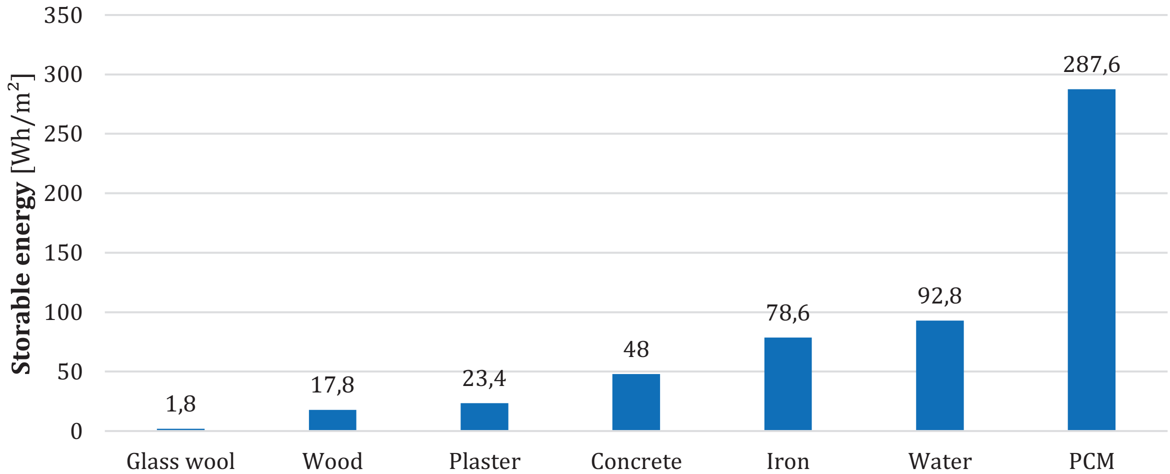


Figure 4.24 Maximum storable energy between 18 °C and 26 °C for 10 mm of material, for 24 hours (Liu 2016a)

Daylight is crucial for human wellbeing and visual comfort. It also has a number of qualities which artificial light cannot achieve on its own. In the efforts to minimize energy consumption for artificial light, daylight plays an important role. However, letting in daylight will also let solar radiation and thereby heat into the house.

In old leaky houses, like most of the target houses of this project, it is preferred to have a high amount of solar radiation through the window panes to compensate for a high heat loss caused by e.g. infiltration through a leaky building envelope. As detailing and materials have advanced, new buildings have become very airtight. Adding the fact, that using glass in building facades are widely implemented, modern buildings are now very sensitive to solar radiation and overheating is a common problem.

Renovating an old house e.g. by applying insulation on the roof and on the external walls, replacing windows, will most likely improve the airtightness of the house and increase the risk of overheating. Solar radiation control is the primary design measure for heat gain protection. There are different measures to take, in order to achieve satisfying thermal and optical performances (Heiselberg 2008):

- Sizing the windows in relation to the room the window is placed in
- Accounting for the local insulation conditions
- Using various internal and/or external shading devices
- Changing the aforementioned properties of the window pane

Figure 4.25 depicts three different external shading solutions. The overhang will block the high solar radiation in summertime, but allow for solar radiation during winter, when the Sun is lower on the sky. The few large horizontal louvers might have the same effect as the miniature louvers when it comes to blocking the solar radiation, but one solution could be more transparent than the other, depending on the material used.

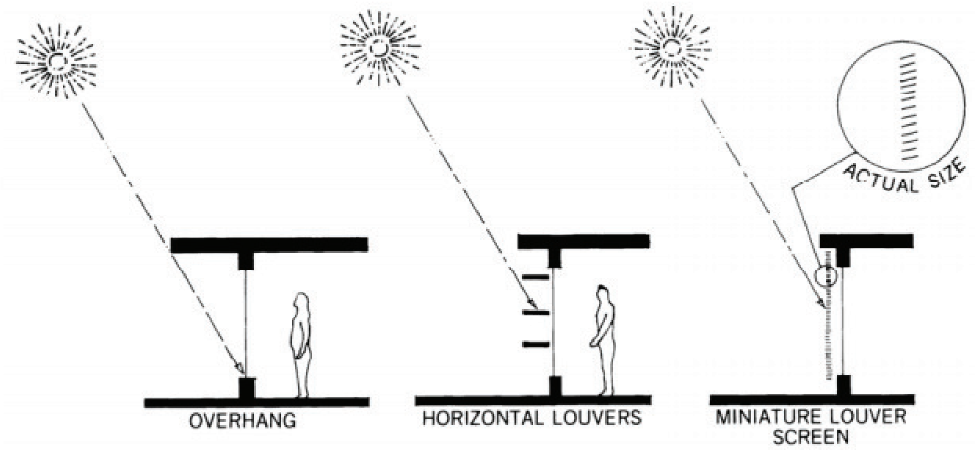
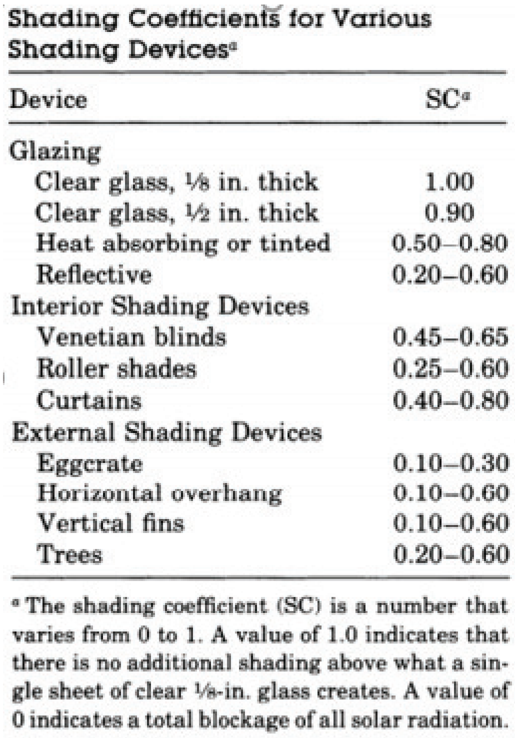


Figure 4.25 Three different types of external shading (Heiselberg 2008).

If the renovation includes measures that improves the building envelope significantly, it should be considered to add shading or use glass panes that makes the house less vulnerable to overheating. Figure 4.26 shows the different measures and their efficiency.



Shading Coefficients for Various Shading Devices[a]

Device	SC[a]
Glazing	
Clear glass, 1/8 in. thick	1.00
Clear glass, 1/2 in. thick	0.90
Heat absorbing or tinted	0.50–0.80
Reflective	0.20–0.60
Interior Shading Devices	
Venetian blinds	0.45–0.65
Roller shades	0.25–0.60
Curtains	0.40–0.80
External Shading Devices	
Eggcrate	0.10–0.30
Horizontal overhang	0.10–0.60
Vertical fins	0.10–0.60
Trees	0.20–0.60

[a] The shading coefficient (SC) is a number that varies from 0 to 1. A value of 1.0 indicates that there is no additional shading above what a single sheet of clear 1/8-in. glass creates. A value of 0 indicates a total blockage of all solar radiation.

Figure 4.26 Different measures for solar radiation control and their efficiency (Heiselberg, 2008)

As seen on the figure, the best shading is external shading like overhangs, fins, trees or anything that stops the radiation from entering the house.

NATURAL AND PASSIVE COOLING

An analysis of potential overheating and the demand for cooling will be performed in the tool, done on a monthly basis. If there is an indication of overheating, the tool will describe different possibilities of reducing the overheating, and thereby the cooling demand.

Passive cooling is used to prevent heat gains, and natural cooling is used to remove excess heat (Liu 2016a). Passive cooling should always be the first step, when designing a building, then natural cooling, and lastly mechanical cooling if the overheating issue persists. However, mechanical cooling is not allowed in residential buildings in Denmark.

There are multiple ways to prevent overheating in a room by considering different parameters during the design phase of a building and involving the following design technique (Heiselberg 2008)

- Microclimate and site design
- Solar radiation control including window protection, protective glazing and shading
- Building form and layout
- Heat avoidance including reduction of transmission gains and reduction of infiltration
- Internal heat gain control
- Behaviour and occupancy patterns (Heiselberg 2008)

Natural cooling can be venting out via windows, ground cooling, evaporated cooling, or radiative cooling, however, the last three are considered extensive for a renovation in a single-family house.

SUNSPACE AND DOUBLE FACADES

A sunspace is a room with a high gain of passive solar radiation that enables heat to be transferred to the rest of the house. The sunspace consists of glass towards the outside, in order to obtain as much solar gain as possible. It is important that occupants can vent the room by natural ventilation during the summer, to reduce the risk of overheating (Liu 2016b).

Double facades also benefit from solar gains. The heat is accumulated in an area between two facades, like a closed box. The heat can be transferred to the occupied area, either by natural air movement or by heating up the thermal mass, which then releases the heat when the Sun has set and during night time (Liu 2016b).

The sunspace and the double facade system can be implemented when renovating a single-family home. A sunspace could be the entrance to the house, and the double facade could be applied if the facade is being renovated. Adding a sunspace to the house can also be a comfort parameter as the area can be used for seating throughout the year, like an orangery.

5 Design and development of the tool

This chapter presents the design and development process of TREE, a decision-making tool. The development revolves around how it should assist the homeowner in decreasing energy consumption while improving the indoor environment by minor adjustments in behavior, performing minor energy saving measures and ultimately extensive energy saving renovations.

5.1 Tool development

This section gives a brief insight of the idea behind the tool. As previously discussed, the initial investigation into the homeowner's motivational factors and needs was heavily based on previous surveys conducted by Bolius (Boligejeranalyse 2016) and Andrea Mortensen

(Mortensen 2015). After thoroughly analysing the two questionnaires/surveys conducted by Bolius and Andrea Mortensen, it was even clearer, that indoor environment and comfort were one of the main motivational factors for the homeowners to perform energy renovations. A very interesting aspect presented in Andrea´s survey was, when homeowners were asked "*What would be the most important parameter in order to increase the number of energy renovation*", as illustrated in Figure 5.1, 33% said "*Easy access to unbiased guidance*" and 24% said "*Information on comfort and indoor environment improvements"* (Mortensen 2015). This supported even further the need for a tool that guides the homeowner to certain energy efficient measures and increases the information level related to comfort and indoor environment improvements.

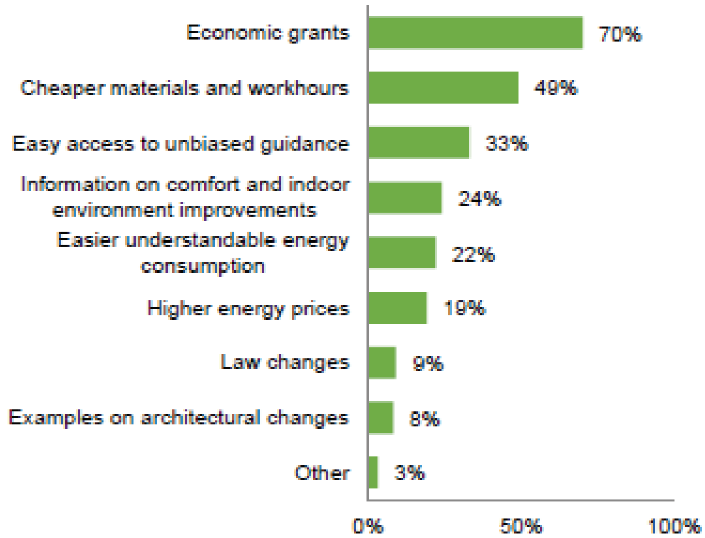


Figure 5.1 The most important parameters when it comes to increasing the number of energy retrofits conducted. The homeowners each picked the three parameters they think are most important (Mortensen 2015).

Another important factor was to consider how to motivate the homeowner to use the tool and catch his interest and curiosity in conducting energy efficient renovation. To do that, various approaches were considered. According to Harvard´s Teresa Amabile's research, it was found that progress is very motivating for people. Therefore, achieving a number of minor successes could act as motivational factors for people to reach for further success (Amabile 2011). Thus, the tool is based on easily achievable measures that require minimal effort, but deliver certain results to comfort and indoor environment. Next, the second category requires more demanding measures that will also provide higher energy savings and improved indoor environment. The tool starts with these steps of progress that serve to inspire, motivate and provide the homeowner with confidence that makes it more likely for him to embark on to more extensive energy renovations. These factors, among the previously presented aspects, shape the basis for the development of the tool, which will be described in the following chapter.

5.2 TREE description

In this section, the tool is described for the reader to gain an understanding of the set up. This tool was created to inspire homeowners to take actions towards decreasing energy consumption in their house, and in the meantime, achieve improved indoor environment, which has shown to be one of the main motivational factors that inspire homeowners to perform energy renovation.

The tool is developed for the homeowner to use. The tool was developed in MS Excel workbook, as Excel has the capabilities to perform the calculations needed for the analysis while being commonly used and easily accessible, increasing the potential user group.

5.2.1 Tool setup and navigation

In this section, the tool setup and navigation are explained. Throughout the tool, many aspects of energy savings and comfort are being dealt with. As such, there are many worksheets included within the workbook to provide a clear overview to the user. In this tool, eight worksheets will be used: 1. Introduction, 2. Questionnaire, 3. Questionnaire Summary, 4. Comfort Measures, 5. Energy Saving Measures, 6. Building Current Conditions, 7. Renovation Measures, 8. Final Results which can be seen in Figure 5.2.

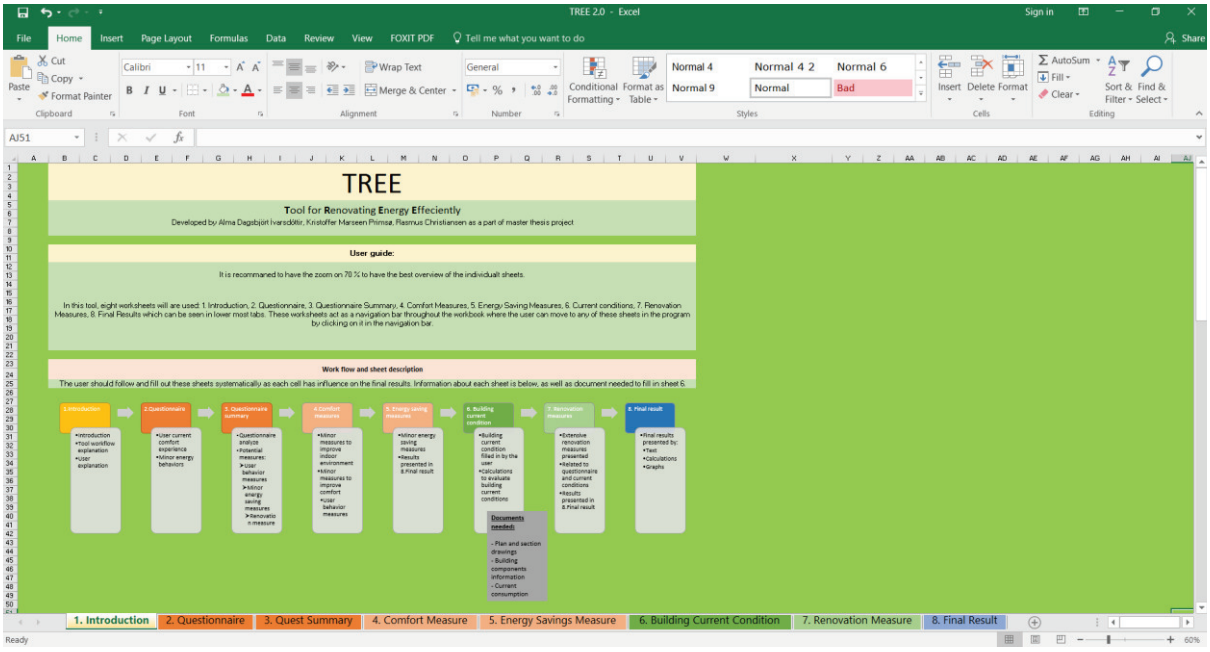


Figure 5.2 Navigational bar in the TREE tool (lowermost tabs)

These sheets present the input, and the results are shown separately to avoid confusion when using the tool. In some sheets, answers and information should be filled in by the homeowner, while others present a summary and potential measures that can be taken as well as several other sheets which hold relevant data and results, this will be explained further in the following chapter. The final output is presented with a result data sheet accompanied with a graphical display of the selected alternatives versus the current state of the building.

These worksheets act as a navigation bar throughout the workbook, where the user can move to any of the sheets in the program by clicking on it in the navigation bar, however, the user should follow and fill out these sheets systematically.

The sheets contain options, descriptions, graphs, and summaries, as well active cells where data is either chosen from a drop down list or manually entered. To avoid confusion and provide further help to the user in each sheet, the cells have been colour coded, as presented in Table 5.1.

Cell colour in tool	Information
Yellow	Headlines and explanation text
Orange	Filled in by the user with relevant values (input)
Blue	Dropdown menu with provided options for user (input)
Red	Results from calculations made by the tool based on users input (output)
Light pink	Recommended measures and solutions (output)
Dark red	Potential non-energy benefits (output)

Table 5.1 Colour coding in the TREE

Throughout this chapter, the eight sheets are referred to by their sheet number and the name, underlined.

5.3 TREE structure

This section describes the structure and the workflow steps of the tool. The main focus was making the tool easy to understand and simple to use. The two main steps in the tool are called *Minor measures* (includes sheet 4 and 5) and *Extensive measures* (includes sheet 7), which form the basis for TREE, as illustrated in Figure 5.3. TREE is then divided into 8 sheets as previously explained.

When the user opens the tool, sheet 1. Introduction is displayed as shown in Figure 5.3. The *Minor measures* (orange in Figure 5.3.) are based on the homeowner's experiences and satisfaction with the current comfort and indoor environment, which are evaluated through 2. Questionnaire. After the questionnaire has been answered, 3. Questionnaire Summary is presented based on the answers. The minor measures are divided into two categories, 4. Comfort Measures and 5. Energy Saving Measures. Minor comfort measures concern optimizing the indoor climate and comfort level in the house, in terms of non-energy benefits, that the homeowner can profit from by changing minor aspects and behavior. The minor energy saving measures regard smaller measures, like insulating pipes, changing to LED bulbs, or replacing a circulation pump that will result in relative small energy savings and improve the indoor comfort. The next step is sheet 6. Building Current Conditions, where the current condition of the housing needs to be registered. Based on the current conditions and the questionnaire, extensive renovation measures will be recommended in 7. Renovation Measures. These measures form the second step of the tool and are called *Extensive measures.* They should be implemented to increase the energy efficiency of the building while improving the comfort of the indoor environment. Results from the energy saving measures and the renovation measures are then presented in 8. Final Result. In the following chapter, each sheet is further described.

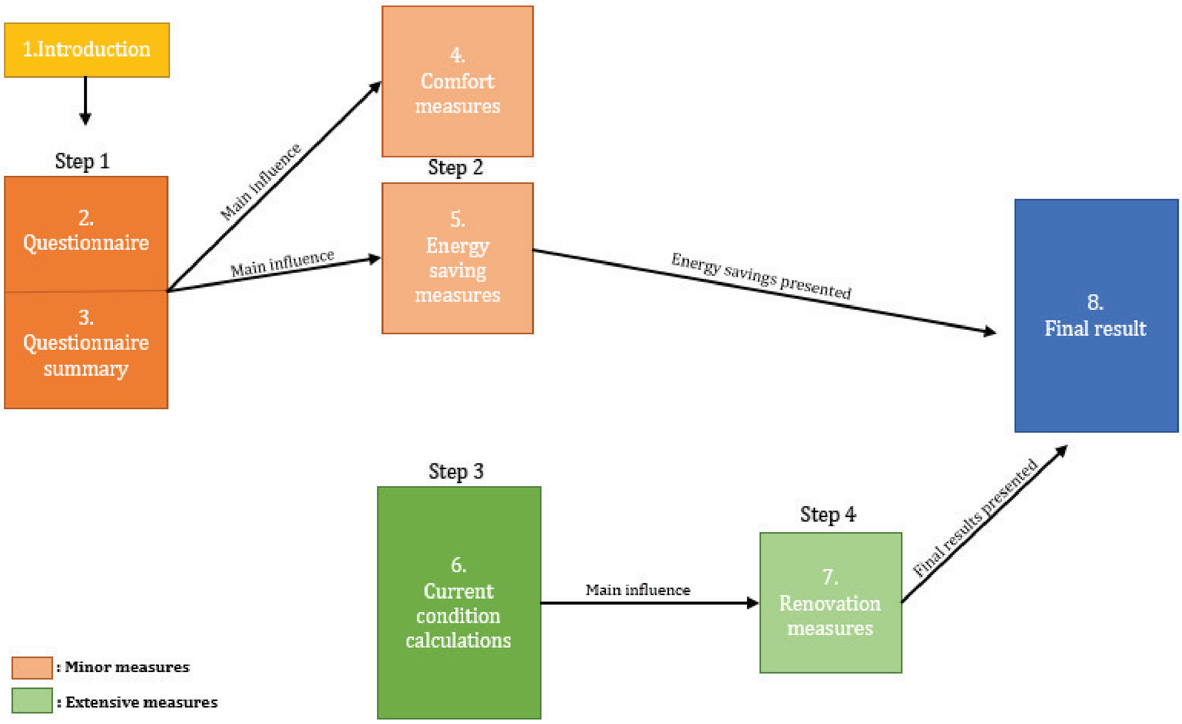


Figure 5.3 Structure and work/process flow steps from 1-5 in the tool

5.4 TREE worksheet introduction

In this chapter, each excel sheet is introduced. As presented in Figure 5.4, the tool sheets contain various type of data and information and should be handled in certain ways. Therefore, a detailed explanation and description are made of each sheet in the following sections, starting with the introduction sheet.

