Technical University
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Estimated and measured energy consumption for specific buildings

Master's Thesis

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Estimated and measured energy consumption for specific buildings

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Summary

The main topic of this thesis has been to study the relationship between the measured and estimated energy consumption of specific buildings, across different building energy performance and construction periods. The objective of the study is to find a way to minimise the discrepancy between the expected and measured energy consumption of the buildings.

In chapter 2, the international literature study revealed that the measured energy consumption is expected to be more than the estimated figure for buildings with low energy demands, and less than the estimated value for buildings with high expected consumption. These conclusions have been examined using two DTU case studies, in which data on the expected and measured energy use in buildings 127 and 210 has been gathered. These case studies were also evaluated with respect to their estimated and measured energy use. Additionally, a dataset of all of the buildings at DTU has been supplied by the DTU Campus service.

In chapter 3 the measurements are described, e.g., the measurements of outside temperature, inside temperature and energy consumption, as well as the measurements used to calculate and verify the expected energy use. The measurements were performed for a period of 29 days, from December 1 2016 to December 31 2016. During this period, the building used 43,15 kWh/m^2/year for heating. The mean inside and outside temperatures were 22^{o}C and 6^{o}C. All of the measured results were compared with the estimated results. The energy estimation was performed using two methods, a simple formula and Be15 software. The comparisons resulting from these two methods show that, generally, the simple calculation overestimates energy consumption whereas Be15 underestimates it.

In chapter 4, the measurements, calculations and Be15 results described in chapters 2 and 3 are given. Building 127's total energy consumption for heating, cooling, ventilation, and domestic hot water use was calculated to be 55.5kWh/m^2 per year, where 23.2 kWh/m^2/year of the total is used for heating and 14.7 kWh/m2/year is used for cooling. According to the actual energy use found by the measurements, the building is not qualified to be included in the low energy class 15. For this building to qualify in this class, the actual energy use would need to be six times lower. For building 210, the actual energy use is 102.4 kwh/m2 per year. For this building to use the same amount of energy as was originally estimated by Birch & Krogboe A/S, the building and its users would need to reduce the actual energy use by 41.5%.

Preface

This Master's thesis was written at the Department of Civil Engineering at the Technical University of Denmark, from September 2016 to February 2017. The project corresponds to 15 ECTS credits.

The thesis inspects the energy consumption of buildings 127 and 210 of Lyngby campus. It has been written in order to get a better understanding of the discrepancy between the expected and the measured (actual) energy consumption in these buildings. The investigations performed are, therefore, based on these two case studies. The analysis, discussion and conclusions drawn can be used to create a more detailed overview of the energy consumption of these buildings, and the issues around this.

Kongens Lyngby, February 02, 2017

Kapuya Jean-Paul B. Nyembwe

Acknowledgments

I would like to give special thanks to my supervisor, associate professor Jan Karlshøj, and assistance professor Christian Anker Hviid for their excellent guidance and support through the project period, and for their willingness to resolve all the problems that occurred during this process.

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Finally, I would like to thank DTU campus service, which has been of great assistance in providing data, drawings and other useful documents.

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CHAPTER 1

Introduction

Human activities have an impact on energy consumption and the environment. Some of those activities, e.g. heating or cooling buildings, result in emissions of greenhouse gases (Dodoo 2011). The ambition of the European Union (EU) is to reduce greenhouse gas emissions and energy savings in buildings by 2020 (EU 2010).

Existing buildings need to be renovated and new buildings need to be constructed according to the new energy performance requirements in order to comply with EU Directive 2002/91/EC (European Commision 2002). This EU Directive was fully implemented in Denmark in 2016 after first being introduced for new buildings in 2005 (Building regulations 1995). In these regulations, the legislation was tightened, outlining a classification system for low energy buildings: “low energy class 1” and “low energy class 2” constructions, which correspond to reductions of 50% and 75% of the minimum energy required in BR 98 (Building regulations 1995).

The above-mentioned regulation applies to both new and existing buildings. Therefore, when renovating existing buildings, the requirements are met by the full replacement of the building’s components (new roof, windows, insulation in the external walls, etc.). Although the Danish government has tightened the requirements on energy consumption in buildings, it has been recorded that new buildings still use more energy than expected (Strategy n.d.). Last year, a report from Kirsten Hanssen (SBI) found that the expected energy use may not be the same as the actual energy use measured when a building is occupied by a household (Gram-Hanssen & Rhiger Hansen 2016).

The Directive on the Energy Performance of Buildings (EU Directive, 2002) was implemented in the EU, in which each member of the European Union needs to adapt to the rules, where new buildings have to be certified for energy performance yet also fulfil the national requirements. The goal of the EU is to achieve the "20-20-20" plan by 2020, which is to reduce emissions of greenhouse gases by 20%, increase energy efficiency by 20%, and ensure that 20% of energy consumption is from renewable sources (EU 2010). Each member state has to review their national laws in order to achieve the goal of sustainable development (Wade et al. 2011). In Denmark 40% of the total energy consumption across the country is represented by heating buildings and operating the equipment within, etc. Energy consumption for heating accounts for 35% of the final energy consumption total (Government 2014).

Hypothesis

"The discrepancy between the expected and measured energy consumption in buildings should be minimised."

In this project, two case-studies have been conducted at "Transform DTU", buildings 127 and 210 at Lyngby campus. Building 127 was designed according to the building code BR10 (Danish Government 2010), whereas building 210 was designed according to the building code from 1995. These buildings were chosen because DTU has a plan to renovate and construct new buildings with good energy performances to reduce consumption. The goal is to find the discrepancy between the expected and measured energy consumption levels, and analyse and discuss this discrepancy. In the proposed solution, it will be suggested how the discrepancies can be avoided in the future.

Aims of the Project

The aim of this thesis is to compare the expected, measured and calculated energy consumption rates according to requirements in the building regulations, and to identify the main factors that cause a discrepancy between the three figures.

Main objective:

- **How can the discrepancy between the expected and measured energy consumption in buildings be minimised?**

Specific objectives:

1. Identify the factors that cause building 127 and 210 to fail to reach their goals of low energy consumption.
2. Discuss the methods by which energy consumption can be reduced.

Methodology

The methodology is used to carry out the entire report. The research method is quantitative, using an inductive research approach. A data collection process, literature review and semi-interviews, plus analyses, case -studies and discussions, have been conducted in this report.

In this report, several sources have been used to find empirical data for the estimated and actual energy consumption levels for buildings 127 and 210 at DTU Lyngby campus. To be able to complete this investigation, several project managers have been contacted and interviewed to gain additional data for the buildings. The expected energy calculations were provided by the engineering firm that worked on the construction of the buildings, and the actual energy consumption data was retrieved from the energy data warehouse EnergyKeys. Access to drawings was provided by the DTU BIM database, which contains additional useful information about the buildings. The collected data have been used to evaluate the result, which will be beneficial in comparing the figures for the expected energy use and the actual numbers, to see if the energy use requirements meet the demand.

The literature review focuses on energy performance requirements in the Danish building code and the Danish energy policy handbook, coupled with other sources. The most prominent source of information will be from the BR, because they have a wide range of documents or requirements on energy requirements for new and old buildings. An analysis will be carried out in comparing the building regulation demands, the energy performance calculation from the engineering firm’s perspective (done before getting a building permit) and the measurements after an occupant has occupied the building. The Danish energy policy handbook has several different strategy plans for reducing the energy consumption of buildings by 2020.

The Danish Building Research Institute has been used as another source for this report. Publications and reports from the SBI were explored to get a solid understanding the current issues regarding energy consumption in Danish building stock. The documents mentioned and general articles on energy consumption from other countries have also been used also as references. The Danish energy equivalents of ´”actual energy use and expected energy use” were searched in SBI reports, articles, publications, and the information media.

After the literature review, all data collated on the actual and expected energy consumption levels have been analysed and compared with the results from the energy performance requirements in the original building regulations, to verify if the building still hold the energy class they were estimated to hold. As the expected energy use for different parameters is not given by the engineer firm, they only give a figure for the total energy that the building should use. Due to the lack of these values for different parameters in the data on expected energy use, the simple calculation method and Be15 software are both used to estimate the parameters and total energy use.

The Be15 software is used when estimating energy consumption for building 127 only. The heating consumption for building 210 was calculated with an old software programme, BV95, and this software is no longer in use. The energy estimations for this building are made with a standard calculation and Excel is used to calculate heating and cooling consumption.

The other tool used in this investigation is the thermography camera. The thermography camera was used to take pictures of the different building components, which were then analysed to find what may have caused the building’s energy consumption to increase.

CHAPTER 2

Literature review.

Danish Energy Performance Directive

Danish energy policy intends to reduce energy consumption in buildings over the period 2006 to 2020. Other goals have already been planned as well. By 2035, all heating and electricity supply should be completely based on renewable energy. And by the end of 2050, all new buildings must be zero CO2 (Anon, 2014). The aim is to do this incrementally for the years 2010, 2015 and 2020, with the help of energy classes. The classes are currently voluntary, but imposed by governing building regulations 2015 and 2020. Figure 1 shows the long-term plan made by the Danish authority for energy consumption in buildings.

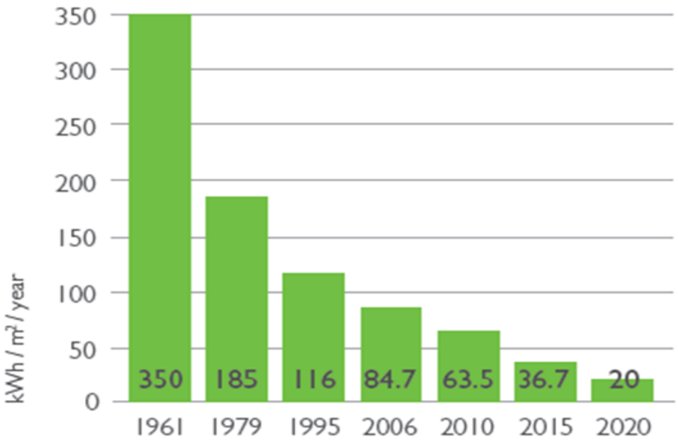


Figure 1: ***Danish building codes from 1961 to 2020 and the maximum energy requirements per year/ m². The total energy supplied includes ventilation, domestic hot water, heating and cooling*** (Toolkit 2013)

Denmark intends to continue its efforts in energy efficiency and intelligent energy management in construction to achieve a sustainable society. The Danish Energy Agency and the Danish transport and construction agency are working in collaboration to develop sustainable policies and Denmark's representative to the European Commission is helping with the development and implementation of the legislative system in the field (OECD/IEA 2012).

The Danish Building Regulation regarding energy consumption

Denmark first time introduced energy requirements in BR61, and they have been tightened many times since then, e.g. about air tightness requirements and the thermal insulation of a dwelling. As a result of the global oil crisis in the 1970s, the Danish government tightened its energy requirements. In addition, the Kyoto Protocol agreement for reducing emissions of greenhouse gases also called for its aims to be achieved by the strengthening of requirements in national building regulations (BR) 1995 (Building regulations 1995).

The revision of the building regulations has furthermore tightened the rules in order to fulfil the requirements in the Energy Performance of Buildings Directive (EU 2010). Moreover, the Danish Transport and Construction Agency has defined requirements that regulate the energy efficiency, health, environment, construction and safety of buildings (the Danish Ministry of Economic and Business Affairs Danish Enterprise and Construction 2015). These requirements for construction are compiled in a set of regulations called BR15. To reduce the energy consumption in Danish buildings, regulations for specific energy use have been established.

The Danish Transport and Construction Agency has implemented requirements for specific energy consumption, depending on the type of building. The vision of the Danish authorities is to reduce energy use by 25% for new buildings in 2010, 50% in 2015, and finally by 75% in 2020, with the year 1990 as a baseline (Denmark et al., 2015). Table 1, below, shows the specific regulation on energy use for a new building.

Characteristic Values		**Energy frame 2010**	**Energy frame 2015**	**Energy frame 2020**
	Residential buildings (houses, hotels, etc.)	52.5 + 1650/A in kWh/m²yr	30 + 1000/A in kWh/m²yr	20 kWh/m²yr
	Non-residential buildings (offices, schools, institutions)	71.3 + 1650/A in kWh/m²yr	41 + 1000/A in kWh/m²yr	25 kWh/m²yr
	Electricity	2.5	2.5	1.8
	District heating	1.0	0,8	0,6
Airtightness	Tested at a pressure difference of 50 Pa	1,5 l/s per m²	1.0 l/s per m²	0,5 l/s per m²
Heat recovery rate		0,70/0.80*	0,70/0.80*	0,75/0.85*
Fan power		1800 J/m³**	1800 J/m³**	1500 J/m³ / 800 J/m³*

Table 1 shows a comparison of the energy performance requirements for 2010, 2015 and 2020 set in the Building Code

A is the heated gross floor area.
* Single dwelling ventilation systems
*** The fan power consumption must not exceed 1800 J/m³ Fresh air*

Building Condition

In 2005, the authorities introduced requirements for low energy building into the Danish building code. The requirement is that old buildings, if under renovation, and new buildings should both be well-insulated by increasing the thickness of the insulation, to avoid the situation where the heat loss exceeds the expected values. Table 2 shows how the U-value has changed compared with previous building codes.

Class	Component	U value (W/m^2 K)	Approximate insulation thicknesses (mm)
2010	External/ walls	0.19	150
	Roof	0.16	200
	Floor	0.17	150
	Floors and partition walls	0.40	75
2015	External/ walls	0.14	200
	Roof	0.11	300
	Floor	0.13	200
	Floors and partition walls		
2020	External/ walls	0.15	300
	Roof	0.12	300 – 400
	Floor	0.10	300
	Floors and partition walls	0.40	75

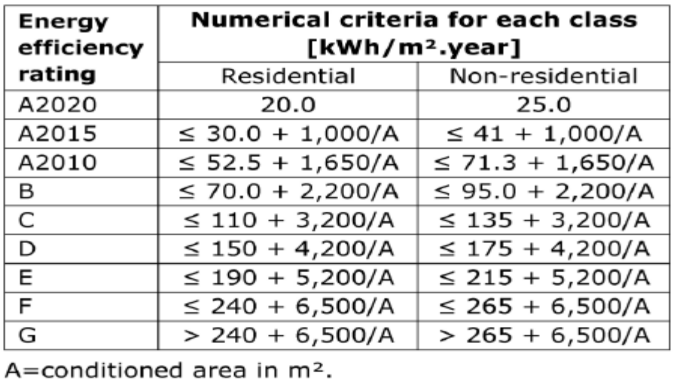
Table 2 shows insulation thicknesses and the U-value have been improved compared with previous building codes

Building certification

The Danish Energy Agency is responsible for the implementation of energy performance certificates in Denmark. According to the EU Directive and Danish national legislation, it is mandatory to provide a valid energy performance certificates (EPC) to a tenant or new owner if the building is to be sold or rented out (Denmark et al. 2015). The label should also provide an overview of the energy performance.

The scale marks indicate which energy classes a building is placed in. The brand scale goes from A to G and the EPC is valid for 10 years (Pohl 2016). Moreover, there are different methods of labelling sustainable buildings in different countries: LEED (US), BREEAM (Great-Britain), HQE (Holland) and DGNB (Germany).

In 2012, Denmark introduced the DGNB certification. DGNB is used to certify many buildings, such as offices, hospitals, institutions, houses and other types of building. According to studies done by Andaloro (Andaloro et al. 2010), on whether energy certification in buildings have been adopted across the 27 EU countries, the results suggested that in 2010, most of the 27 countries were still in the process of achieving the goal of having energy certification for buildings. This means that they have not yet completely implemented building certification, and they have not fully adopted the energy efficiency measures so far. Among the 27 European countries studied, Denmark was the first EU member to start using building certification, before the (EPBD) (2002/91/EC), and in 2010 many buildings were already certified (Andaloro et al. 2010).



Energy efficiency rating	Numerical criteria for each class [kWh/m².year]	
	Residential	Non-residential
A2020	20.0	25.0
A2015	≤ 30.0 + 1,000/A	≤ 41 + 1,000/A
A2010	≤ 52.5 + 1,650/A	≤ 71.3 + 1,650/A
B	≤ 70.0 + 2,200/A	≤ 95.0 + 2,200/A
C	≤ 110 + 3,200/A	≤ 135 + 3,200/A
D	≤ 150 + 4,200/A	≤ 175 + 4,200/A
E	≤ 190 + 5,200/A	≤ 215 + 5,200/A
F	≤ 240 + 6,500/A	≤ 265 + 6,500/A
G	> 240 + 6,500/A	> 265 + 6,500/A

A=conditioned area in m².

Table 3 shows the *Scale and numerical criteria for primary energy use in Danish Energy Performance Certificates* (Denmark et al. 2015)

In 2007 DGNB was founded in Germany, and the method has spread to many European countries. In Denmark, many buildings have been certified with DGNB. The idea of the certification is to encourage architects, contractors and other professionals to think about reducing energy use in buildings, and to ensure that there is low-energy impact from the design phase to the construction stage, thus meeting the requirement of building certification in Denmark (Green Building Council Denmark 2012).

Energy consumption in buildings

Energy consumption means the amount of energy consumed by a building, and that depends on the activity or object of the building. House illumination is one of the most common forms of energy use; for instance, increasing the energy consumption in a house by lighting a bulb. But there are other forms too: using a radiator to heat up the room, cooking on an electric stove and using electronic items such as computers, mobile phones and the TV (International Energy Agency 2015).

Moreover, when calculating the energy consumption of buildings, there are many parameters that must be included in the calculation. Some of the parameters are shown in Figure 3. The following section will introduce the different parameters that are included in the energy consumption calculation.

Parameters for energy use calculation

There are different criteria that need to be considered during calculation of energy use. Buildings must have a healthy indoor climate and a comfortable interior temperature, and avoid overheating. The thermal comfort temperature designs are based on Danish standards (DS 474) and European standards. Thermal comfort has a significant impact on health, psychology and sociology, as well as situational factors including clothing. In general, it is influenced by the indoor air temperature and humidity. Indoor air is controlled through the ventilation system in sustainable building practice.

