Energy renovation of multi-storey buildings with heritage value
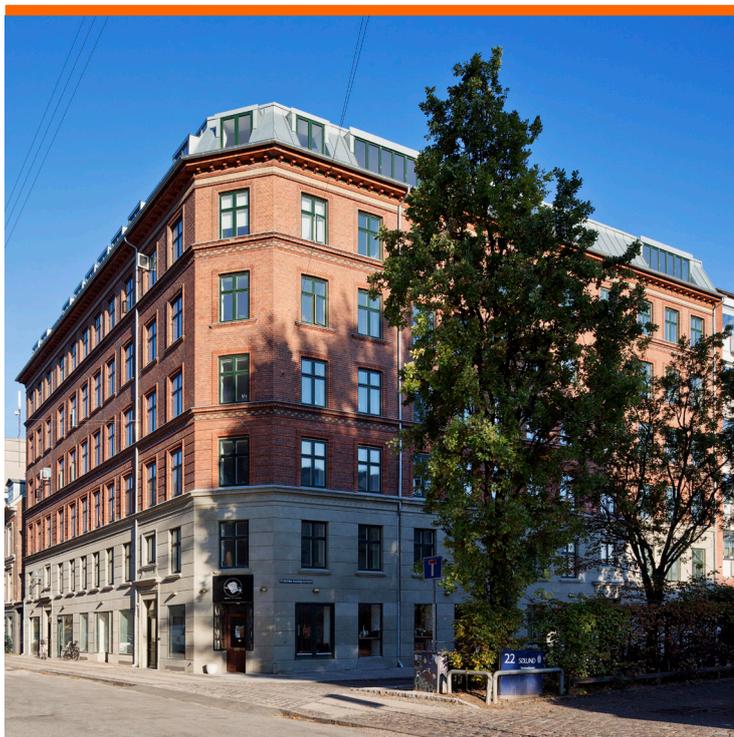
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Preface

This thesis is submitted as a partial fulfilment of the requirements for the Degree of Doctor of Philosophy at the Technical University of Denmark, Department of Civil Engineering. The thesis is the result of three years of full-time research in the area of energy renovation of residential multi-family heritage buildings.

I am grateful to my supervisor Professor Svend Svendsen, Department of Civil Engineering, for his excellent supervision, guidance and encouragement during the course of this work. I also want to thank my co-supervisor Associate Professor Toke R. Nielsen, Department of Civil Engineering, for providing help whenever I needed it.

I would like to thank all my colleagues in the Section of Building Energy and especially Kevin M. Smith, PhD fellow and good friend, for many helpful suggestions on various aspects of this work as well as lots of support during the three years, and for his valuable friendship.

I would also like to express my appreciation to Professor Agis M. Papadopoulos, Aristotle University of Thessaloniki, for giving me the chance to work with him and his research team during eight inspiring months from late 2013 to mid-2014.

I would like to express a huge thank-you to my good friend Ifigeneia Theodoridou for helping and supporting me during my stay in Thessaloniki, and for always being there whenever I needed help with various graphical designs related to my work. Also a big thank-you to the E2 architects (GR) for insightful discussions and a friendly atmosphere.

A big thank-you to all my friends and especially to my good friend Stine Bang for always supporting me and for a generous amount of patience, especially during the last six months of my work. I would like to express a huge thank-you to my good friend Mikel Urroz Oyarzabal for always being there for me (even at distance) in difficult and challenging work- and life situations.

My last and greatest thanks are addressed to my family for always believing in me and for their continued support throughout this endeavour. My thoughts and love go to my grandfather, who died a few months before the end of this journey.

Kgs. Lyngby, 30th December 2014
Maria Harrestrup

Abstract

The EU has a goal of reducing greenhouse gas emissions and energy consumption by 20% by 2020, by 40% in 2030 and by 80% in 2050 compared to 1990-levels, and Denmark has set the even more ambitious goal of being completely fossil-fuel-free by 2050. On the way to this goal, the aim is that the energy-supply mix for buildings including heating and electricity should be free of fossil fuels as early as 2035 including heating and electricity. Urgent action is therefore needed to meet these requirements for the future energy system.

A balance needs to be found between saving energy in buildings and supplying energy from district heating based on renewable energy resources and waste incineration. This research took a new approach combining heat savings in buildings with heat supply from district heating and seeing them as two segments that reinforce each other, instead of seeing them as two separate competitive instances. The question was to what extent we should supply renewable energy and to what extent we should save energy in buildings to optimise the costs and energy at a societal level. Calculations showed that the socioeconomic cost of reducing heating consumption in buildings by 30-65% is similar to the socioeconomic cost of supplying the same amount of district heating using renewable energy sources. For the district heating system in the Copenhagen area, socioeconomic calculations indicate that it is slightly more cost-beneficial to invest in energy renovations from 2013, so that we can reduce the heat demand, before investing in new renewable energy supply technologies. However, the results from the socioeconomic calculations are very sensitive to the discount rate assumed. The higher the discount rate is, the more beneficial it will be to postpone large investments, i.e. the energy renovations. However, the conclusion is that it does not make a great difference which scenario is chosen from a socioeconomic point of view. The costs for supplying heat and saving heat are at comparable levels. But investing in energy renovation from today will reduce the investment costs for new supply capacity significantly and result in more competitive heat prices.

Recently, there has been a lot of focus on 4th generation district heating, i.e. low-temperature district heating with a supply temperature of 55°C. This research looked at the possibility of supplying low-temperature district heating to old existing multi-storey buildings when the buildings undergo various levels of renovation. The investigation aimed at keeping the existing heating system and the existing district heating distribution network. Theoretical investigations showed that low-temperature district heating can be supplied to existing buildings most of the year if they have been energy-renovated to moderate levels, without replacing the existing heating system in the buildings and without replacing the existing district heating distribution network. However, the supply temperature will have to be increased to 60-70°C during cold periods corresponding to approximately 5% of the year. Furthermore, the lower the level of energy renovation, the longer the period required with this increased supply temperature.