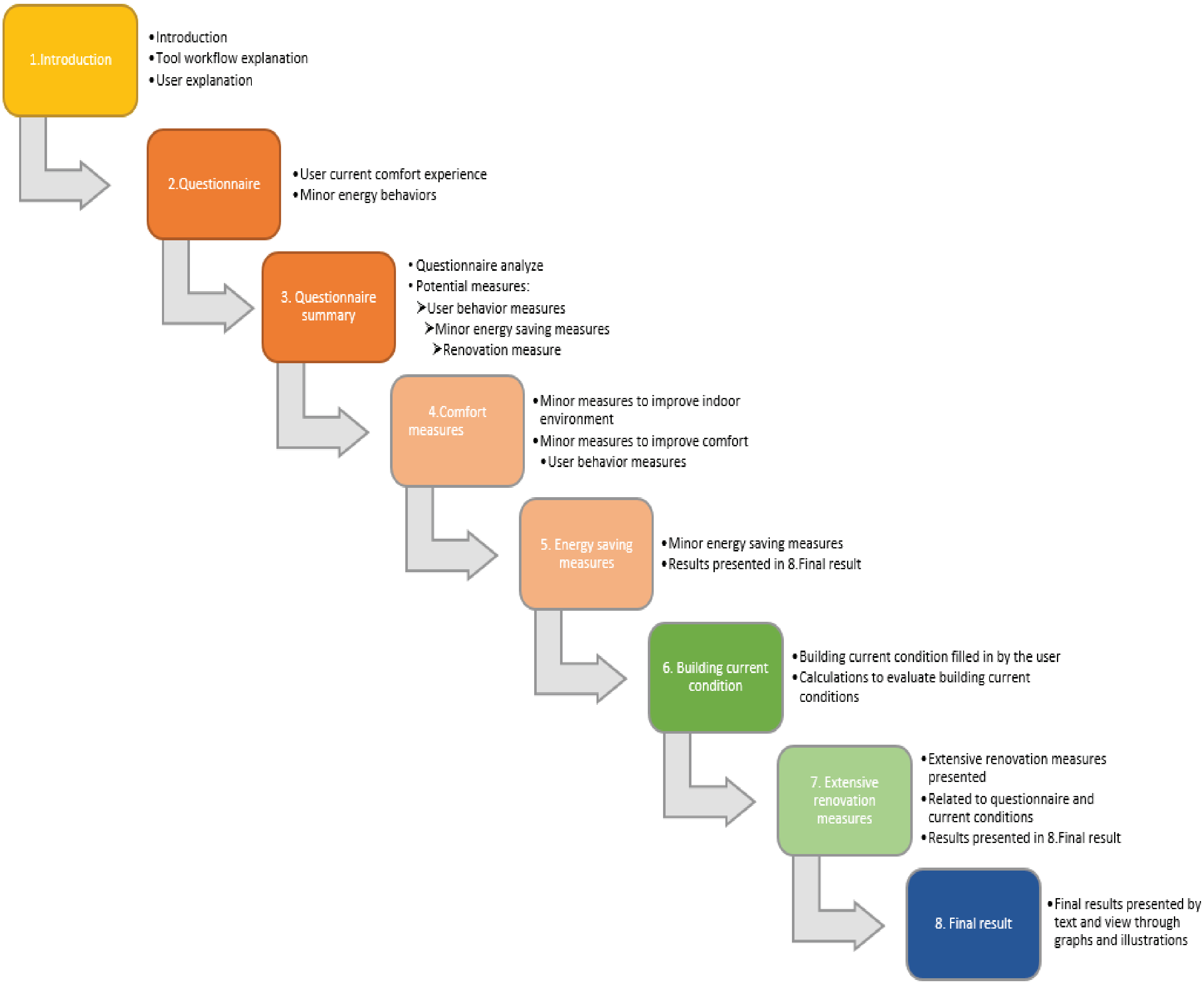


Figure 5.4 TREE excel worksheet structure

5.4.1 Introduction sheet

This sheet introduces the TREE tool and what the user can expect to accomplish from using it. A user guide is then presented with a short description and explanation of each sheet, how the tool should be used and how to navigate between each page, as partly shown in Figure 5.5.

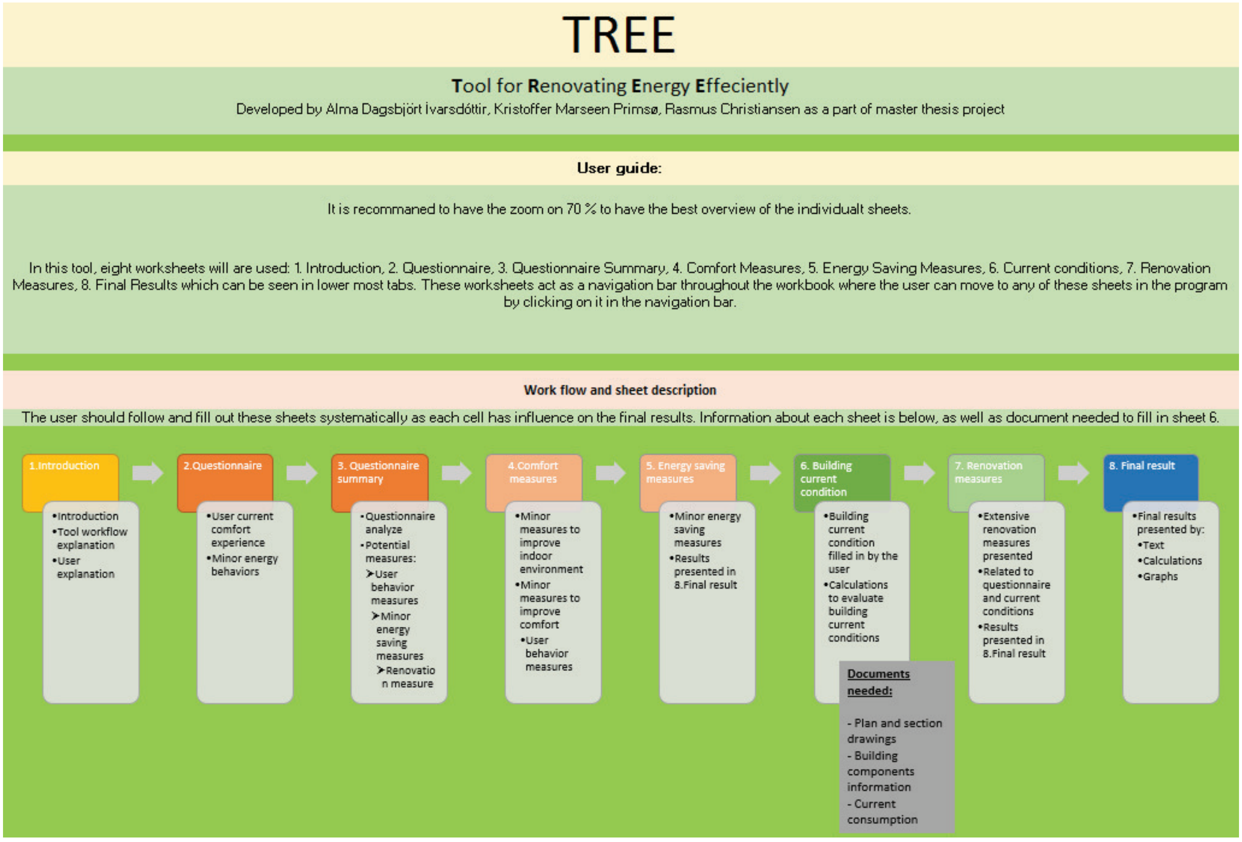


Figure 5.5 Part of the 1. Introduction sheet

5.4.2 Questionnaire sheet

One of the first goals of TREE is to evaluate the homeowner's experiences with the current comfort, discomfort and indoor environment to evaluate the potential of minor improvement measures with a questionnaire. This should also increase the homeowner's awareness of the current conditions in his house. However, many homeowners do not realize how bad their indoor climate is and have adapted their everyday behaviour to avoid discomfort. However, the time the tool is used needs to be considered and could be problematic, asking the homeowner in July if he experienced cold temperatures during the winter can be difficult to judge.

The questionnaire is divided into five categories:

1. Thermal comfort
2. Indoor air quality
3. Visual comfort

4. Acoustic comfort
5. Energy and other

The questionnaire includes questions related to perceived indoor climate, comfort, minor energy measures and user behaviour, such as venting of their house, use of exhaust and indoor temperature settings. These questions are related to their knowledge of the current situation. The evaluation presented in sheet 6. Building Current Conditions.

Few of the questions in 2. Questionnaire are related to energy use and installations, where there is need for minor evaluations of the building heating source, pipes, pumps and artificial lighting by the homeowner. This is an important optimization possibility, and therefore, included in the tool. However, the user is not asked to fill out all the artificial lighting types and the total output in Watt, because it was considered too complicated for the user. Therefore, possible answers are presented as percentage of the light bulbs in the house to get an estimation. Not having the 100 % correct value will of course affect the result of possible savings, therefore, the results will be presented per light bulb.

The answers from these questions will provide the basis for the *Minor measures* in the tool e.g. measures that are not necessarily cost or energy reducing, but will increase the quality of the indoor environment. The questions will also influence the *Extensive measures* in a small portion.

The questions mainly consist of closed questions. Closed questions are easier and faster to answer by the homeowner. The questions are answered from a drop down list, where multiple single-word or short-phrase answers will be found and one option must be chosen, as illustrated in Figure 5.6.

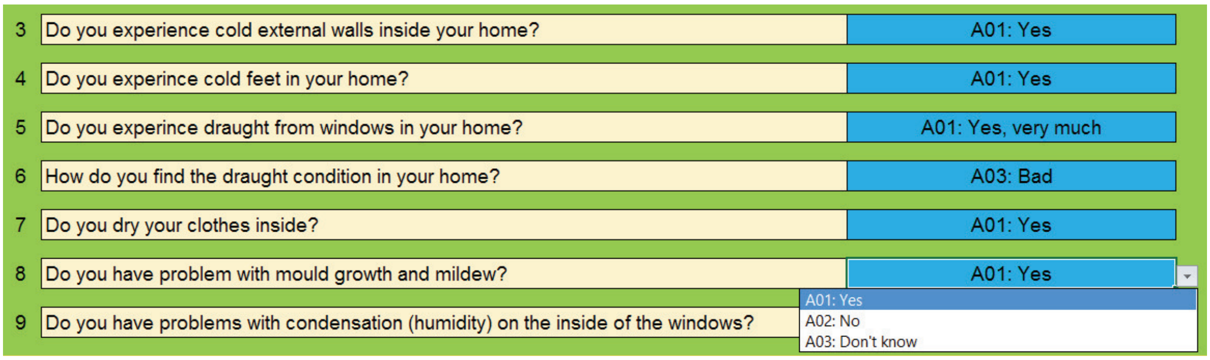


Figure 5.6 Examples of questions in category *1. Thermal comfort* and illustration of drop down menu

The questions are partly based on two surveys. The tenant survey created by Henrik N. Knudsen and Ole M. Jensen, in the project; *Tenants experience and satisfaction with renovated and energy retrofitted social housing*: SBi 2015:28 (Knudsen & Jensen 2015) and the *Bolius Homeowner analysis 2016*, conducted by Bolius Homeowners Knowledge Center (Boligejeranalyse 2016). All questions are presented in 4.2.4 Questionnaire - Non-energy benefits.

5.4.3 Questionnaire Summary sheet

In this section, the 3. Questionnaire Summary sheet will be presented. This sheet is based on the answers to the questions in the questionnaire on sheet 2. It presents the potential cause of the discomfort experienced by the homeowner. It gives a short overview of what could be done in each category: *Minor (comfort and energy savings), and Extensive measure (renovation)*, to improve the comfort level and increase energy savings, as illustrated in Figure 5.7. This gives the homeowner the opportunity to consider potential problems occurring in his building, and how to solve them through minor and/or extensive measures.

Question #	Potential discomfort caused by:	Indication of:	4. Comfort measure:	5. Energy savings measure:	6. Renovation measure:	Report ref:
Thermal comfort						
1	Too high indoor temperature in the summer	Indication of overheating in the house, which can lead to uncomfortable thermal comfort	Internal shading	External shading (shading overhang in south facade retractable awnings), east and west: louvers, trees	-	
2	Too low indoor temperature in the winter	Indication of badly insulated and leaky building envelope, leaky windows, insufficient heating system	Close the curtains at night (decreases heat loss)	-	Adding insulations to the building envelope	
3	Cold wall surface temperature due to cold thermal radiation	Indication of badly insulated and leaky external walls with possible thermal bridges	-	Identify air leaks. Air seal with sealant and caulk.	Adding insulations to the building envelope	
4	Cold floor surface temperature	Indication of badly insulated and leaky floor construction	Lay thick rugs on floor	-	Insulate floor construction (consider the floor material, some can cause higher discomfort)	
5	Cold draught from windows and doors	Indication of leaky and insufficient windows with possible thermal bridging	-	Identify air leaks. Air seal with sealant and weather strip.	Install better windows/doors and improve the airtightness around the frame	

Figure 5.7 Example of overview from 3. Questionnaire Summary

From this overview, the tool user can go into the relevant sheet to read more information about each measure and potential energy savings and non-energy benefits. From there he can choose if the measure will be chosen to be included in the improvements and/or renovation.

5.4.4 Comfort Measures sheet

In this section, the 4. Comfort Measures sheet will be presented. The comfort measures were based on actions that increase the occupants' comfort level and have been previously analysed in Chapter 4. These measures are rather inexpensive while increasing the occupants' comfort level and can mostly be performed by the occupant. The sheet contains five measures:

1. Natural ventilation
2. Internal shading
3. Paint
4. Low-emission materials
5. Exhaust fans and kitchen hood

To simplify the understanding of the sheet and text behind each cell, the line numbers on the left side of the sheet, as illustrated in Figure 5.8, will follow each explanation. Each measure is presented in a separate suggestion box in the sheet, as illustrated in Figure 5.8. The suggestion box provides, starting from the top left side; a thorough *Description* of the measure (line 14-15), *What to be aware* of when performing or installing this measure (line 16-17), *Advantages* (line

18-19) and *Disadvantages* (line 20-21) that follow use of this measure. On the right side, *Non-energy benefits* that are achieved by using/performing this measure are presented. This overview gives the homeowner information concerning each measure and a good impression what can be achieved by performing this measure.

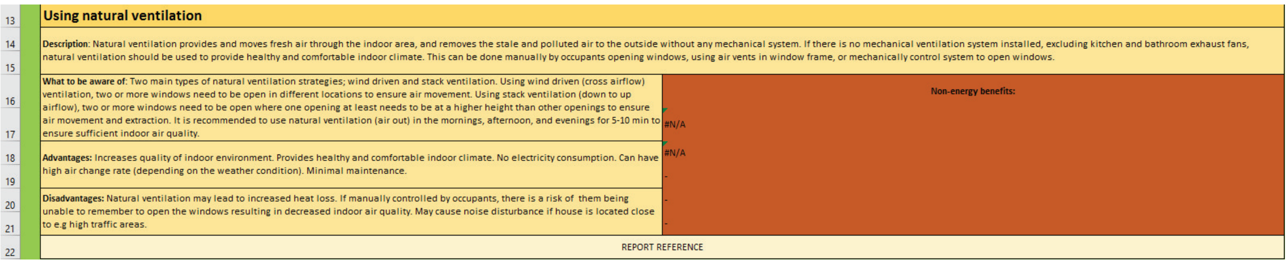


Figure 5.8 Suggestions box from 4. Comfort Measure sheet concerning natural ventilation

These measures are considered comfort measures to increase quality of the occupant's indoor environment, thus, the result of each measure greatly depend on the user behaviour and usage level. Due to the form of these measures, they cannot be chosen to be included in the 8. Final Result. In the bottom of each suggestion box, the relevant chapter number from the report is presented (line 22).

5.4.5 Energy saving measures sheet

In this section, the 5. Energy Saving Measures sheet will be presented. The energy saving measures presented in this sheet are based on actions that can achieve minor energy savings. These measures are somewhat simple and inexpensive to implement, while others are more complicated and expensive. All measures have previously been analysed in Chapter 4. The sheet contains seven measures:

1. Circulation pump
2. Control of heating
3. External shading
4. Sealing of air leakages
5. Pipe insulation
6. Artificial lighting
7. Operative temperature

The energy savings achieved by each measure will vary, as well as the instalments cost. The installation method can also vary significantly between homeowners, current condition of building and location. Each measure is presented in a separate suggestion box in the sheet, as illustrated in Figure 5.9. The uppermost suggestion box (line 14-21) provides the same overview as presented previously in chapter 5.4.4.

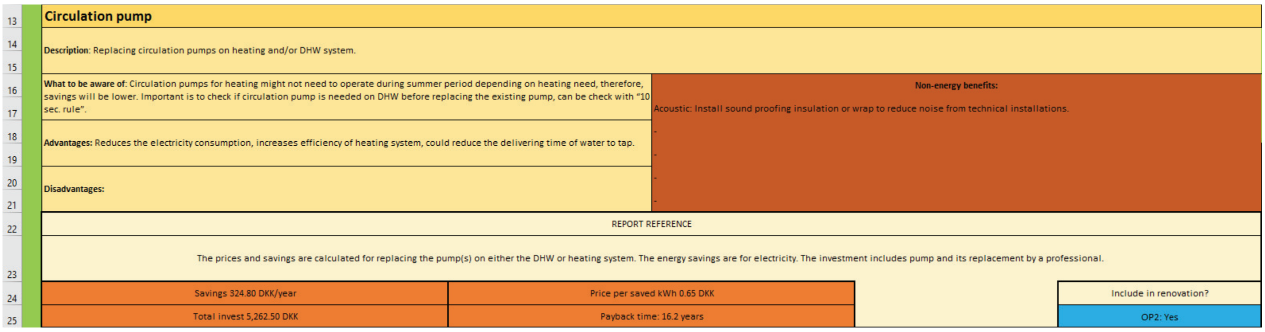


Figure 5.9 Suggestions box from 5. Energy Savings Measure sheet concerning circulation pump

The lower section, starts out with description (line 23) of what is included in the price and energy saving calculations. All prices are then presented in the four boxes in the bottom.

- Left side (line 24): The savings are presented in saved Danish kroner each year, kWh saved, multiplied by the price of the source used
- Left side (line 25): Total investment, the material cost is included and in some cases the instalment cost by professional. It is always stated in the description box if this measure can be performed by homeowner or professional
- Right side (line 24): Price per saved kWh through the lifetime (years) of the component/installation as recommended by BR15
- Right side (line 25): Payback time of chosen measure

Considerations of cost-efficiency should be made before each measure is chosen. On the furthest right side in line 25 (blue), the user should choose if this measure will be included or not.

5.4.6 Building current conditions sheet

In this section, the 6. Building Current Conditions sheet will be presented. During the evaluation phase of the current conditions of a renovation project, it is necessary to make a rough calculation of heating and cooling requirements for a building. It gives a good estimate of the current energy frame and whether the building will comply with energy frame requirement when renovation measures are chosen. Therefore, it was chosen to apply a specific calculation method to the tool called the Monthly Average Calculation (MAC) made by Aalborg University, forming the calculation core of TREE (Larsen 2008). The original calculations are made in four spreadsheets, which have been used in the tool, but simplified to one visual sheet, 6. Building Current Conditions, plus the results are illustrated on sheet 8. Final Result.

The MAC uses the DRY-v2 weather file in the calculations. The Danish Design Reference Year (DRY-v2) weather data came out in 1995 based on climate data from the period 1975-1989 and has been used for many years. The weather data in the TREE tool is fixed to a chosen destination, Copenhagen, and cannot be changed.

To simplify the input for the user of the tool, it was chosen to fix specific parameters that are most likely the same for most single-family houses. The following parameters from the MAC were fixed based on recommended values from SBi 2013; *Energy requirements for buildings - Calculation guide* (Grau & Pedersen 2011), and therefore cannot be changed:

- Internal load
  - Heat contribution from a person: 1,5 W per m^2 heated floor area
  - Appliances and lighting in occupied hours: 3,5 W per m^2 heated floor area
- Room temperature in case of heating:
  - All rooms inside the heated floor area are heated to a monthly average temperature of 20 °C in all months of the year
- Room temperature in case of cooling:
  - For all rooms inside the heated floor area, it is assumed that possible cooling is activated when room temperature in periods exceeds 24 °C
- Service hours:
  - 168 hours/week
- Domestic hot water:
  - Yearly consumption of 250 liters per m^2 heated floor area
- Design temperature, DS418:
  - External temperature: -12 °C
  - Room temperature: 20 °C
  - Ground temperature: 10 °C

Note that neither the Monthly Average nor the TREE tool should be used for final energy frame calculation, although the values are compared to Renovation classes from BR15 as guidance and estimation in the tool. The method is based on rough monthly calculations of heat loss and useable heat gain for the building and are not as accurate as Be15. In order to use it for energy frame calculation, more details about the building is needed e.g. in relation to mechanical ventilation system.

In this section, the sheet will be presented. To simplify the understanding of the sheet, text and the calculations behind each cell, the line numbers on the left side of the sheet, as illustrated in Figure 5.10, will follow each explanation.

The first step of the sheet is to fill out basic information as shown in Figure 5.10. The first information related to the building address (line 3-5) are only used to give the user an overview of the project. Next the user fills in information concerning the house area and number of occupants (line 8). This information is later used in further calculations e.g. for the total operation consumption and energy frame.

Next the user is asked to fill out the total operation consumption and the heating source (line 9-17). The chosen heating source (line 11) and amount (units depending on chosen source) will form the basis of the current price calculation of the heating and will be used to calculate the potential reduction. If it is chosen to change the heat source out when renovating, the prices for saving are recalculated according to the energy prices for chosen source.

In the 8. Final Results sheet, the current heating consumption and the calculated savings are presented and compared. By using the current consumption, the client gets more realistic saving potential. However, it needs to be kept in mind that user behaviour and outdoor temperature influence the actual consumption. All calculations have been performed in chapter 4.2.3 HVACHeating systems. The water and electricity consumption then have to be filled out (line 14 and 17). The water consumption is used for calculating the solar heating system, and electricity is used for calculating the PV-cell system and a more accurate saving for artificial lighting.

#	BASIC INFORMATION	The following is basic information about the current condition			
1 2	Information	Fill in with text			
3	Project name				
4	Address				
5	Postal Code				
6 7	Information	Net area m²	Gross area m²	Occupants people	
8	The House		55.00	4	
#	CONSUMPTION	The following is regarding the consumption of the last known year			
9 10	Consumption *Heating*	Amount kWh			
11	C01: District heating, kWh		If unkown then use 'District Heating, kWh' and 10,536 kWh		
12 13	Consumption	Amount kWh			
14	Electricity		If unknown then use 3,950 kWh		
15 16	Consumption	Amount m³			
17	Water		If unkown the use 156.00 m³		

Figure 5.10 Basic information and consumption boxes from top of the sheet

It is important that the user does not get stuck if consumption is unknown. Therefore, values for common consumptions in single-family houses were calculated based on "*Household energy- and water usages; SBi 2005:09*". These values are recommended to the user to fill in if consumption is unknown, as shown in Figure 5.10.

The next step for the user is to fill out all information´s regarding to construction components and windows, as shown in Figure 5.11. To simplify the use of the tool, TREE, has suggestions based on previous investigations of common construction types from the years 1961-1978, which can be seen in Chapter 4.2. These suggestions are placed in the blue dropdown menu for each component. If the component has been renovated since those years, there is a possibility of selecting values according to different building codes. In all cases the user has the possibility to overwrite the U-values with their own if none of the suggested fits the current condition. As can be seen in Figure 5.11, the user is asked about the roof slope, the slope area of the roof, and the orientation of the roof for later user to calculate the potential for PV-cells. Most single-family houses from that period have limited ground around the house that is not shaded by e.g. the house, trees, or neighbour buildings. Therefore, TREE suggests and calculates only the roof mounted PV-cell.