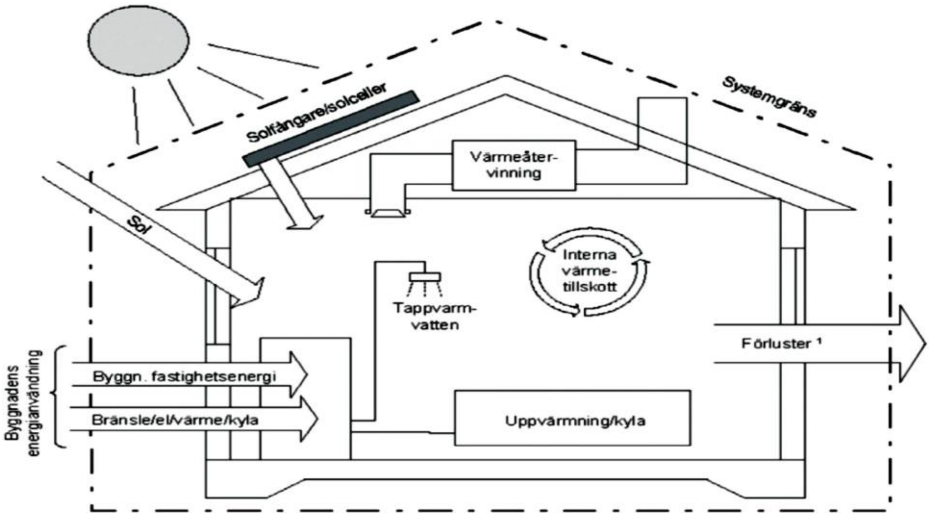


Figure 2 shows the building parameters included in the calculations (Ebenmark & Ab 2015)

The interior temperature variation depends on the number of occupants of a building and their behaviour. It is the main parameter key that influences energy consumption in the building. The indoor climate is also linked to the choice of materials used in the building, the planning of the building and the windows, the heating and cooling processes, and the disposition of the building and solar screening, in winter and summer. Therefore, insulation is not the only option for meeting energy savings requirements, or providing a comfortable temperature (reference).

Building regulations set the energy requirements for a building's component. However, the specifications and requirements of indoor climate are described in the DS 474 Danish Code for Indoor Climate, and in DS/EN ISO 7730. When evaluating the energy consumption in the building, the expected indoor temperature must be taken into account to achieve thermal comfort: the indoor temperature needs to be 20-26 °C. Moreover, a temperature of +26 Celsius for a maximum of 100 hours/year and an indoor temperature of +27 Celsius for a maximum of 25 hours/year is recommended for energy consumption estimations (Bygninger 2015).

Heat recovery

Ventilation is one of the main criteria which can influence energy consumption in a building (Liddament & Orme 1998). It may have an uncertain effect on energy consumption, and depend on which parameters are included in the household's behaviour. In addition, the mechanical ventilation system is based on a ventilation rate, which provides quality and quantity air for a particular building type throughout the year. Buildings using mechanical ventilation system remove bad air from the kitchen and the bathroom and deliver fresh air into the bedroom and the living room. Moreover, with a heat exchange box – where heat from the removed air is transferred to the supply of cool air from outside – the installation of a ventilation system can be combined with heat recovery. In a dry temperature efficiency of at least 70%, the ventilation that supplies the air in a dwelling must be combined with heat recovery, in that the temperature efficiency cannot be less than 80% according to the regulations (the Danish Ministry of Economic and Business Affairs Danish Enterprise and Construction 2015). Figure 3 shows how mechanical ventilation functions in a building.

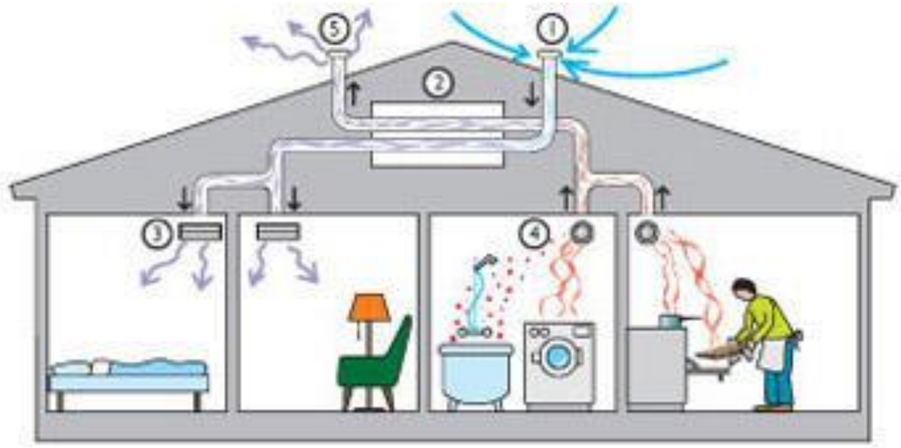


Figure 3 shows the MV-system: 1. Supply air 2. Heat Exchanger 3 Heated supply air 4. Exhaust air and 5. Chilled Exhaust air (Ebenmark & Ab 2015)

Windows: energy efficiency and airing

Building a ventilation system is a parameter that affects the energy consumption in housing and relates to the occupant's activities. The amount of air an occupant needs depends on which ventilation system type that has been installed in the building, and the quantity of wind exposed in the building is related to the behaviour of the occupant. There are many works of research that mention that airing has a significant impact on energy consumption in a building (Knudsen et al. 2012). Windows also have a big impact, which can cause heat loss in the building. The new building regulations, which came into force on January 2016, have a new requirement for newly designed and constructed buildings. The table below shows the maximum energy frame for windows (the Danish Ministry of Economic and Business Affairs Danish Enterprise and Construction 2015).

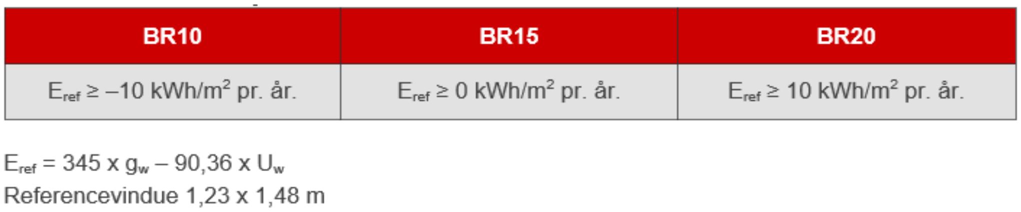
Windows and glass exterior walls

BR10	BR15	BR20
$E_{ref} \geq -33$ kWh/m² pr. år.	$E_{ref} \geq -17$ kWh/m² pr. år.	$E_{ref} \geq 0$ kWh/m² pr. år.
Energimærke C	Energimærke B	Energimærke A
U = 1,4 W/m² K	U = 1,1 W/m² K	U = 0,8 W/m² K

$E_{ref} = 196{,}4 \times g_w - 90{,}36 \times U_w$
Referencevindue 1,23 x 1,48 m

Table 4 shows the energy framework requirements for windows from different building classes (Anon 2017a).

Skylights



BR10	BR15	BR20
$E_{ref} \geq -10$ kWh/m² pr. år.	$E_{ref} \geq 0$ kWh/m² pr. år.	$E_{ref} \geq 10$ kWh/m² pr. år.

$E_{ref} = 345 \times g_w - 90{,}36 \times U_w$
Referencevindue 1,23 x 1,48 m

Table 5 shows the energy framework requirements for skylights from different building classes (Anon 2017a)

Solar heat gains

Solar heat gain in buildings in northern Europe is by direct radiation through the windows. The maximum heat gains in a building with the windows facing south tend to occur in the spring and autumn, when the lower angle of the sun causes radiation to fall more directly onto vertical surfaces. The estimation of solar heat gain is done with various software in Denmark. The Danish Building Research Institute has developed a program known as Be15 to calculate energy gains. The Be15 program provides monthly to hourly heating gain values by using the global solar radiation horizontal surface information, according to the Danish Design Reference Year (DRY). The solar heat gains can bring uncertainty to the final results, e.g. by ignoring the orientation of the facade. However, in the Be15 software, façade orientation is included, as well as window shading and shadow from obstructions (Aggerholm & Grau 2014). The table below shows the yearly weather average for both the summer and winter periods.

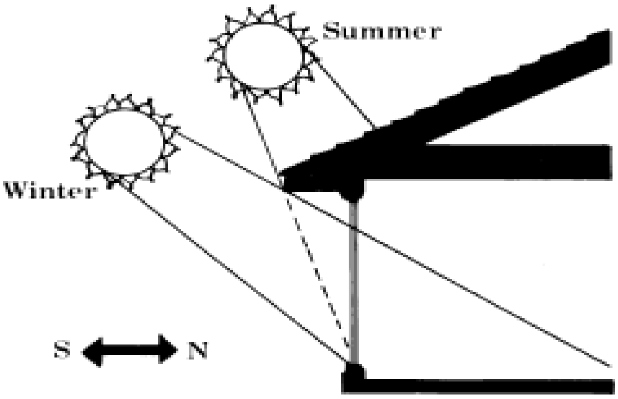
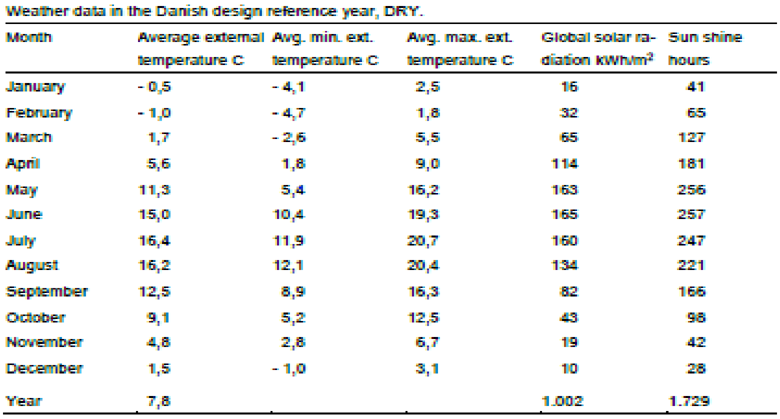


Figure 4: The overhang allows in the winter sun, while shading the south-facing glass in the summer

(Image from www.ncsc.ncsu.edu)



Weather data in the Danish design reference year, DRY.

Month	Average external temperature C	Avg. min. ext. temperature C	Avg. max. ext. temperature C	Global solar radiation kWh/m²	Sun shine hours
January	- 0,5	- 4,1	2,5	16	41
February	- 1,0	- 4,7	1,8	32	65
March	1,7	- 2,6	5,5	65	127
April	5,6	1,8	9,0	114	181
May	11,3	5,4	16,2	163	256
June	15,0	10,4	19,3	165	257
July	16,4	11,9	20,7	160	247
August	16,2	12,1	20,4	134	221
September	12,5	8,9	16,3	82	166
October	9,1	5,2	12,5	43	98
November	4,8	2,8	6,7	19	42
December	1,5	- 1,0	3,1	10	28
Year	7,8			1.002	1.729

Table 6 shows weather data in the Danish design reference year, DRY (Aggerholm 2013)**.**

Internal heat gain from occupants

The heat gain from an occupant's presence in the building helps with the heating-related energy consumption. Additionally, the number of occupants, as well as their surroundings and the activities performed (e.g., sleeping, dancing, working, sedentary activities, etc.), can also release body heat in two different ways: as latent or sensible heat. Sensible heat is produced due to higher temperatures, and human skin can react according to the surrounding climate. Table 7 below shows that an adult person can deliver

100 watts of heat per day, for example for people living in an apartment. Moreover, the heat rate may be increased with higher activity (Melorose et al. 2015).

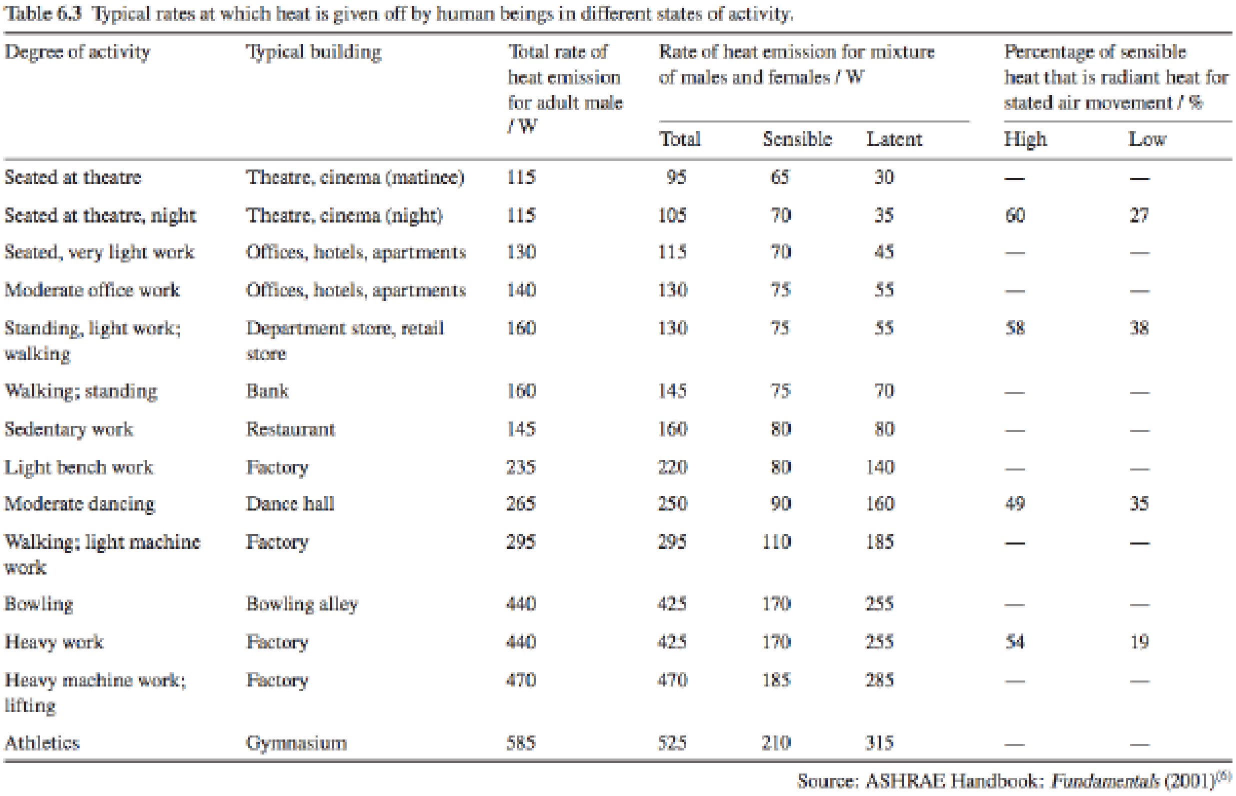


Table 6.3 Typical rates at which heat is given off by human beings in different states of activity.

Degree of activity	Typical building	Total rate of heat emission for adult male / W	Rate of heat emission for mixture of males and females / W			Percentage of sensible heat that is radiant heat for stated air movement / %	
			Total	Sensible	Latent	High	Low
Seated at theatre	Theatre, cinema (matinee)	115	95	65	30	—	—
Seated at theatre, night	Theatre, cinema (night)	115	105	70	35	60	27
Seated, very light work	Offices, hotels, apartments	130	115	70	45	—	—
Moderate office work	Offices, hotels, apartments	140	130	75	55	—	—
Standing, light work; walking	Department store, retail store	160	130	75	55	58	38
Walking; standing	Bank	160	145	75	70	—	—
Sedentary work	Restaurant	145	160	80	80	—	—
Light bench work	Factory	235	220	80	140	—	—
Moderate dancing	Dance hall	265	250	90	160	49	35
Walking; light machine work	Factory	295	295	110	185	—	—
Bowling	Bowling alley	440	425	170	255	—	—
Heavy work	Factory	440	425	170	255	54	19
Heavy machine work; lifting	Factory	470	470	185	285	—	—
Athletics	Gymnasium	585	525	210	315	—	—

Source: ASHRAE Handbook: *Fundamentals* (2001)[6]

Table 7 provides the average heat emissions from a male during different activities, and the mixture heat rate emission from males and females (Melorose et al. 2015)

Heat gains from appliances and number of people

According to the SBI, all appliances and lighting that consume electricity, such as the TV, the radio and other equipment, turns into internal heat gains (Gram-Hanssen 2014).

Electricity consumption, 1 person

Electricity consumption, 3+ persons

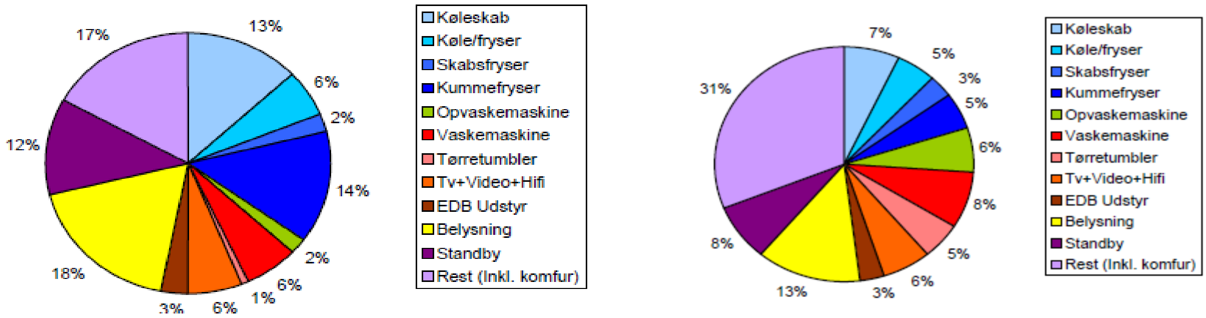


Figure 5 shows *a Kofod investigation on electricity consumption for 100 houses in Odense, for a person living alone and a large family. Source* (Kofod C 2005)

Figure 5 shows the different distributions of electricity in the building according to the number of occupants. Here, it is clearly shown from the above figures that people living alone consume more energy using cold appliances, but this is not the same when using other appliances like washing machines, tumble dryers and dishwashers.

The use of space heating appliances in a building depends on the number of occupants in a house. Thus, too many people living in a house will make the electricity consumption larger. But the use of space heating appliances in a house may become smaller due to the energy gain discharge of many occupants. Separately, dishwashers, washing machines and tumble dryers are the most common devices found in a house with many occupants, and a big family with many members uses a machine more often than a small family.

The number of residents in a house does not only influence the amounts of energy consumed, but also the sharing of the electricity by the end users. Moreover, electricity consumption in the building depends on the age group of occupants and the lifecycles of some families. The most energy is consumed in houses inhabited by people of between 30 to 50 years of age (Gram-Hanssen & Bech-Danielsen 2004). The use of electrical appliances like freezers and refrigerators is no different among different age groups. Appliances like washing machines, dryers and dishwashers represent a smaller percentage of the energy consumption in a house occupied by an older man, compared with a house occupied by young people, whereas older people use more energy on lighting and younger people use more energy on television, computers, radios and other electronics. According to Gram-Hanssen & Bech-Danielsen (Gram-Hanssen & Bech-Danielsen, 2004), people living alone use more energy on heating. This also depends on age. Older people may use less energy when it comes to winter time, if they prefer and/or are able to stay in a warm country during this period of the year.