To be able to renovate old heritage buildings to high energy performance standards we need to find robust solutions. The solutions on the market today for

heritage-valued buildings have still not been documented to the extent needed for the building sector to take responsibility for applying them on a large scale. While old heritage buildings have similar constructional trends, each is unique in its specific design, so solutions are difficult to standardize. Yet we need to find standard solutions that are both technically and economically feasible for the energy renovation of this segment of buildings. One solution to save energy is to use internal insulation, since exterior façade insulation is clearly not an option due to the need to preserve the building's appearance. This research investigated the application of internal insulation with regard to the risk of moisture problems behind the insulation and in the wooden beam construction embedded in the brick wall. The approach was to find a balance between energy savings and moisture safety, so the focus was firstly to ensure moisture safety and secondly to achieve energy savings. Two solutions were investigated; (i) with a gap in the insulation above the floor construction, and (ii) with a gap in the insulation above and below the floor/ceiling. Due to the uncertainty of the actual rain exposure on the façade, it is difficult to draw conclusions from the results. However, if the façade is exposed to low amounts of driven rain and the façade is orientated towards west, the solution with a gap above and below the floor/ceiling could be moisture safe. But further research is needed to draw final conclusions. It is recommended not to apply 80mm insulation, but only a maximum of 40mm (with λ=0.019 W/mK). Moreover, based on the results from this investigation, it not recommended to apply internal insulation on a north-orientated wall with a thickness of 1.5 and 2 bricks, and caution should be exercised if it is applied on a west-orientated wall. Investigations were only carried out for 1.5 and 2-brick walls and wall orientations towards north, west and south. Internal insulation applied on thicker walls (2.5-3.5 bricks) and/or other wall orientations might show different results.

Resumé

EU har en målsætning om at reducere drivhusgasudledninger og energiforbrug med 20 % i 2020, 40 % i 2030 og 80 % i 2050 sammenlignet med 1990-niveauer. Danmark har sat et endnu mere ambitiøst mål om at være fuldstændig fossilfri i 2050. Derudover skal energiforsyningen til bygninger være fossilfri allerede i 2035, dvs. varme- og elforsyningen. For at kunne møde de fremtidige krav til energisystemet, er der brug for handling med det samme.

Der er behov for at finde en balance mellem varmebesparelser i bygninger og varmeforsyning fra fjernvarme baseret på vedvarende energiressourcer og affaldsforbrænding. Indgangsvinkelen er at kombinere varmebesparelserne i bygningerne med varmeforsyningen fra fjernvarme. Derved opstår et sammenspil mellem de to segmenter, i stedet for at de ses som to konkurrerende enheder. Spørgsmålet er, hvor meget varme skal vi spare i bygningerne, og hvor meget fjernvarme, baseret på vedvarende energiressourcer, skal vi forsyne for at optimere omkostninger og energien på samfundsniveau. Beregninger viste, at de samfundsøkonomiske omkostninger ved at energirenovere bygningerne med 30-65 % svarer nogenlunde til omkostningerne til at forsyne den samme mængde varme fra fjernvarme baseret på vedvarende energiressourcer. De samfundsøkonomiske beregninger indikerede, at det er lidt mere fordelagtigt at investere i energirenoveringer her og nu, således at varmeforbruget reduceres, før der investeres i nye vedvarende forsyningsteknologier. Dog er beregningerne meget sensitive over for diskonteringsrenten. Jo højere en diskonteringsrente jo mere fordelagtig er det at udskyde store investeringer og hermed også energirenoveringerne. Konklusionen er dog, at det ikke gør den store forskel, hvilket scenarie der vælges ud fra et samfundsøkonomisk synspunkt, da omkostningerne for at forsyne og spare energi er på sammenlignelige niveauer. Derimod er det en stor fordel for fjernvarmeselskaberne, at der investeres i energirenoveringer allerede fra i dag, da det vil reducere investeringen i ny forsyningskapacitet betydeligt samt skabe mere konkurrencedygtige forsyningspriser.

På det seneste har der været stor fokus på 4. generations fjernvarme, dvs. lavtemperatur fjernvarme med en fremløbstemperatur på 55 °C. Muligheden for at forsyne ældre eksisterende etagebygninger med lavtemperatur fjernvarme er undersøgt i takt med, at de bliver energirenoveret til forskellige niveauer. Undersøgelsen har til hensigt at bevare det eksisterende varmesystem i bygningen samt det eksisterende fjernvarmenet. Teoretiske undersøgelser viste, at det er muligt at forsyne bygningerne med lavtemperatur fjernvarme i langt den største periode af året, hvis bygningerne gennemgår moderate energirenoveringer og stadigvæk bevarer det eksisterende varmesystem og fjernvarmenet. I kolde perioder er det dog nødvendigt at hæve fremløbstemperaturen til 60-70° C svarende til en periode på omkring 5 % af året. Derudover vil lavere niveauer af energirenovering kræve en længere periode med hævet fremløbstemperatur.

For at kunne energirenovere de ældre bevaringsværdige bygninger til høje energistandarder, er der et behov for at udvikle robuste løsninger. De eksisterende løsninger, som findes på markedet i dag tilegnet bevaringsværdige bygninger, er

ikke blevet dokumenteret tilstrækkeligt til at bygningssektoren vil tage ansvar for brugen af dem. Selvom de ældre bevaringsværdige etagebygninger ligner hinanden konstruktionsmæssigt, har de alle et unikt design, og det er svært at standardisere løsningerne. Der er et behov for at udvikle standardløsninger til dette bygningssegment, som både er teknisk og økonomisk mulige. En løsning er at bruge indvendig efterisolering, eftersom udvendig efterisolering ikke er en mulighed pga. bygningens bevaringsværdighed. Anvendelsen af indvendig isolering er undersøgt med henblik på at skabe fugtsikre løsninger, så fugtproblemer undgås bagved isoleringen og i bjælkekonstruktionen indlagt i murværket. Fugtsikre løsninger er dermed prioriteret over energibesparelser. To løsninger blev undersøgt: (i) den indvendige isolering blev stoppet 200mm over gulvkonstruktionen, og (ii) den indvendige isolering blev stoppet 200mm over og under gulv-/loftskonstruktionen. På grund af usikkerheder på de faktiske mængder af slagregn på facaden er det svært at konkludere på resultaterne. Hvis facaden er udsat for små mængder slagregn samt er vestvendt, er løsningen, hvor isoleringen er stoppet 200mm over og under gulv-/loftskonstruktionen en mulig fugtsikker løsning. Yderligere forskning er dog nødvendigt, før der kan drages endelige konklusioner. Det anbefales ikke at sætte 80mm indvendig isolering op, men at holde det til maksimum 40mm (med λ=0.019 W/mK). Baseret på resultaterne fra undersøgelsen anbefales det ikke at sætte indvendig isolering op på en nordvendt facade med tykkelser af 1.5 og 2 mursten, og beregningerne viste, at hvis der opsættes indvendig isolering på en vestvendt facade, bør der udvises forsigtighed. Undersøgelsen omfattede udelukkende murtykkelser på 1.5 og 2 mursten samt orienteringer mod nord, vest og syd. Større murtykkelser (2.5-3.5 mursten) samt andre facadevendte retninger kan vise andre resultater.