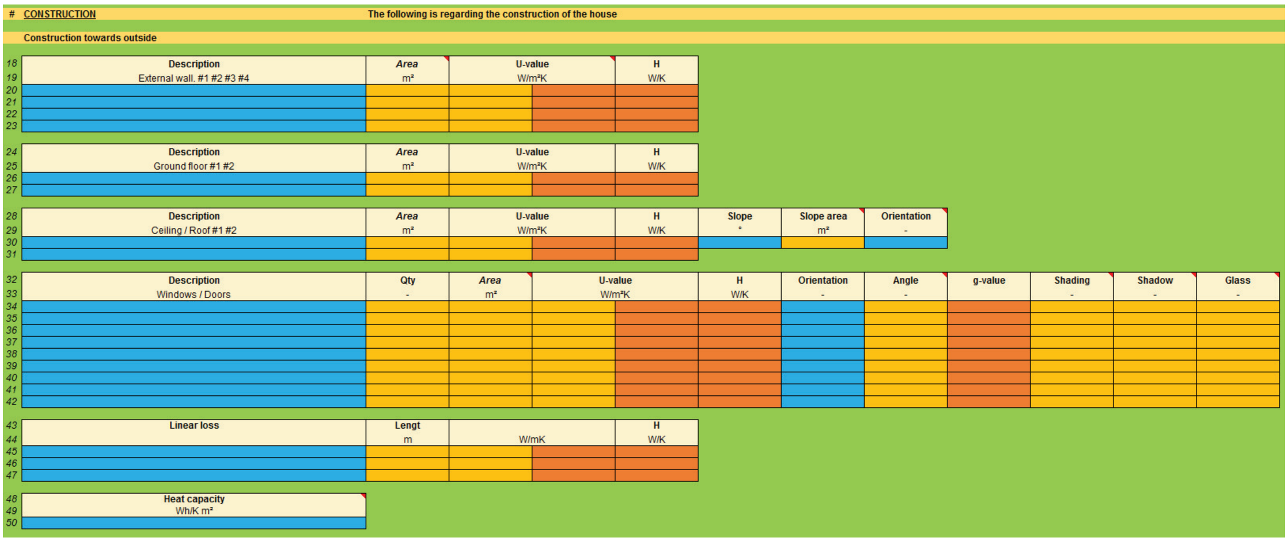


Figure 5.11 Construction information boxes from the middle of the sheet

Window types should also be chosen and all information filled in, if in doubt what to fill in, the user can hover over the heading cell (e.g. Shading) of the box to get suggestions what to fill in. These suggestions are from the Monthly Average.

Unlike the Monthly Average calculation sheet, TREE operates with linear losses separately. The linear loss could have been included in the U-values, however, it has been decided to separate it from the U-values to simplify it for the user, so he can compare different construction disregarding the air tightness.

The building heat capacity should then be chosen, which is very important for internal constructions in walls, ceilings and floors, while windows, doors and furniture have smaller effect. Typical values for the heat accumulation in buildings with different internal construction were chosen for the tool based on DS418.

Next, the current ventilation and infiltration levels are filled in. Housings from this period were usually built with natural ventilation through windows and/or valves in the facades. However, options that are available in the scroll down menu include also mechanical ventilation. All values are based on Energihåndbogen (Klimaministeriet 2016) and are of different types varying from natural to mechanical ventilation from the years 1995 – 2015. With this the user has the possibility to choose if a mechanical ventilation system has been installed. Further information can be seen in 4.2.3 HVAC.

Ventilation

51	**Ventilation**	**Summer**	**Winter**
52	Natural / Mechanic	L/s*m²	L/s*m²
53			

54	**Infiltration**	**All year**
55		L/s*m²
56		

Figure 5.12 Ventilation information boxes from the bottom of the sheet

The infiltration can be difficult to measure for an unprofessional user, and it has been simplified to options as normal, leaky, and very leaky building. These terms are still very relative. The optimal solution would be to conduct a blower door text. This, however, will be expensive and slow down the process, therefore, it has been decided to use the recommendations from Energihåndbogen (Klimaministeriet 2016).

As seen in Figure 5.13, different prices for energy is presented. These prices are used in the report and as default prices in the tool. The user may change the prices to fit their own prices. The price for district heating is an average of all district heating distributors in Denmark from August 2016. Electricity prices are from the third quarter of 2016 (Energitilsynet 2016) and the rest of the prices are from 2015 (Byggeri & Teknik I/S 2015). All prices are including VAT and connection fee.

Energy

57	**Cost for energy**	**Nature gas**	**EL - heating**	**District heating**	**Biofuel**	**Oil**	**Electricity**
58	Cost incl. VAT and contract	DKK/kWh	DKK/kWh	DKK/kWh	DKK/kWh	DKK/kWh	DKK/kWh
59	Prices may be changed	0.80	2.27	0.56	0.63	1.00	2.27

Figure 5.13 Energy price information boxes from the bottom of the sheet

5.4.7 Renovations measures sheet

In this section, the 7. Renovation Measures sheet will be presented. The renovation measures presented in this sheet depend on the current condition of the building and partly the questionnaire. Here, extensive renovation measures are presented that can be complicated and expensive, but deliver high energy savings. All measures have previously been analysed and calculated in Chapter 4.2. The sheet contains 8 measures:

Constructions

1. Windows
2. External wall
3. Ground floor
4. Roof / ceiling

HVAC and Energy producing systems

5. Heat source
6. PV-cells
7. Solar heating
8. Mechanical ventilation

The energy savings achieved by each measure will vary, as well the instalments cost. The installation method and cost could also vary significantly between homeowners, current condition of building and location.

The renovation measures and the calculation approaches vary significantly between the measures in this sheet. For the construction solutions, different types of insulation can be chosen and the desired U-value as well. In the other renovation measures, desired solution can be chosen from fixed solutions. Each measure is presented in a separate suggestion box in the sheet, as illustrated by the example in Figure 5.14, note that the set up can vary between solutions. The uppermost part suggestion box (line 30-40) provides the same overview as presented previously in chapter 5.4.4. In the solutions for external wall, either internal or external insulation is recommended.

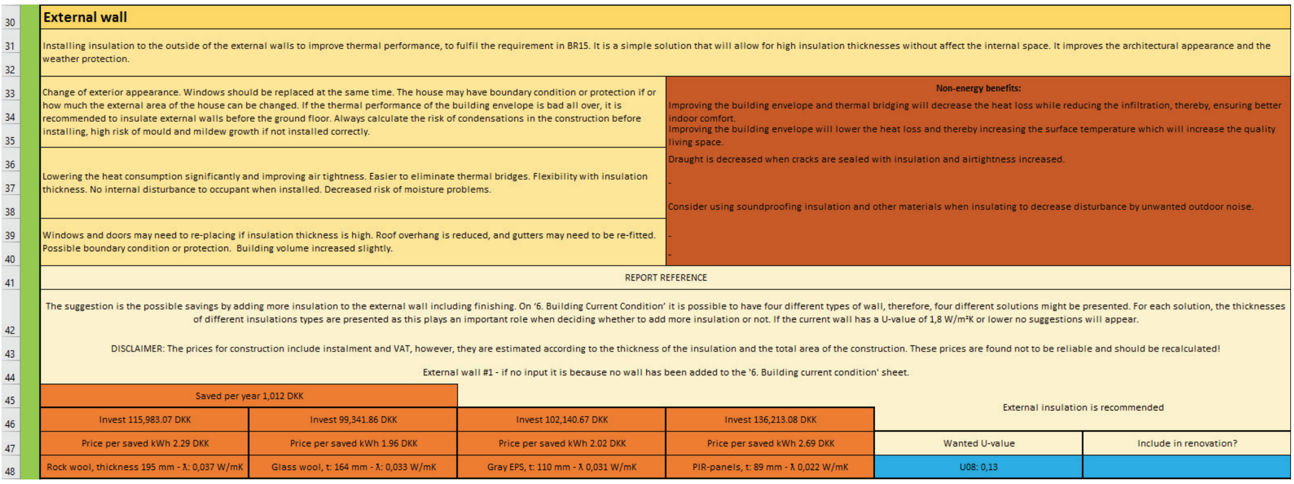


Figure 5.14 Suggestion box from the sheet concerning external wall

The lower section starts with description (line 42-44) of what is included in the price and energy saving calculations. The price savings per year are then presented in line 45, in relation to the energy savings. On the left side in line 46-48 the different types of insulation materials are presented. Line 45 presents the investment cost for each material, including the instalment cost and finishing. Line 47 presents the price per saved kWh through the lifetime (years) of the component. Line 48 presents the insulation thickness needed to achieve the desired U-value along with the resistance value of the insulation material. The user can choose the desired U-value on the bottom right side (blue) of the box. The desired U-value will affect the energy savings significantly. It is recommended to try to achieve as low U-value as possible, due to higher energy savings through the lifetime with minimal extra investment cost, making it very cost-effective.

The user should then go through each box and select the one that is to be executed. These measures will then be used to calculate the potential overall energy saving for the building. However, in some situations TREE will not recommend a solution, then it will be illustrated with a text saying: Not relevant. For instance, if the wall construction has been renovated recently and the user has no complaints about draught or acoustics, the tool will not recommend to insulate the wall as it does not lead to any major improvement and will not be cost efficient. All building envelope solutions have been analysed and calculated in chapter 4.2.2 Building envelope.

Note that all solutions are fixed to each category. For instance, replacing a light bulb with a new LED is considered a minor energy saving measure compared to instalment of PV-cells to the roof. Both will lower the electricity consumption, and will not obstruct each other. However, the savings from installing PV-cells are depending on the consumption, therefore, the savings are presented including the instalment of LED (if LED is suggested in TREE and chosen by user). This is done because lowering the consumption should always be the first step in a renovation process before adding a new source. The solutions inside the category are not presented in a specific way and are randomly placed. Further improvements should be made where solutions are ranked according to importance and need.

5.4.8 Final Result sheet

In this section, the 8. Final Result sheet will be presented. This sheet will illustrate all the potential energy savings and consumption. The results are shown both for the current state and the renovated state, so the homeowner can have a clear view of the savings. Only the savings selected by the user are shown in these results. The energy mark for the building is also presented for the current building and the renovated state, as illustrated in Figure 5.15. This gives the homeowner an overview of the potential rise in his energy mark, which will in most cases increase the square meter price of his building. The estimated energy frame is then illustrated below the energy label. It is then compared to the Renovation class 1 and 2 from BR15.

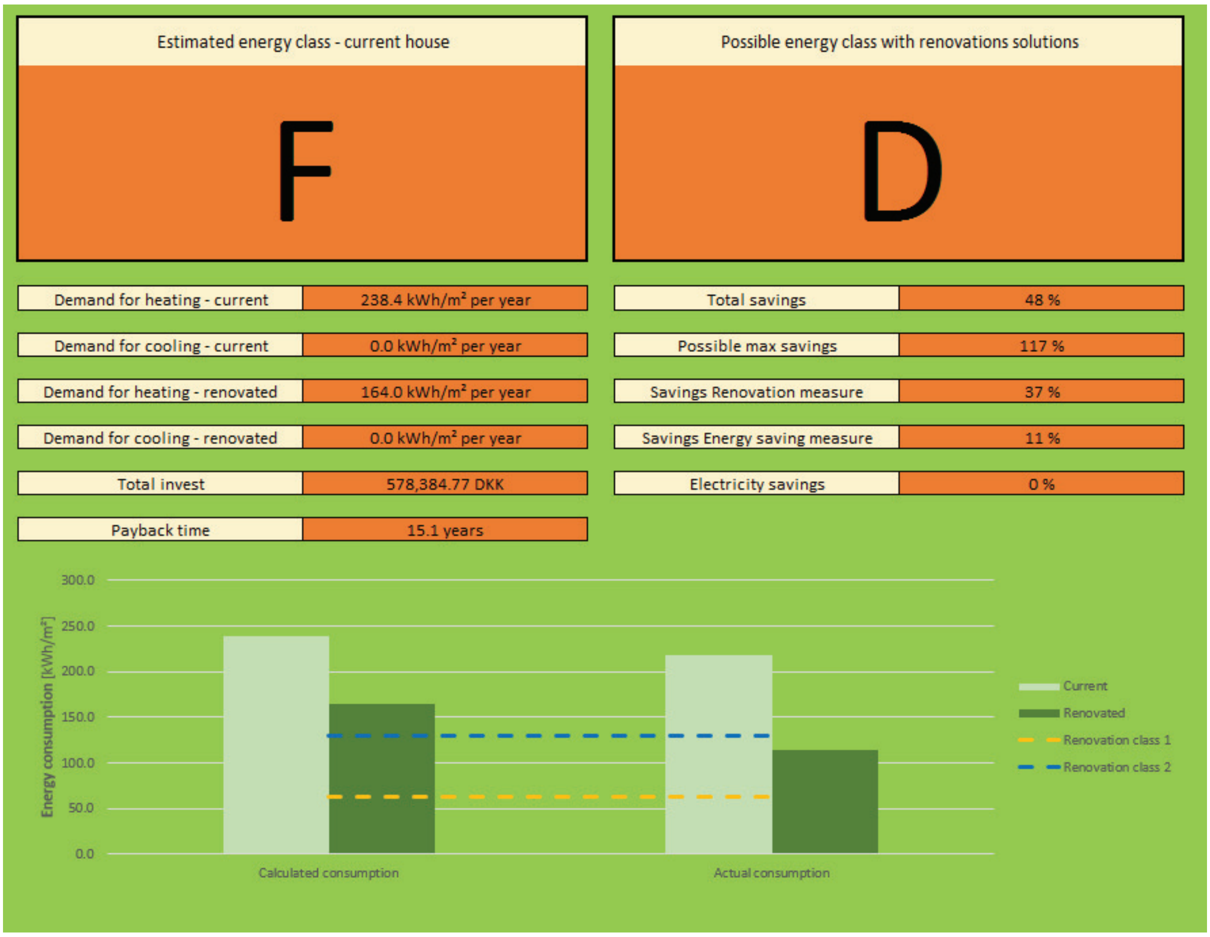


Figure 5.15 Final results illustrating energy consumption and energy mark

Below these results, the potential heating and cooling demand is presented, based on calculations from sheet 7, Figure 5.16.

Figure 5.16 Top graph illustrates the potential heating and cooling demand and the graph below illustrates the price per saved kwh if renovation measure is performed

For some of the renovation measures, for instance, HVAC, an estimated price is presented. The prices are calculated according to V&S Price books for renovation, however, even though the prices are from real cases and updated each year, these prices should only be used as a guideline. As the user, has not been asked details about the different components there may be cases where the suggestion recommended by TREE is not possible or suitable. Therefore, the suggestion should always be accompanied by a recommendation from a professional. As an example, TREE does not take into consideration the different types of soil when recommending a geothermal heat pump, or the statics of the roof when suggesting adding PV-cells. After these results, the ratio between the energy measures and the renovated measures is presented along with achieved non-energy benefits from the renovation measures.

5.4.9 Summary

This tool will allow the user to reflect upon the current comfort and discomfort experienced in the house and get an overview of what could be potentially causing it through a questionnaire. Thereafter, based on the questionnaire, the user is guided towards potential changes he could make in his user behaviour to decrease the energy consumption slightly and increase his comfort. He will also be presented with minor energy saving measures, which can be performed by himself on the next sheet. The user is then guided into more extensive analysis of the current conditions of the house, concerning building envelope and energy consumption. Based on this analysis and the questionnaire, extensive renovation measures are recommended to decrease energy consumption and increase indoor environment. The user can then visualize which renovation measures are optimal and beneficial for his house concerning energy savings. This will increase the homeowner's understanding of needed measures to decrease energy consumption and improve his comfort. Afterwards, he can seek help from a professional in the building industry for the extensive renovation measures.

5.5 Comparison between Be15 and TREE

To investigate the accuracy of the TREE tool, a comparison with Be15 was performed. Both tools, Be15 and TREE, were conducted with the same values, therefore, the results can be compared. This means that the input, for instance, U-values, g-factors, b-factors, areas, and linear losses are the same in both tools. TREE has a fixed energy consumption of 13,1 kWh/m^2 per year for DHW, which is based on the value Be15 uses. To perform the test, reference houses B, C, D and E were used. For the tests Be15, version 8.16.2.4 – calculation core, version 8.16.1.6 was used.

The results came out as shown in Table 5.2, where the total energy consumption is presented per area per year. The results indicate a general overshoot, and for three of the cases it is at +12 %, and the first case (Ref. B) has a larger overshoot of +21 %.

	Be15 *[kWh/m^2 pr. year]*	**TREE** *[kWh/m^2 pr. year]*	**Accuracy** *[%]*
Ref. B	139,9	176,3	+21
Ref. C	218,0	246,3	+12
Ref. D	156,9	178,9	+12
Ref. E	93,0	105,8	+12

Table 5.2 Results of comparison between Be15 and TREE

In the following part a further investigation is made to find out where the differences occur. It is important to know why TREE is overestimating the results and how improvements can make the results more accurate. The investigation will be done with Ref. E as it has a similar accuracy as 75 % of the test cases, and can therefore, be trusted as reliable for the average results.

Analysis of different DRY-files

The first step was to compare the weather files used by each tool. TREE uses DRY-v2 weather as the main calculation base, in TREE it is constructed from AAU Monthly average calculations, which uses this weather file. However, Be15 uses a newer weather file, DRY_2013 weather file. This will pose a difference in outdoor temperatures that will affect the calculations. For future improvements of TREE, the weather file could be changed to DRY_2013.

The Danish Design Reference Year (DRY-v2) weather data came out in 1995 based on climate data from the period 1975-1989 and has been used for many years. Since then the climate conditions in Denmark have changed, and therefore, an updated reference dataset was made for the period 2001-2010, published in 2013, named The Danish Design Reference Year 2013 (DRY_2013). As seen in Figure 5.17, over the period of 2001-2013 (DRY_2013) higher temperatures have been occurring for longer times and more frequent over the year compared to the temperatures from 1975-1989 (DRY-v2). This can be due to the global climate change affecting the Earth, where the global temperatures have been rising through the years, largely due to the greenhouse gasses produced by human activities. The global temperatures will most likely continue to rise for decades to come if nothing is changing.

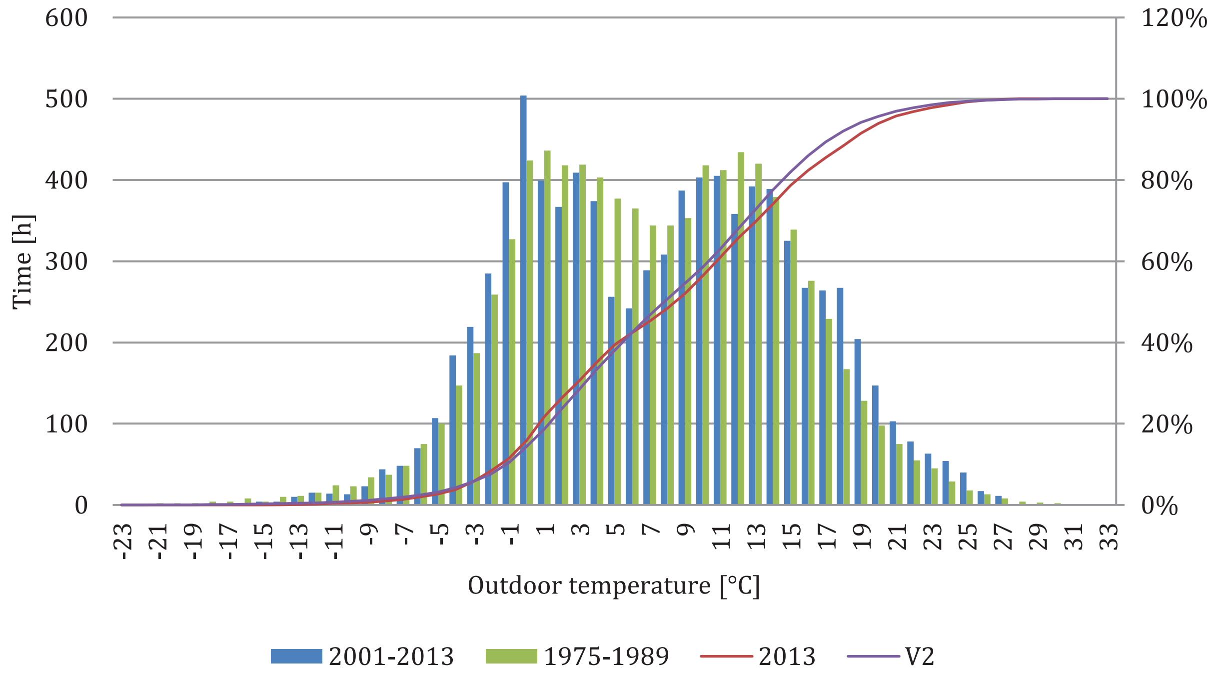


Figure 5.17 Cumulative distribution of hourly average temperature differences between DRY-v2 and DRY_2013

CALCULATIONS

The first step is to check if the two tools calculate the losses and gains similar. As the same inputs are used in both tools, the results can be compared. In Table 5.3 it strikes out that the linear losses are not the same. This has shown to be due to the fact that it is not possible in TREE to change the b-factor, because in TREE the b-factor for ground floor is always 0,7. However when calculating the linear losses around foundations, the b-factor will always be 1,0. In Be15, the linear losses at the foundation are set to a b-factor of 0,7.

Component [-]	Be15 [W/K]	TREE [W/K]	Accuracy [%]
External wall	28,69350	28,69350	+0
Ground floor	22,95220	22,95216	+0
Ceiling	18,86000	18,86000	+0
Linear loss, external wall	8,35072	11,92960	+30
Linear loss, inner walls	1,06974	1,52820	+30
Linear loss, windows	3,70480	3,70480	+0
Windows/Doors	37,54220	37,54224	+0

Table 5.3 Comparison of the components

VENTILATION AND HEAT LOSS

In Be15 it is not possible to separate ventilation and heat loss unlike in TREE, therefore, these are compared together. Table 5.4 shows an overshoot of +5 % in the calculations of TREE. Even by changing the b-factor for the foundations, as described earlier, TREE still has an overshoot of +3%. The Be15 tool uses the method of black box, therefore, some of the calculations can be difficult to compare with TREE. However, the calculations use the outdoor temperature and as TREE uses DRY-v2 weather file and Be15 uses DRY_2013 weather file there will be a difference in temperature as previously discussed. As seen in Figure 5.17, the outdoor temperature is higher in DRY_2013, which can be the explanation for lower losses in Be15 compared to TREE.