Occupant behaviour and indoor climate

Occupant behaviour has a significant impact in terms of the indoor climate, and it can considerably increase or reduce the energy consumption in a building. In another way, the indoor temperature can affect user behaviour, and even change their way of using energy in the building. Similarly, indoor climate may change user behaviour as a result of health problems (such as allergies and asthma) caused by the bad indoor environment (Brohus et al. 2010).

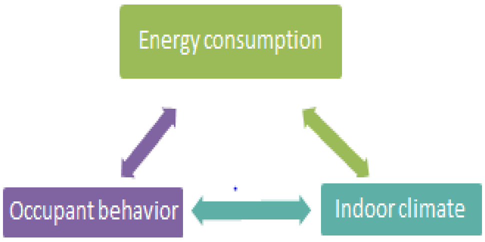


Figure 6 shows the interactions between occupant behaviour, indoor climate and energy consumption can lead to better or bad house standards

Indoor climate may affect occupant behaviour – that can be seen in our daily life. When the indoor climate is not comfortable, that may cause the occupant to act, by increasing or reducing the temperature (adjusting a thermostat), adjusting the air-conditioning, or opening or closing a window. Moreover, if the air quality in the building is not comfortable, it will cause the occupant to open a window to remove bad odours or increase the airflow of ventilation. In winter time, when there is flow of supplied cold fresh air through an inlet in the building, the occupant may close the inlet, and that can cause a reduction of the ventilation in the building. This investigation has been defined by Nicol & Humphreys (Nicol & Humphreys 1986), who state: "If a change occurs such as to produce discomfort in a building, the occupant may react in ways which may restore their comfort." This analysis shows how indoor climate and occupant behaviour may affect energy consumption in the building.

As a result of occupant behaviour, energy consumption in the building may be increased or reduced. Moreover, the use of a thermostat for temperature control in the form of taps may have an effect on the occupants of a building, meaning they are more aware of the temperature, which causes them to act by turning it on more often than in other buildings without a thermostat system. These small analyses show the use of thermostat has a significant effect in terms of occupant behaviour (Brohus et al. 2010). Programmable thermostats can save on heating energy in the house; on the other hand, having them installed in a residential house may not deliver the expected energy saving (Brohus et al. 2010). This could be the case if a building component was not well-built in the first place.

Workmanship competence

In the Danish building regulation guidance for small dwellings, chapter 7.1.1 outlines the different requirements for craftsmen in construction works, highlighting how work involving water and gas installations must be only executed by companies or people with accredited authorisation according to Act no. 206 of 27 March 2001, on carrying out work in water, gas and electrical installations. These are some of the requirements for craftsman competence in the Danish building sector (Nyman 2004).

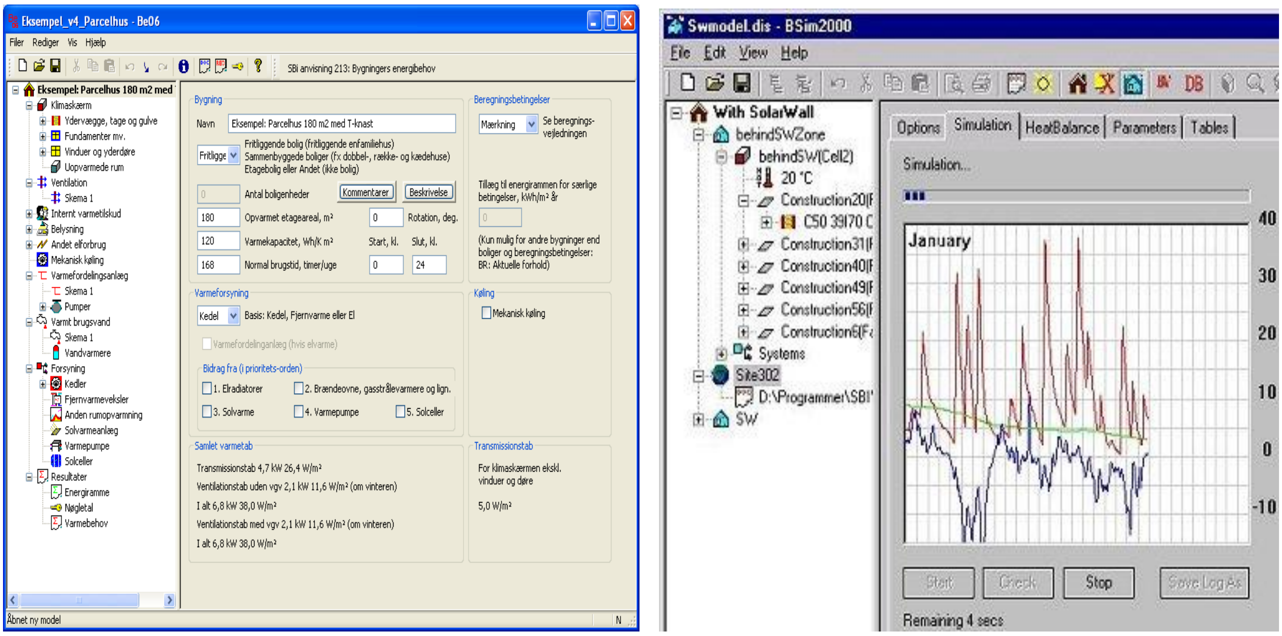
Denmark has joined the Build-up Skills organisation to develop training and education programs for craftsmen, including qualifications and courses for energy technologists (inspectors), energy efficiency experts, woodworkers, bricklayers, plumbers and joiners. This training or skills upgrade for craftsmen in the country could well contribute to Denmark reaching the EU 2020 goals on energy efficiency and renewable energy (Europe 2013). But besides upgrading skills through training and education, there are some other barriers to constructing high-quality buildings, including economic factors. Due to the unsustainable economy, the incentives for constructing good buildings may be reduced. In these cases, the implementation of boundary conditions may be applied to increase the quality of excellent workmanship.

In addition, the lack of competence in many professional firms (contractors, architects, industrial firms, etc.) led to a framework in which some companies are certified for specific works, or people with high competences relating to good quality work are also recognised. Therefore, upgrading skills for all building professionals is a good step, to cover the gaps in skills and realise Danish goals for energy efficiency in buildings. Many architects and engineers have been certified as passive house designers, accredited for designing low-energy buildings (Europe 2013).

Thermal building simulation tools

The Danish authorities use the Be15 programme for calculating the energy performance of buildings and verifying whether the energy requirements have achieved the BR demands (Jensen et al. 2009).

The Be15 calculations are based on solar radiation and monthly temperature values. They also include solar panels, hot water, heat recovery, ventilation, human, U-values, windows, areas, etc. The programmes simplify the calculations of the energy needed in a building, for instance for heating and cooling, ventilation, lights and hot water. The two figures below show the most common software types used to calculate energy consumption in a building.



Navn: Eksempel: Parcelhus 180 m2 med T-knast

Fritligge: Fritliggende bolig (fritliggende enfamiliehus) Sammenbyggede boliger (fx dobbel-, række- og kædehuse) Etagebolig eller Andet (ikke bolig)

0 Antal boligenheder

180 Opvarmet etageareal, m²

0 Rotation, deg.

120 Varmekapacitet, Wh/K m²

Start, kl. 0 Slut, kl. 24

168 Normal brugstid, timer/uge

Mærkning: Se beregnings-vejledningen

Tillæg til energirammen for særlige betingelser, kWh/m² år: 0

(Kun mulig for andre bygninger end boliger og beregningsbetingelser: BR: Aktuelle forhold)

Kedel: Basis: Kedel, Fjernvarme eller El

☐ Varmefordelinganlæg (hvis elvarme)

☐ 1. Elradiatorer ☐ 2. Brændeovne, gasstrålevarmere og lign.

☐ 3. Solvarme ☐ 4. Varmepumpe ☐ 5. Solceller

☐ Mekanisk køling

Transmissionstab 4,7 kW 26,4 W/m²

Ventilationstab uden vgv 2,1 kW 11,6 W/m² (om vinteren)

I alt 6,8 kW 38,0 W/m²

Ventilationstab med vgv 2,1 kW 11,6 W/m² (om vinteren)

I alt 6,8 kW 38,0 W/m²

For klimaskærmen ekskl. vinduer og døre

5,0 W/m²

Simulation...

Remaining 4 secs

Figure 7: On the right is Be10, and on the left the BSim. These tools are used to calculate energy consumption in a building (Aggerholm & Grau 2014)

When there are high temperatures during summer periods, the indoor climate calculation should relieve the overheating problem. It is important to focus on overheating issues from the design phase, since overheating in an office building, institution or house are expensive to repair when a building is complete and in use. The Danish Enterprise and Construction Agency has introduced a requirement for controlling and documenting temperatures in the critical room in a low-energy building (Anon 2017b). Moreover, the indoor thermal environment is analysed with specific software that has to be included in the documentation (March & Svendsen 2011).

According to Larsen, the lack of appropriate software for analysing the indoor environment is an issue in designing a comfortable building. The Be15 software is suitable only for energy calculations during the design phases, not for the indoor environment, because of some uncertainties with the Be15. Therefore, it is recommended to use an advanced software programme like BSim (IES VE) rather than Be15 (Larsen et al. 2012).

The BSim has the capability to calculate the maximum temperature in summer period. Calculations are made with many necessary parameters (window size, solar shading, U-Value) including the thermal indoor environment simulations. The BSim gives a good result on how to reduce overheating in the building. The Be15, meanwhile, is based on a monthly calculation and for a single zone, so it may provide uncertain values as it calculates buildings based on a room zone, which can cause issues with the results for a room facing south with a large window area, where solar radiation amounts are high (Larsen 2014).

Energy consumption and labelling

Several studies have been done about the difference between the energy performance calculated with the building simulation software and the actual energy consumption measured. There were 16 different studies of buildings between 1995 and 1999, and most concluded that the actual energy consumption of most of the buildings studied was higher than the energy consumption calculated. Discrepancies were found between the values assumed in the simulation software and the actual energy consumption values (Bordass et al. 2001)..

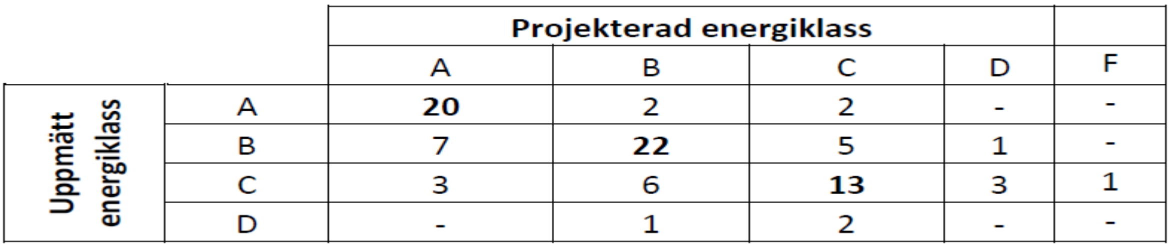
This energy performance discrepancy was also found in other studies in the United Kingdom, for example in secondary schools (Pegg, I. M.; Cripps, A.; Kolokotroni 2007), where it was found that 80% of the investigated buildings used more energy than expected, in both commercial and residential buildings. Similar case studies in EU countries such as Italy presented the same results (Tronchin & Fabbri 2010). In Denmark, researchers (Petersen & Hviid 2012) also found discrepancies of up to 30% between the expected energy consumption and the actual energy consumption in the simulation tool. The results also reflect a report published in the UK, which showed a difference of 40% in office buildings and 30% in education buildings (UCL Energy Institute 2013).

In Sweden, the discrepancies between the actual and calculated energy consumption have increased by up to 20% due to user behaviour and simulation software mistakes. The figure below shows the discrepancy between the different analyses from Denmark, the Netherlands and Sweden, and how the divergence does not match the demands expected for the buildings according to the different studies made about energy consumption in buildings. It has been mentioned that user behaviour has a significant impact that can influence energy use in buildings. User behaviour cannot be implemented in simulation software, and that can increase the discrepancy in the energy performance. According to some studies (Hirst et al. 1985), occupants in buildings have a tendency of increasing the indoor temperature in winter time to feel comfortable, which leads to the energy use being higher than expected. Studies with similar results were undertaken in many different countries, like the UK, Austria, Norway, Canada and the US, where they investigated user behaviour and estimated energy use.

Sweden

The Swedish authority (*Boverket)* has implemented requirements for energy performance in a building, whereby new buildings have to be built according to the prescribed energy performance values in the building regulations, and the actual energy consumption needs to be measured and reported over the 24 months after the building has been occupied. A report from LÅGAN (Programme for Buildings With Very Low

Energy Use) compared the actual and estimated energy used in some building in Sweden, as shown in table 8.



		Projekterad energiklass				
		A	B	C	D	F
Uppmätt energiklass	A	**20**	2	2	-	-
	B	7	**22**	5	1	-
	C	3	6	**13**	3	1
	D	-	1	2	-	-

Table 8 above shows the placement of buildings in different energy classes, A and B, for new buildings in Sweden (Rapport 2016)

The target was to investigate 88 building projects, comparing the estimated energy use and the measured use, to see if the projects met the energy consumption demands according to their energy class. As mentioned, there are discrepancies between the estimated energy and the measured energy use: the table below shows that 38% of the different cases did not match the estimated energy use with the measured use, and therefore did not match the class they were in (Rapport 2016).

Table 8 shows the number of projects where the energy measured rating was the same as for the estimated use (Table 8 also shows buildings that were designed to be energy class B but ended up receiving energy class C when in use, by measuring their energy consumption).

Denmark

The Danish Building Research Institute investigated some buildings by comparing the actual and calculated consumption. It looked at 230,233 houses with energy labels and the energy consumption of 135,443 houses (Gram-Hanssen & Rhiger Hansen 2016). The calculated and actual heat consumption were calculated per square metre of housing, and compared within each category of energy class. The graph from the analyses, below, shows that the energy use in buildings with poor technical energy efficiency is, on average, considerably lower than anticipated in the standardised energy-calculations in the energy certification scheme for buildings, and that the actual energy consumption in buildings with high technical energy standards is, in contrast, found to be higher than anticipated in the energy calculations.

The building energy certification scheme below shows that the difference in energy consumption per m^2 between a G-graded and a D-graded building is approximately 140 kWh, and also how for an A-graded and a C-graded building, the estimated energy use was lower than the energy calculated.

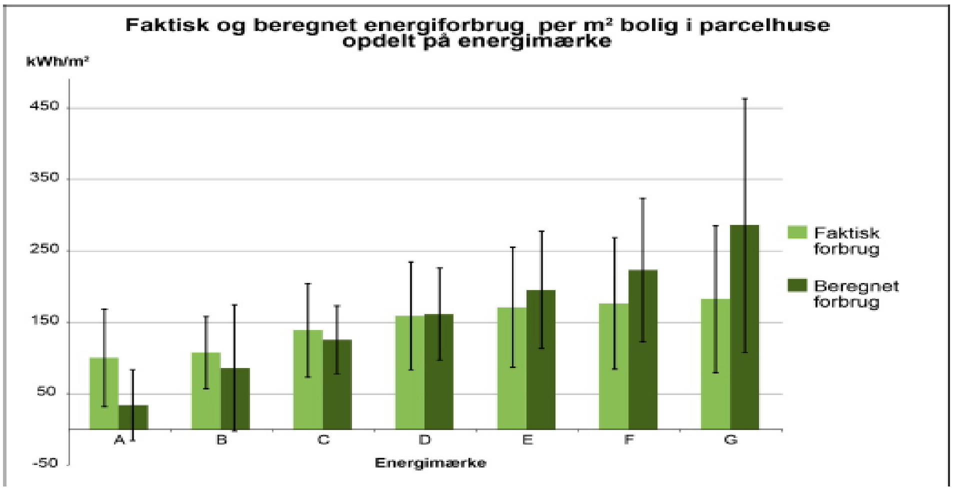


Figure 8 shows a ***comparison of average actual consumption and average estimated consumption for each energy label*** (Gram-Hanssen & Rhiger Hansen 2016)

The analyses of the graph above may have two different suggestions for what is causing the differences between the estimated energy use and measured use in old and new building. Some of the differences could be linked to "prebound effects" and "rebound effects".

Prebound effects are when people living in a house with low technical energy standards keep the house at a low indoor temperature, or only heat part of the building, and rebound effects are when people occupying a dwelling with a high technical energy standard develop less energy efficient practices. This is because some of the potential energy savings related to energy renovations are used to increase the comfort level of the indoor climate. According to Gram-Hanssen and Rhiger Hansen: "It is thus important for the long-term performance of the buildings to consider the re-bound and pre-bound effects when trying to improve energy performance" (Gram-Hanssen & Rhiger Hansen 2016).

The Netherlands

The energy efficiency of Dutch building stock has been improved by 28% in the period between 1990 and 2008. This is due to the strength of the building regulations in the Netherlands and the implementation of the EPC in 1995 (Majcen et al. 2013). Dasa Majcen has been conducting research on Dutch buildings by investigating the actual and theoretical gas and electricity consumption in the buildings, starting with the gas consumption in buildings (Majcen et al. 2013). Figure 9 shows the actual and theoretical gas consumption per square metre of dwelling. The Figure clearly shows that they was a large difference between the actual gas use and the theoretical estimation for each energy label. For the most energy efficient categories, A, A+ and A++ as well as for category B, actual gas consumption is larger than the theoretical consumption figure. For the label C buildings, the theoretical and actual gas consumption figures are quite similar. For classes D, E and F, the theoretical gas calculation is largely overestimated; the theoretical gas consumption is double the actual gas consumption. Generally, as the theoretical gas consumption estimates rise from categories A to G, the more likely it is that the figures are an overestimation of the actual gas use.

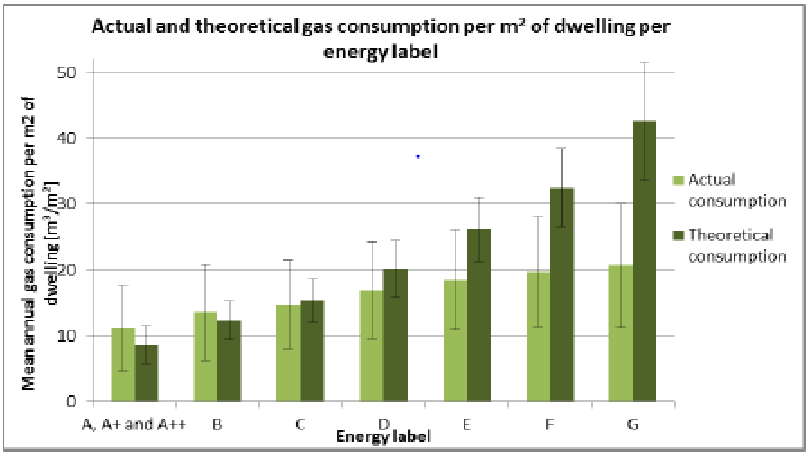


Figure 9 shows the actual and theoretical gas consumption/m2 of floor area per energy label (Majcen et al. 2013)

For electricity use, figure 10, below, shows that both the actual and theoretical electricity use values bear little relation to the label allocated. The figure shows clearly that the actual electricity consumption is higher than the theoretical electricity consumption figure. The actual electricity use is higher in class D and E, and according to Majcen et al., the actual electricity consumption may be higher due to mechanical ventilation or space heating and the heating of water (Majcen et al. 2013). However, as the plot for the actual electricity consumption has a convex shape and the theoretical electricity use has a concave shape, as is shown on the figure, the label does not appear to be very significant for looking at the electricity use of a building. However, the gaps between electricity use estimation and reality are very small compared with gas consumption.