1. Introduction

1.1. Background

1.1.1. Energy targets in the EU and Denmark

The EU has a goal of reducing greenhouse gas emissions and energy consumptions by 20% by 2020, 40% in 2030 and 80% in 2050 compared to 1990-levels (European Commission, 2010), and Denmark has set an even more ambitious goal: being completely fossil-fuel-free by 2050. On the way to this goal, the aim is that the energy-supply mix for buildings should be free of fossil fuels as soon as 2035 (Danish Ministry of Climate, 2010); Danish Energy Agency, 2010) including heating and electricity. Urgent action is therefore needed to meet the requirements for this future energy system. The solution is to combine energy savings and renewable-energy (RE) supply in an optimal way. The building stock accounts for approximately 40% of overall energy use in Europe (EU, 2012; Lechtenböhmer and Schüring, 2011; Atanasiu et al., 2011), of which 79% is for heating consumption (Lapillonne et al, 2014). This means that heating consumption in buildings accounts for 32% of the total energy consumption in Europe. This energy consumption needs to be reduced by carrying out energy renovations and increasing energy efficiency, and the energy used needs to be based on renewable energy sources. The design of new low-energy buildings has been in focus in recent years and much research has been carried out to design buildings optimised from an energy perspective (Abel, 1994; Chwieduk, 2001; Karlsson and Moshfegh, 2007; Thyholt and Hestnes, 2008; Zhu et al.. 2009). However, on average less than 1% of the building stock is replaced per year with new low-energy buildings in Europe (Hartless 2003), which underlines the importance of looking at the existing building stock, which will be around for many years. The potential for energy savings here is large (Kragh, 2010; Kragh and Wittchen, 2010; Weiss et al., 2012) and several studies (Kragh, 2010; Kragh and Wittchen, 2010; Lund et al., 2010; Rasmussen, 2010; Tommerup et al., 2010) show that reductions on the scale of approximately 50–75% can be achieved, but that it will take significant investments to achieve such reductions (Kragh and Wittchen, 2010). Various legislative frameworks have been introduced in the area of energy efficiency and buildings, but the main legislative instrument in Europe is the Energy Performance in Buildings Directive (EPBD) implemented in 2002 (EU, 2002). In 2010 a recast of the directive was introduced stating that new and retrofitted buildings should consume 'nearly zero' energy (EU, 2010). The 2012 Energy Efficiency Directive complements the EPBD by encouraging ambitious renovations. It is required that Member States establish strategies for the renovation of national building stocks by April 2014, and that the renovation rate for building stock owned by the central governments should be 3% annually (EU, 2012).

1.1.2. Building typology

1.1.2.1.   Building typology in Europe

The characterisation of the European building stock based on type, age, usage etc. was analysed by the Building Performance Institute Europe (BPIE) in 2011 (Atanasiu et al., 2011). At that time, there were 27 countries in the EU and the useful floor area

was estimated at approximately 25 billion m². Figure 1-1 shows the floor area distribution per country divided between residential and non-residential. Residential buildings make up by far the largest share, a fact also expressed in Figure 1-2, which shows the total share of residential and non-residential buildings and their corresponding building types. The residential sector accounts for 75% of the building stock in Europe. It has been calculated that the residential building stock accounts for two thirds of the overall building consumption globally (Urge-Vorsatz et al., 2012).
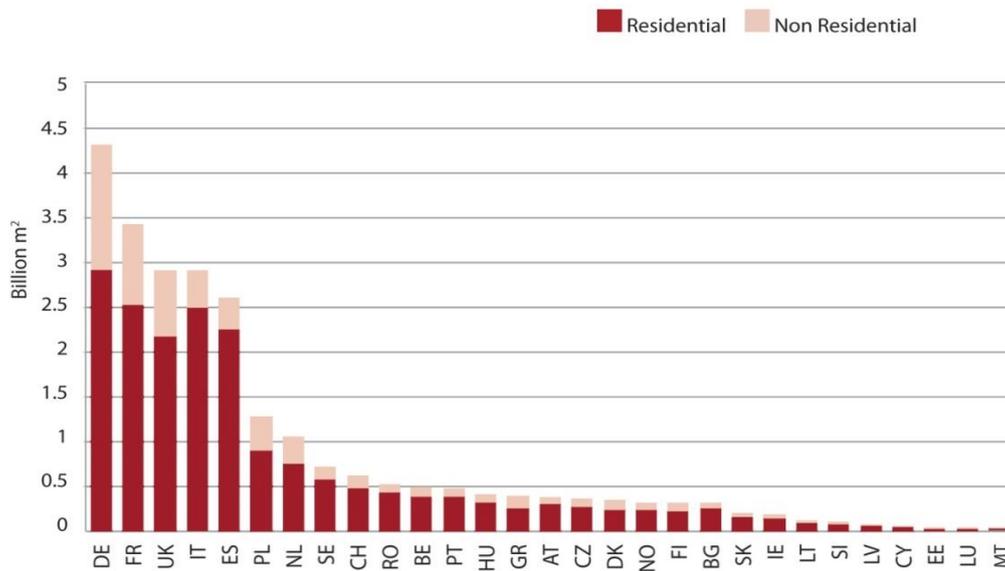
Figure 1-1: Floor area distribution per country divided between residential and non-residential (Atanasiu et al., 2011)
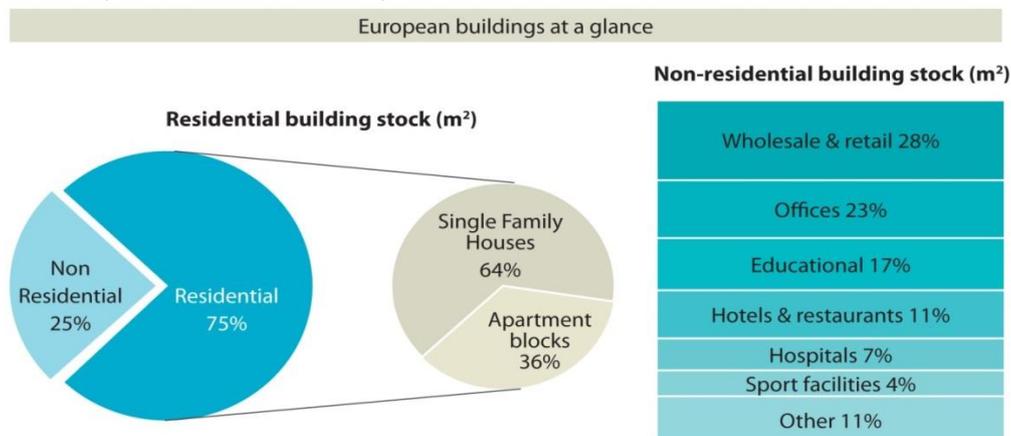
Figure 1-2: Distribution of residential and non-residential buildings (Atanasiu et al., 2011).