Components [-]	Be15 [kWh/year]	TREE [kWh/year]	Accuracy [%]
Ventilation and heat loss	22.130	23.340	+5%

Table 5.4 Comparison of ventilation and heat loss

UTILIZATION FACTOR

The last part of the investigations is regarding the utilization factor. The factor is used for the ratio between time in use and maximum time. The calculation for the final heat demand is dependent on the utilization factor, therefore, it has a great impact on the result. The core of TREE is based on the Monthly Average calculation which has a summer and winter utility factor, however, only one is used at a time, changing each month. This is another example where TREE and Be15 calculates differently. The two tools do not use the same winter and summer utilization factor in the same months. The calculation of the utilization factor is calculated by using the time constant, which is calculated with the heat capacity and losses. Depending on the losses, different utilization factors are in use. In Table 5.5 the comparison of the average utilization factor used in the calculations is presented.

	Be15 [-]	TREE [-]	Accuracy [%]
Utilization factor (average for the year)	0,8667	0,8996	+4

Table 5.5 Comparison of utilization factor

A test was performed, where Be15 utilization factor, ventilation and heat loss, and linear loss parameters were transferred into TREE, where these parameters overruled the current TREE factors. The final TREE results illustrated an energy consumption of 100,7 kWh/m^2 per year, however, it was still 8 % higher than the Be15 calculation. Another test was then performed where ventilation, heat loss and linear loss were overruled in TREE. Then TREE uses the utilization factors from the Monthly Average calculations and determines when to use the winter and summer utilization factor. This made the final TREE energy consumption 93,7 kWh/m^2 pr. year and the overshoot is down to 1 %. It can, therefore, be concluded that further work should be done in relation to sensitivity analysis, focusing on making the losses more accurate. This will lead to make the TREE tool more comparable and accurate.

If the same test is made for Ref. B, where the original overshoot was +21 %, it is lowered to 9 %. This happens if ventilation, heat loss and linear loss in TREE are overruled by Be15 parameters, resulting in the utilizations factor being recalculated in TREE. There is still an uncertainty of a 9 % difference between the two calculation tools. This should be investigated further by performing a sensitivity analysis to decrease the difference and increase the accuracy.

6 Discussion

Increased energy efficiency in the existing building stock in Denmark is an essential part of reducing the overall consumption and fulfil the goal of becoming independent from fossil fuels by 2050. The target housing of this project was narrowed down to single-family housing from 1961 – 1978. In this period, the largest amount of potential energy savings is found due to a combination of the sheer amount of housing constructed in this period, and the limited use of insulating materials.

Numerous tools have been developed in order to assist and guide in the process of renovating energy efficiently. Very few of these are aimed at single-family housing. The most relevant guide for energy renovations of single-family housing in Denmark, was found to be the Besparelsesberegner[13] tool and the web based guide from SparEnergi. None of these tools take non-energy benefits, that comes with an energy renovation, into consideration, even though they have proven to have great influence on motivating the homeowners. The overall use of the tools has been disappointing, leading to the evaluation report made by Epinion. While Epinion recommended increased awareness by potentially costly advertising, a solution of increasing the number of motivational factors had not been investigated yet.

Literature points to the fact that economy is both the greatest barrier and motivational factor. The low renovation rate could point towards economy as a greater barrier than it is motivational. At least, the sum of barriers is greater than the sum of the motivational factors. Homeowners might have little interest in spending money on cumbersome, time consuming renovations performed to increase energy efficiency and initially resolve a problem, which is basically the society's problem, more than it is the individual homeowners' problem. Economy is only a driver when the energy consumption can be reduced to an extent that it will affect the homeowners' private economy. Increased comfort and indoor climate, however, has proven to be a great motivational factor for the individual.

TREE is made with the intention of including the homeowners' perceived comfort and indoor parameters, to increase motivational factors and the incentive and interest in using the tool. The tool starts with a simple questionnaire and progresses to more complicated inputs, where documentation of the current condition is required.

Combining economy, energy savings, comfort and indoor climate in terms of non-energy benefits, perceives the problem from an unprecedented angle, where an increased number of motivational factors should inspire and motivate people to perform energy renovations. Therefore, these parameters formed the foundation of TREE. However, linking economy, energy savings and non-energy benefits proved to be complicated and difficulties were experienced.

[13] http://www.sparenergi.be10.sbi.dk/

The perceived comfort of indoor environmental parameters can vary significantly between homeowners; therefore, it was chosen to base the initial investigation of comfort and indoor climate on a questionnaire, with the aim of increasing the quality of the occupants' comfort. This is done by illustrating the potential non-energy benefits that come with the different measures.

Determining the current conditions in terms of comfort and indoor environmental parameters, without taking measures on site, proved to be a challenge. Observations from literature and investigation of the reference houses were used to estimate the current conditions.

Calculating the energy saving from implemented passive solutions, without measurements or in depth simulation, was deemed unrealistic with the given timeframe and could be further investigated to display the potential energy savings and add to the motivational factors.

The current conditions of 40 – 60-year-old building components vary a lot and can influence the suggested renovation solution. The database from V&S pricebook was used to determine prices of renovation solutions, but the database had limited construction types with fixed prices and only two types of insulation materials. Therefore, users should be aware that the prices for materials and instalment included in the tool, are not valid for every type of wall. The price is based on one type of wall and changes according to the amount of insulation used.

The current conditions were calculated using the Monthly Average Calculations. It uses an old weather data file and should be updated to DRY_2013 according to regulation. The Monthly Average has been modified to include linear losses and DHW to make the results more reliable. However, the use of different weather files creates an uncertainty when you compare the results of TREE with Be15. Therefore, TREE does not constitute as a replacement for Be15, which should still be used to calculate the energy frame of a house.

In order to provide the individual homeowner with specific suggestions of energy saving measures, TREE is based on the clarification of problematic areas in the individual housing, suggesting improvements in terms of energy saving measures that mainly seek to improve the comfort and indoor climate of the house. By doing this, the barrier between the tool and the user should be decreased, as the number of motivational factors increases. When the user has gained confidence in the tool, possibly through experiencing an increase in comfort by following the suggestions, he should feel inspired and motivated to embark on the extensive renovations that have significantly higher impact on reducing the energy consumption and at the same time improving his comfort by potential non-energy benefits.

TREE makes it possible to compare the energy saving from minor measures and extensive measures. TREE does not make suggestions on how the extensive renovations should be carried out, due to the potential variation in current conditions of the building. The extensive renovation measures are considered suggestions including estimations of their impact, concerning energy savings, installation cost and non-energy benefits. TREE is a decision-making tool that enables the homeowner to make informed decisions on energy saving measures. Next step for the homeowner is to contact a professional to realize the selected energy saving measures.

7 Further investigation

To determine if TREE has the motivational factor needed to inspire homeowners in performing energy saving measures, TREE should be tested thoroughly by both quantitative questionnaires and qualitative interviews. This could also determine if TREE is easy to understand and navigate in, or if maybe a FAQ or manual is needed. Furthermore, the manual could provide the homeowner with information on user behaviour and how it can impact the energy consumption and the indoor environment of the house.

As of now, the tool does not rank the extensive renovations in any way. It is up to the homeowner himself to make the decision based on the information provided by the tool. Ranking could be implemented to ensure that renovation is non-obtrusive. It could also be ranked depending on cost-efficiency in terms of estimated kWh saved per DKK spent.

The tool could also relate to the regulations in the Renovation Class 1 & 2 in order to make sure that demands for energy performance framework (Class 1 & 2) and indoor climate, ventilation and artificial lighting (Class 1) are achieved.

The tool does not account for heat loss related to added comfort measures e.g. the loss of energy that comes from increased use of natural ventilation.

A sensitivity analysis is needed to determine which uncertainties have the highest impact on the calculations in TREE.

TREE should not be used to make energy frame calculations, a Be15 calculation is also needed. Further investigation should be put into exporting and importing data between the two tools and reduce the workload.

8 Conclusion

This thesis revolved around the creation and development of the decision-making tool *TREE*; Tool for Renovating Energy Efficiently.

Evaluation of existing tools showed a general and justified focus on economy as it was proven to be both the greatest motivational factor and barrier. The need for energy renovations are increasing when the amount of existing buildings wearing out in Denmark is rising, and the need will only increase over the next 30-50 years.

With the low renovation rate and an increasing need, it was considered necessary to inspire and motivate homeowners to perform private energy renovations by a new approach. As revealed by the literature review, the importance of non-energy benefits related to indoor environment cannot be neglected in either of the three homeowner groups. Therefore, combining the energy savings and non-energy benefits achieved by energy renovations, in a simple and easily accessible tool, in order to create a stepping stone for single-family homeowners to increase energy renovations performed in Denmark.

The starting point of TREE is based on the current issues that the homeowner may have in connection with comfort and indoor climate. Problematic areas are defined by a questionnaire and solutions are subsequently presented in actions of respectively minor comfort measures and minor energy saving measures. These minor improvements are easily accessible and do not require much money to be performed, leaving the user with great incentive to perform them, as motivation is high and barriers are small. The first step in TREE provides awareness of the problems, how to handle them and should contribute to an increased interest in energy efficient renovations and non-energy benefits in general, inspiring and motivating the homeowner to aim higher and conduct extensive renovations. Therefore, the next step in TREE will present the homeowner with extensive renovation measures based on the current conditions of the building, including the potential savings, instalment costs and non-energy benefits. By this the homeowner can see the potential energy savings and non-energy benefits he could achieve when energy renovating. This progressive approach guides the homeowner through tasks of increasing difficulty and relies on the studies from Harvard, showing that progress in general is a great motivational factor.

By introducing a new and simple tool like this, to promote energy savings for single-family homeowners, it will contribute to the goal of decreasing the energy consumption in buildings and ultimately assist in the goal of becoming independent from fossil fuels by 2050.

9 References

ActiveHouse, 2015. *Active house - the guidelines*, Brussel. Available at: http://www.kfs-boligbyg.dk/wp-content/uploads/active_house_guidelines_version_1.pdf [Accessed December 29, 2016].

Almlund, P., Jessen, A. & Elle, M., 2002. *Økologisk renovering og vedligeholdelse af parcelhuse*,

Alternative Energy Tutorials, 2015. Evacuated Tube Collector for Solar Hot Water System. Available at: http://www.alternative-energy-tutorials.com/solar-hot-water/evacuated-tube-collector.html [Accessed January 13, 2017].

Amabile, T., 2011. The Best Way To Motivate People. *Harvard*. Available at: http://www.bakadesuyo.com/2012/06/what-is-the-most-powerful-management-techniqu/ [Accessed January 10, 2017].

Andersen, A., 2014. Cavity wall insulation – Nordic Renovation Center. *Nordic Renovation Center*. Available at: http://www.nordicrenovationcenter.fi/tools/eps-project/renovation-guide/walls-insulation/cavity-wall-insulation/ [Accessed December 21, 2016].

Anker, P. & Maslesa, J.E., 2013. RENO-EVALUE.

Autodesk, 2013. Human Thermal Comfort. *Autodesk Sustainability Workshop*. Available at: https://sustainabilityworkshop.autodesk.com/buildings/human-thermal-comfort [Accessed December 30, 2016].

Birgisdottir, H. et al., 2013. *Kortlægning af bæredygtigt byggeri*, Available at: http://www.sbi.dk/miljo-og-energi/beredygtighedsvurdering/kortlaegning-af-baeredygtigt-byggeri/sbi-2013-09/at_download/file.

Boiler Guide, 2016. Carbon Monoxide Safety. Available at: https://www.boilerguide.co.uk/articles/carbon-monoxide-safety [Accessed November 3, 2016].

Boligejer, 2016. GUIDE: Radon - Hvad er radon? - Radonguiden.dk - Boligejer.dk. Available at: http://boligejer.dk/hvad-er-radon [Accessed December 18, 2016].

Boligejeranalyse, B., 2016. Bolius Boligejeranalyse 2016 Bolius Boligejeranalyse 2016 Bolius Boligejernes Videncenter. , p.96.

BOLIUS, 2008. Passer mit hus til varmegenvinding? Available at: https://www.bolius.dk/passer-mit-hus-til-varmegenvinding-19723/.

Bolius, 2012. Elvarme – nej tak. Available at: https://www.bolius.dk/elvarme-nej-tak-5970/ [Accessed November 3, 2016].

Bolius, 2014. Fordele og ulemper ved huse fra 60'erne og 70'erne. Available at: https://www.bolius.dk/fordele-og-ulemper-ved-huse-fra-60erne-og-70erne-17894/.

Bolius, 2015a. Opvarmning med elradiatorer. *Opvarmning med elradiator*. Available at:

https://www.bolius.dk/opvarmning-med-elradiator-17060/ [Accessed November 3, 2016].

Bolius, 2015b. Sundhedsskadelige imprægneringsvæsker i byggematerialer. Available at: https://www.bolius.dk/sundhedsskadelige-impraegneringsvaesker-i-byggematerialer-18708/.

Bonin, J., *Heat Pump Planning Handbook*,

BPIE, 2011. *Europe´s Buildings Under The Microscope*,

BR, 2015. Danish Building Regulations 2015. , 2015(810), pp.10–12.

BYG-ERFA, 2015. Dampspærrematerialer og fugttransport.

BYG-ERFA, 2005. Tagkonstruktioner med lille hældning – ventilation og fugtforhold.

Byg-Erfa, 2015. (13) 141210 Radonsug – i eksisterende enfamiliehuse. , (13), pp.8–9.

BYG DTU, 2009. Kompendium 7 - Ruder og vinduers energitilskud.

Byggeri & Teknik I/S, 2015. Privat - Sammenligning af energipriser. Available at: http://www.byggeri-teknik.dk/wp-content/uploads/2015/11/Energipriser_2015-10-30_sammenligning.pdf [Accessed November 18, 2016].

Cauwerts, C., Parameters of Visual Comfort. *Environmental Design in university Curricula and Architectural Training in Europe*. Available at: https://www.educate-sustainability.eu/kb/content/parameters-visual-comfort [Accessed December 31, 2016].

CMHC Corporation, 2012. Energy Efficiency Building Envelope Retrofits for Your House | CMHC. *Canada mortage and housing corporation*. Available at: https://www.cmhc-schl.gc.ca/en/co/grho/grho_011.cfm [Accessed December 4, 2016].

CMHC Corporation, 2016. Insulating Your House | CMHC. *Canada mortage and housing corporation*. Available at: https://www.cmhc-schl.gc.ca/en/co/grho/grho_010.cfm [Accessed December 4, 2016].

Crumbaker, K. & McCarty, P., Introduction to Domestic Solar Hot Water Systems - 10.627 - Colorado State University ExtensionColorado State University Extension. Available at: http://extension.colostate.edu/topic-areas/family-home-consumer/introduction-to-domestic-solar-hot-water-systems-10-627/ [Accessed January 13, 2017].

Danfoss, 2015. *VVS-Guide 8*,

Danish Energy Policy, 2012. *Aftale om den danske energipolitik*,

Danish Energy Agency / Energi Styrelsen, 2015. *Introduktion til LCC på Bygninger*, Energistyrelsen.

Danish Knowledge Centre for & Energy Savings in Buildings, 2015. Besparelsesberegner. *Danish Knowledge Centre for Energy Savings in Buildings*. Available at: http://sparenergi.be10.sbi.dk/ [Accessed January 3, 2017].

Danish Knowledge Centre for Energy Savings in Buildings, 2016. *Energy Requirements of BR15*, Available at: http://www.byggeriogenergi.dk/media/1903/br15_uk.pdf [Accessed January 3, 2017].

Dansk Gasteknisk Center a/s, 2016. Naturgas i Danmark — Naturgasfakta. Available at: http://www.naturgasfakta.dk/copy_of_miljoekrav-til-energianlaeg/naturgas-i-danmark [Accessed October 19, 2016].

Dansk Standard, 2011. *DS 418: Beregning af bygningers varmetab* 7, ed.,

Dréau, J., 2015. *Indoor Environmental Analysis and Thermal Comfort*,

DTU, 2008. *Energirenovering af typisk parcelhus opført i perioden 1960-1980*,

Dufour, V., 2012. *Insulation solutions - Polyurethanes*,

Duka, 2016. Duka Ventilation.

E2ReBuild, 2014. European Retrofit Advisor. *E2ReBuild*. Available at: http://www.e2rebuild.eu/en/events/workplan/pd/retrofitadvisor/Sidor/default.aspx [Accessed January 3, 2017].

E2ReBuild, European Retrofit Advisor. Available at: http://www.e2rebuild.eu/en/events/workplan/pd/retrofitadvisor/Sidor/default.aspx.

Energi- Forsynings- og Klimaministeriet, 2014. Strategi for energirenovering af bygninger.

Energistyrelsen, 2016a. Biobrændsel. Available at: http://sparenergi.dk/forbruger/varme/biobraendsel [Accessed November 3, 2016].

Energistyrelsen, 2016b. Dansk energipolitik | Energistyrelsen. Available at: https://ens.dk/ansvarsomraader/energi-klimapolitik/fakta-om-dansk-energi-klimapolitik/dansk-energipolitik [Accessed September 15, 2016].

Energistyrelsen, 2013. *Ny Pære - Hvad skal jeg vide, før jeg køber?*,

Energistyrelsen, 2016c. sparenergi.dk. Available at: http://sparenergi.dk/forbruger/vaerktoejer/bygningsguiden/parcelhus-1960-76/tag [Accessed October 4, 2016].

Energistyrelsen, 2014. Strategi for energirenovering af bygninger. Available at: http://www.ens.dk/sites/ens.dk/files/byggeri/Strategi-for-energirenovering-af-bygninger/strategi-for-energirenovering-af-bygninger-web-050514.pdf.

Energistyrelsen, 2016d. Varme. *www.Sparenergi.dk*.

Energistyrelsen, 2004. Varmeforsyning i Danmark.

Energistyrelsen, 2016e. Varmt vand. *www.Sparenergi.dk*.

Energitilsynet, 2016. Elprisstatistik 3 kvartal 2016 v 1.2.docx. Available at: http://energitilsynet.dk/fileadmin/user_upload/Elprisstatistik_3__kvartal_2016.pdf

[Accessed November 29, 2016].

Energitjenesten, 2016a. Nye regler for olie- og gasfyr. Available at: http://www.energitjenesten.dk/nye-regler-for-oliefyr.html.

Energitjenesten, 2016b. Vinduer teknisk set. Available at: http://www.energitjenesten.dk/vinduer-teknisk-set.html [Accessed October 5, 2016].

Energivinduer.dk, Certifikatet « Energivinduer. *2013*. Available at: http://energivinduer.dk/certifikatet/ [Accessed November 29, 2016].

Ferreira, M. & Almeida, M., 2015. Benefits from energy related building renovation beyond costs, energy and emissions. *Energy Procedia*, 78, pp.2397–2402. Available at: http://dx.doi.org/10.1016/j.egypro.2015.11.199.

Flourentzou, F., Genre, J.L. & Roulet, C.-A., 2002. TOBUS software — an interactive decision aid tool for building retrofit studies. *Energy and Buildings*, 34(2), pp.193–202.

Forsyningen, A., 2016. Vandtakster for boligkunder - januar 2016.

Government, the D., 2011. Energy Strategy 2050. *Energy Policy*, (February), p.66. Available at: http://www.bfe.admin.ch/themen/00526/00527/?lang=en.

Grau, K. & Pedersen, J.P., 2011. *Energy requirements for buildings Calculation guide* 2nd ed., Danish Building Research Institute.

GreenGuard, 2016. The Importance of Healthy Air in the Home - Indoor Air Quality Information for Consumers. *Green Guard Certification*. Available at: http://greenguard.org/en/consumers/consumers_iaq.aspx [Accessed December 29, 2016].

GreenSpec, 2016a. Housing Retrofit: Cold Roof (loft) Insulation. *GreenSpec*. Available at: http://www.greenspec.co.uk/building-design/loft-insulation/ [Accessed December 21, 2016].

GreenSpec, 2016b. Housing Retrofit: Ground Floor Insulation. *GreenSpec*. Available at: http://www.greenspec.co.uk/building-design/ground-floor-insulation/ [Accessed December 19, 2016].

GreenSpec, 2016c. Housing Retrofit: Timber Flat Roof Insulation. *GreenSpec*. Available at: http://www.greenspec.co.uk/building-design/timber-flat-roof-insulation/ [Accessed December 21, 2016].

Grundfos, 2016. COP (Coefficient of performance) | Grundfos. Available at: http://www.grundfos.com/service/encyclopedia-search/cop-coefficient-ofperformance.html [Accessed November 1, 2016].

Hakkinen, T. et al., 2012. Methods and concepts for sustainable renovation of buildings - T26.pdf. *VTT Technical Research Centre of Finland*, p.325. Available at: http://www.vtt.fi/inf/pdf/technology/2012/T26.pdf [Accessed October 31, 2016].

Hamborg, B. et al., 2016. DELRAPPORT – PRIVATE HUSSTANDE Evaluering af SparEnergi.

Heiselberg, P., 2007a. *Daylighting*,

Heiselberg, P., 2007b. *Microclimate of buildings*, Aalborg.

Heiselberg, P., 2008. *Passive and natural cooling*,

Hoon Lee, S., Hong, T. & Ann Piette, M., 2014. Review of Existing Energy Retrofit Tools.

Jaggs, M. & Palmer, J., 2000. Energy performance indoor environmental quality retrofit — a European diagnosis and decision making method for building refurbishment. *Energy and Buildings*, 31(2), pp.97–101.

Jensen, H.S., 2016. Bæredygtig håndtering af affald ved nedbrydning og renovering af.

Keiding, L. et al., 2003. *Miljøfaktorer i danskernes hverdag – med særligt fokus på boligmiljø*, Statens Institut for Folkesundhed, By og Byg - Statens Byggeforskningsinstitut.

Klimaministeriet, E.-F., 2016. *Håndbog for Energikonsulenter*,

Knudsen, H.N. & Jensen, O.M., 2015. *SBI 2015:28 - Tenants' experiences and satisfaction with renovated and energy retrofitted social housing*,

Kragh, J., 2016. *Renoveringsklasser for eksisterende bygninger*,

Larsen, T.S., 2008. *SIMPLIFIED METHOD FOR CALCULATION OF HEATING AND COOLING REQUIREMENTS (MONTH AVERAGE)*,

Liu, M., 2016a. *Passive cooling, natural ventilation and thermal mass*,

Liu, M., 2016b. *Solar Heating & Solar Control*,

Lysexperten, 2016. Omregningstabel Watt. Available at: http://www.lysexperten.dk/omregningstabel-watt/.

Mortensen, A., 2015. *Energy renovation of danish single-family houses*,

Mortensen, A., Heiselberg, P. & Knudstrup, M., 2014. Economy controls energy retrofits of Danish single-family houses. Comfort, indoor environment and architecture increase the budget. *Energy & Buildings*, 72, pp.465–475.