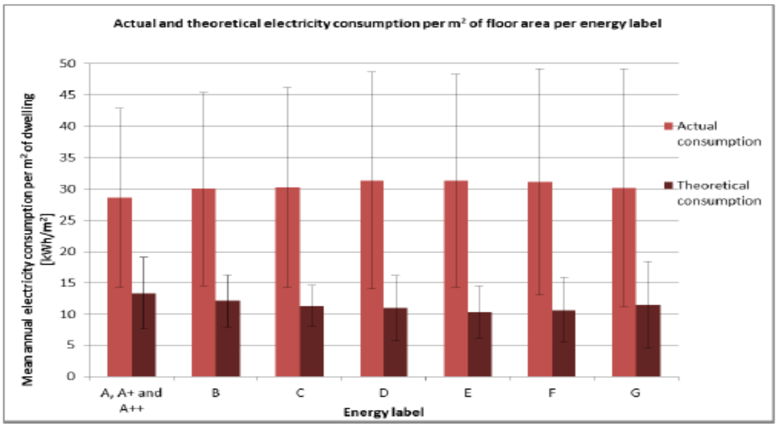


Figure 10: Electricity consumption per m2 dwelling in different label categories (Majcen et al. 2015)

Majcen et al. mention that research being done at the same time as their paper, about the renovation of labelled buildings, showed that in all different label categories, there was not enough of an energy reduction during the first four years after the purchase of the building by the owner (Majcen et al. 2015). However, there was an exception in dwellings with the A label, because there had been reductions in energy consumption in the first two years after the owner occupied the house (which took place while the Dutch team was not doing similar research).

In the next section, I will look at the case studies, in which I will measure and estimate the energy consumption in two buildings at DTU.

CHAPTER 3

Case studies

First case study: Building 127

One of the case studies chosen for this project is building 127 on DTU Lyngby campus, which is described in details below. The case is an existing building project that is currently in use, and the study estimates the energy consumption of the building and investigates the cause that are leading to the building using more energy than expected. The analysis depends on answers to the questions asked within the problem statement.

The building was constructed between 2012 and 2013, and has a total area of 2,323 m2. It has a pleasant design and excellent facilities, including the classrooms and small group rooms of different sizes, which the students use for group meetings. It also has a large open hall which students may use for events, exhibitions and presentations. Building 127 is connected with the existing laboratory building 117. The gable façade of the building was constructed with concrete elements covered with metal mesh. On the high street side of the building, there is a large glass façade with smart shading that brings daylight into the building without overheating.

Figure 11 shows the inside view – building 127 is located right next to building 117 (DTU 2012)

The energy consumption of building 1s27 was calculated with the Be10 and Bsim software programmes. Based on this analysis, figure 12 shows that the building complied with the energy framework to be in the low energy class 2015, with an energy consumption of 54.4 kWh/m^2 per year, with an additional 13.7 kWh/m^2 per year due to a high air change in some parts of the building. Figure 11 also shows the different energy classifications calculated by Alectia A/S.

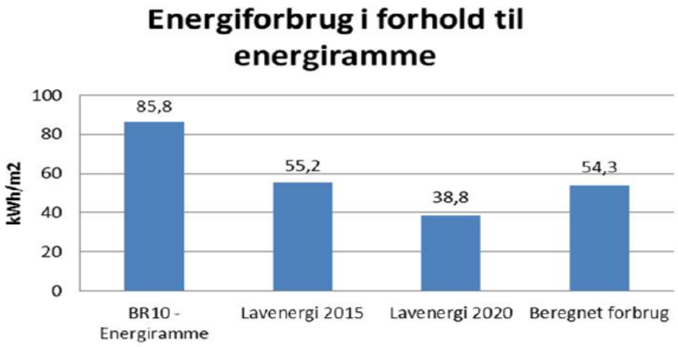


Figure 12 shows the class 15 energy consumption estimation (Alectia)

The next section is a summary of the actual energy consumption of the building for different parameters.

Summary of actual energy consumption

Energy consumption in buildings may be affected by many different parameters. These could be in the technical solutions, such as the insulation, windows, and indoor temperature, ventilating and construction materials. From the data collection analyses, it is shown that the low energy class 2015 goals are unrealistic in building 127. The building uses more energy than expected. Table 9 displays the actual energy consumption measured for two different years. The energy consumption measurements for 2015 were from June to December, and for 2016 from January to December. Table 8 shows the actual energy consumption.

Parameter	Expected value [kWh/ m^2 year]	2015 Measured value [kWh/ m^2 year]	2016 Measured value [kWh/ m^2 year]
Cooling	Not given	28050	109330
El (light and power)	Not given	58.49	129.96
El-Ventilation/varme	Not given	33.8	72.29
El- Elevator	Not given	0.94	2.34
District heating	Not given	40	50
Total Energy use	54.3		

Table 9 shows the actual energy consumption for different parameters

The bar graph in Figure 13 shows the actual energy consumption for the different parameters. Some of the parameters are the electricity used for cooling, light and power, ventilation/ heating, the elevator and central heating. By analysing the graph, it shows that the energy consumption for cooling is the highest total, followed by the electricity use for light and power, ventilation and heating and district heating.

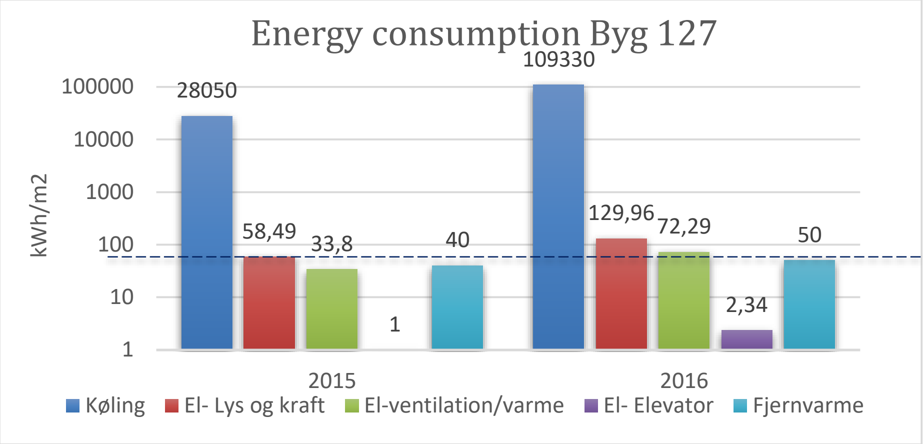
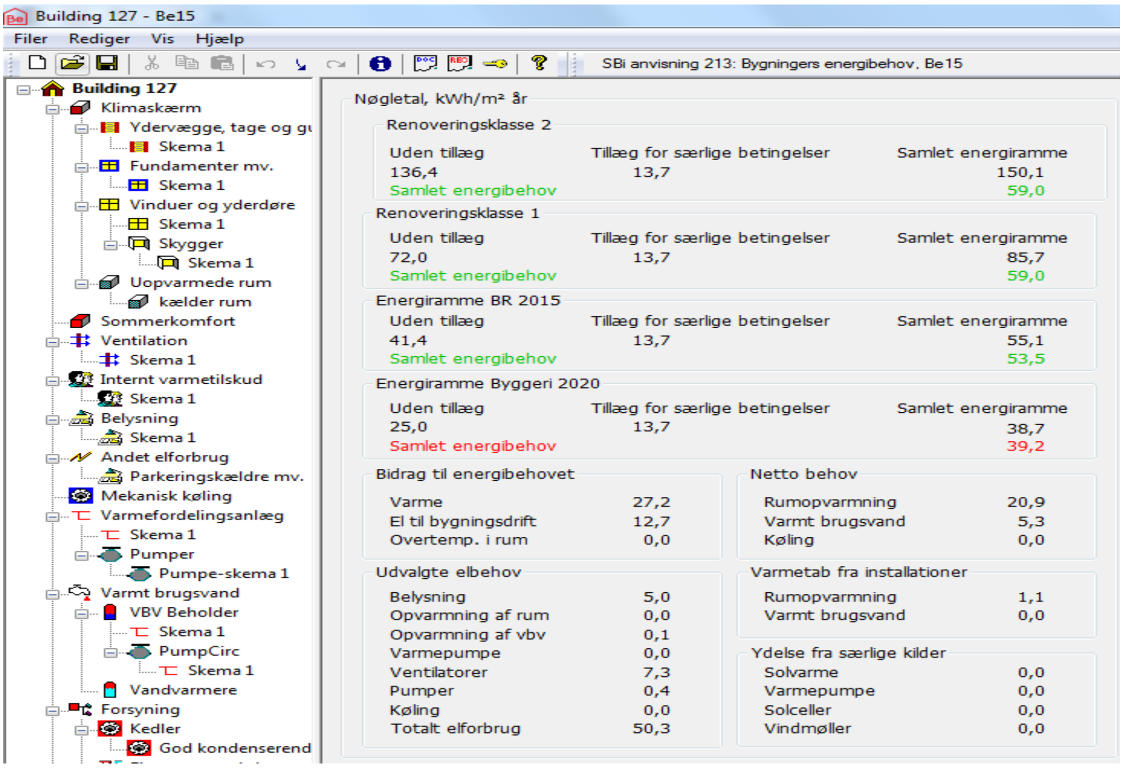


Figure 13: *Energy consumption measured at different times in building 127*

Table 9 and figure 13 show the actual energy consumption of the building but not the expected energy use, due to a lack of expected energy use values. As the measurements for energy use are now known, in the next section, I will estimate the energy consumption for each element of the building, and make an analysis of these figures compared with the actual energy use.

Energy estimation with Be15



Nøgletal, kWh/m² år

Renoveringsklasse 2

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
136,4	13,7	150,1
Samlet energibehov		59,0

Renoveringsklasse 1

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
72,0	13,7	85,7
Samlet energibehov		59,0

Energiramme BR 2015

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
41,4	13,7	55,1
Samlet energibehov		53,5

Energiramme Byggeri 2020

Uden tillæg	Tillæg for særlige betingelser	Samlet energiramme
25,0	13,7	38,7
Samlet energibehov		39,2

Bidrag til energibehovet

Varme	27,2
El til bygningsdrift	12,7
Overtemp. i rum	0,0

Netto behov

Rumopvarmning	20,9
Varmt brugsvand	5,3
Køling	0,0

Udvalgte elbehov

Belysning	5,0
Opvarmning af rum	0,0
Opvarmning af vbv	0,1
Varmepumpe	0,0
Ventilatorer	7,3
Pumper	0,4
Køling	0,0
Totalt elforbrug	50,3

Varmetab fra installationer

Rumopvarmning	1,1
Varmt brugsvand	0,0

Ydelse fra særlige kilder

Solvarme	0,0
Varmepumpe	0,0
Solceller	0,0
Vindmøller	0,0

Figure 14 shows the energy consumption calculated with Be15

Figure 14 shows the Be15 energy consumption calculation. The calculation verifies the estimate made with Be10 by Alectia in figure 12, where the energy consumption was estimated as 54.4 kwh/m^2 per year. Figure

14 shows that the energy estimation with Be15 is 53.5 kwh/m^2 per year, without cooling. According to the results, or my findings, the Be15 calculation assumes that building 127 does not need mechanical cooling. This backs up the statement of Tine Steen Larsen that “the program (Be15) treats the building as a single zone” (Larsen et al. 2012). The Be15 calculations are attached in the appendix in more detail. Following on from the results from the Be15 programme, in the next section I am going to use other methods to estimate the energy consumption of the building, where sensitive analyses will be used to estimate the cooling consumption for each room.

Estimation of energy consumption in the building

Energy consumption is calculated according to building regulation requirements. In Denmark, the authorities want energy use to be calculated with the software Be10, Be 15, Bsim and other simulation programmes. In my case, I use two methods of calculating energy consumption: the first is a standard calculation, and the second uses Be15. This was also to see the differences between the results from the software and the standard way of calculation. Below, I start with the standard calculation.

Transmission losses

The building may have high transmission and heat loss through materials. The building regulations have a stated transmission value for the individual structural elements, which must not exceed the (U- value) values. In this case, the maximum allowable transmission loss for windows and glass exterior walls should not be less than -33kWh/m2/year, and the transmission loss calculation are in Equation 1.0 below:

$$-33 \text{ kWh/m2/year} = 196;4 \text{ kWh/m2/year} - g - 90;36 \text{ K} - U \qquad (1.0)$$

$$-33 \text{ kWh/m2/year} = 196;4 \text{ kWh/m2/year} - 0;48 - 90;36\text{K} - U$$

$$U = 1;40\text{W/ (m2K)}$$

The transmission figure for the other building elements found in the BR, and the heat loss through transmission, are both calculated using Equation 1.1:

$$Q = \sum U.\ A.\ (t_{\text{indoor}} - t_{\text{outdoor}}) \qquad (1.1)$$

U	Transmission coefficient [W / (m^{2}K)]
A	Construction /element area [m^2]
t_{indoor}	Inside temperature [$^\circ$C]
t_{outdoor}	Outside temperature [$^\circ$C]

The specific heat loss through the building is calculated from the floor area multiplied by the U-value.

Facade	Area [m^2]	U-value [W / (m^{2}K)]	Specific heat loss [W/K]
Window	570	0.8	460
Door	58	0.8	46
Roof	1014	0.09	91.2

External wall	332	0.14	46.4
Basement wall	306	0.13	40
Blindfelter	496	0.14	79.5
Floor	742	0.08	69.4
Basement floor	270	0.08	31
Total	3105	-	416.4

Table 10 shows the *Results of heat loss from the transmission assessment*

The total heat loss through transmission can then be calculated as 49.5 kWh/m2/year using equation 1.1, where building regulations set the indoor temperature to 20° C and outdoor to -12° C.

Ventilation

The building uses both natural and mechanical ventilation where it is both supplied with fresh air and the used air is removed trough an exhaust system. Moreover, the ventilation requirements are based on the DS447 guiding norm. The heat loss through ventilation is calculated using Equation 1.2.

$$Q_{\text{vent}} = P.\ V.C_P.\ (t_{\text{indoor}} - t_{\text{outdoor}}) \tag{1.2}$$

P	Air density is set to 1.205 [kg / m3]
V	Volume of ventilated air [m3]
C_P	Specific heat of air is added to 1.005 [kJ / kg K]

For simplification, I used 1 l/(m2). The recommended ventilated air quantity is calculated in Equations 1.3 and 1.5.

$$\begin{aligned} V_{\text{open time}} &= 1\text{l}/\ (\text{sm2}) * 2323\ \text{m}^2 * 9\ \text{hours} * 5\ \text{days} * 52\ \text{weeks} \\ &= 5.4 * 10^6\ \text{m}^3/\text{year} \end{aligned} \tag{1.3}$$

$$\begin{aligned} V_{\text{closing time}} &= 0.3\text{h}^{-1} * 2323\ \text{m}^2 * 24\ \text{hours} * 2\ \text{days} * 52\ \text{weeks} + \\ &\quad 0.3\text{h}^{-1} * 3.5\ \text{m} * 2323\ \text{m}^2 * 15\ \text{hours} * 5\ \text{days} * 52\ \text{weeks} \\ &= 1.2 * 10^7\ \text{m}^3/\text{year} \end{aligned} \tag{1.4}$$

$$V = 1.9 * 10^7\ \text{m}^3/\text{year} \tag{1.5}$$

The building is considered to have natural ventilation in the form of infiltration. The infiltration is assumed to be 0.13 l/(sm^2), since this is the maximum infiltration permitted in low-energy buildings. The air volume served as a result of the infiltration is calculated in Equation 1.6.

$$\begin{aligned} V_{\text{nature}} &= 0.13\ \text{l/s m}^2 * 2323\ \text{m}^2 \\ &= 1.1 * 10^7\ \text{m}^3/\text{year} \end{aligned} \tag{1.6}$$

The required mechanical ventilation is calculated as:

$$\begin{aligned} V_{\text{mechanic}} &= 1.9 * 10^7\ \text{m}^3\ \text{pr. year} - 1.1 * 10^7\ \text{m}^3/\text{year} \\ &= 8.6 * 10^6\ \text{m}^3/\text{years} \end{aligned} \tag{1.7}$$

The difference between natural and mechanical ventilation is that mechanical ventilation has a heat recovery ratio of at least 70%. The chosen building class A requires a heat exchange with an efficiency of 80%.

Ventilation heat loss is calculated in equation 1.8:

$$Q_{\text{vent}} = P.\ C_P.\ (V_{\text{nature}} + V_{\text{mechanic.}}\ (1 - \text{vgv}))\ {*}(t_{\text{indoor}} - t_{\text{outdoor}}). \qquad (1.8)$$

$$= 1.9 * 10^5 \text{ kWh}$$

Heat loss through ventilation is calculated to be 6.2 kWh/m^2 year.

Lighting

The light requirements are prescribed in the Building Code and in the DS700 for different types of buildings. Furthermore, rooms with sufficient daylight supplied and with daylight control aim to achieve an energy-efficient lighting system. To achieve a satisfactory level of light, four fluorescent lamps with an output of 6W were built in, and it is assumed that the light is automatically controlled by a light sensor with an on and off system. In this project, the basement and other rooms have a light level of 50 lux, with 200 lux in the remaining parts of the building; the sufficient light needed is 6 W/m^2. Also, it is assumed that the lights are on for seven hours a day. That makes the total energy consumption for lighting 4 kWh/m^2 per year.

Internal heat gain

Internal heat gain is supplied through heat sources in the building, such as the people and equipment. The most valuable time for heat gain in a school building is when it is in use, when the technical installations for heating, ventilation and light are in normal operation. In our case, the usage time of the building is between 8 and 17 hours a day, which is 45 hours per week for an entire year excluding weekends and holiday periods. The calculation assumes internal heat gain from people and apparatus below, in equations 1.9 and 1.10, which give a total internal energy saving of 24.5 kWh/m2/year.