A significant proportion of the residential buildings are very old and approximately 40% of the buildings were built before 1960 (Figure 1-3), many of which have heritage value and therefore require special attention during energy-renovation. Figure 1-3 shows that the age distributions in the three climate zones in Europe are similar, though the North and West has the largest share of buildings from the oldest construction period, i.e. pre 1960.

Figure 1-3: Age Categorisation of housing stock in Europe based on number of buildings (Atanasiu et al., 2011).

1.1.2.2. Building typology in Denmark

The distribution of building types in Denmark, including residential, non-residential and others, can be seen in Figure 1-4. Residential buildings account for approximately 65% of all buildings, of which single family houses make up 73% and multifamily buildings make up 27%. In the non-residential sector, offices have the largest share, followed by educational buildings.
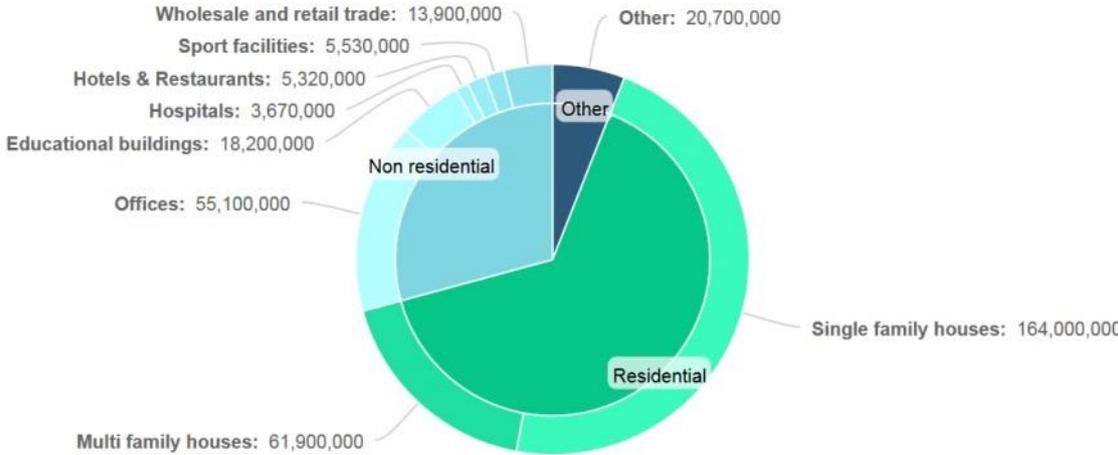
Figure 1-4: Breakdown of the Danish building stock by building types based on m^2 (BPIE Data Hub, 2013).

Figure 1-5 shows the distribution of residential buildings based on type and construction age (Statistics Denmark, 2014). As seen the multifamily housing accounts for a large share of the buildings built before 1960. After 1960, terraced houses gain a larger market share. According to the Ministry of Social Affairs (2006), it is expected that Denmark has around 300,000 buildings built before 1940 with heritage value as well as approximately 75,000 buildings built after 1940. However, in the database of Protected and Heritage Building (FBB-database) from the Danish Agency of Culture so far only 125.000 are registered. The Danish classification of heritage-value buildings is based on the SAVE classification system, which classifies buildings on a scale from 1-9 with 1 being strongly heritage and 9 being slightly