Nielsen, A.N. et al., 2016. Early stage decision support for sustainable building renovation – A review. *Building and Environment*, 103, pp.165–181. Available at: http://www.sciencedirect.com/science/article/pii/S0360132316301238 [Accessed April 18, 2016].

NK Design, 2017. NK Design - Portfolio. Available at: http://nkdesignx.weebly.com/ [Accessed January 12, 2017].

Pasanisi, A. & Ojalvo, J., 2007. A multi-criteria decision tool to improve the energy efficiency of residential buildings. *EDF-R&D*. Available at: http://fcds.cs.put.poznan.pl/FCDS2/ArticleDetails.aspx?articleId=135 [Accessed January 3, 2017].

Peuhkuri, R. & Rode, C., 2010a. *Indvendig efterisolering: Sådan dimensioneres løsninger, som giver holdbare konstruktioner*, Available at: http://www.byggeriogenergi.dk/media/1800/notat_om_indvendig_efterisolering__s_dan_dimensioneres_l_sninger__som_giver_holdbare_konstruktioner__2_.pdf [Accessed December 15, 2016].

Peuhkuri, R. & Rode, C., 2010b. *Indvendig efterisolering: Sådan dimensioneres løsninger, som giver holdbare konstruktioner*,

Pomianowski, M., 2016. *Energy Producing Systems - PV Cells*,

Pullen, T., 2014. Insulating Lofts, Roofs and Floors | Homebuilding & Renovating. *Homebuilding&Renovating*. Available at: https://www.homebuilding.co.uk/insulating-lofts-roofs-and-floors/ [Accessed December 21, 2016].

Pullen, T., 2015. Internal Wall Insulation | Homebuilding & Renovating. *Homebuilding&Renovating*. Available at: https://www.homebuilding.co.uk/internal-wall-insulation/ [Accessed December 15, 2016].

Rationel, 2016. Funktionsruder - Ruder med ekstra funktioner - Rationel. Available at: http://www.rationel.dk/inspiration/ruder [Accessed December 22, 2016].

Realkredit Danmark, 2013. Energimærkning og boligøkonomien. , (november), pp.1–7.

REHVA, 2011. Definition of theat pumps and their use of renewable energy sources. Available at: http://www.rehva.eu/fileadmin/hvac-dictio/01-2012/04-2011/Definition_of_heat_pumps_and_their_use_of_renewable_energy_sources.pdf [Accessed December 26, 2016].

REHVA, 2013. Energy Labelling - State of play and conceptions for future: REHVA. Available at: http://www.rehva.eu/publications-and-resources/rehva-journal/2013/022013/energy-labelling-state-of-play-and-conceptions-for-future.html.

RIBA CPD, 2012. *Thermal Insulation of Floors*, Available at: http://www.designforhomes.org/wp-content/uploads/2012/03/ThermalInsulation.pdf [Accessed December 19, 2016].

SBi, 2009. Anvendelse af faseskiftende materialer i fremtidens bygninger.

SBi, 2015. *Genbrug af byggevarer*, Copenhagen.

SBi, 2005. *SBi 2005:09 Husholdningers energi- og vandforbrug*,

SBi, 2014. *SBi 213 - Bygningers Energibehov*,

SBi, 2013:30, 2013. *Levetider af bygningsdele ved vurdering af bæredygtighed og totaløkonomi* 1st ed. N.-J. Aagaard et al., eds., Copenhagen: SBi Statens Byggeforskningsinstitut. Available at: https://is.gd/8ShdJr.

SEAS-NVE, 2016. Cirkulationspumpe. Available at: https://www.seas-nve.dk/privat/spareraad/spar-energi-i-din-hverdag/bryggers/cirkulationspumpe.

SKAT, 2016. SKAT: E.A.4.3.6.2 Regler for elektricitet til opvarmning af helårsboliger (elvarmeafgift) før 1. april 2016. Available at: https://www.skat.dk/SKAT.aspx?oID=2061621.

Statistics Denmark, I., 2016. Statistics. Available at: http://www.statistikbanken.dk/statbank5a/default.asp?w=1360.

Taginfo, 2016. Eternit tag - Historien om Eternit tag og oprindelse. Available at: http://www.taginfo.dk/eternit-tag/ [Accessed September 23, 2015].

Teknologisk Insistut, 2016. Standardværdikatalog For Energibesparelser (Catalog For Energy Improvements). *Teknologisk Institut*. Available at: http://svk.teknologisk.dk/Pages_open/Default.aspx.

The Ministry of Climate, E. and B., 2014. *Strategy for energy renovation of buildings*, Copenhagen. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/2014_article4_en_denmark.pdf [Accessed January 11, 2017].

The Renewable Energy Hub, 2012. How does insulation work? *The Renewable Energy Hub*. Available at: https://www.renewableenergyhub.co.uk/insulation-information/how-insulation-works.html [Accessed December 15, 2016].

Thorpe, D., 2016. Should I be insulating a solid wall internally, externally or both? *SuperHomes*. Available at: http://www.superhomes.org.uk/resources/insulating-a-solid-wall/ [Accessed December 15, 2016].

Trafik- og Byggestyrelsen, 2016. Ændringer i BR15 - BR15. Available at: http://bygningsreglementet.dk/vaendringer/0/40 [Accessed September 26, 2016].

Umweltbundesamt und Öko-institute e. V., 2015. Faktencheck Obsoleszenz | Umweltbundesamt. Available at: http://www.umweltbundesamt.de/presse/presseinformationen/faktencheck-obsoleszenz.

V&S Prisdata, 2016. Price book.

varmepumpe-guiden.dk, 2016. Beregn el forbruget på din luft til luft varmepumpe nemt her. Available at: http://varmepumpe-guide.dk/beregner-til-varmepumper/.

Velux, 2014. *Daylight, Energy and Indoor CLimate Basic Book*,

Videncenter for energibesparelser i bygninger, 2012. *Produktguide: Valg af isoleringsmaterialer*, Available at: http://bdb.dk/wp-content/uploads/2013/05/Valg-af-isoleringsmaterialer.pdf [Accessed December 13, 2016].

Virén, K., Svendsen, M. & Geyer, L., 2011. Isolering og varmetab. *Bolius*. Available at: https://www.bolius.dk/isolering-og-varmetab-17834/ [Accessed December 4, 2016].

Volker Quaschning, 2004. German Energy transition. Available at: http://www.volker-quaschning.de/articles/fundamentals4/index_e.php.

Wiseman, T. & Summerson, G., Sustainable refurbishment of domestic buildings using BREEAM A guide to BREEAM Domestic Refurbishment and how to incorporate. Available at: www.breeam.com.

Wittchen, K.B., 2009. *Potentielle energibesparelser i det eksisterende byggeri*, Hørsholm: Statens Byggeforskningsinstitut, SBi, Denmark.

10 List of figures

Appendix A BR15: Conversions and other alterations

Conversions and other alterations

Conversions and other alterations:
When something is rebuilt, renovated or altered in a manner that does not fall under change of use or extension. E.g. new roofing, new roofing membrane or plastering of a façade that has not previously been plastered.

At **www.eksempelsamling.bygningsreglementet.dk** (Danish) you can see more examples of construction projects that require making them more energy efficient.

Requirement	Chapter in BR
Requirements for thermal insulation concerning cost-effective energy improvements (calculation of cost-effectiveness must be made if requirements are not complied with)	7.4.2 par. 1
OR	
Energy performance framework for existing buildings - called "renovation classes"	7.4.3

Conversions and other alterations to the building (cost-effectiveness) and replacement of building parts. Chapter 7.4.2	U value W/m² K
External walls and basement walls in contact with the soil	~~0.20~~ → 0.18
Suspended upper floors and partition walls (adjoining rooms/spaces that are unheated or lightly heated*)	0.40
Ground slabs, basement floors in contact with the soil and suspended upper floors above open air or a ventilated crawl space	~~0.12~~ → 0.10
Ceiling and roof structures, including jamb walls, flat roofs and sloping walls directly adjoining the roof	~~0.15~~ → 0.12
Doors/gates	~~1.65~~ → 1.80
Hatches to the outside or to rooms/spaces that are unheated or lightly heated*	~~1.65~~ → 1.40
New secondary windows	~~1.65~~ → 1.40
Renovated secondary windows	- → 1.65
Skylight domes	~~1.65~~ → 1.40
Requirements for linear loss for joints between building elements	Ψ value W/m K
Foundations	0.12
Joints between external walls, windows, external doors, glazed external walls, gates and hatches	0.03
Joints between roof construction and roof lights or skylight domes	0.10

Figure 13

Approximate insulation thicknesses mm
200 (heavy) / 250 (light)
75
300
300

Figure 14

Lightly heated = 5° C or more below the temperature in the room concerned

Changed compared to BR10 (Building Regulation 2010)

There are legal requirements to carry out energy saving measures during conversions and alterations of existing buildings to the level that the investment is cost-effective - and in connection with outright replacements (read about replacements on page 16). Maybe you cannot quite fulfil the requirements of chapter 7.4.2 (see figure 13) - but you must still improve to a possible lower and cost-effective level.

Digging out an existing ground deck can, for example, require a depth that is below the foundation in order to satisfy the U value requirement. This can result in the foundation having to be undercasted at great expense. In such cases, retrofitting of insulation must only be done to a level that it is structurally safe to dig to.

What is cost-effectiveness?
Cost-effectiveness indicates how rewarding an energy-saving measure is. Or in other words: Does the building owner save more money in the long term than was used to invest in the measure?

Cost-effectiveness is calculated like so:

$$\frac{\text{Lifetime in years x annual savings in DKK}}{\text{Extra investment}} \geq 1.33$$

If the cost-effectiveness is greater than or equal to 1.33, the investment is considered cost-effective for the building owner. This corresponds to the measure being repaid within ¾ of the expected lifetime.

The investment sum used in the calculation should only include the price of extra labour and materials for the actual energy improvement - e.g. the insulation and any labour resulting thereof. It is often the case that retrofitting of insulation, for example, is more cost-effective when you are already doing other renovation work.

When determining the lifetime, you can use figure 15, which also appears in BR15's appendix 6, Cost-effective energy savings.

If an investment is cost-effective, you must adhere to the requirements for heat insulation and linear loss that are specified in BR15's chapter 7.4.2 (see figure 13).

New installations must meet the requirements of BR15's chapter 8 that regulate which types of facilities are legal (read more on page 18).

Lifetimes that can be used to calculate cost-effectiveness	Years
Retro-fitted insulation to building elements	40
Windows with secondary windows and coupled frames	30
Heating systems, radiators and underfloor heating and ventilation ducts and fittings including insulation	30
Heat appliances, etc., for example boilers, heat pumps, solar heating systems, ventilation units	20
Lighting fittings	15
Automation for heating and climatic control equipment	15
Joint sealing works	10

Figure 15

Useful guide for assessing cost-effectiveness

A guide from the Danish Transport and Construction Agency about constructions that are often cost-effective demonstrates a range of the typical cost-effective retrofitting measures during conversions and other alterations.

You can find it at **www.bygningsreglementet.dk** (Danish) under *Vejledninger* [Guides].

Justifiable moisture- and energy-wise

Constructional conditions can mean that the regulations of chapter 7.4.2 cannot be met in a justifiable manner in relation to cost-effectiveness or moisture. There may, however, be an opportunity to carry out less extensive work that reduces the energy demand. This would then be the work that needs to be done.

An example:
You are to renovate an outer wall. It is a cavity wall with no room for satisfying the U value requirement of figure 13. You will therefore carry out cost-effectiveness calculations on external an internal retrofitted insulation. But neither turns out to be cost-effective. This means that by insulating the cavity wall to the possible level, you have satisfied the energy requirements.

Energy performance frameworks for existing buildings
During larger building renovations, as an alternative to satisfying the U values and linear losses of BR15's chapter 7.4.2 (figure 13), you can choose to use the energy performance frameworks for existing buildings - also called renovation classes.

This new method of satisfying the energy requirements during larger conversions and other alterations is voluntary and has been introduced to allow developers greater flexibility.

This means that instead of having requirements for achieving heat savings by re-insulating per building element and with accompanying cost-effectiveness calculations, the energy performance framework gives the freedom to carry out other energy saving measures that in total bring the building's energy demand down to a future-proof level.

Note, however, that when completely replacing a building element - e.g. an entire roof structure including new trusses, etc., or an installation - the requirements of figure 13 must always be met.

To fulfil the renovation classes, an energy performance framework must be satisfied, and the energy demand must be reduced by at least 30 kWh/m^2 per year. Furthermore, there must be a percentage of renewable energy in the total energy supply to the building. For Renovation Class 1, the requirements for a satisfactory indoor climate as specified in BR15's chapter 6.2, 6.3.1 and 6.5.3 must also be met.

Read the guide and case to learn more
A more detailed guide on the energy performance framework for existing buildings has been compiled with case examples in the pipeline. You can find it at:

http://sbi.dk/miljo-og-energi/energibesparelser/renoveringsklasser-for-eksisterende-bygninger-vejledning-og-eksempler/renoveringsklasser-for-eksisterende-bygninger (Danish)

Practical savings calculator

In order to calculate the expected savings for single-family houses, terraced houses and tower blocks, you can use the savings calculator at **www.ByggeriogEnergi.dk** (Danish)

Energy performance framework for existing buildings

Dwellings, student accommodations, hotels, etc.			**Energy label**
Renovation class 1	$52.5 + \frac{1,650}{\text{heated floor area}}$	kWh/m^2 per year	A
Renovation class 2	$110 + \frac{3,200}{\text{heated floor area}}$	kWh/m^2 per year	C
Offices, schools, institutions, etc			**Energy label**
Renovation class 1	$71.3 + \frac{1,650}{\text{heated floor area}}$	kWh/m^2 per year	A
Renovation class 2	$135 + \frac{3,200}{\text{heated floor area}}$	kWh/m^2 per year	C

Figure 16

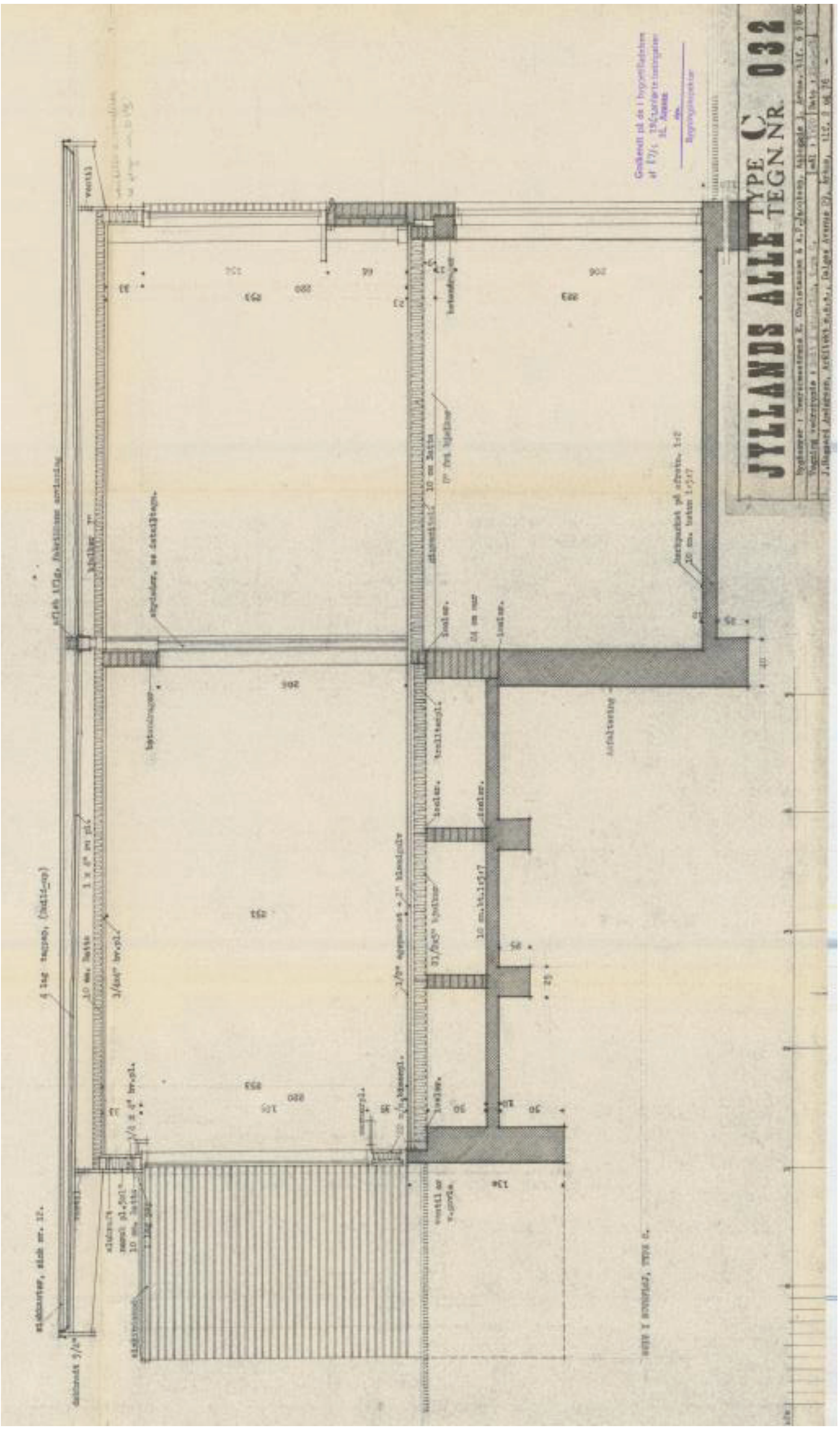
Appendix B Macroeconomic benefits of cost effective energy related renovation measures

Category	Non-energy benefit	Description
Environmental	Reduction of air pollution	Outdoor air pollution is reduced through reduced fossil fuel burning and the minimization of the heat island effect in warm periods. Less air pollution has positive impacts on environment, health impacts and building damages
	Construction and demolition waste reduction	Building renovation leads to reduction, reuse and recycling of waste compared to the replacement of existing buildings by new ones.
Economic	Lower energy prices	Decrease in energy prices due to reduced energy demand
	New business opportunities	New market niches for new companies (like ESCOs) resulting in higher GDP growth
	Employment creation	Reduced unemployment by labour intensive energy efficiency measures
	Rate subsidies avoided	Decrease of the amount of subsidized energy sold (in many countries energy for the population is heavily subsidized)
	Improved productivity	GDP/income/profit generated as a consequence of new business opportunities and employment creation
Social	Improved social welfare, less fuel poverty	Reduced expenditures on fuel and electricity; less affected persons by low energy service level, less exposure to energy price fluctuations
	Increased comfort	Normalizing humidity and temperature indicators; less air drafts, more air purity; reduced heat stress through reduced heat islands.
	Reduced mortality and morbidity	Reduced mortality due to less indoor and outdoor air pollution and reduced thermal stress in buildings. Reduced morbidity due to better lighting and mould abatement.
	Reduced physiological effects	Learning and productivity benefits due to better concentration, savings/higher productivity due to avoided “sick building syndrome”.
	Energy security	Reduced dependence on imported energy

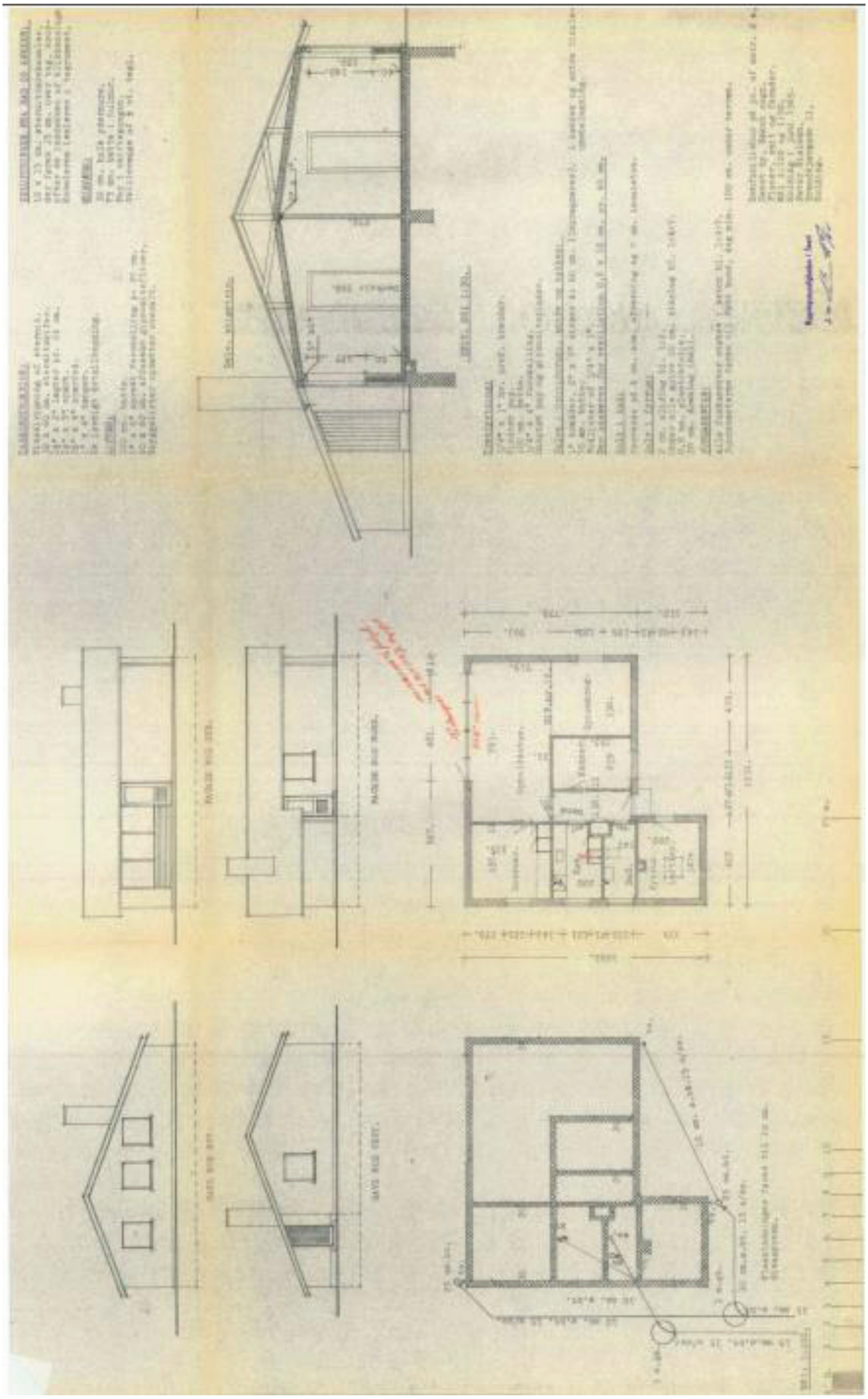
Table 10.1 Typology of macroeconomic benefits of cost effective energy related renovation measures (Ferreira & Almeida 2015).