Individual heat load

The heating subsidy from people depends on the activity and clothing of the people in the building, the latent heat released as evaporation from the body surfaces, and the water content in the breath. Sensible heat is emitted by radiation, conduction, convection and exhaled air. According to SBI instructions 202, the sensible heat discharge by a human is 90W. The building has sufficient space for 250 students. As such, the heat gain from people is calculated as shown in equation 1.9:

$$Q_{\text{pers}} = (250 \text{ personer} . 90\text{W/pers } .9 \text{ hour} . 5 \text{ day} . 52 \text{ weeks})/(2323 \text{ m2}) \qquad (1.9)$$

$$= 22 \text{ kWh /m}^2 \text{ year}$$

Apparatus

It is assumed that each student has a laptop, tablet and phone. The regular break time is between 12:00 to 13:00, where the lights, projectors and laboratory equipment are off or on in standby. Other things have also been calculated: the heat load from the copier that is assumed be in operation for three hours per day, and the refrigerator, which is in operation continuously. The average heat load from the apparatus is designed to be 2,515 W per hour.

Q_{app} = (2515 W/time* 9 Hours *5 days *52 weeks)/ (2323 m2) (1.10)
= 2.5 kWh/m2

Solar radiation

Heat gain from the sun has been taken into consideration, where during the daytime, the building receives solar energy from the sun's rays through the windows. Moreover, the high rate of heat gain depends on the building's orientation. The heating subsidy from the sun is calculated using Equation 1.11.

$Q_{sun} = g. F. A_{win}. I_{Sun.}$ (1.11)

$F = f_{beta}. F_{shield} .f_{skyg}. F_{win}$ (1.12)

g	window g-value
F_{beta}	angle factor
F_{Shield}	shielding factor [-]
F_{win}	window area glass share [-]
A_{win}	Window area [m2]
I_{sun}	exterior solar radiation [kWh / m2. year]
A_{Win}	window area [m2]
F	reduction factor [-]

The reduction factor is calculated using SBI Direction 202.

- Glass g-value read on the manufacturer's website as 0.48.
- Angle factor takes into account the angle of incidence, that is, the angle between the sunlight and glass surface. Angle factor varies in the range of 0-45° C, where the value is 1.0 to 0.9.
- Shielding factor indicates the reduction in solar radiation due to the shielding of the window.
- Shadow factor indicates the reduction due to the surrounding terrain, buildings, planting and installation conditions. With a free horizon, the assumed shadow factor value is 0.9. of the window area.
- Share is estimated to assume the value 0.9, which is a mean for ordinary windows.

The reduction factor is calculated in Equation 1.13.

F = 0; 9. 0; 1. 0; 9. 0; 9 = 0; 0729 (1.13)

The heating subsidy from the sun, depending on the façade orientation, is shown in Table 3.

Orientation	A_{win} [m^2]	I_{sun} [kWh / m^2/ years]	Heat gain specific [kWh / year]
North	28,608	33,893	3,676
South	28,512	83,639	9,040
East	3,444	61,943	809
West	2,496	60,755	575

Total	-	-	14,100

Table 11 *shows the results of the heat gain from the sun*

Solar radiation can be calculated to 6.0 kWh/m^2/year.

Domestic hot water

The calculation of energy consumption for domestic hot water (Q hot water) is dependent on the type of building analysed. For housing, including dormitories, or old people's homes, etc., the normal annual hot water consumption is at least 0.25 m3/m2 of heated floor area. This consumption is normally assumed to be distributed over the year. For other buildings, there are significant variations, but for school buildings, the annual consumption can be anticipated on average to be 0.10 m3/m2 of the heated floor area.

$Q_{\text{hot water}}$ for a whole year can then be calculated as: 1.14.

$$Q_{\text{hot water}} = \rho \cdot c \cdot \Delta t \cdot V \cdot 0.278 / 10^6 \text{ [kWh]}$$

$Q_{\text{hot water}}$	energy consumption for hot water in kWh for a whole year
ρ	water density = 1000 kg / m^3
C	water specific heat = 4190 J / kg / ^{0}C
Δt	heating of water from. 10^{0}C to 55^{0}C
V	volume of water to be heated in m^3
0,278 / 10^6	conversion factor from Joules to kWh

$$Q_{\text{hot water}} = 1000 \text{ kg / m}^3 \cdot 4190 \text{ J / kg / }^0\text{C} \cdot 55 \cdot 350 \cdot 0.278 / 10^6 \text{ [kWh]} \quad (1.14)$$
$$= 2, 2 \text{ kWh}$$

Electricity consumption

The power for ventilation and lighting has a factor of 2.5 for electricity according to the BR10. For a ventilation system with a constant air flow, the electricity consumption for air transport is not more than 2100J/m3 outside air. As such, the requirement of the electricity consumption for the ventilation system is assumed to be 2100J/m^3, and is calculated based on the following equation, 1.15.

$$E_{\text{vent}} = 2100\text{J/m3} * 8, 6 * 10^6\text{m}^3\text{/year} \quad (1.15)$$
$$= 5017 \text{ kWh/year}$$

Electricity consumption for ventilation is, thus, 1.9kWh/m2/year. The electricity consumption for lighting was intended to be 3.1kWh/m2/year from the light calculations, plus 2.2 kWh/m2 for hot water. Using the aforementioned factor of 2.5, the total electricity consumption 18 kWh/m2/year.

Sensitivity analysis

To ensure that the total cooling results are "correct", and as seen in the Be15 calculation, it was indicated that the building does not need cooling. Another issue is that the windows facing south are sheltered. This also suggests that there is no need for a cooling system.

An analysis from each room and the cooling estimations for them are shown in the table below. The total cooling values shown are going to be used in the total energy consumption estimation. The table below shows the different room sizes, volumes and cooling requirements (Kwh/m2/ year). For the whole calculation, see the appendix.

	Room (m2)	Room volume (m^3)	Cooling ($Kwh/m^2/year$)
Class room 012	156	624	1.7
Class room 013	156	624	1.7
Laboratory 014	247	988	2.2
Group room 111	19,2	76,8	1.4
Group room 112	60	240	1.5
Computer room 116	51	204	1.2
Group room 117	20	80	0.3
Class room 119	258	1008	2.3
Hall			1.5
Hall 1 floor			1.9
Total			15.7

Table 12, the sensitivity analysis showing the energy consumption for cooling for each room

The table above shows that each room has different values, except for rooms 012 and 013, because these rooms have the same volumes – plus the same window sizes, which face in the same direction – so the rooms may receive the same rate of heating and need cooling by the same rate. As we know, different types of windows and orientations have a big influence on heating and cooling. During the analysis, it became clear that two of the group rooms that are situated in the middle of the building have windows, but do not have any direct contact to sun, meaning the risk of overheating is less, and that means the cooling for these rooms is estimated to be 1.5 Kwh/m^2.

Because the windows what face south are sheltered, this indicates that the halls do not need cooling – but at the same time, there are some windows on the east and west sides of the building that give a change in cooling requirements, suggesting the halls may need some cooling. The cooling calculation was done in Excel, and can be seen in the appendix.

Energy Frame

The BR10 has determined the energy framework for all types of buildings. In this report, the energy consumption focuses on institutional building energy demands, in which the "total energy required in the building for the supply of heating, ventilation, cooling, domestic hot water and lighting are calculated in kWh/m2 for the heated floor area. The result should not be more than 71.3kWh/m2 per year, plus 1,650 kWh/year and divided total floor area" (BR10). This means that the energy consumption is calculated as shown in Equation 1.16.

(71.3 + 1650/A) kWh/m²/year (1.16)

And for class 2015 low energy buildings, the low energy performance framework is:
(41 + 1100/A) kWh/m²/year (whereby A is the heated floor area).

The energy consumption for heating is calculated in Equation 1.17. The heating power is calculated so that the building maintains a constant temperature.

$$Q_{heating} = Q_{\text{vent}} + Q_{\text{Trans}} - Q_{\text{interne}} - Q_{\text{Sun}} - Q_{\text{lights}} \quad (1.17)$$

$$= 6.2\ \text{kWh/m}^2\text{/year} + 50\ \text{kWh/m}^2\text{/year} - 24.5\ \text{kWh/m}^2\text{/year} - 6.0\ \text{kWh/m}^2\text{/year} - 3.1\ \text{kWh/m}^2\text{/year}$$

$$= 23.2\ \text{kWh/m2/year}$$

The total energy consumption of building 127 is calculated in the following equation 1.18.

$$E_{\text{total}} = E_{\text{heating}} + E_{\text{cooling}} + E_{electricity} \quad (1.18)$$

$$E_{\text{total}} = 23.2\ \text{kWh/m}^2\text{/year} + 14.7\ \text{kWh/m}^2\text{/year} + 18\ \text{kWh/m}^2\text{/year}$$

$$E_{\text{total}} = 55;5\ \text{kWh/m}^2 \text{ per year}$$

The energy consumption calculated with the standard method is 55.5 kWh/m² per year, compared with the totals estimated in figures 12 and 14, where Alectia estimated the energy consumption to be 54.4 kWh/m² per year and the Be15 software showed energy consumption of 53.5 kWh/m² per year. In observing the three energy consumption results, it seen that building 127 would still be in the low energy class 2015 based on these numbers. The next section will focus more on the estimated energy consumption and the actual totals.

Actual heating consumption vs. estimated

The energy consumption for heating the building has been estimated to be 102,158.4 kWh per year, which becomes 42 kWh/m² per year, and the actual heating consumption is 50 kWh/m² per year. This shows that the building uses 8 kWh/m² more than expected. Although the estimation gives 42 kWh/m²/year, the estimated value is still higher than the building could normally use according to the regulations. That is due to the increase of the indoor temperature from 20°C to 23°C, as is required in the building regulations.

The heating calculation results for each month, compared with the actual energy use, are given in Table 13.

$$H_{\text{eating}} = 6.2\ \text{kWh} + 49.5\ \text{kWh}.\ (T_{\text{in}} - T_{\text{out}}).\ \text{Days} - Q_{\text{Sun}} - Q_{\text{interne}} = \text{kwh/m}^2$$

	Jan	Feb	Mar	April	Oct	Nov	Dec
Outside temperature	-2	2	7	10	15	7	6
Inside temperature	23	23	23	23	23	23	23
Actual KWh/m²	11.7	9.3	9.9	4.9	3.2	7	6.4
Expected kWh	29043	20966.5	13502.7	8322.6	7392.5	13502.7	15229.4
Expected KWh/m²	9	7	5.8	3.5	2.2	5.8	6

Table 13 shows the temperature measured and the estimated energy use and actual energy use

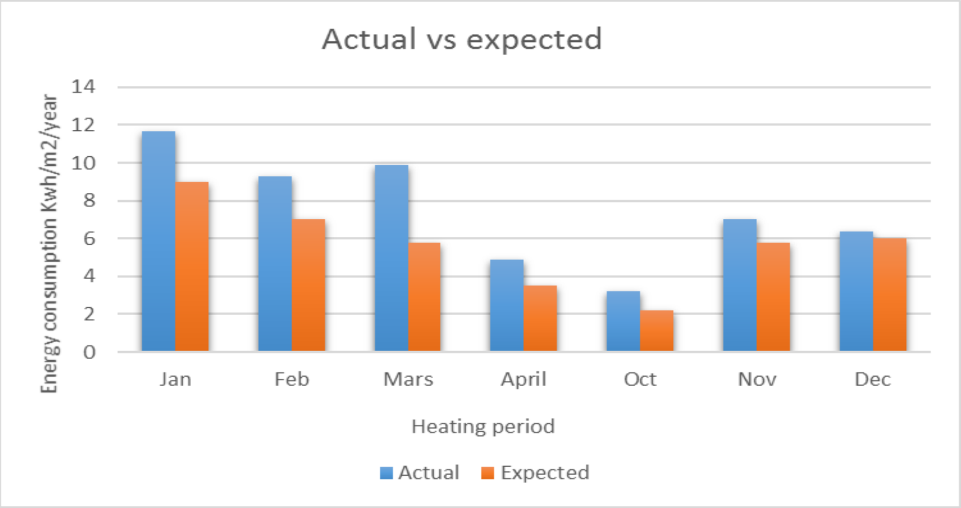


Figure 15: The actual and theoretically calculated values for heating consumption

The graph determines the energy consumption measured over seven months, which shows that the theoretically calculated heating consumption underestimated the actual consumption (Fig. 15). Actual heating consumption was much higher than expected. By observing energy consumption in December, it is shown that expected energy use is higher than the actual consumption rate. This may be due to the fact that the outdoor temperature was low, and the rooms were heated with the electrical radiator for some of the period. The equation below is used to determine the expected energy consumption.

Heating vs. cooling estimation

Table 15 displays the estimated energy consumption of cooling and heating the building over a 12 month-period. According to the calculation, the cooling energy consumption has been estimated to be 34 MWh/year, equivalent to 14.7 kWh/m^2 per year, and the actual cooling consumption is 109,330 kWh/ m^2 per year. The heating energy consumption has been estimated to be 54 MWh/year, or 23.2 Kwh/ m^2, and the actual heating energy consumption is 72.28 kWh/m^2 per year. The heating estimation has been calculated according to the outdoor and indoor temperatures.

Month	Number of days	Cooling MWh/month	Heating MWh/month	Month	Number of days	Cooling MWh/month	Heating MWh/month
Jan	31	0.00	14.28	Jul	31	10.03	0.00
Feb	28	0.00	9.61	Aug	31	8.34	0.00
Mar	31	0.00	5.76	Sep	30	0.94	0.09
Apr	30	0.00	1.02	Oct	31	0.00	1.79
May	31	5.05	0.06	Nov	30	0.00	7.53
Jun	30	9.73	0.00	Dec	31	0.00	13.66

Table 14 shows the cooling and heating estimations and the period when each system needs to work

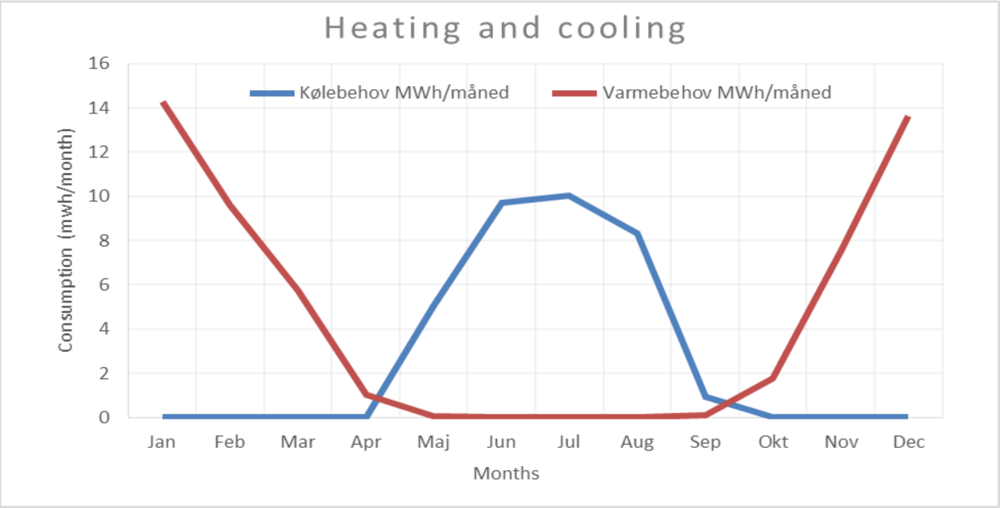


Figure 16 shows the periods when each system needs to work and the maximum energy for each system

Table 15 and figure 18 display how the specific and total energy consumption of the heating and cooling systems are calculated. The theoretical heating and cooling consumption figures underestimated the actual consumption totals (figures 16 and 17). By comparing figure 16 and figure 18 for heating consumption, it is shown that the heating system was also used in the summer period. Despite the fact that figure 18 shows in which months the heating is needed, on the graph it is shown that the heating was needed from January to April and from October to December.

Heating and cooling analysis

The graph shows the actual energy consumption for heating, and demonstrates how actual heating consumptions are much higher than the estimated values. By analysing the graph, it shows that the heating system is used in the building from January to December - where the normal heating period was only thought to be in winter time. The heating consumption decreases in July and starts to increase again in August. The actual heating consumption figures seen to be unrealistic when the building is being heated in the summer time.

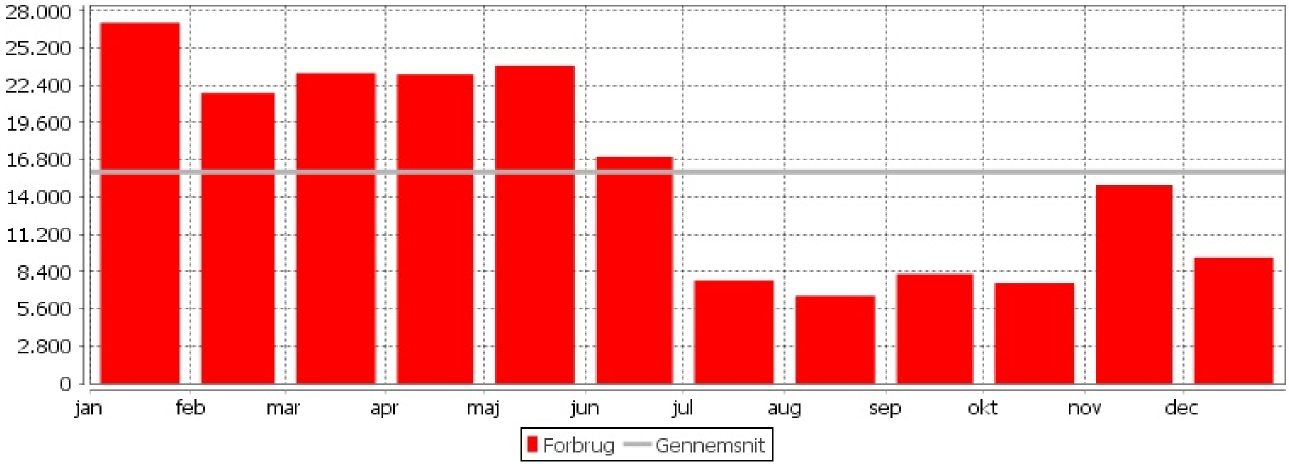


Figure 17 shows the actual heating consumption from January to December

The graph below shows the actual energy consumption used for cooling. As with the heating system, by analysing the graph, it can be seen that the building's cooling system works all year, across winter and summer. There is a decrease in the cooling consumption by 65% from June to August. It increases again in September by 40%. When observing the winter period – when the cooling system is not supposed to be in use in the building – it can be seen that from January to April, the energy consumption is constant at 10,000 MWh, but in November and December the building uses almost the same amount of cooling energy as in August.