heritage. A large proportion of the multifamily buildings built before 1940 were constructed with solid masonry red brick walls and wooden beam floors embedded in the walls (Engelmark, 1983). These buildings often fall into Category 4 of the SAVE classification system meaning that the architectural expression of the buildings, i.e. façades, windows and roofs, cannot be changed without permission from the municipality. This creates challenges for reducing energy consumption in this building segment, since external insulation and the replacement of windows are often not possible solutions. However, this segment of building still offers a large potential for energy savings and is therefore an important segment to focus on so that solutions can be developed and standardised, and energy consumption can be decreased while durability is ensured. The average thermal transmittance for the exterior walls, roofs, windows and floors are shown in Figure 1-6 based on building type and construction year. The thermal transmittance are particularly large for buildings built before 1950, underlining the importance of developing solutions to decrease heat losses. Approximately 20% of the buildings have poorly insulated roofs. The majority of the buildings have insulation thicknesses less than 100 mm, very few have more than 350 mm, and many buildings built before 1972 have uninsulated exterior walls. The share of the buildings with old double-glazed windows is more than 70% (Kragh, 2010). This means there is a large energy-saving potential if the old inefficient windows are replaced with new energy efficient windows.
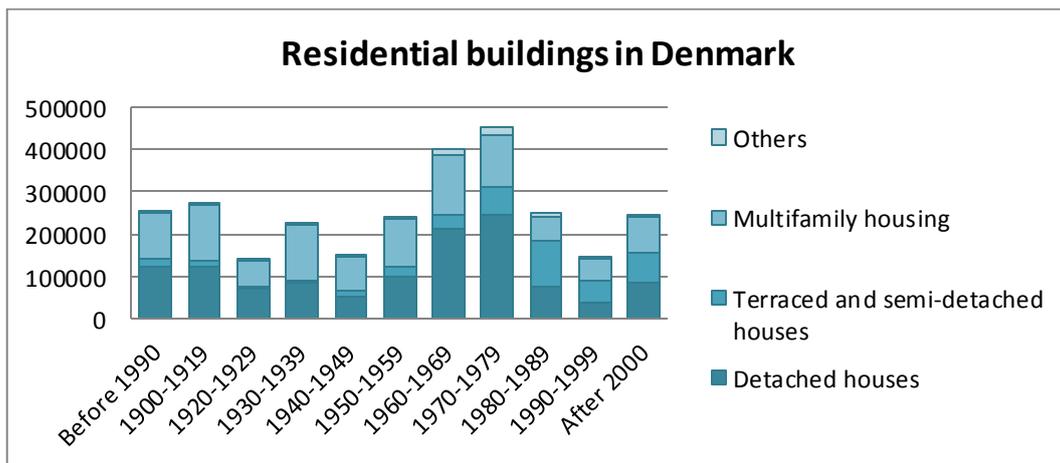
Figure 1-5: Residential buildings divided by building type and construction year (Statistics Denmark, 2014).
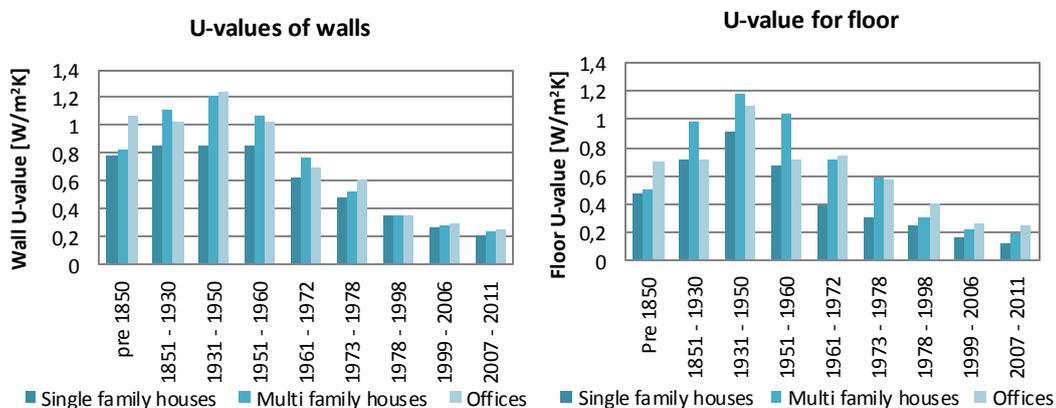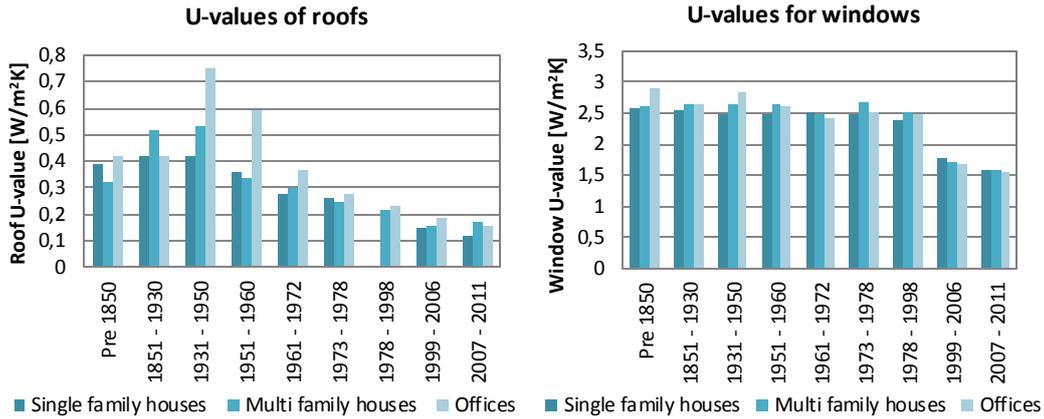
Figure 1-6: U-values of different components divided by building type and construction year (BPIE Data Hub, 2013).

1.1.3. Danish Building regulations

The latest building regulations are from 2010 (BR10, 2010) and include requirements for the energy performance of new buildings. Energy performance is the sum of the energy for space heating, ventilation, domestic hot water and cooling. According to BR10, the energy performance framework for new residential buildings is defined as:

$$EP_{BR10} = \left(52.5 + \frac{1650}{A}\right) \text{ kWh}/(\text{m}^2 \cdot \text{year})$$

where A is the heated floor area. It is planned to modify the building regulations in 2015 (BR15) and 2020 (BR20) and that the energy performance framework of residential buildings will be tightened to lower levels:

$$EP_{BR15} = \left(30 + \frac{1000}{A}\right) \text{ kWh}/(\text{m}^2 \cdot \text{year})$$
$$EP_{BR20} = 20 \text{ kWh}/(\text{m}^2 \cdot \text{year})$$

When a building undergoes renovation, the regulations also have some requirements with regard to the individual building components. The requirements for the thermal transfer coefficients for the various building parts and for the linear thermal transmittance for joints are listed in Table 1-1. However, if the buildings are protected or have heritage value, these building regulations requirements do not apply.

Table 1-1: U-values for the renovated building parts from BR10

U-values for building parts	W/m²K
Exterior wall and basement walls	0.20
Interior walls and horizontal divisions to unheated rooms or rooms that are heated to a temperature 5K or more lower than the room in question.	0.40
Ground deck or horizontal division over exterior air or ventilated crawl spaces.	0.12
Ceiling and roof constructions.	0.15
Renovated windows with extra frame.	1.65

Linear thermal transmittance	W/mK
Foundations	0.12
Joints between exterior walls, windows and doors and hatches.	0.03
Joints between roof constructions and skylight windows	0.10

1.1.4. Barriers for energy renovation

1.1.4.1.   Heritage buildings

One problem in the renovation of heritage buildings is that the building façade cannot be changed. This creates technical barriers for reducing the energy consumption, because external insulation cannot be applied and other solutions are needed, such as internal insulation. However, internal insulation is still not a completely safe solution, since problems with moisture and risks of mould growth are common. There is no doubt that a certain proportion of the buildings in Denmark should be preserved due to their heritage value, but, questions could be raised whether the current regulations for urban and local plans might be out-dated and are a barrier to the implementation of energy renovation.