Appendix C Reference Houses

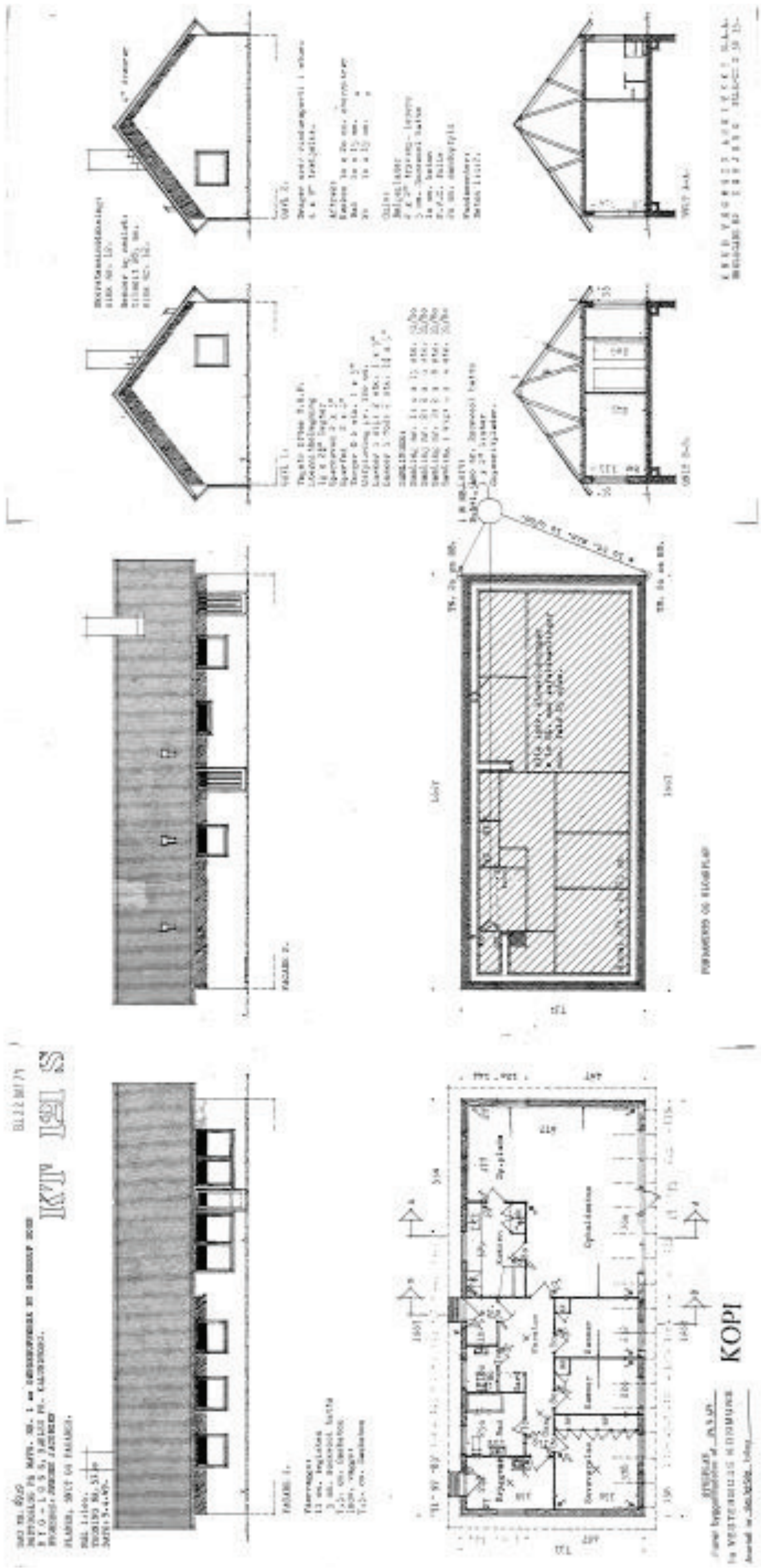
Reference House A



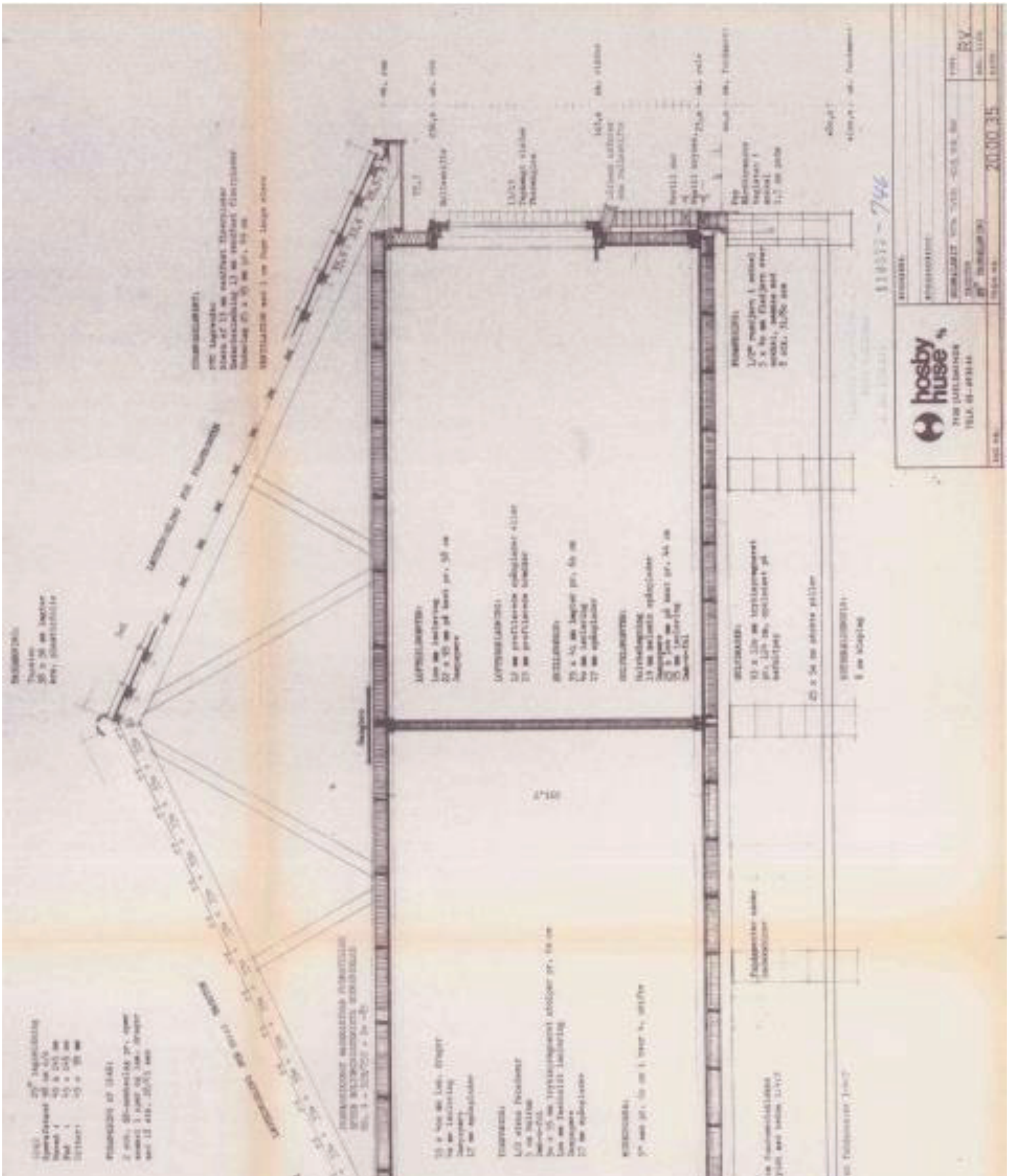
Reference House B



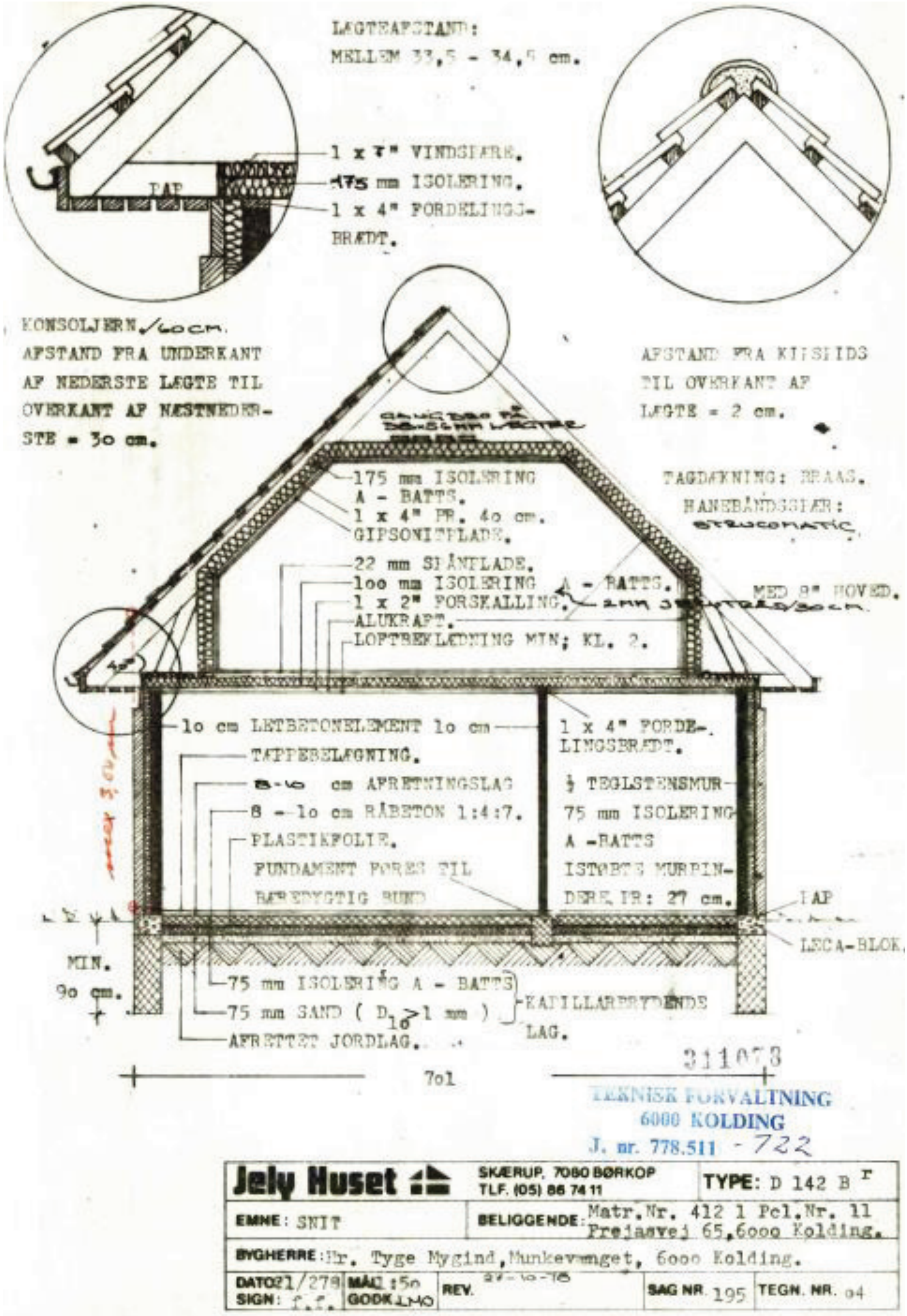
Reference House C



Reference House D



Reference House E



Appendix D Insulation

In this appendix, prices for each insulation material is presented. Same prices were used to calculate the prices for all construction components as price estimation for the tool.

Insulation material	**Thickness [mm]**	**Price pr.m2**
Glass wool	100	81
Rock wool	120	110
Expanded Polystyrene (EPS)	110	101
Polyisocyanurate foam (PIR)	70	185
Foam glass	120	404
Grey EPS	95	122
Vacuum insulating panels (VIP)	25	820
Cellulose fibre	125	185
Mineral fiber	130	162
Expanded perlite	135	297

References:

https://energy.gov/energysaver/types-insulation

http://www.bygmax.dk/jackon-super-eps-80-facade-50x600x1200mm-864m2-pk.html

https://www.jackon.dk/produkter/jackon-eps/jackon-super-eps-2/jackon-super-eps-80-facadeplader-2/

http://www.kingspaninsulation.eu/getattachment/Price-List-International-Sales-March-2014.pdf.aspx

http://www.ai.dk/blog/posts/2014/baeredygtig-isolering/

http://www.uvalueinsulations.co.uk/images/U_Value_Price__Guide_4.pdf

Appendix E Be15: Reference Houses

Be15: Reference House B

Model: Ref B 1966 El-vej 17, 6000 Kolding - 1966	SBi Beregningskerne 8.16.1.6
Be15 key numbers: Ref B 1966 El-vej 17, 6000 Kolding - 1966	
Transmission loss, W/m²	
Building envelope excl. of windows and doors	13,6
Renovation class 2, kWh/m² year	
Energy frame renovation class 2, without addition	141,5
Addition for special terms	0,0
Total energy frame	141,5
Total energy requirement	135,3
Renovation class 1, kWh/m² year	
Energy frame renovation class 1, without addition	68,7
Addition for special terms	0,0
Total energy frame	68,7
Total energy requirement	135,3
Energy frame BR 2015, kWh/m² year	
Energy frame low energy 2015, without addition	39,8
Addition for special terms	0,0
Total energy frame	39,8
Total energy requirement	108,3
Energy frame Buildings 2020, kWh/m² year	
Energy frame Buildings 2020, without addition	20,0
Addition for special terms	0,0
Total energy frame	20,0
Total energy requirement	81,2
Contribution to energy requirement, kWh/m² year	
Heating	135,3
El. for service of buildings	0,0
Excess temperature in rooms	0,0
Net requirement, kWh/m² year	
Room heating	135,3
Domestic hot water	13,1
Cooling	0,0
Selected el. requirements, kWh/m² year	
Lighting	0,0
Heating of rooms	0,0
Heating of domestic hot water	0,0
Heat pump	0,0
Ventilators	0,0
Pumps	0,0
Cooling	0,0
Heat loss from installations, kWh/m² year	
Room heating	0,0
Domestic hot water	0,0
Output from special sources, kWh/m² year	
Solar heat	0,0
Heat pump	0,0
Solar cells	0,0
Wind mills	0,0
Total el. requirement, kWh/m² year	
El. requirement	30,7

Be15: Reference House C

Model: Ref C Rønnesholm 8, 4200 Slagelse - 1968	SBi Beregningskerne 8.16.1.6
Be15 key numbers: Ref C Rønnesholm 8, 4200 Slagelse - 1968	
Transmission loss, W/m²	
Building envelope excl. of windows and doors	14,9
Renovation class 2, kWh/m² year	
Energy frame renovation class 2, without addition	136,2
Addition for special terms	0,0
Total energy frame	136,2
Total energy requirement	215,4
Renovation class 1, kWh/m² year	
Energy frame renovation class 1, without addition	66,0
Addition for special terms	0,0
Total energy frame	66,0
Total energy requirement	215,4
Energy frame BR 2015, kWh/m² year	
Energy frame low energy 2015, without addition	38,2
Addition for special terms	0,0
Total energy frame	38,2
Total energy requirement	172,3
Energy frame Buildings 2020, kWh/m² year	
Energy frame Buildings 2020, without addition	20,0
Addition for special terms	0,0
Total energy frame	20,0
Total energy requirement	129,2
Contribution to energy requirement, kWh/m² year	
Heating	215,4
El. for service of buildings	0,0
Excess temperature in rooms	0,0
Net requirement, kWh/m² year	
Room heating	215,4
Domestic hot water	13,1
Cooling	0,0
Selected el. requirements, kWh/m² year	
Lighting	0,0
Heating of rooms	0,0
Heating of domestic hot water	0,0
Heat pump	0,0
Ventilators	0,0
Pumps	0,0
Cooling	0,0
Heat loss from installations, kWh/m² year	
Room heating	0,0
Domestic hot water	0,0
Output from special sources, kWh/m² year	
Solar heat	0,0
Heat pump	0,0
Solar cells	0,0
Wind mills	0,0
Total el. requirement, kWh/m² year	
El. requirement	30,7

Be15: Reference House D

Model: Ref D Klintevej 73, 6000 Kolding - 1975	SBi Beregningskerne 8.16.1.6
Be15 key numbers: Ref D Klintevej 73, 6000 Kolding - 1975	
Transmission loss, W/m²	
Building envelope excl. of windows and doors	14,7
Renovation class 2, kWh/m² year	
Energy frame renovation class 2, without addition	141,1
Addition for special terms	0,0
Total energy frame	141,1
Total energy requirement	154,2
Renovation class 1, kWh/m² year	
Energy frame renovation class 1, without addition	68,5
Addition for special terms	0,0
Total energy frame	68,5
Total energy requirement	154,2
Energy frame BR 2015, kWh/m² year	
Energy frame low energy 2015, without addition	39,7
Addition for special terms	0,0
Total energy frame	39,7
Total energy requirement	123,4
Energy frame Buildings 2020, kWh/m² year	
Energy frame Buildings 2020, without addition	20,0
Addition for special terms	0,0
Total energy frame	20,0
Total energy requirement	92,5
Contribution to energy requirement, kWh/m² year	
Heating	154,2
El. for service of buildings	0,0
Excess temperature in rooms	0,0
Net requirement, kWh/m² year	
Room heating	154,2
Domestic hot water	13,1
Cooling	0,0
Selected el. requirements, kWh/m² year	
Lighting	0,0
Heating of rooms	0,0
Heating of domestic hot water	0,0
Heat pump	0,0
Ventilators	0,0
Pumps	0,0
Cooling	0,0
Heat loss from installations, kWh/m² year	
Room heating	0,0
Domestic hot water	0,0
Output from special sources, kWh/m² year	
Solar heat	0,0
Heat pump	0,0
Solar cells	0,0
Wind mills	0,0
Total el. requirement, kWh/m² year	
El. requirement	30,7

Be15: Reference House E

Model: Ref E Frejasveh 65, 6000 Kolding - 1978	SBi Beregningskerne 8.16.1.6
Be15 key numbers: Ref E Frejasvej 65, 6000 Kolding - 1978	
Transmission loss, W/m²	
Building envelope excl. of windows and doors	11,1
Renovation class 2, kWh/m² year	
Energy frame renovation class 2, without addition	131,1
Addition for special terms	0,0
Total energy frame	131,1
Total energy requirement	91,7
Renovation class 1, kWh/m² year	
Energy frame renovation class 1, without addition	63,4
Addition for special terms	0,0
Total energy frame	63,4
Total energy requirement	91,7
Energy frame BR 2015, kWh/m² year	
Energy frame low energy 2015, without addition	36,6
Addition for special terms	0,0
Total energy frame	36,6
Total energy requirement	73,4
Energy frame Buildings 2020, kWh/m² year	
Energy frame Buildings 2020, without addition	20,0
Addition for special terms	0,0
Total energy frame	20,0
Total energy requirement	55,0
Contribution to energy requirement, kWh/m² year	
Heating	91,7
El. for service of buildings	0,0
Excess temperature in rooms	0,0
Net requirement, kWh/m² year	
Room heating	91,7
Domestic hot water	13,1
Cooling	0,0
Selected el. requirements, kWh/m² year	
Lighting	0,0
Heating of rooms	0,0
Heating of domestic hot water	0,0
Heat pump	0,0
Ventilators	0,0
Pumps	0,0
Cooling	0,0
Heat loss from installations, kWh/m² year	
Room heating	0,0
Domestic hot water	0,0
Output from special sources, kWh/m² year	
Solar heat	0,0
Heat pump	0,0
Solar cells	0,0
Wind mills	0,0
Total el. requirement, kWh/m² year	
El. requirement	30,7

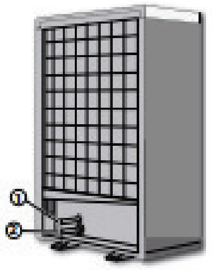
Appendix F Heating

ENGINEERING TOMORROW

Danfoss

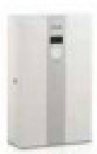
Tekniske specifikationer **DHP-AQ**

Tilslutninger
1 Fremløb varmeanlæg (alle størrelser) - 28 mm Cu
2 Returløb varmeanlæg (alle størrelser) - 28 mm Cu

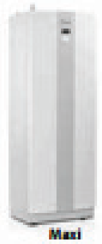


Indedel

Mini: Styring til DHP-AQ (6 til 36 kW) Leveres uden varmtvandsbeholder, skal installeres med elpatron
Midi: Styring til DHP-AQ 6 til 18 kW cirkulationspumpe, El-patron, trevejsventil. Leveres uden varmtvandsbeholder
Maxi: Styring til DHP-AQ 6 til 13 kW, varmtvandsbeholder (180 l), cirulationspumpe (A-mærket), El-patron trevejsventil


Mini


Midi


Maxi

DHP-AQ			6	9	11	13	16	18
Kølemiddel	Type		R407C	R407C	R407C	R407C	R407C	R407C
	Mængde	kg	4,0	4,3	5,0	5,1	5,7	6,0
	Testtryk	MPa	3,4	3,4	3,4	3,4	3,4	3,4
	Maks. tryk	MPa	3,1	3,1	3,1	3,1	3.1	3,1
Kompressor	Type		Scroll	Scroll	Scroll	Scroll	Scroll	Scroll
	Olie		POE	POE	POE	POE	POE	POE
Elektriske data 3-N, ~50Hz	Netspænding	Volt	400	400	400	400	400	400
	Mærkeeffekt, kompressor	kW	2,2	2,9	3,3	4,2	5,0	6,1
	Mærkeeffekt, ventilator	kW	0,2	0,2	0,2	0,3	0,3	0,7
	Startstrøm	A	12	10	18	17	18	18
	Sikringsstørrelse	A	10	10	16	16	16	16
Ydelse	COP[1]		4,7	4,7	5,0	4,7	4,6	4,3
	COP[2]		4,3	4,4	4,7	4,4	4,1	4,0
	Varmeffekt[2]	kW	6,5	8,6	11,1	12,3	15,2	17,6
	Indgående effekt - opvarm.[2]	kW	1,5	2,0	2,4	2,8	3,7	4,4
	EER[3]		2,2	2,4	2,5	2,4	2,3	2,3
	Køleeffekt[3]	kW	4,2	5,9	7,5	8,9	10,4	13,1
	Indgående effekt - køling[3]		1,9	2,5	3,0	3,7	4,5	5,7
Energiklasse - pakke[9]	Gulvvarme (35°C)/Radiator (55 °C)		A+/A+	A+/A++	A++/A+	A++/A++	A++/A+	A+/A+
Energiklasse - produkt[10]	Gulvvarme (35°C)/Radiator (55 °C)		A+/A+	A+/A++	A++/A+	A+/A++	A++/A+	A+/A+
	Varmtvandsbeholder		B	A	A	A	B	B
Nominelt flow[4]	Varmekreds	l/s	0,150	0,216	0,263	0,299	0,372	0,432
Driftsområde (udendørs)		°C	-20~+45°C	-20~+45°C	-20~+45°C	-20~+45°C	-20~+45°C	-20~+45°C
Maks. temperatur[8]	Varmekreds	°C	60	60	60	60	60	60
Trykniveauer	Lavtryk	MPa	0,05	0,05	0,05	0,05	0,05	0,05
	Drift	MPa	2,85	2,85	2,85	2,85	2,85	2,85
	Højtryk	MPa	3,1	3,1	3,1	3,1	3,1	3,1
Lydeffektniveau	Normal[6]	dB(A)	61	61	61	62	66	76
	Lavt[6]	dB(A)	60	59	60	61	64	71
Lydtrykniveau (1 meter)	Normal[7]	dB (A)	46	46	46	47	51	61
	Lavt[7]	dB (A)	45	44	44	46	48	55
Vægt	Udedel	kg	125	131	150	155	185	191
	Mini / Midi / Maxi	kg	18/21/106	18/21/106	18/21/106	18/21/106	18/21/ -	18/21/ -
Udedel	Bredde x dybde x højde	mm	856x510x1272	856x510x1272	1016x564x1477	1016x564x1477	1166x570x1557	1166x570x1557
Mini (Indendørskit)	Bredde x dybde x højde	mm	380x204x600					
Midi (Indendørskit)	Bredde x dybde x højde	mm	420x255x625 (+50 mm rør)					
Maxi (Indendørskit)	Bredde x dybde x højde	mm	596x690x1845 ±10					

Ønskes en varmepumpe med en kapacitet over 18 kW, skal der installeres to udedele og en indedel.