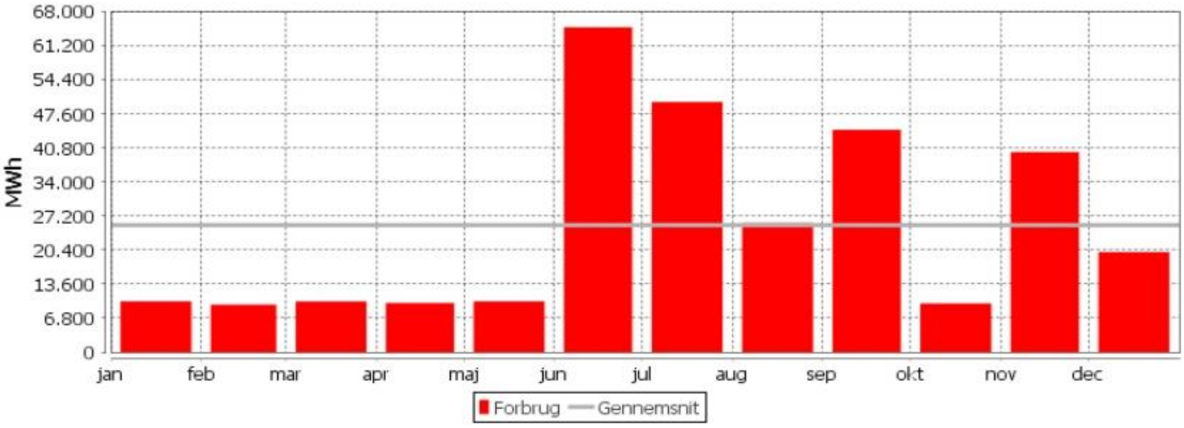


Figure 18 shows the actual cooling consumption of the building from January to December

In figure 17 and figure 18, we can see that the cooling system is used in both the summer and winter periods, and this means the energy consumption of the cooling system is higher than expected. Figure 18 shows that cooling is really needed in the building only in the summer time, from April to September. Generally, by observing figure 16 and figure 17, it is clearly inefficient to use cooling and heating at the same time. In the summer, this will cause overheating in the building, and when using cooling in the winter, it will mean more energy is needed to heat up the building.

Figure 19 shows the electrical radiator that was used in some group rooms and some classes, due to the uncomfortable indoor temperatures.

Figure 19 shows the electrical heater used in the building, which indicates that the heat delivered from the central heating system does not deliver as much heat as was estimated.

Electricity consumption

The electricity consumption of the building has been measured as 129.96 Kwh/m2/year. That includes light, power, ventilation and elevator use. According to the electricity estimation, the electricity use was estimated to be 18 kWh/m2/year. That is seven times less than the actual electricity consumption. This discrepancy may be due to many different things, such as the use of the electrical heater, which may have used more energy than expected. The energy estimation for the electricity heater is as follows. The heater uses 2000W and was in use for one month in November. The use time is 7 hours per day, which would be:

2000 W * 7 hours * 5 day * 4 weeks = 280 kWh per month
= 5 * 280 Kwh per month = 1400 kWh
= 0.7 kWh/ m^2

Due to the large discrepancy between the actual energy consumption and the estimated energy use in the building, thermography images have been used to analyse the building, and the results from the thermography analysis will lead to answers to some of the key questions. The following section concentrates more on the thermography analyses.

Thermography image analyses

The thermography of building structures has shown the occurrence of thermal bridges, which have not been taken into account in connection with the previous calculations. However, it is difficult to put precise figures on the importance of these cold bridges, and therefore they are not taken into account as conditions in the calculations. The following, though, presents a few examples of how thermography can show the unexpected cold bridges and heat loss issues in the building.

In Figures 20, from left to right, there is a thermography image which shows a thermal bridge that should not readily occur, alongside a general photograph of the external door and window. The thermal bridge is caused by the use of a poor door frame. The right-side corner of the thermography image also shows that the corner of this area is affected with a thermal bridge, or moisture.

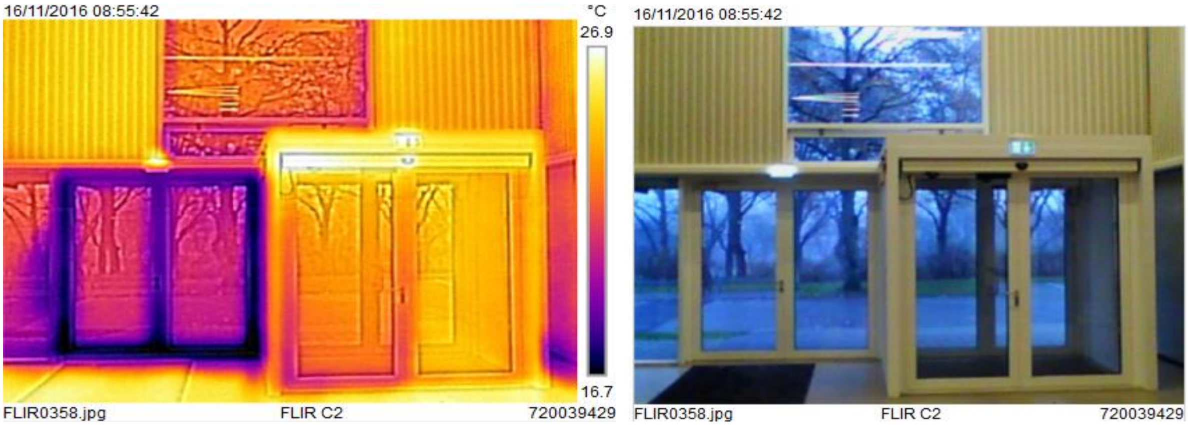


Figure 20 shows the bad door frame that produces a thermal bridge

The thermography image below shows that the outer wall should be fully isolated with 250 mm insulation. Figure 21 shows that there is a region in the image where there may be a thermal bridge. The reason for this thermal bridge is not transparent, but the insulation may be broken to some extent in this area. This could be a full or partial penetration of the insulation by other materials, or it may be that the insulation is simply missing, or has somehow become wet in this area.

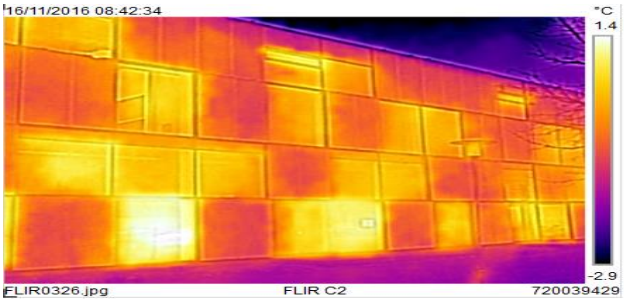


Figure 21 shows that the external wall may have less insulation in some area, causing heat loss

Figure 22 and figure 23 show the supply and return pipes for cold water, which are used for cooling the building. Figure 22 shows that there is cold water circulating in the pipe, which means the cooling system is working. Earlier, figure 17 showed that the cooling system is used in the building from January to December. That has been confirmed by observing the thermography images in figures 22 and 23.

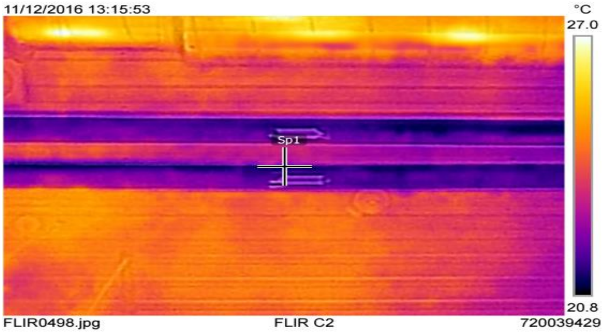


Figure 22 shows the system as water circulates in the pipes

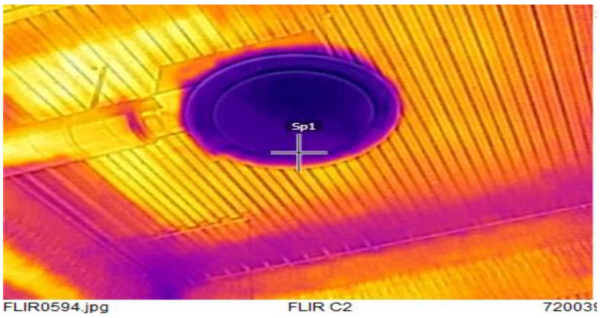


Figure 23 shows the system as cooling happens

In figure 24 and figure 25, we can see that the cooling system has been stopped after the interview with the DTU campus service about the use of cooling at the same time as heating. In the interview with Andres Wang, he clarified that the cooling system should only be used only in summer time, and as such the cold water circulation maybe had some kind of valve problem. Figures 24 and 25 were taken after the interview.

Figure 24 shows the system after the interview

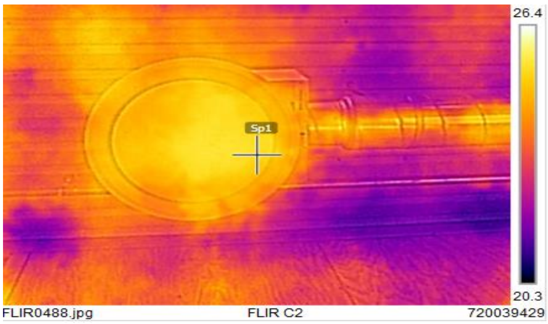


Figure 25 shows the system once it was working properly

The results from the energy consumption section, the thermography images and the analysis between the actual and theoretical estimations of energy use will be investigated further in the discussion section.

The next section will work with the second case study, where I will analyse the energy consumption of building 210.

Second case study: Building 210

Building 210 at Lyngby campus was built between 2003 and 2006. It has approx. 4,600 m^2 of floor space on the first and second floors. There are some classrooms and group rooms which vary in size, accommodating between 20 and 300 students. The building facade and walls are made of bricks, cladding and glass. The glass is used for allowing daylight into the innermost part of the building. The figure below shows the connection from building 210 to building 208.

.

Figure 26 ***the external overview of building 210*** (DTU 2003)

Building 210 was built under the BR95 energy requirement, in which the energy consumption of the building was based on the heating consumption. Therefore, this case study is more focused on heating demands, as BR95 is.

The energy consumption was calculated with the BV98 computer program, and the heating energy was estimated to be 144 MJ/m^2/year or (40 kWh/m^2/year), which shows that the building fulfilled the energy framework requirements. In order to evaluate whether the actual energy consumption of the building still fits with the energy framework, data from previous years has been taken into consideration. The data below shows the energy consumption levels for different years.

Parameter	Expected value [kWh/ m^2 year]	2014 Measured value [kWh/m^2 year]	2015 Measured value [kWh/m^2 year]	2016 Measured value [kWh/m^2 year]
Energy for heating	40	82.4	84.8	103.8

Table 15 shows the collected data for heating consumption

The next section is going to measure and estimate the energy consumption of the building. The first step is to measure the actual consumption and compare it with the expected consumption.

Estimation of energy use in the building

To make an estimation of the energy consumption in this building, I will start by calculating some parameters, such as the building transmission loss, ventilation, and internal heating gain. The transmission is calculated by using Equation 2.0.

$$Q = \sum U.\, A.\, (t_{in} - t_{out}) \tag{2.0}$$

U	Transmission coefficient [W / (m^{2}K)]
A	Construction /element area [m^2]
T_{in}	Inside temperature [$^\circ$C]
T_{out}	Outside temperature [$^\circ$C]

The transmission figure for the building envelope components was used to calculate the specific heat loss through the building envelope – see Table 16, below.

Facade	Area [m^2]	U-value [W / (m^{2}K)]	Specific heat loss [W/K]
Window	2076	0.1	201.6
Roof	1656	0.2	331.2
External wall	906	0.3	271.8
Basement wall	336	0.2	67.2
Floor	791	0.2	158.2
Basement floor	865	0.3	138.4
Total	4554	-	966.8

Table 16 shows the heat loss estimation for this building

The total heat loss through transmission can then be calculated to be 33.5 kWh/m^2 per year, using Equation 3.6. The outdoor temperatures are based on monthly estimations according to the SBI Direction 202. In addition, building regulations have set a requirement for the indoor and outdoor temperatures during calculations: 20^o C for the indoor temperature, and -12^o C for the outdoor temperature.

Ventilation estimation

The building uses natural ventilation and mechanical ventilation, where it is supplied with fresh air and used air is removed trough an exhaust system. The ventilation requirements are based on DS447 guiding norms. Heat loss through ventilation is calculated using Equation 2.1.

$$Q_{vent} = P.\, V.C_P.\, (t_{in} - t_{out}) \tag{2.1}$$

P	Air density is set to 1.205 [kg / m3]
V	Volume of ventilated air [m3]

C_P	Specific heat of air is added to 1.005 [kJ / kg K]

$$V_{\text{open time}} = 1\text{l}/(\text{sm2}) * 3244\ \text{m}^2 * 9\ \text{hours} * 5\ \text{days} * 52\ \text{weeks}$$
$$= 7.5 * 10^6\ \text{m}^3/\text{year}$$

$$V_{\text{closing time}} = 0.3\text{h}^{-1} * 3244\ \text{m}^2 * 24\ \text{hours} * 2\ \text{days} * 52\ \text{weeks} +$$
$$0.3\text{h}^{-1} * 3.5\ \text{m} * 3244\ \text{m}^2 * 15\ \text{hours} * 5\ \text{days} * 52\ \text{weeks}$$
$$= 1.5 * 10^7\ \text{m}^3/\text{Year}$$
$$V = 2,1 * 10^7\ \text{m}^3/\text{Year}$$

The building is considered to have natural ventilation in the form of infiltration. The infiltration is assumed to be 0.13 $\text{l}/(\text{sm}^2)$, since this is the maximum infiltration permitted in low-energy buildings. The air volume served due to infiltration is calculated in Equation 2.2.

$$V_{\text{nature}} = 0.13\ \text{l/s m}^2 * 3244\ \text{m}^2$$
$$= 1.2 * 10^7\ \text{m}^3 / \text{year}$$

The required mechanical ventilation is calculated as:

$$V_{\text{mechanic}} = 2.1 * 10^7\ \text{m}^3\ \text{pr. year} - 1.2 * 10^7\ \text{m}^3 / \text{year}$$
$$= 9.1 * 10^6\ \text{m}^3 / \text{years}$$

The difference between natural and mechanical ventilation is that mechanical ventilation has a heat recovery ratio of at least 70%, and for buildings within the chosen energy class, A, it should have a heat exchange efficiency of 80%.

Ventilation heat loss is calculated in Equation 2.1 below.

$$Q_{\text{vent}} = P.\ C_P.\ (V_{\text{nature}} + V_{\text{mechanic.}}\ (1 - \text{vgv}))\ *(t_{\text{in}} - t_{\text{out}}) \qquad (2.1)$$
$$= 1.8 * 10^5\ \text{kWh}$$

Heat loss through ventilation is calculated to be 7.4 kWh/m^2 year.

Internal heat gain

The internal heat gain comes from the building's heat sources, such as the people and equipment within it. The most valuable time for heat gain in a school building is when it is in operation, and the technical installations for heating, ventilation and light are in normal operation. The building use life is 45 hours per week, which is believed to occur across five days, from 08:00-17:00. From the calculations in Equations 2.3 and 2.4, the total internal energy savings are calculated to be 21.5 $\text{kWh/ m}^2/\text{year}$.

Human heat gain

The heating subsidy from people depends on their activity level and clothing, latent heat released as evaporation from their body surfaces, and water content in the breath. Sensible heat is emitted by radiation, conduction, convection and exhaled air. According to SBI instructions 202, the sensible heat discharge by a human is 90W. As the building has sufficient space for 300 students, in this case, the heat gain from people can be calculated as shown, in Equation 2.3 below.

$$Q_{\text{pers}} = \frac{300\text{ personer}\,\_\,90\text{W/person}\,\_\,9\text{timer}\,{*}5\text{dage}\,\_\,52\text{uger}}{3244\text{ m2}a} = 19\text{ kWh /m2 per year} \qquad (2.3)$$

Apparatus

It is assumed that each student has a laptop, tablet and phone. The normal break time is between 12:00 to 13:00, when the lights, projectors and other kitchen equipment are switched off or on in standby. Other things have also been calculated, such as the heat load from the copy machine, which is assumed be in operation for three hours per day, and the refrigerator, which is in operation continuously. The total heat load of the apparatus is assumed to be 3,500 W per hour.

$$Q_{\text{app}} = \frac{3500\text{ W/time}\,\_\,9\text{timer}\,\_\,5\text{dage}\,\_\,52\text{uger}}{2323\text{ m2}a}\ 2.5\text{ kWh/m2} \qquad (2.4)$$

Solar radiation

Heat gain from the sun has been taken into consideration. During the daytime, the building receives solar energy from the sun's rays through the windows. The rate of the heat gain depends on the building's orientation. The heating subsidy from the sun is calculated using Equation 2.5.

$$Q_{\text{sun}} = g.\ F.\ A_{\text{win}}.\ I_{\text{sun}} \qquad (2.5)$$

$$F = f_{\text{angle}}\ .\ F_{\text{shield}}.\ F_{\text{win.}}\ G \qquad (2.6)$$

g	Window g-value
F_{angle}	Angle factor
F_{Shield}	Shielding factor [-]
F_{win}	Window area glass share [-]
A_{win}	Window area [m2]
I_{sun}	Exterior solar radiation [kWh / m2. year]
A_{Win}	Window area [m2]
F	Reduction factor [-].

The reduction factor is calculated using. SBI Direction 202nd

- Glass g-value read on the manufacturer's website as 0.48.
- Angle factor is the angle between the sunlight and the glass surface. The angle factor varies only slightly in the range 0 <45° C, where the values can be calculated with 1.

- Shielding factor indicates the reduction in solar radiation due to the shielding of the window.
- Shadow factor indicates the reduction of solar radiation due to the surrounding terrain, buildings and plants. As a result of the free horizon, I assume a shadow factor value of 0.85.
- Share is estimated to be 0.85, which is for ordinary windows.

The reduction factor is calculated in Equation 2.6.
F = 0, 85. 1. 0; 85. 0; 85 = 0; 596
The heating subsidy from the sun depending on the façade's orientation, as shown in Table 18.

Orientation	*A* $_{win}$ [m^2]	*H t* [w/K]	Qs [kWh / year]
North	771	771	428
South	745	45	465
East	221	221	178
West	339	339	105
Total	2076	2076	1.176

Table 17 shows the results of the heat gain from the sun's radiation

Solar radiation can be calculated to 2.7 kWh/m^2/year.

Analysis of measurement results

The section reviews the measurements that have been taken in the building, such as heating consumption and indoor and outdoor temperature. These measurements are used for comparison between the theoretical energy consumption calculated before the building was built, and the actual energy consumption used in reality. In addition, there have been several measurements of the temperature that are used in the calculations to determine the building's heating needs.
Two types of measurement have been made, the monthly and daily analyses. The monthly measure was taken during the seven months when heating is needed in the building, and the daily measurement aims to measure the heating consumption of each day in a given period of time.