1.1.4.2.   Economy and regulations

Energy Service Company (ESCO) models are an obvious way of financing energy renovation projects, because the owner then takes no economic risk. Many of the barriers to energy renovations are related to cost, and the challenge is to find the money to carry out large-scale energy renovations.

Other means to encourage energy renovation are related to regulations that promote the investment. These could include green taxes on buildings as is seen today on cars. Compulsory savings intended for energy renovation would also be a solution. Regulations on compulsory energy renovation in connection with damage repairs, as well as large tax benefits for investment in energy renovation, could also encourage energy renovation. In district heating areas, however, the cost of heating is relatively low. If regulations were made making it mandatory to be connected to the district heating network in district heating areas and the price of heating was increased, this might remove one barrier to investment in energy renovation. If occupants experience increased and varying energy prices, they will have an incentive to reduce their energy consumption.

1.2. Aim

The aim of this PhD project was to develop methods for carrying out energy renovation in old heritage multi-storey buildings, since this segment of buildings represents a large energy-saving potential. A balance needs to be found between saving energy in the buildings and supplying energy from for instance district heating based on renewable energy resources and waste incineration. The aim is to take a new approach and combine the energy savings in buildings and the supply from district heating and seeing them as two segments that reinforce each other, instead of seeing them as two separate competitive instances. The question is to what extent we should supply renewable energy and to what extent we should save energy in the buildings to optimise the costs and energy at a societal level.

Recently, there has been a lot of focus on 4th generation district heating, i.e. low-temperature district heating. This PhD-study also focused on the possibility of supplying low-temperature district heating to old existing multi-storey buildings as the buildings undergo various levels of renovation.

There is a need to find robust solutions for energy savings in the old heritage building stock. The solutions on the market today for heritage-valued buildings have still not been documented to the extent needed for the building sector to take responsibility for applying them on a large scale. While old heritage buildings have similar constructional trends, each is unique in their specific design, so solutions are difficult to standardize. Yet we need to find standard solutions for the energy renovation of this segment of buildings that are both technically and economically feasible. One solution to save energy is to use internal insulation since exterior façade insulation is clearly not an option due to the need to preserve the building's appearance. The aim was to investigate whether internal insulation can be implemented as a standardized solution without risking moisture problems in the interface between the insulation and the solid masonry brick wall or in the wooden beam construction embedded in the brick wall. The approach was to find a balance between energy savings and moisture safety, so the focus was not on obtaining as many energy savings as possible but giving first priority to moisture safety and secondly to achieving energy savings.

Many of these buildings are in need of renovation in the near future. Investigations and case studies in this field are therefore of great importance for enabling the building sector to take the step towards fossil-fuel-free building operation.

1.3. Scope

The scope of this research is limited to the energy renovation of heritage buildings and does not include the research question on the demolishment of old buildings and their replacement by new buildings versus energy renovation. This subject is covered in Morelli et al. (2014), which is also included in the Appendix 8.

1.4. Hypothesis

This part presents the main hypothesis and the sub-hypotheses tested in the PhD-project, which are then explained and reformulated as research questions.

1.4.1. Main Hypothesis

The main hypothesis investigated in this research work was:

It is technically possible and economically feasible to improve the energy performance of the old existing buildings by carrying out energy renovations given that Denmark and Europe are aiming to become fossil-fuel-free societies and that the architectural values of heritage buildings have to be preserved.

1.4.2. Sub-hypotheses

The sub-hypotheses (SH1-SH5) described below helped in testing the main hypothesis.

SH1:
The socioeconomic cost of reducing heating consumption in buildings by 30-65% is similar to the socioeconomic cost of supplying the same amount of district heating using renewable energy sources.

SH2:
It is possible to supply low-temperature district heating to existing buildings if they are energy-renovated to moderate levels, without replacing the existing heating system in the buildings and without replacing the existing district heating distribution network.

SH3:
It is possible to carry out moisture-safe energy renovation in old existing multi-storey buildings with heritage value and still save 50% of the building's energy consumption using existing technologies.

SH4:
It is possible to apply internal insulation on the solid masonry brick wall in old heritage multi-storey buildings and achieve a thermal transmittance of 0.2 $W/m^2 K$ for the exterior wall, corresponding to the requirements for renovation in the Danish Building regulations of 2010, without creating a risk of mould growth on masonry wall.

SH5:
It is possible to apply internal insulation on the solid masonry brick wall in old heritage multi-storey buildings and achieve a thermal transmittance of 0.2 $W/m^2 K$ for the exterior wall, corresponding to the requirements for renovation in the Danish Building regulations of 2010, without creating risk of mould growth on the wooden beams embedded in the masonry brick wall or the risk of wood degradation.

1.4.3. Research questions

The research questions (RQ1-RQ5) related to each sub-hypothesis are described below:

RQ1:

To what extent should we save energy in the existing building stock and to what extent should we supply heat from district heating based on a 100% renewable supply?

RQ2:

How much energy renovation is required in order to be able to supply low-temperature district heating to old multi-storey buildings, without compromising on thermal comfort and without replacing the existing heating system and district heating distribution network?

RQ3:

Is it possible to save 50% of the energy consumption in an old heritage multi-storey building by energy renovation and still ensure moisture safety?

RQ4:

Is it possible to apply internal insulation in old heritage multi-storey buildings constructed with wooden beams and brick walls, without creating a risk of mould growth between the insulation and brick wall?

RQ5:

Is it possible to apply internal insulation in the old heritage multi-storey buildings constructed with wooden beams and brick walls, without creating moisture problems in the wooden beam construction?

1.4.4. Papers on tests of the sub-hypotheses

Tests of the sub-hypotheses are described in the appendixes in papers referred to in the text as Papers 1-4. Furthermore, during the PhD-study three conference papers (Papers 5-7), one scientific paper (Paper 8) and two reports (Reports 1 and 2) were published, but are not included in this thesis. They have formed the background for the work for the scientific papers included in the PhD thesis, and they are therefore all included in the appendix except for the reports.