Målingerne* er udført på et begrænset antal varmepumper, hvilket kan forårsage variationer i forbindelse med resultaterne. Tolerancer i målemetoderne kan også forårsage variationer.

1) Ved A7/W35 Δ10K varm side. (EN 255)
2) Ved A7/W35 iht. EN 14511.
3) Ved A35/W7 iht. EN14511
4) Nominelt flow: varmekreds Δ10K.
5) Ved udetemperatur 0°C
6) Iht.SS-EN 12102, EN ISO 374
7) Iht.ISO 11203
8) Gældende for varmepumper med rene veksler
9) Når varmepumpen er del af en pakkeløsning
10) Når varmepumpen er uden tilbehør

A++ energieffektivitetsklassen når varmepumpen er del af en pakkeløsning, gælder for DHP-AQ 13

A++ energieffektivitetsklassen når varmepumpen er uden tilbehør, gælder for DHP-AQ 13. Energiklasse i følge Eco-design Directive 811/2013

Appendix G Solar Collectors

A solar collector absorbs solar radiation, then the collector converts it into useful heat that is then transferred into the system by the heat transfer fluid. There are many different types and design concepts of collectors available on the marked - e.g. Table 10.2.

Solar Collector Types	Absorber Types	Cover Types
Flat - plate collector	Fluid collector	Optically plane collector
Evacuated tube collector	Air collector	Foils
Concentrated collector		Structured (layered) covers

Table 10.2 Collector, Absorber and Cover types

- **Flat-plate collectors**
  The most popular and most sold solar collectors are of the flat-plate variety. They are as well the most commonly used collectors in domestic water system, like needed in this project. A normal flat-plate collector can be described as a large, shallow metal box with glass or plastic cover (called glazing) on the top as shown in Figure 10.1.

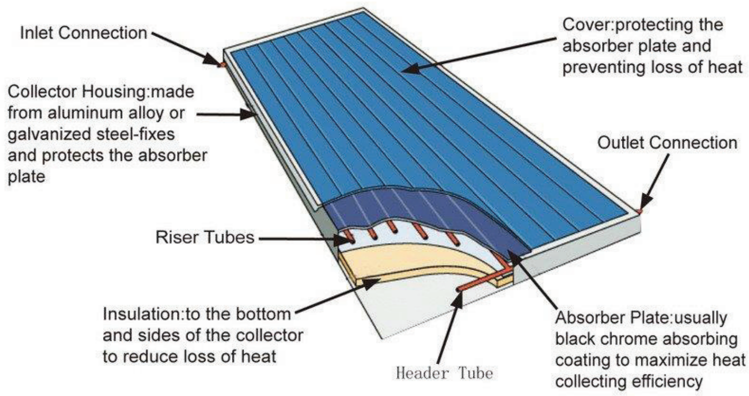


Figure 10.1 A typical flat plate collector construction (P.McCarty & K.Crumbaker, 2013)

The front cover must be well sealed to the collector box so that heat does not escape, and dirt, insects or humidity does not get into the collector. The properties of the glazing is very important because it can have a big influence/effect on the efficiency of the collector. Underneath the glass cover at the bottom of the box is dark-coloured absorber plate, separated with an air gap. Small absorber tubes run though the box attached underneath the absorber plates and carry the fluid, e.g. water or antifreeze, which will get heat up. The absorber plates then convert the sunlight to heat and transfer it to the fluid passing though in the absorber tubes. The fluid is then moved through the system from the collector to the storages tank by controllers and pump. The sides and the bottom of the collector box are then insulated to minimize the heat loss as shown in Figure 10.2.

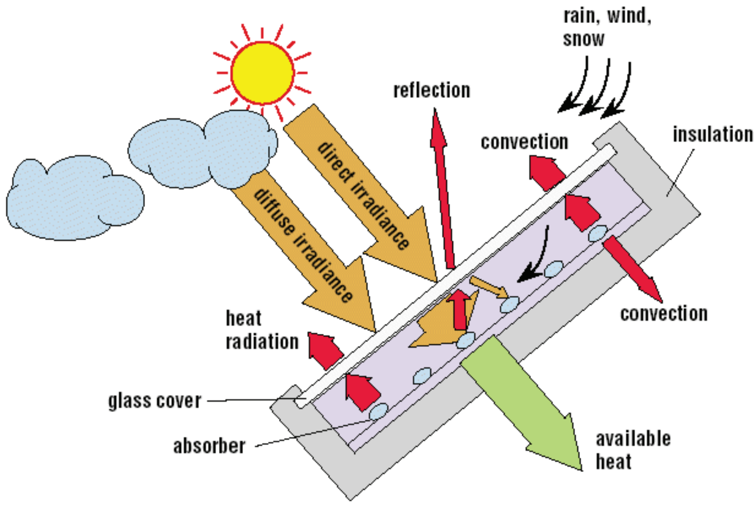


Figure 10.2 Example of flat plate collector and its processes (Volker Quaschning 2004)

However, mostly due to the temperature between the absorber and the ambient air, some convective and radiative heat losses due occur in the collector (Volker Quaschning 2004). The convectional heat loss is caused by air movements, while the radiative hear loss is caused by exchange of heat by radiation between the absorber and the atmosphere/environment, as shown in Figure 10.2. However, the glazing covering of the collector helps to prevent most of the convection losses and reduces the heat radiation from the absorber into the environment. Small part of the sunlight is then reflected when it hits the glazing, which means it never reaches the absorber at all (Crumbaker & McCarty n.d.).

- **Evacuated tube collectors**

An evacuated tube collector has rows of transparent closed glass tubes; each tube contains a glass outer tube and inside there is a metal heat absorber sheet/plate with a metal absorbent heat pipe in the middle, as shown in Figure 10.3.

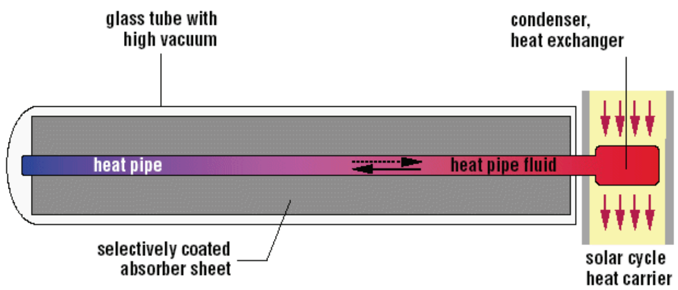


Figure 10.3 Cross-section view of an evacuated tube collector with a heat pipe (Volker Quaschning, 2004)

The heat pipe in the middle then contains a special temperature sensitive fluid such as methanol or alcohol that travels in the pipe. Inside the glass tube there is high vacuum around the absorbers that increases the resistance and minimizes heat loss, which as well helps absorb solar energy under cloudy conditions (Crumbaker & McCarty n.d.). A condenser and heat exchanger is on the top of the glass tube, as shown in Figure 10.3.

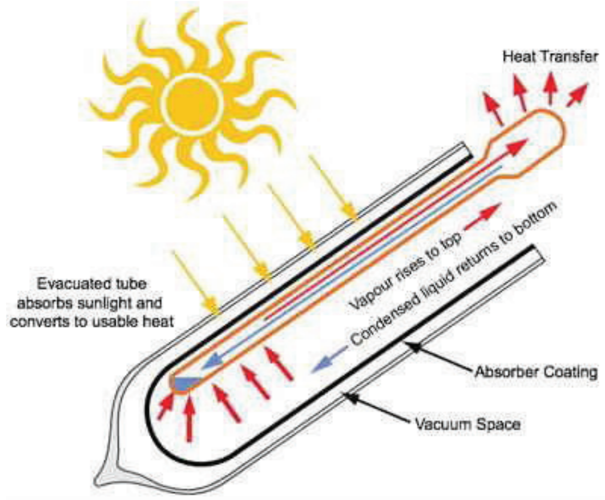


Figure 10.4 The principals from the process when the evacuated tube absorbs the sunlight and converts to usable heat (Apricus Australia, u.d.)

When the sun heats up the tube and the fluid in the heat pipe vaporizes, the vapor rises up to the top of the pipe where the condenser and heat exchanger are located, as shown in Figure 10.4. When the vapor reaches the condenser and heat exchanger, it condenses and transfer the heat to the heat carrier of the solar cycle, usually water with antifreeze agent. Then the condensed fluid turns back into liquid returning to the bottom of the heat pipe, and then the process starts over again. It is important to keep in mind that the pipes must have a minimum angel of inclination, so the vapor can rise and the fluid can flow back (Volker Quaschning 2004).

A better overview of the area where the condenser and heat exchanger are located on the top of the pipe can then be seen in Figure 10.5. All the pipes in the evacuated tube collector are connected to a common insulated supply pipe in a manifold (heat exchanger). The cold water is led in on one side by the circulation pumps that moves the liquid through the collector; the condenser from each tube then heats up the water that goes through, and then the hot water is carried back to a storages tank that prepares the hot water.

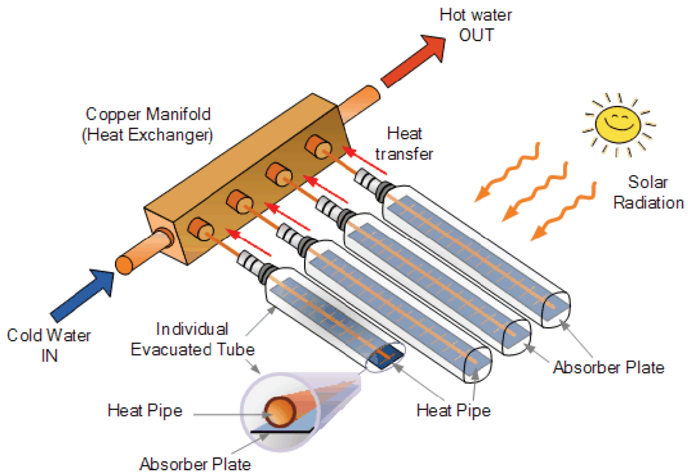


Figure 10.5 The heat transfer process of a whole evacuated tube collector. (Alternative Energy Tutorials, 2015)

Due to the high insulating values caused by the vacuum inside the glass tube, the evacuated tube collectors can perform very well and have higher total efficiency in all areas compared to the standard flat plate collectors. Even in cold weather, they can heat water to fairly high temperatures when the flat plate collectors perform poorly due to the high heat loss. Even on humid, overcast days with no direct sunlight, they can operate and extract heat out of the air.

The disadvantage of the evacuated tube collectors is that they can be quite expensive compared to the standards flat plate collectors. There is as well a weak point in the collector, where the heat pipe connects to the supply pipe in the manifold, but this point needs especially to be considered and taken care of with vacuum. If the heat pipe would crack or brake, it could affect the efficiency of the system.

The evacuated tube collector can achieve extremely high temperatures, which make them more suitable for industrial and commercial hot water heating applications. They can as well be a good alternative to the flat plate collectors for domestic space heating, especially in places where it is often cold and cloudy (Alternative Energy Tutorials 2015).

- **Concentrating collectors**

The concentrating collectors achieve very high temperatures by using mirrors, reflectors or lenses to concentrate the suns radiant energy into a single area or beam, as shown in Figure 10.6. If a magnifying glass or a mirror are used to focus the sunlight onto a specific point, an intense heat would be produced on that specific point.

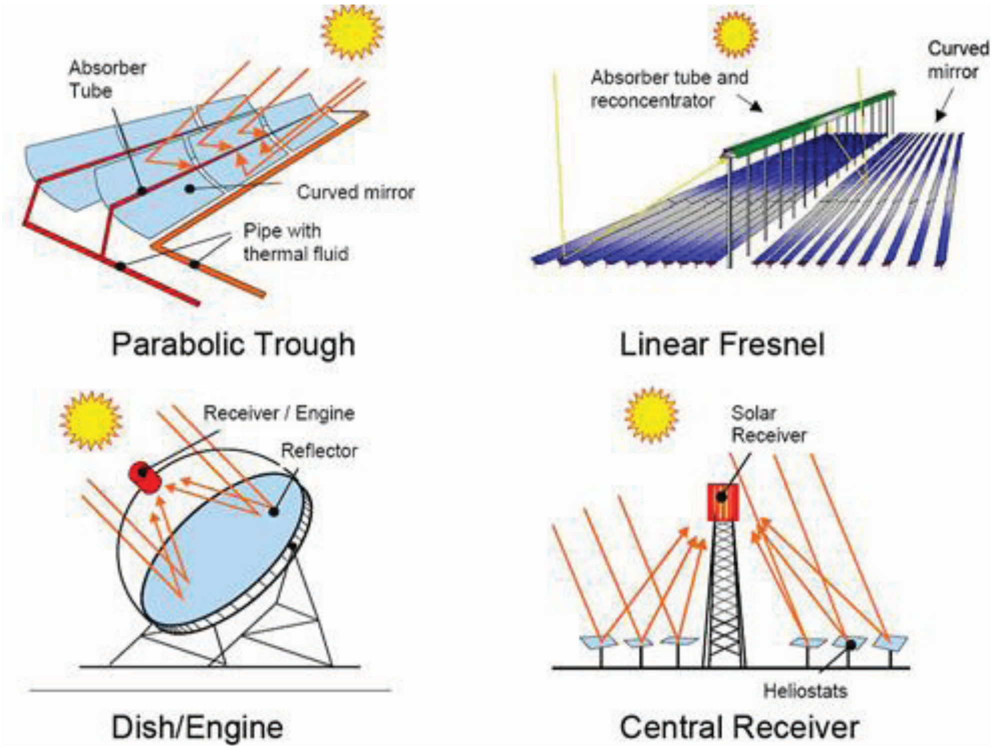


Figure 10.6 Different types of Concentrating collector systems/ power plants (Meteorological Reactors , 2016)

When the Concentrating collectors are compared to non-concentrating collectors, e.g. flat plate collectors or evacuated tube collector, the temperatures level that can be achieved differ significantly. While the temperature levels in the non-concentrating collectors are limited, the high temperatures achieved in the Concentrating collectors by concentrating the sunlight at a specific point results in an increased efficiency of the system and making it more flexible.

Different kinds of collector systems are available, as show in Figure 10.6. The most common types are the Parabolic Though and the Dish reflector. The Parabolic Though system concentrates the solar power onto an absorber tube by using mirrors, which then heats up the fluid inside it and creates hot water. The Dish reflector, uses reflective dish (looks like a TV satellite) to focus sunlight on a receiver that is positioned above the dish. Then there are special Concentrating collectors - fields/power plants, like shown on the right side in Figure 10.6. Those fields are usually covered with mirrors that all concentrate the sun power at a specific receiver creating an extremely high temperature (Alternative Energy Tutorials 2015).

The heat produced by this kind of collector could be used for conventional domestic and industrial hot water heating but they are generally used more for electric power production due to the high temperature system, e.g. the Linear Fresnel uses the heat collected in the overhead collector tube (Figure 10.6) to produce super-heated steam to turn generators. However, this kind of system can take up allot of space and is considerable more expensive than non-concentrating systems (Alternative Energy Tutorials 2015).

Appendix H Heat Pumps

Theoretical Background[14]

A heat pump is a mechanical-compression cycle refrigeration system that can be reversed to either heat or cool a controlled space. A compressor circulates refrigerant that absorbs and releases heat as it travels between the indoor and outdoor units - Figure 10.7.

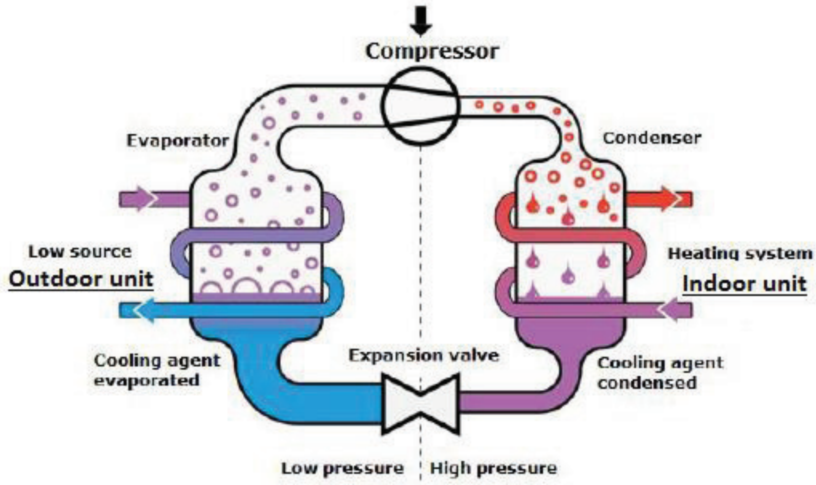


Figure 10.7 Principle diagram of a heat pump

The working fluid, in its gaseous state, is pressurized and circulated through the system by a compressor. On the discharge side of the compressor, the now hot and highly pressurized vapour is cooled in a heat exchanger, called a condenser, until it condenses into a high pressure, moderate temperature liquid. The condensed refrigerant then passes through a pressure-lowering device also called a metering device. This may be an expansion valve, capillary tube, or possibly a work-extracting device such as a turbine. The low pressure liquid refrigerant then enters another heat exchanger, the evaporator, in which the fluid absorbs heat and boils. The refrigerant then returns to the compressor and the cycle is repeated.

When it comes to generating hot water, the heat pump needs to 'pump' the heat to a higher temperature level, to a flow temperature of 55 °C. The heat pump has to work harder to reach this higher flow temperature, and this requires more electrical energy.

That means that the higher the required flow temperature, the harder a heat pump needs to work. Therefore, it is extremely important that the temperature difference between the heat source (e.g. groundwater, brine or air) and thermal heat (e.g. flow temperature for heating) is as small as possible. This observation demonstrates that a water-water heat pump with a source temperature of around 10 °C will need less auxiliary energy than a brine-water heat pump with a source temperature of around 0 °C. It is also clear that the flow temperature should be as low as possible. This is easy to achieve for underfloor or wall surface heating. It is also

[14] Theoretical description and comparison of the different types of heat pumps is based on "Heat Pump Planning Handbook" by Jürgen Bonin

clear that it makes little or no sense to use a heat pump to heat radiators with high flow temperatures (Bonin n.d.).

In the following sub-chapters different heat pumps will be described according to their low energy source – water-to-water, brine-to-water and air-to-water heat pumps.

10.1 Geothermal (Brine To Water)

Brine-to-water heat pump system extracts heat from the ground (geothermal heat generation) via a closed brine circuit. This circuit contains glycol-water mixture (30/35% – 70/65%), which prevents it from freezing in the evaporator. The temperature of the heat source for the pump is generally assumed at 0°C and the return temperature of the circuit at -3°C. The reason of having lower temperatures than water-to-water system is that after period of operation the brine circuit cools the ground temperature around it.

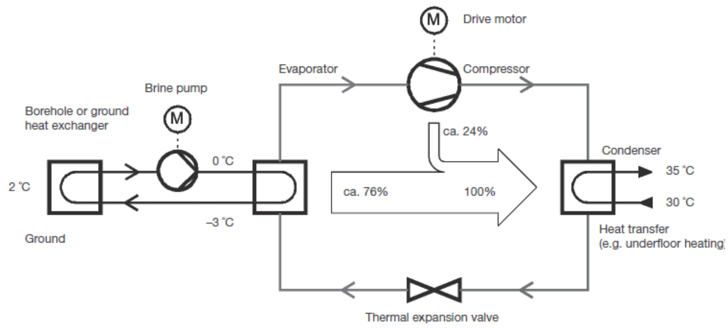


Figure 10.8 Principle diagram of brine-to-water heat pump

The brine-to-water heat pump system sustains from hot water tank, storage tank, heat pump and heat exchangers. There are two types of such heat pump systems and they are defined by the type of the heat exchangers, which can be borehole or ground. The difference between them is that borehole are installed vertically into the ground, making the installation cost very high, and ground heat exchangers are installed horizontally, which is a cheaper solution. Both solutions efficiency is similar, excluding the fact that ground heat-exchangers cannot provide free cooling.

10.2 Air to Water

Air-to-water heat pump system extracts heat from the ambient air (aero thermal energy extraction). This type of system consists of intake air duct, exhaust air duct, hot water tank, storage tank, heat pump and evaporator. As the specific heat capacity of the air is very low, large volumes of air need to be circulated and accordingly large ventilators are required, which results in big amount of operating power. The biggest disadvantage of such systems is that the heat source is coldest at times when the demand is highest. Therefore, they have low operational efficiency level during these periods. There is also high risk of the evaporator to freeze, especially when operating in damp air.

Appendix I Electricity

Appliances

The electricity used by household appliances may vary. Some electrical appliances use a lot of electricity while others do not. This is very important to take into consideration when choosing appliances for the household.