There is data available for a total of 7 months of monthly measurements, and 31 days for the daily measurement. The monthly measurements run from 1 January to April, and from 1 October to 31 December, and the daily measurements begin on 1 December 2016 and end on 31 December 2016.

Temperature measurement

The outdoor temperature was measured with a thermostat, from 22 December 2016 to 31 December. For the other months, the outdoor temperature was collected from a weather forecast data base. The indoor temperature was measured with a thermostat installed in all classrooms and group rooms. The table below shows the different temperatures for each month.

	Jan	Feb	Mar	Apr	Oct	Nov	Dec
Outdoor temperature	-2	2	7	10	15	7	6
Indoor temperature	22	22	22	22	22	22	22

Table 18 shows the different temperatures measured for each month

Energy consumption

The building's energy use throughout the period were measured with energy meters installed in the basement. Since the building was built with the old regulation, BR 95, the energy consumption for electricity has been taken into account in the assessment.

	Jan	Feb	Mar	Apr	Oct	Nov	Dec
KWh /m^2	20.4	16.9	10	16.4	8.8	15.1	14.8

Table 19 show the heating consumption for each month period.

Table 20 and figure 27 show the energy consumption of the heating system. Month one corresponds with 1 January 2016, and six months (where the greatest energy consumption occurs) corresponds with 31 December 2016. The graph also shows that from March to December the use of the heating system was constant, although the temperature was not constant from March to December.

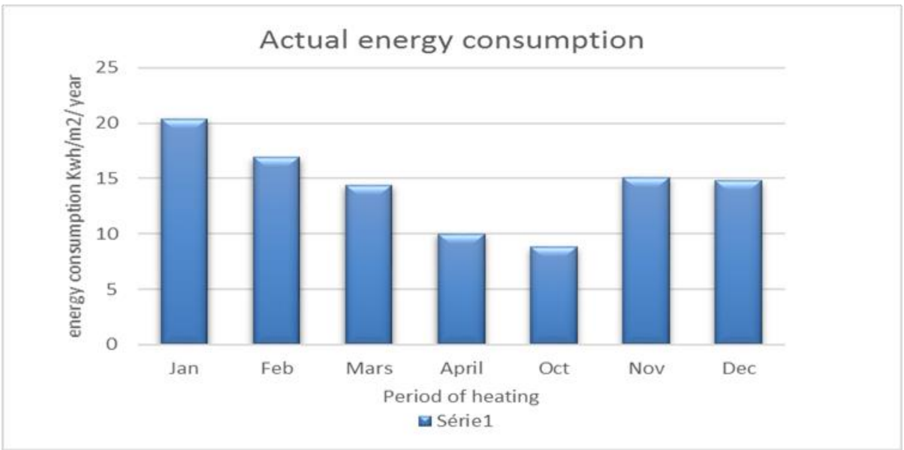


Figure 27 shows the energy consumption of the heating system in 2016

Summary of measured values

In these section, the measured results are summarised. The parameters which directly affect the building's indoor climate and energy consumption are summarised in Table 20 for each month. As was mentioned in the preview paragraph above, the energy consumption from March to December does not correspond with the outdoor temperatures.

Period	Outdoor temperature	Indoor temperature	Energy use
January	-2	22	20.4
February	2	22	16.9
Mar	7	22	10
April	10	22	16.4
October	15	22	8.8
November	7	22	15.1
December	6	22	14.8

Table 20 shows the total measurement results for temperature and energy use for seven months

Actual energy use vs. estimated

Comparisons between calculations and measurements will be made in this section. In part, the measurement results are compared with simplified calculations based on the house's total heat loss coefficient.

The calculation of the building's expected heating demand is based on the measured indoor and outdoor temperatures, and solar energy gains. The theoretical heat loss coefficient of the building can therefore be determined in the following, Equation 2.7.

$$Q_{total} = Q_{heat\ loss} + Q_{vent} \tag{2.7}$$

Q_{total}	is the total heat loss coefficient of the housing
$Q_{heat\ loss}$	is the heat transfer coefficient
Q_{vent}	is the heat transfer coefficient for ventilation losses/infiltration

$$Q_{total} = \tag{2.8}$$

$$Q_{heating} = Q_{\text{vent}} + Q_{\text{Trans}}.\ (T_{\text{in}} - T_{\text{out}}).\ P_{\text{eriod}} - Q_{\text{Sun}} - Q_{\text{interne}} \tag{2.9}$$

Q_{heating}	is the expected heating need
T_{in}	is the inside temperature
T_{out}	is the average outside temperature
T_{period}	is the number of hours in the period
Q_{s}	is the total solar energy subsidies into the building
Qi	is the total internal heat gain to the building

The internal heat gains have been calculated in Equations 2.3 and 2.4. The heat gains in the building are assumed to occur from 08:00 to 17:00 daily, when building is in use and there is also the presence of solar radiation because of the daylight. To estimate the heating consumption in the building, the measured and calculated values have been used in the formula below to determine the total heating consumption.

H_{eating}= 7.4 kWh + 33.5 kWh. (20 - (-12)). 196 days – 1176 – 21.5 = 151,158.4 kWh

The total heat requirement for the period is calculated as 151,158.4 kWh/year; that becomes 44 kWh/m^2/year, and the actual energy used for heating is 90 kWh/m^2 per year. As such, it is shown that the building uses 46 Kwh/m^2 more than expected. The heating calculation results for each month compared with the actual energy use are given in Table 22.

$H_{\text{eating}} = Q_{\text{vent}} + Q_{\text{Trans}}.\ (T_{\text{in}} - T_{\text{out}}).\ \text{days} - Q_{\text{Sun}} - Q_{\text{interne}} = \text{kwh/m}^2$

	Jan	Feb	Mar	April	Oct	Nov	Dec
Outside temperature	-2	2	7	10	15	7	6

Inside temperature	22	22	22	22	22	22	22
Actual KWh/m^2	20.4	16.9	16.4	10	8.8	15.1	14.8
Expected kWh	32233	26343.5	20222	16527.5	10392.5	20222	22089.9
Expected KWh/m^2	9.9	8.1	6.2	5	3.2	6.2	6.8

Table 21 shows the indoor and outdoor temperatures and the total energy use expected

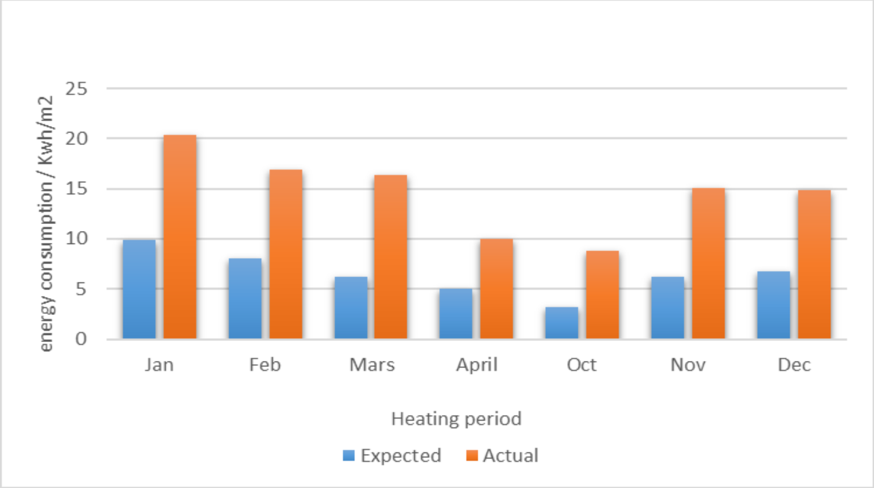


Figure 28 shows the actual and estimated heating energy consumption per month

The graph shows the actual energy consumption measured across the seven months alongside the expected totals, and clearly demonstrates that the theoretical calculations for heating consumption underestimated the actual consumption (Fig. 28). Not only does it show that actual heating consumption was much higher than the theoretical calculations, but also, by observing the graph, it can be seen that January and February are the months when the building consumes more heating energy than the other months. When analysing the other months, it can be seen that from March to December, the heating consumption decreases by 50% of the total heating consumption for January and February.

The decrease of the energy consumption in this period is from 20 kWh/m^2 per year to 10 kWh/m^2 per year, which could be achieved by fixing errors in the building. But although the energy use has been reduced by 50%, the building still uses more energy than expected when comparing the actual and theoretical use totals. The heating consumption in building 210 cannot be constant due to the outdoor temperature variation. The equation below is used to determine the expected energy consumption.

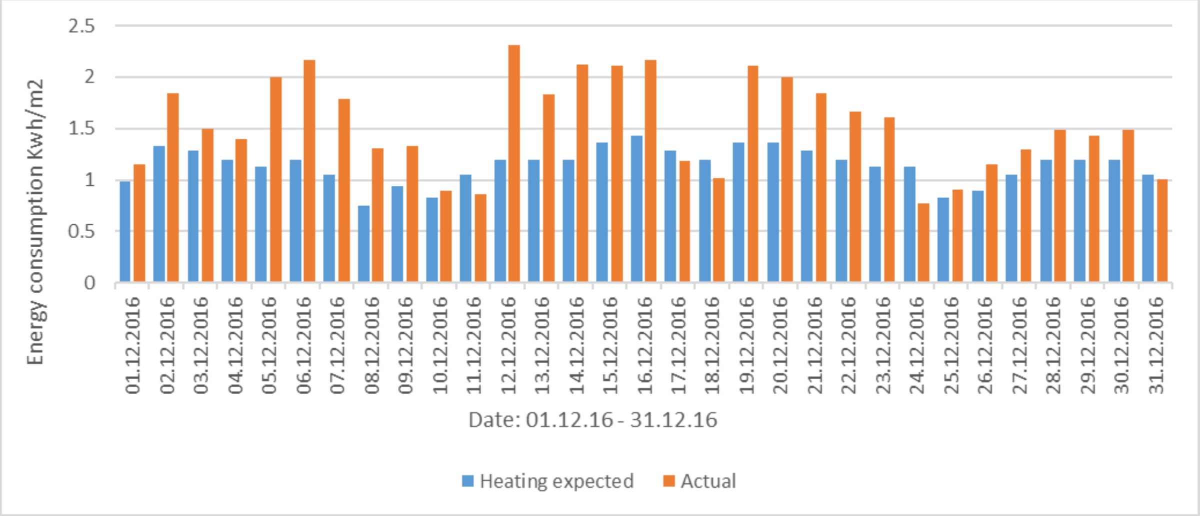
$H_{eating} = Q_{vent} + Q_{Trans}. (T_{in} - T_{out}). 9\ h - 3.2 - 0.059 = kwh/m^2$

Period	Out Temp	In Temp	Actual	Expected	Period	Out Temp	In Temp	Actual	Expected
01.12.16	9	22	1.15	0.98	16.12.16	3	22	2.16	1.43
02.12.16	7	22	1.84	1.13	17.12.16	5	22	1.19	1.28
03.12.16	5	22	1.5	1.28	18.12.16	6	22	1.02	1.20
04.12.16	6	22	1.4	1.20	19.12.16	4	22	2.11	1.36
05.12.16	*7*	*22*	2	1.13	20.12.16	4	22	2	1.36
06.12.16	*6*	*22*	2.16	1.20	21.12.16	5	22	1.84	1.28

07.12.16	8	22	1.79	1.05	22.12.16	6	22	1.66	1.20
08.12.16	12	22	1.31	0.75	23.12.16	7	22	1.61	1.13
09.12.16	10	22	1.33	0.90	24.12.16	7	22	0.77	1.13
10.12.16	11	22	0.86	0.83	25.12.16	11	22	0.91	0.83
11.12.16	8	22	0.86	1.05	26.12.16	10	22	1.15	0.90
12.12.16	*6*	22	2.31	1.20	27.12.16	8	22	1.3	1.05
13.12.16	*6*	22	1.83	1.20	28.12.16	6	22	1.49	1.20
14.12.16	*6*	22	2.12	1.20	29.12.16	6	22	1.43	1.20
15.12.16	4	22	2.11	1.36	30.12.16	6	22	1.49	1.20
					31.12.16	8	22	1.01	1.05

Table 22 shows the estimated and measured heating that the building uses per day

Figure 29 shows the actual energy consumption vs. the estimated energy use



In this section, daily heating consumption has been taken in account by measuring and analysing the actual heating consumption on a day-to-day basis. From figure 29, we can see that the theoretical calculations underestimated the actual heating consumption – this is in contrast with the rest of the categories, for which the theoretical calculations largely overestimated the actual consumption. The actual heating use in the building is much higher than the theoretical use. The theoretical and actual values only coincided on 10, 11, 17, 18, 24, 25 and 31 December 2016.

So the theoretical heating calculations were significantly higher than the actual use. By analysing table 21, it can be seen that the weather in December was not cold but a bit warm for the season. By observing the actual heating consumption in the graph, for 12-14 December, it can be seen that the actual heating use is very high when compared with the theoretical calculation. The reason for this could be that the cooling system and the heating system were switched on at the same time. This will be analysed in the next section using thermography images, and the analysis will lead to answers to the main questions of this research work.

Thermography analyses

The thermography of building structures has shown the occurrence of thermal bridges in many buildings, which has not taken into account in connection with the previously mentioned detailed calculations. It is difficult to put precise figures on the importance of these cold bridges, and they are therefore not taken into account in the calculations. However, the following presents some thermography images showing the unexpected cold bridges in the building.

Figure 30 shows a thermal image which indicates a thermal bridge around the windows, and a general photograph of the window and the outer wall. Figure 31 shows that a small window in the building is open, causing a serious thermal bridge in the building allowing heat to escape. It has been noticed that many small windows in the building are often left open instead of closed. Figure 30 was taken in the classroom, and figure 31 in the hall.

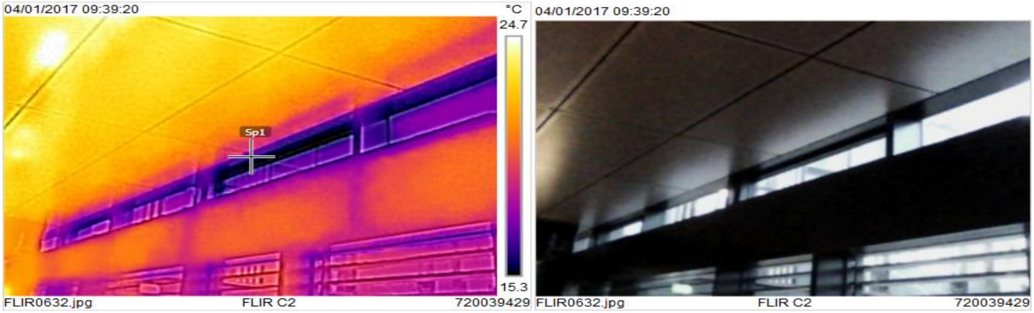


Figure 30 shows the thermal bridges around the window and the walls

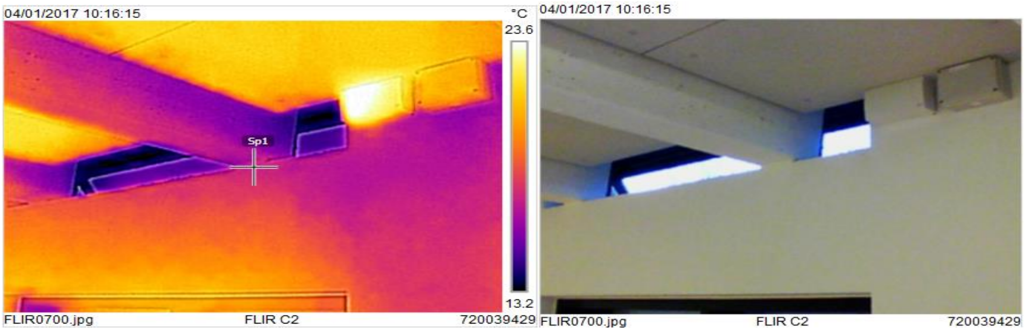


Figure 31 shows that a window is open, causing a thermal bridge in the building

In Figure 32 the air infiltration in the building is shown. As the open windows in the building show, these issues are not about building structure, but human behaviour: for example when a student opens a window in the hall or group room, and leaves it open...

Figure 32 shows air infiltration into the room through the window

Figures 33 and 34 show a thermal image demonstrating the presence of a thermal bridge in the outer wall, as well as a general photograph of the east façade. Figure 33 shows clearly insufficient insulation on the outer wall and considerably more heat loss from the window and wall as well. Figure 34 also shows the insufficient insulation in the outer wall and the high heat loss, indicated by the warmer colours.

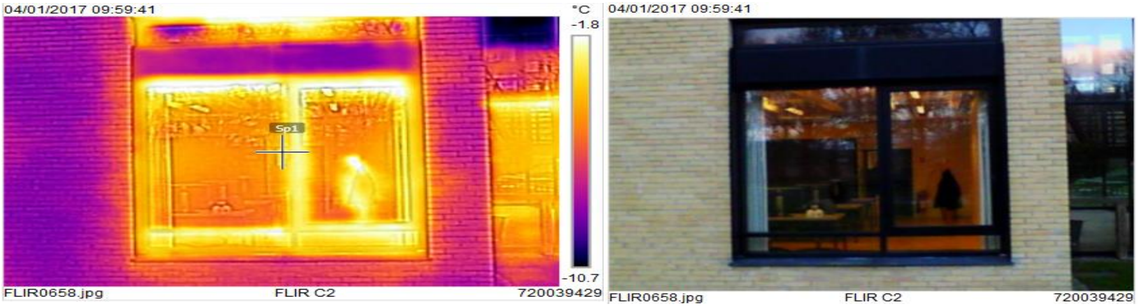


Figure 33 shows heat loss through the outer wall and windows

Figure 34 shows insufficient insulation on the outer wall and high heat loss

The estimated energy consumption, the thermography image analysis and the comparison of the actual energy consumption and the theoretical figures will be discussed in the following discussion section, which will lead to answers for the questions in this work.

CHAPTER 4

Discussion and conclusion

In this chapter, the aims and research questions of the thesis are discussed and analysed. The research question is: how can the discrepancy between the expected and measured energy consumption in buildings be minimised? And the aim is to identify the factors causing building 127 and 210 to not reach their goals in terms of the expected energy consumption. The other aim is to discuss the ways in which energy consumption can be reduced in the buildings. The discussion is constructed as follows: first, building 127 is discussed, then building 210 follows, and then the conclusion is presented. The discussion is based on the data collected from January to December 2016.