Papers used to test the hypotheses in the PhD project (Appendix 1-4):

Paper 1:   M. Harrestrup, S. Svendsen, (2014). Heat planning for fossil-fuel-free district heating areas with extensive end-use heat savings: A case study of the Copenhagen district heating area in Denmark, Energy Policy, 68(2014)294–305

Paper 2:   M. Harrestrup, S. Svendsen, (2013). Changes in heat load profile of typical Danish multi-storey buildings when energy-renovated and supplied with low-temperature district heating, International Journal of Sustainable Energy, Special Issue: Energy supply in insular systems. Volume 34, Issue 3-4, p. 232-247, 2015, DOI: 10.1080/14786451.2013.848863.

Paper 3:   M. Harrestrup, S. Svendsen (2015). Full-scale test of an old heritage multi-storey building undergoing energy retrofitting with focus on internal insulation and moisture. Building and Environment, 85(2015)123-133

Paper 4:   M. Harrestrup, S. Svendsen (2014). Internal insulation applied in heritage multi-storey buildings with wooden beams embedded in solid masonry brick façades. Submitted to Journal of Building Physics the 30th December 2014.

Papers that are not used to test the hypothesis in this PhD project, but have formed the background for the scientific papers (Appendix 5-8):

Paper 5:   M. Harrestrup, S. Svendsen (2012). Planning of the district heating system in Copenhagen from an economic perspective comparing energy-savings versus fossil-free supply, The 13th International Symposium on District Heating and Cooling, Copenhagen, September 3-4.

Paper 6:   M. Harrestrup, S. Svendsen (2013). Changes in heat load profile of typical Danish multi-storey buildings when energy-renovated and supplied with low-temperature district heating. 4th International Conference on Renewable Energy Sources & Energy Efficiency, Nicosia, June 2-6.

Paper 7:   M. Harrestrup, S. Svendsen, A.M. Papadopoulos (2014). Energy retrofitting of an old multi-storey building with heritage value. A case study in Copenhagen with full-scale measurements, 10th Nordic Symposium on Building Physics, June 2014, Lund. Full paper no. 147. ISBN: 978-91-88722-53-9.

Paper 8:   M. Morelli, M. Harrestrup and S. Svendsen (2014). Method for a component-based economic optimisation in design of whole building renovation versus demolishing and rebuilding. Energy Policy 65:305–314

Reports not included in this thesis:

Report 1:   M. Harrestrup, M. Lemgart, S. Svendsen, T. Duhn, TM. Moos. Plan C – Energirigtig renovering (2012). Fremtidig fjernvarmeforsyning og energirenovering, Gate 21 – Sustainable future forum (in Danish), available December 2014 at: http://www.plan-c.dk/Modeller-og-vaerktoejer/Fremtidig-fjernvarmeforsyning-og-energirenovering/

Report 2:   LR. Pedersen, M. Harrestrup, MG. Minzari, S Mikkelsen, T. Kildemoes. EUDP 2009: "Udvikling og 1:1 demonstration af koncepter til renovering af ældre etageboliger til lavenergiklasse 1": Slutrapport: resultater og erfaringer fra energirenovering af Ryesgade 30, 2014.

Paper 1 investigates the feasibility of carrying out energy renovation in the buildings compared to supplying heat from district heating based on 100% renewable energy supply. The analysis is carried out on a community scale and the Copenhagen district heating area is used as the case study. Different scenarios from 2010-2070 are compared. The research question was to what extent we should save energy in the existing building stock and to what extent we should supply heat from district heating

based on a 100% renewable supply. The hypothesis describes a range from 30-65%, which has to be seen as a range covering deeper energy renovations. The hypothesis therefore includes not only the easy and obvious energy savings but also more profound energy renovations.

Paper 2 investigates whether it is possible to supply low-temperature district heating to old existing buildings without changing the existing heating system in the building and the existing district heating distribution network, and without compromising on thermal comfort in the building.

Paper 3 investigates whether it possible to save 50% of the total energy consumption when deep holistic energy renovation is carried out in old heritage buildings and still ensure moisture-safe solutions. Since the building has heritage value internal insulation is investigated.

Paper 4 uses detailed hygrothermal simulations to investigate the risk of mould growth behind the insulation and in the wooden beam construction due to altered moisture and temperature conditions when internal insulation is applied.

1.5. Structure of thesis

The thesis is divided into 6 main chapters. Chapter 1 is the introduction. Chapter 2 provides a literature study on the state of the art related to energy renovation of heritage buildings in preparation for future fossil-fuel-free societies. Chapter 3 presents the method, and Chapter 4 presents the description of the case-studies used to test the method. Chapter 5 provides the results and discussion of the results. The conclusions are presented in Chapter 6 and answer the main hypothesis and sub-hypotheses.

The content of the research is divided into three main topics to create a logical structure for answering the hypotheses. The three topics are consistent throughout the thesis and consist of:

1. Energy savings versus energy supply
2. Low-temperature district heating for old existing buildings undergoing energy renovation
3. Energy renovation of old heritage multi-storey buildings

2. State of the art

2.1. Energy renovation in Europe and Denmark

In recent years, a lot of focus has turned towards the energy renovation of existing buildings in order to meet the future goals for reducing energy consumption and CO_2 emissions. Reducing energy consumption by implementing energy renovation in existing buildings will also reduce peak loads and ensure a more stable energy supply, which will decrease the dependency and vulnerability of the energy supply. The European Union has implemented the Energy Performance in Buildings Directive and many countries have implemented national building codes and various tools and regulations to encourage energy renovation. Various EU projects have monitored and categorised buildings in Europe in order to optimise the energy renovation process by making data available and comparable between countries. Recent projects include the *Typology Approach for Building Stock Energy Assessment* (TABULA) (Loga et al., 2012), the subsequent *Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in EU Housing Stocks* (EPISCOPE) (Diefenbach et al., 2014), and the *Quality Assurance System for Energy Efficient Retrofitting and Multifamily Buildings* (SQUARE) (Mjörnell et al., 2010), as well as several others.