Household appliances sold in EU is marked with an energy mark to indicate the energy consumption. All white goods, light bulbs, TV's etc. needs to have this mark when it is sold in the EU in order for the consumer to compare products. Figure 10.9. illustrates an energy mark for a fridge. It gives the overall score according to electricity consumption on a scale from A+++ to G, and use per year (280 kWh/annum). Extra info on the bottom of the mark, is the volume and noise level. This information varies depending on the product, size and type.

Figure 10.9 EU Energy Mark - Fridge (REHVA 2013)

Typically, the freezer and refrigerator are in use all year around, using a lot of electricity. These appliances have a long service life, average of 13 years, so it is a good idea, when the goal is to decrease the electricity consumption of the household, to check the energy consumption of the appliances and see if they need to be replaced with a new and more energy efficient model (Umweltbundesamt und Öko-institute e. V. 2015). Example of the running cost difference between energy mark A or A+++ for a fridge, freezer, or chest freezer is indicated in Table 10.3.

Appliances / DKK	A		A+		A++		A+++	
	Year	Lifespan	Year	Lifespan	Year	Lifespan	Year	Lifespan
Fridge, 200 L	166	2,158	132	1,716	99	1,287	66	858
Freezer, 200 L	357	4,641	285	3,705	214	2,782	143	1,859
Chest freezer, 200 L	291	3,783	233	3,029	175	2,275	117	1,521

Table 10.3 Electricity consumption of household appliances in DKK (Energistyrelsen 2016c). Lifespan are 13 years (Umweltbundesamt und Öko-institute e. V. 2015).

So, choosing the correct size of the fridge with the best energy mark possible will help avoiding unnecessary energy consumption. Rule of thumb when buying a fridge is 100 Litres for one person and extra 50 Litres for each extra person (Energistyrelsen 2016c). A price search for the cheapest shows that a fridge around 200 Litres A+ cost 1,967 - 2,488 DKK whereas an A+++ 6,746 – 9,159 DKK (all prices from *Skousen* and *Wupti*, October 19th, 2016). Comparing the lifespan prices in Table 10.3 reveals that it would not be a profitable investment to choose the A+++ compared to an A+. There are other parameters to take into account such as size (length, width, and depth, design, and different features (taps, LED light, noise level).

Some other electricity saving methods to have in mind is the placement of the appliances and the temperature of the room. Placing the fridge or freezer in a room with only 16°C instead of 20°C can lead to savings up to 10 % of the electricity consumption. Fridge and freezer should be cleaned frequently and have enough air movement on the backside in order for optimal functionality. Changing the user behaviour to thawing food in the fridge will also have a positive effect on the electricity consumption (Energistyrelsen 2016c).

Other appliances, common in a household, are indicated in Figure 10.10. User behaviour has a great influence on consumption. Switching the appliances completely off when they are not in use, instead of using the standby function, will save energy. The standby function is not included in Figure 10.10, however, for a smart TV it is estimated to be up to 40 kWh/year or 100 DKK/year (Energistyrelsen 2016c). To be able to minimize the standby, a master turn-off switch/socket or timer can help the consumer remembering to turn everything off when not in use. Having in mind Figure 10.10 when buying new appliances and what it will be used for, is also important to reduce the electricity consumption. For example, the consumer should consider if he needs both a TV, a laptop and a tablet when maybe the tablet covers all his needs. Buying or replacing a TV and a digital receiver with a combined version, is a similar way of lowering the consumption where the number of appliances in the household is reduced.

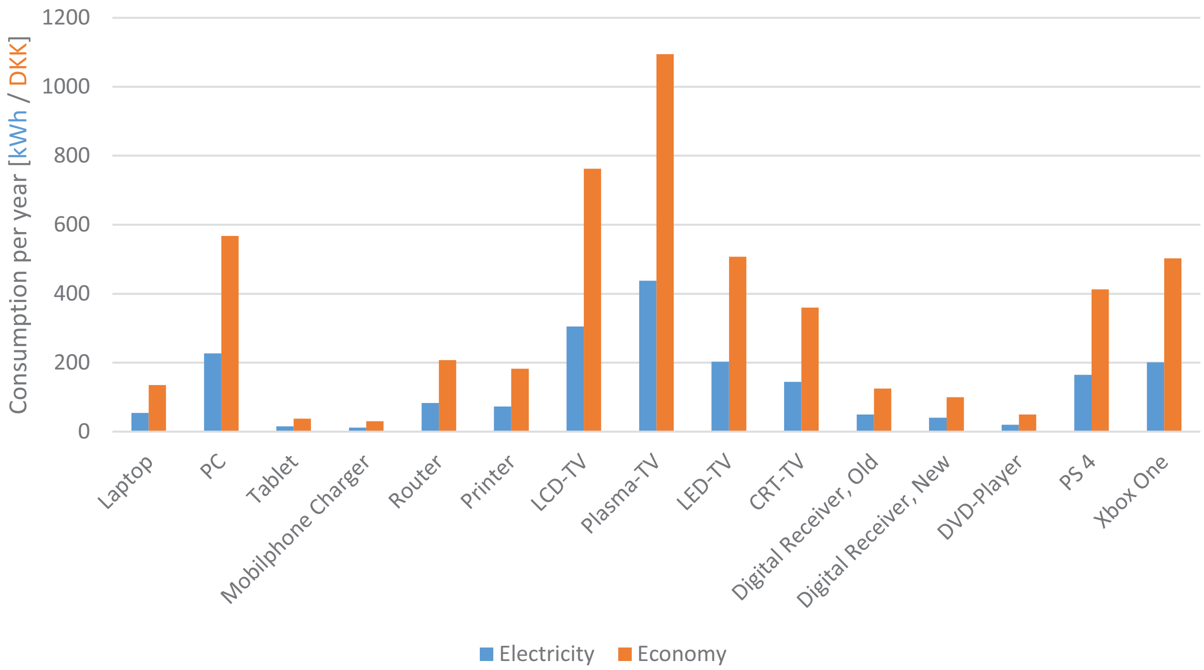


Figure 10.10 Appliances – average energy consumption. 2.50 DKK

Washing machines and dryers have the same energy mark as described for fridge, freezers, and TV's. For washing machines, the mark also takes the water consumption into consideration. The more clothing the machine can handle [Kg] the more water the machine uses.

The water used for the washing machine can either come from the drinking water, or the more sustainable solution, using rainwater. In Table 10.4 the water consumption for different sizes of machines is 44 % higher from a 3 - 5 Kg to the large one with 8 Kg. Using the right washing powder allows the user to wash clothing at temperatures as low as 20°C, making the process more sustainable. Sometimes higher temperatures are needed (e.g. if there are allergic people in the house). Typically, washing machines are using electricity to raise the water temperature. Connecting the machine to the hot water tap, when the heating system is district heating or a renewable source, could prove to be a more sustainable solution (Energistyrelsen 2016c).

Machine Size *[Kg]*	**Water Consumption per wash** *[Litres]*	**Price per wash** *[DKK]*
3 – 5	39	0.52
6 – 7	44	0.60
8	56	0.75

Table 10.4 Washing Machines consumption (Energistyrelsen 2016c). 13.31 DKK/m^3 (Forsyningen 2016)

Generally speaking, it is a good idea to reduce the energy consumption before renewable sources are added.

Appendix J V&S Price book

Heating Source

Nr	Tekst	Mængde	Samlet KP	Avance	DB	Rabat	Salgspris	Samlet DG	Samlet DB
Boiler replaced with Gas Boiler 3-16 kW									
11.2-8.5,01	Udskifte kedel og VVB med gaskedel, ydelse 3-16 kW	1	54.567,42	6.321,28	0,00	0,00	60.889,00	0,104	6.321,58
			54.567,42	**6.321,28**	**0,00**		**60.889,00**	**0,104**	**6.321,58**
Boiler replaced with Air/Water heat pump incl. DHW tank									
11.2-8.7,01	Udskifte kedel og VVB med varmepumpe luft/vand, ydelse 6,2 kW	1	99.901,92	11.080,36	0,00	0,00	110.982,00	0,1	11.080,08
			99.901,92	**11.080,36**	**0,00**		**110.982,00**	**0,1**	**11.080,08**
Boiler replaced with Geothermal heat pump incl. DHW tank									
11.2-8.8,01	Udskifte kedel/VVB med varmepumpe jord/vand, ydelse 5,3 kW	1	105.627,15	11.999,64	0,00	0,00	117.627,00	0,102	11.999,85
			105.627,15	**11.999,64**	**0,00**		**117.627,00**	**0,102**	**11.999,85**
Boiler replaced with Gas Boiler 3-16 kW incl service line									
11.2-8.5,01	Udskifte kedel og VVB med gaskedel, ydelse 3-16 kW	1	54.567,42	6.321,28	0,00	0,00	60.889,00	0,104	6.321,58
(50)42.05,01	Gasledning af PE, Ø 63 mm	20	4.945,07	636,80	0,00	0,00	5.582,00	0,114	636,93
			59.512,49	**6.958,08**	**0,00**		**66.471,00**	**0,105**	**6.958,52**
Boiler replaced with district heating									
(50)54.05,02	Fjernvarmeledninger, Ø 26,9/110 mm	20	33.835,67	3.732,33	0,00	0,00	37.568,00	0,099	3.732,33
11.2-7.5,01	Udskiftning af pladevarmeveksler, ydelse 28 kW	1	4.259,18	482,38	0,00	0,00	4.742,00	0,102	482,82
			38.094,85	**4.214,71**	**0,00**		**42.310,00**	**0,1**	**4.215,15**
Boiler replaced with Bio									
11.2-8.9,01	Udskifte kedel/VVB med stokerfyr, ydelse 15 kW, og ny VVB	1	75.787,96	8.531,31	0,00	0,00	84.319,00	0,101	8.531,04
			75.787,96	**8.531,31**	**0,00**		**84.319,00**	**0,101**	**8.531,04**
Totalsum			**433.491,77**	**49.105,38**	**0,00**		**482.598,00**	**0,102**	**49.106,23**
Moms (25%)							**120.649,50**		
Totalsum inkl. moms							**603.247,50**		

Heating Pipes

Nr	Tekst	Mængde	Samlet KP	Avance	DB	Rabat	Salgspris	Samlet DG	Samlet DB
Insulation									
11.2-6.2,02	Isolere varmerør, Ø 22 mm, med rørskåle, 30 mm og Isogenopak	5	1.490,12	211,82	0,00	0,00	1.702,00	0,124	211,88
			1.490,12	**211,82**	**0,00**		**1.702,00**	**0,124**	**211,88**
11.2-6.2,01	Isolere varmerør, Ø 18 mm, med rørskåle, 20 mm og Isogenopak	5	1.233,44	177,72	0,00	0,00	1.411,00	0,126	177,56
			1.233,44	**177,72**	**0,00**		**1.411,00**	**0,126**	**177,56**
Totalsum			**2.723,57**	**389,55**	**0,00**		**3.113,00**	**0,125**	**389,43**
Moms (25%)							**778,25**		
Totalsum inkl. moms							**3.891,25**		

Photovoltaic Cells (PVs)

Num	Text	Quantity	Total CP	Avance	DB	Rabat	Salgspris	Samlet DG	Total GM
Solar Cells									
12.1-4.1,01	Solcelleanlæg, ydelse 5,7 kWp	1	71.197,60	8.439,58	0,00	0,00	79.637,00	0,106	8.439,40
			71.197,60	**8.439,58**	**0,00**		**79.637,00**	**0,106**	**8.439,40**
Solar Cells									
12.1-4.1,02	Solcelleanlæg, ydelse 1,14 kWp	1	45.992,31	5.153,55	0,00	0,00	51.146,00	0,101	5.153,69
			45.992,31	**5.153,55**	**0,00**		**51.146,00**	**0,101**	**5.153,69**
Total amount			**117.189,91**	**13.593,13**	**0,00**		**130.783,00**	**0,104**	**13.593,09**
VAT (25%)							**32.695,75**		
Total amount incl. VAT							**163.478,75**		

Circulation Pump

Nr	Tekst	Mængde	Samlet KP	Avance	DB	Rabat	Salgspris	Samlet DG	Samlet DB
11.2-7.1,01	Udskiftning af cirkulationspumpe, bolig 150 - 160 m^2	1	3.787,59	422,14	0,00	0,00	4.210,00	0,1	422,41
			3.787,59	**422,14**	**0,00**		**4.210,00**	**0,1**	**422,41**
Totalsum			**3.787,59**	**422,14**	**0,00**		**4.210,00**	**0,1**	**422,41**
Moms (25%)							**1.052,50**		
Totalsum inkl. moms							**5.262,50**		

Solar Heating

Nr	Tekst	Mængde	Samlet KP	Avance	DB	Rabat	Salgspris	Samlet DG	Samlet DB
Solar Heating (DHW)									
11.2-9.4,02	Anlæg med 4 solfangere 1,09 m2, for 3-4 personer	1	42.979,94	4.825,83	0,00	0,00	47.806,00	0,101	4.826,06
			42.979,94	**4.825,83**	**0,00**		**47.806,00**	**0,101**	**4.826,06**
Totalsum			**42.979,94**	**4.825,83**	**0,00**		**47.806,00**	**0,101**	**4.826,06**
Moms (25%)							**11.951,50**		
Totalsum inkl. moms							**59.757,50**		

Constructions

Nr	Tekst	Mængde	Samlet KP	Avance	DB	Rabat	Salgspris	Samlet DG	Samlet DB
External Wall, internal									
2.6-4.1,04	Forsatsvæg, træskelet/165 mm isolering/gips	50	70.703,38	9.399,91	0,00	0,00	80.103,00	0,117	9.399,62
			70.703,38	**9.399,91**	**0,00**		**80.103,00**	**0,117**	**9.399,62**
Ground Floor, no crawl space									
5.1-6.9,01	Udskifte terrændæk med slagger	140	206.603,98	25.041,03	0,00	0,00	231.645,00	0,108	25.041,02
			206.603,98	**25.041,03**	**0,00**		**231.645,00**	**0,108**	**25.041,02**
Roof, horizontal									
9.3-3.1,04	Efterisolering af tagrum med 350 mm Loftgranulat	140	48.524,43	5.996,30	0,00	0,00	54.521,00	0,11	5.996,57
			48.524,43	**5.996,30**	**0,00**		**54.521,00**	**0,11**	**5.996,57**
Ground Floor, with crawl space									
5.1-1.5,03	Efterisolere, 195 100 mm, krybekælderdæk	140	67.871,13	8.599,12	0,00	0,00	76.470,00	0,112	8.598,87
			67.871,13	**8.599,12**	**0,00**		**76.470,00**	**0,112**	**8.598,87**
Roof, new construction									
9.3-6.2,02	Efterisolering af skråvæg med gipsplader, 165 mm mineraluldsplader	140	118.167,84	14.969,89	0,00	0,00	133.138,00	0,112	14.970,16
1.1-6.5,03	Efterisolere tag med tagpap, 180 mm mineraluld	140	155.516,30	18.114,57	0,00	0,00	173.631,00	0,104	18.114,70
			273.684,14	**33.084,46**	**0,00**		**306.769,00**	**0,108**	**33.084,86**
External wall, external									
2.5-1.1,02	Isolering, REDArt, 200 mm mineraluld og puds	50	93.991,00	11.261,15	0,00	0,00	105.252,00	0,107	11.261,00
			93.991,00	**11.261,15**	**0,00**		**105.252,00**	**0,107**	**11.261,00**
Totalsum			**761.378,06**	**93.381,97**	**0,00**		**854.760,00**	**0,109**	**93.381,94**
Moms (25%)							**213.690,00**		
Totalsum inkl. moms							**1.068.450,00**		

Appendix K

TOXINS IN BUILDING MATERIALS

As indicated in Table 4.49, the roofing was often made of asbestos-cement roofing. All asbestos-cement roofing from before 1984 are today classified as asbestos material. Asbestos is a mineral that can cause cancer. This roofing material cannot be recycled and has to be removed (Taginfo 2016).

In the years 1950 – 1977 PCB was a common material used in Denmark for many products. PCB made materials flexible and fireproof without losing too much load-bearing capacity, therefore, was often used in joints for example between windows and walls. It is possible to find PCB used in some windows, manufactured abroad, but sold in Denmark until 1980. PCB increases the risk of cancer and other harmful diseases (Jensen 2016).

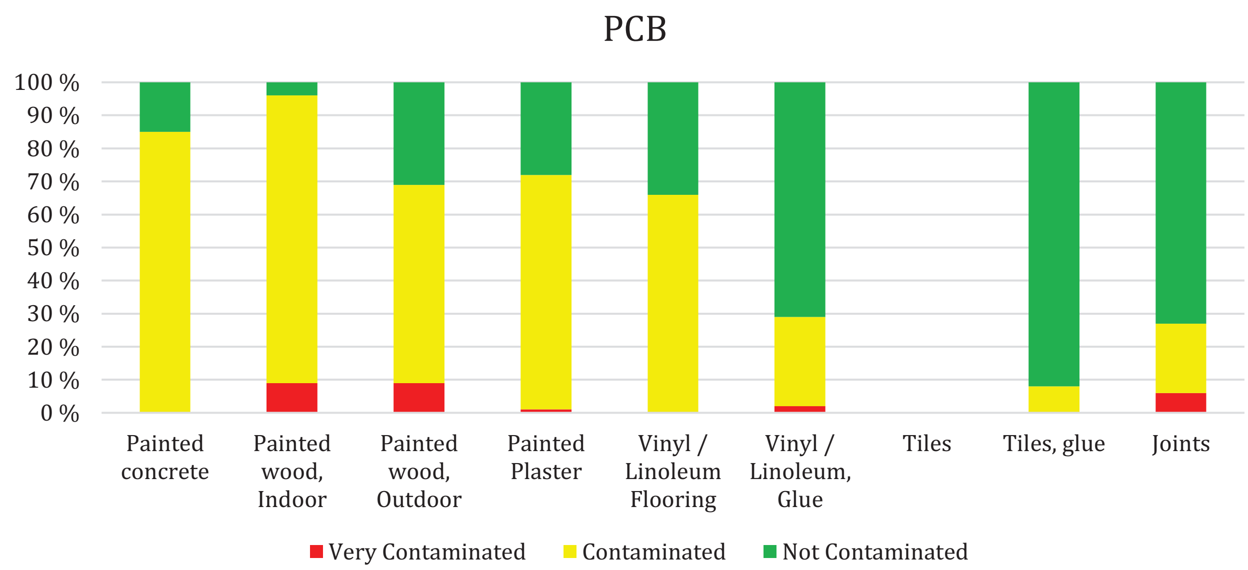


Figure 4.24 Test of 36 single-family homes for PCB, built in the period of 1890 – 1990 (Jensen 2016)

The results in Figure 4.24 are very interesting when considering that the contaminated part (yellow) did not include PCB when manufactured, however, they have been erected near a material containing PCB. This shows the significant impact of contamination by a PCB containing material. The results, from the research made by Hanne Sadolin Jensen (DGE Group), indicate that the issue with PCB is not as big in single-family housing as it is in larger buildings (schools, offices etc.) built in the same period (Jensen 2016).

Heavy metals have been used in many materials. Even though they are a natural mineral, they have a negative influence on humans and animals. Figure 4.25 indicates that the issue with heavy metals has to be taken into account when working with a single-family house. This overview is made from 33 tests in each house, but many of the materials with these metals are well known, therefore, by visual examination of the house the risk areas can be clarified. It is recommended to remove all toxic material from the building, and preferably without using mechanical tools (Jensen 2016).

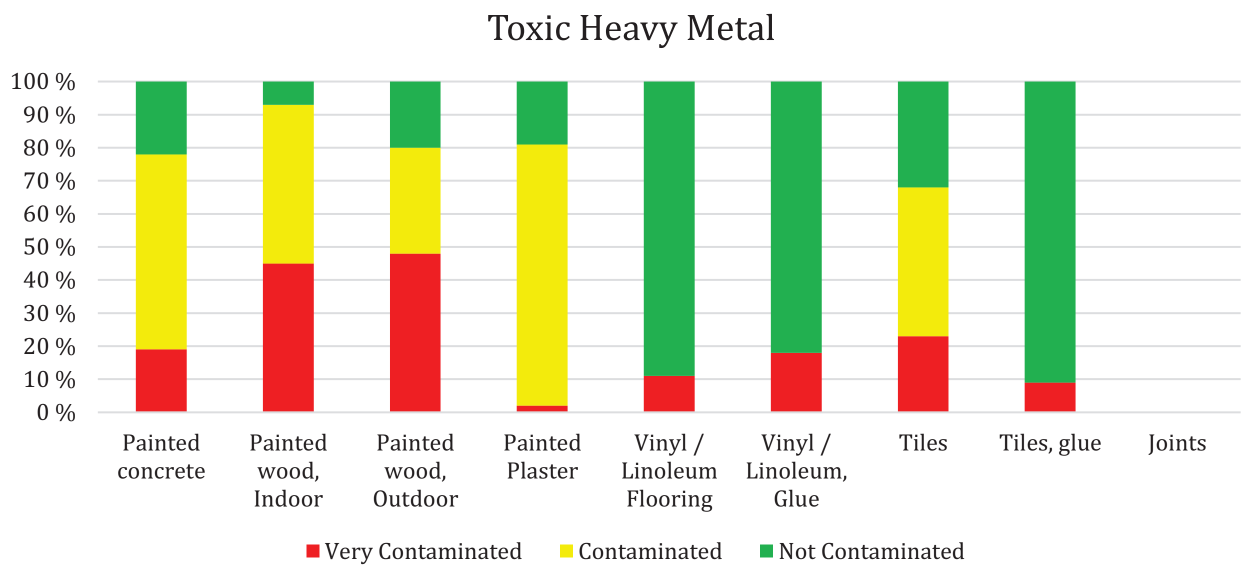


Figure 4.25 Test of 36 single family homes for toxic heavy metal, built in the period of 1890 – 1990 (Jensen 2016)

It is worth mentioning for both Figure 4.24 and Figure 4.25, that they are made for single-family houses built in 1890 – 1990, therefore, it is not conclusive for housing from 1961 – 1978. Nevertheless, PCB were used a lot in that period.

LEGISLATION

As mentioned earlier, BR15 makes reuse of materials more complicated. This is due to the higher energy demands and also the requirements for building materials. Reusing the old windows could be a good way of lowering the construction cost of the renovation and be more sustainable. However, BR15 states that the E-ref should not be less than -17 kWh/m^2 per year for a window (BR 2015). This excludes most old windows, because they do not comply with these requirements. Materials, for instance bricks, should still comply with the requirement of CE-marking to ensure the quality of the brick, before it can be reused. This complicates the process, and presumably increases the cost of the process, therefore many materials end up at the local recycling centre. The recycling centre has the possibility of recycling the materials, not only for roads or heat production, but also for insulation materials, rock- (bricks, concrete) or glass- (glass) wool, or reproduction of, for example PVC. Insulation and PVC pipes are some of the building materials mainly produced from recycling in Denmark (SBi 2015).