Discussion for building 127

The measured values obtained from the Energykey (database) show that building 127's energy use is higher than the expected values. According to Alectia A/S, the estimated energy consumption per year was expected to be 54.4 kWh/m^2. The data for the different parameters were accessible from Alectia, so based on this and my own estimations I came to 55.5 kWh/m^2 (expected value), which almost corresponds to Alectia's estimation. Since the Danish authorities recommend the use of Be15 software to estimate energy consumption, I made another estimation for building 127 using this software, which came to 53.3kWh/m^2. However, I found that the Be15 programme does not include energy consumption for the mechanical cooling of the building, and I therefore assumed that Be15 has some uncertainty in terms of estimating the consumption of the cooling system in the building. However, when the same data were compared to the actual values from the Energykey database, it showed that in reality, the building was consuming six times more energy than the above figures for the 2016 period.

Since the actual consumption is six times higher than the estimated value (expected value), it is important to establish the cause of the differences. Energy consumption calculations involve indoor and outdoor temperatures. According to building regulations, estimated energy consumption in the building should be calculated using 20°C as the indoor temperature and -12°C for the outdoor temperature. When the measurements were carried out, the indoor temperature was 23°C and the outdoor temperature was 6°C. In this case, the increased indoor and outdoor temperatures have an impact on the actual value for energy consumption for building 127.

The following elements and activities also had an impact on the higher than expected energy consumption. In 2016, January was colder than the rest of the months, and this resulted in high energy use for heating the building. Moreover, the main entrance door to building 127 was often open during the day for certain periods of time, and as a result there was an increase in heat loss from the building. Also, from January to December, the building was using both its cooling and heating systems at the same time, as indicated from the data collected from Energykey. The heating system should have been off from May to September (see figure 16, page 35) but the data showed that the heating system was operating during that period (see figure 17). Similarly, the cooling system should also have been off from January to April as well as from October to December (see figure 16, page 35), but the output showed that the cooling system was running during that period (see figure 18). Therefore, it was shown that building 127 was using heating during both the winter and the summer time. Using heating in the summer is obviously a waste of energy that will cause overheating in the building and mean that the cooling system has to use more energy to reduce the heat of the building. Separately, electrical heaters were used to heat some the rooms in the building in winter, and this also contributed to an increase in the actual energy consumption values for the building. The findings show that students were given heaters to supplement the heating system when the rooms were not warm enough, and in many cases the heaters were left on in empty rooms.

As was seen in figure 13, electricity consumption for building 127 is higher than expected. This is due to the issues above, like the electrical heaters, and some parameters that were not used in the original energy estimations, such as the use of the copy machine and drinks machines. These elements have a significant influence on energy use in a building, and may have caused the increase. There could be other elements that caused the actual energy use to be higher than predicted, but these are not focused on in this project.

Since the building is classified as low energy class 15, it is important to investigate further the other elements that could be contributing to a higher energy consumption for the building. Therefore, a thermography camera was used to detect and analyse heat loss and cooling through the building's elements. The results showed that the cooling system was running during the winter time (figure 22, page 38). Also, thermal bridges around the three main doors were detected. In addition to these issues, it was also possible to identify, through the thermal camera, that there may be heat loss through the outer wall as well (figure 21 pag). Concerning the cooling system installed in the ceiling, I spoke to the supervisor about why the system was running during the winter. The supervisor was not aware of this until our conversation, and presumed that it was not supposed to be working. Therefore, the staff investigated the problem and later mentioned that there was something wrong with the valve, causing the system to be switched on when it was not in demand.

Discussion for building 210

As seen in Figure 22, the energy consumption estimate for building 210 is 44 kWh/m^2 per year. Though this is an estimated value, it is quite consistent with the average value of 144 MJ/m^2 per year or (40 kWh/m^2 per year) that was calculated separately by the consulting company, Birch & Krogboe A/S. In this calculation, all of the important parameters are given the mean value of the figures listed by the construction company. When comparing the expected and actual energy consumption values, we can see that that the energy consumption was actually 41.5% higher than expected, at 62.4 kWh/m^2 per year. The goal of using only 40 kWh/m^2 per year will therefore be missed, by 22.4 kWh/m^2 per year. According to the Danish Meteorological Institute (DMI), 2016 was warmer than previous years, which means that the energy use totals for 2016 are unrealistic for the long-term.

As seen in Figure19, the indoor temperature is of importance. For each degree that the indoor temperature goes up, the energy consumption also increases. Since the actual value is two times more than the estimated value (expected value), it is important to establish the cause of the differences between the two. The energy consumption calculation involves indoor and outdoor temperature calculation. According to building regulations, when energy use in a building is being estimated, the indoor temperature should be assumed to be 20°C and the outdoor temperature should be -12°C. When the measurements were carried out, the indoor temperature was 22°C and the outdoor temperature was 6° C, higher than the recommended temperatures in the BR. In this case, the increases in the indoor and outdoor temperatures had an impact on the actual value for energy consumption for building 210.

As seen in Figure 30, the building has significant thermal bridges around the windows and wall joints. For the windows, the thermal images showed that the use of poor window frames allowed cold air to infiltrate into the building. By observing the wall element connections, it could be seen that cold air infiltrates through poor mastic seals, causing the walls to be colder than expected, as seen in figure 31. Many small windows in the hallway and classrooms were also discovered to be regularly left open – for example, one small window I identified seems to always be open, and is located where no-one would notice this. Other windows – including five big windows in the hallway, as seen in figure 32 – were also occasionally left open. This human behaviour is one of the reasons why more energy was used in the building than expected.

By observing figures 33 and 34, it was seen that the windows and external doors have high heat loss due to the poor insulation of the window and door frames. The thermography image also showed that the external wall may have insufficient or missing insulation, which could also lead to an increase in the energy use of the building. The other thing that needs to be taken into consideration is the technical installation of the heating system and the meters, because the data collection showed the meters recorded 80 kWh/m^2 per year used in 2014 and 80 kWh/m^2 per year in 2015 – while in 2016, they showed that the building used 102.4 kWh/m^2 per year. According to the DMI (Cappelen 2016), 2015 was colder than 2016, so this divergence of 22.4 kWh/m^2 per year is hard to understand considering the outdoor temperatures. This suggests that the meters and installations need to be investigated to better understand the divergent figures on energy use for this period.

Recommendation solution

The goal for building 127 to fit into the low energy class 15 is unrealistic, due to the high energy consumption of the building in many different parameters, such as cooling and heating the property. However, in this section, solutions for these issues across different parameters will be demonstrated.

Cooling

The cooling system needs to be investigated deeply. According to the analysis, the cooling system functions in both summer and winter. At the same time, it has been recorded that the actual energy consumption of the building is much higher than expected. These issues are almost certainly linked, and in this situation, some of the below solutions need to be considered in order to reduce the energy use of the building.

- The cooling system needs to be tested first. A simple technique for this would be to install an extra meter, that will be directly connected to a computer or testing machine for a period of one week. Then, compare the measurements from the Energykey data and the computer, and if the measurements are the same, this means the installation of the system is not good, and it needs to be replaced or repeated. However, if the measurement data are not the same, that is simple to fix: the meter itself is not working, and needs to be replaced.
- The second thing to be done is to control and fix the valves and taps, to avoid the circulation of cold water in the cooling system.
- Then, it would help to turn off the cooling system when the building is not occupied.

- Finally, the temperature sensors need to be programmed in a certain way, so that over the summer holidays, they switch off and the cooling system does not work while the building is empty.

Heating

The heating system in this building is also not working correctly. When the heating is switched on, it takes days before the building gets warmer, which is why the occupants used an electrical heater on several occasions. There are some solutions for the problem.

- Heater need to be turned off in summer to avoid overheating.
- As it takes a day to heat a building, this shows clearly that the cooling system is not working, and it needs to be replaced or changed.

There are some other issues that were seen on the thermography images. For example, the external wall needs to be investigated to see if insulation is missing. The first thing to do to look into this is to open one wall element and see what the insulation is like. If there is a lack of insulation, it can be assumed that the rest of the wall elements are also missing insulation, which means the rest of the wall needs to be given new insulation.

Heat loss and cold bridges were also found around the windows and doors. It would be good to prevent these by fixing the door and window frames. The other cold bridge in the corner also needs to be investigated – for example, is it caused by a crack, and if so, that will need to be fixed too.

Building 210

Human behaviour has a big impact in this building, where students open window and leave them open. This requires more inspection from the campus services. As it has been found that almost all small windows in the hall and classrooms are routinely left open, the following solutions need to be looked at to reduce energy consumption in the building.

- Campus services need to control whether the windows are closed. This could be done by installing an alarm system that alerts the team if any windows are open after the building closes.
- Heat loss through the windows could be prevented by replacing the window or by fixing the window and door frames.
- The air infiltration through the windows and window frames needs to be fixed, or the parts replaced. This is the same with the air infiltration through the wall - in this situation, the external wall needs its joints fixing.
- As seen on the thermography image, the external wall has less insulation than it needs. The only solution is to renovate the external wall, with new insulation.

- Switch off the cooling system in the period when it is not need, for example. In winter, during holidays and outside working hours.
- Keep checking shading system, if it function correctly, it can increase the energy consumption.

As building127 have large window areas Om the east and south. That can increased the need off cooling the building.

To implement new requirement for technical installation test and verification into the design brief contract and continually to the deliverance of the building. In this way, one can find many mistakes before building get in use.

Other form to reduce the energy consumption caused by technical installation could be to implement a commissioning system. Whereby the performance tests for technical installation will part of a commissioning process. That mean from the design brief to the delivence of the building, include 24 months of energy consumption measured after building has been occupied. During this period the building contractor have a responsibility for any bad energy performance of technical installation and that could claim for a penalty.

Conclusion

The study performed in this thesis aimed to compare the expected, measured and calculated energy consumptions of buildings 127 and 210 on campus, based on an analysis of the measured and estimated energy use for the case studies. The aims were to

1. Identify the factors causing building 127 and 210 to not reach the goals of low-energy consumption.
2. Find an answer to the question: how can the discrepancy between the expected and measured energy consumption in the buildings be minimised?

The study has shown the different reasons the buildings do not reach their goals of low-energy use. Unrealistic assumptions in human behaviour were found in both buildings, whether regarding heating or electricity use. Other parameters that had an effect on the energy consumption included the bad technical installation of the cooling and heating systems. However, there are still large differences between the actual and measured energy use in both buildings. Some of the discrepancies cannot be explained by the parameters used in this thesis. Therefore, it is assumed that there many factors that may increase energy use in a building that are not identified in this thesis.

The energy consumption for building 127 was calculated using Be15 software and the simple method, and according to these estimations, the building fulfilled the low energy class in Danish building regulations. The total energy consumption for heating, cooling, ventilation, and domestic hot water was calculated to be 55.5kWh/m^2 per year, where 23.2 kWh/m^2/year was used for heating and 14.7 kWh/m^2/year for cooling. However, according to the actual energy use measurements taken, the building is not qualified for low energy class 15. To re-qualify for this class, energy use in the building would need to be six times less than the current actual use. A similar situation applies for building 210. As the actual energy use for building 210 is 102.4 kwh/m2 per year, for the building to use the energy originally estimated by Birch & Krogboe A/S, the actual energy use would need to be reduced by 41.5%.

It has also found In SBI at many new low-energy building with the best energy labeling uses more energy than expected, while the houses with the bad energy labeling uses significantly less than expected. (Kirsten Gram-Hanssen. Actually, there is no low or requirement that new buildings actual energy performance should be check, as they dose in Sweden.

References

Aggerholm, S., 2013. *Cost-optimal levels of minimum energy performance requirements in Danish Building Regulations*

Aggerholm, S. & Grau, K., 2014. *Bygningers energibehov : beregningsvejledning*, Available at: https://www.statsbiblioteket.dk/au/#/search?query=recordID%3A%22sb_6144776%22

Andaloro, A.P.F. et al., 2010. Energy certification of buildings: A comparative analysis of progress towards implementation in European countries. *Energy Policy*, 38(10), pp.5840–5866. Available at: http://dx.doi.org/10.1016/j.enpol.2010.05.039

Anon, 2014. Denmark 's National Energy Efficiency Action Plan (NEEAP), (April).

Anon, 2017a. NYBYGGERI - OVERSIGT OVER KRAV. , pp.1–6

Anon, 2017b. The Danish Building and Property Agency - the preferred choice for customers and the state

Bordass, B. et al., 2001. Assessing building performance in use 3: energy performance of the Probe buildings. *Building Research & Information*, 29(2), pp.114–128. Available at: http://www.tandfonline.com/doi/abs/10.1080/09613210010008036

Brohus, H. et al., 2010. Influence of Occupants' Behaviour on the Energy Consumption of Domestic Buildings. *Proceedings Clima*, pp.0–7

Building-regulation, 1995. BR 95, det nye bygningsreglement, (April)

Bygninger, V. for E. i, 2015. Energikravene i BR15

Cappelen, A.J., 2016. Vejret og klimaet i 2015. , 146 (December 2014)

Denmark, I. et al., 2015. Denmark 1

Dodoo, A., 2011. Life Cycle Primary Energy Use and Carbon Emission of Residential Buildings

DTU, 2012. Transform DTU. Available at: https://www.innobyg.dk/media/46875/præsentation af dtu bygning 127_minimeret.pdf

DTU, 2003. Transform DTU. Available at: http://ait-psc03cd05.win.dtu.dk/english/About/PRESS-ROOM/Photos-and-Multimedia/Campuses-and-Science-park1. s.l.:s.n

Ebenmark, R.M. & Ab, E.E., 2015. Åtgärdsrapport Energideklaration av villa, (5444)

EU, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). *Official Journal of the European Union*, pp.13–35

Europe, I.E., 2013. BUILD UP Skills Denmark National Roadmap Colophon, (May), pp.1–47

European Commision, 2002. Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. *Official Journal Of The European Union*, pp.65–71

Government, D., 2014. Strategy for energy renovation of buildings, (May)

Gram-Hanssen, K., 2014. New needs for better understanding household energy consumption – behaviour, lifestyle or practices? *Architectural Engineering and Design Management*, 10(1–2), pp.91–107. Available at: http://www.tandfonline.com/doi/abs/10.1080/17452007.2013.837251

Gram-Hanssen, K. & Bech-Danielsen, C., 2004. House, home and identity from a consumption perspective. *Housing, Theory and Society*, 21(1), pp.17–26

Gram-Hanssen, K. & Rhiger Hansen, A., 2016. Forskellen mellem målt og beregnet energiforbrug til opvarmning af parcelhuse. , p.23

Green Building Council Denmark, 2012. An introduction to DGNB. Available at: http://www.dk-gbc.dk/media/67284/dgnb_dk-gbc_oct_2012.pdf

Hirst, E., White, D. & Goeltz, R., 1985. Indoor temperature changes in retrofit homes. *Energy*, 10(7), pp.861–870

International Energy Agency, 2015. Building energy performance metrics. , p.110

Jensen, J.O., Gram-hanssen, K. & Røpke, I., 2009. Households ' use of information and communication technologies – a future challenge for energy savings? *Most*, pp.1773–1783

Knudsen, H.N., Jensen, O.M. & Kristensen, L., 2012. Occupant satisfaction with new low-energy houses. *10th International Conference on Healthy Buildings 2012*, 1

Kofod C, 2005. electricity consumption composition for 100 households in Odense. virum.Energy Piano

Larsen, T.S., 2014. Overheating and insufficient heating problems in low energy houses up to now call for improvements in future. *HVAC Journal*, 2011(03/2011), pp.1–10

Larsen, T.S., Jensen, R.L. & Daniels, O., 2012. The Comfort Houses - Measurements and analysis of the indoor. , p.98. Available at: http://vbn.aau.dk/files/65267145/The_Comfort_Houses.pdf

Liddament, M.. & Orme, M., 1998. Energy and ventilation. *Applied Thermal Engineering*, 18(11), pp.1101–1109. Available at: http://www.sciencedirect.com/science/article/pii/S1359431198000404

Majcen, D., Itard, L. & Visscher, H., 2015. Statistical model of the heating prediction gap in Dutch dwellings: Relative importance of building, household and behavioural characteristics. *Energy and Buildings*, 105(2015), pp.43–59

Majcen, D., Itard, L.C.M. & Visscher, H., 2013. Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications. *Energy Policy*, 54, pp.125–136. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421512009731

March, R. & Svendsen, S., 2011. Bygningsklasse 2020. , (februar), pp.1–33

Melorose, J., Perroy, R. & Careas, S., 2015. Building's Heat Gains. *Statewide Agricultural Land Use Baseline 2015*, 1

Nicol, J.F. & Humphreys, M.A., 1986. Adaptive thermal comfort and sustainable thermal standards for buildings. , (1936), pp.45–59

Nyman, B., 2004. *Building Sector Regulations: A background to increased exchange between countries in the Baltic Sea region*

OECD/IEA, 2012. *Energy Policies of IEA Countries -Denmark 2011 Review*, Available at: https://www.iea.org/publications/freepublications/publication/energy-policies-of-iea-countries---denmark-2011-review.html

Pegg, I. M.; Cripps, A.; Kolokotroni, M., 2007. Post-Occupancy Performance of Five Low-Energy Schools in the

UK. , 113(2), pp.3–13

Petersen, S. & Hviid, C.A., 2012. the European Energy Performance of Buildings Directive, (September), pp.43–48

Pohl, W., 2016. *Energy Performance of Buildings Directive*, Available at: http://resource.npl.co.uk/docs/networks/tman/23feb05_agenda.pdf%5Cnhttps://ec.europa.eu/energy/sites/ener/files/documents/MJ-04-15-968-EN-N.pdf

Rapport, G.A.N., 2016. SAMMANSTÄLLNING AV LÅGENERGIBYGGNADER I SVERIGE

Strategy, L., Energisyndere i lavenergibyggeri

The Danish Government, 2010. *Building Regulations (BR10)*, Available at: http://bygningsreglementet.dk/

The Danish Ministry of Economic and Business Affairs Danish Enterprise and Construction, 2015. Danish Building Regulations 2015. , 2015(810), pp.10–12

Toolkit, E.P., 2013. Energy Efficiency in New Buildings. Available at: http://www.ens.dk/sites/ens.dk/files/climate-co2/low-carbon-transition-unit/danish-energy-policy-toolkits/energy_efficiency_in_new_buildings.pdf

Tronchin, L. & Fabbri, K., 2010. A Round Robin Test for buildings energy performance in Italy. *Energy and Buildings*, 42(10), pp.1862–1877. Available at: http://dx.doi.org/10.1016/j.enbuild.2010.05.022

UCL Energy Institute, 2013. Summary of audits performed on CarbonBuzz. , p.1. Available at: http://www.carbonbuzz.org/downloads/PerformanceGap.pdf

Wade, J. et al., 2011. National energy efficiency and energy saving targets. *Energy*, 1(May), pp.1–42. Available at: http://www.eceee.org/press/Target_setting/