In Denmark, the government has developed a new strategy for the energy renovation of buildings (Danish Ministry of Climate, 2014) where various tools will be implemented in society to remove barriers and create incentives to carry out energy renovation. One such tool is financial support for creating ESCO-companies where the ESCO-company guarantees a certain energy saving as a consequence of the investment in energy renovation. The ESCO concept is used in many countries, but has so far been less seen on the Danish market. The strategy aims at the energy-renovation of a large proportion of the existing building mass before 2050. Many building components will wear out and require renovation or replacement over the next 30-50 years (Danish Ministry of Climate, 2014), and to make the energy renovation cost effective, it is best for it to take place in connection with another improvement required in the building, such as major repairs, a desire to improve indoor comfort, the modernisation of the kitchen and/or bathroom, or the installation of a balcony, etc.

A general problem has been that the calculated energy savings of a retrofitting project are not realised. The international project Annex 55 - Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) (EBC, 2014) is aimed at developing tools and knowledge that support the use of probability-based design strategies in the retrofitting of buildings to ensure that the anticipated energy benefits can be realized.

The Global Buildings Performance Network (GBPN) carried out an investigation into energy consumption in existing buildings and concluded that it is possible to reduce global energy consumption by 30% despite increasing growth rate, and floor space and comfort levels. This, however, requires a determined effort with a 70% decrease in energy consumption in existing buildings globally. The study concludes that it is proven technically feasible if building technologies are mainstreamed and supported with aggressive policies (GBPN, 2013). Another study (GBPN, 2014) investigates and identifies elements that are critical when developing future energy renovation

policies for residential buildings. The study focuses on deep retrofitting to support the previously-mentioned study on reducing energy consumption in existing buildings by 70%. Six key criteria to ensure that the buildings are energy-renovated towards zero energy consumption were identified in order to develop a state of the art policy package: regulative normative measures, building assessment, financial instruments, economic instruments, capacity building, and overall performance indicators. The performance indicators evaluate the reduction in energy consumption using five indicators (relative, per capita, unit floor area, GDP and homes). Current policy packages already in use in Europe and the US were selected and analysed based on the criteria stated above, and energy reduction was found between 2000 and 2012. The study developed a tool that allows for comparison between the chosen best-practice packages in Denmark, France, Germany, the Netherlands, Sweden and the United Kingdom, and, in the US, California, Massachusetts, New Jersey, New York, Oregon and Vermont. The study concluded that the countries that succeeded in reducing energy consumption were the countries that had developed holistic energy renovation packages that addressed all the key-elements. Furthermore, the study concluded that there was not one best-practice policy package, but that all countries could benefit from sharing. They found that there is a general lack of clear and ambitious goals for the energy renovation of existing building stock among the current best-practice renovation policies. A study from BPIE (Staniaszek et al., 2013) examined a cross section of renovation strategies in 10 EU member states based on the requirements from Article 4 of the Energy Efficiency Directive (EED) (EU, 2012). Article 4 requires member states to establish long-term renovation strategies for renovation of national building stocks. Staniaszek et al. (2013) concluded that, even though the deadline for presenting the strategies was the end of April 2014, six member states had still not met the requirements. The overall level of the compliance with Article 4 was evaluated to be poor. An overall score of only 58% was obtained with the best score obtained within the area of "overview of building stock" and the poorest score obtained within the area "forward-looking perspective to guide investment decisions".

In the Danish building regulations, requirements have been included on individual components when they are replaced or undergo renovation. One study (Wittchen et al., 2014) compares 17 different scenarios to investigate how these and other similar restrictions will affect future energy consumption for buildings in Denmark by 2050. If energy renovations are carried out as building components are degraded, the study states that the building stock can save 28% in energy consumption whereas if the strictest actions are taken 47% can be saved. These saving are obtained with relatively similar marginal costs for investments on proximately 0.8-1.6 €/kWh/year depending on the scenario and the future price development.

2.2. Energy renovation versus energy supply from low-temperature district heating

It is important to take an approach that focuses on energy-renovating buildings and the interaction between the demand side and the supply side. When we energy-renovate our buildings, it will affect the supply side (i.e. production technologies, capacities) as well, and a holistic approach that couples both sides will optimise the steps we take towards a fossil-fuel-free society from a societal point of view.

District heating is a common supply system for space heating and domestic hot water in densely populated areas (Reidhav and Werner, 2008; Persson and Werner, 2011). District heating systems are already established in many countries, but like the rest of the energy supply system, they face new challenges in the future. In Iceland, a large proportion of the district heating supply is based on geothermal heat, and some district heating systems are also supplied from geothermal heat in China, Turkey and the U.S.A. In countries like Denmark, Sweden, and Finland, the district heating supply comes mainly from combined heat and power generation plants (CHP) (Gustafsson and Rönnqvist, 2008). The district heating systems in Denmark will have to be converted from the present supply technologies based mainly on fossil fuels to 100% renewable energy sources. Questions have been raised on how to achieve our future energy goals. Some people question whether there is a need for district heating systems in the future, since space heating demands will decrease to very low levels, and others question the feasibility of investing in energy renovation and the extent to which we should save heat in buildings rather than supply heat from district heating based on renewable energy resources. A study of the district heating network in Malmö, Sweden, (Gustafsson, 1992) found the overall economic feasibility of district heating systems to be problematic when end-use consumption in buildings is reduced. The overall costs strongly depend on the characteristics of the buildings and the district heating system (Gustavsson, 1994a, 1994b). However, a recent study in Denmark (Lund et al., 2010) has shown that even with a reduction of 75% in space heating demand, it is beneficial to supply heat from district heating. The study also shows that an expansion of the district heating network from the present 46% share of the total heat supply in Denmark to a 63−70% share would be beneficial.

Figure 2-1 shows how many of the different types of building in the Danish building stock are connected to a district heating network and the distribution of the different district heating production sources.

Other non-residential buildings: 11,100
Wholesale and retail trade: 1,560
Sport facilities: 2,470
Hotels & Restaurants: 5,280
Hospitals: 8,450
Educational buildings: 9,760
Offices: 28,000
Multi family houses: 73,000

Non residential

Residential

Single family houses: 619,000

other resources : 1,60%
Oil : 5,10%
Natural gas : 28,50%
Biomass : 36,10%
Coal : 20,50%
Waste (non-renewable) : 8,10%
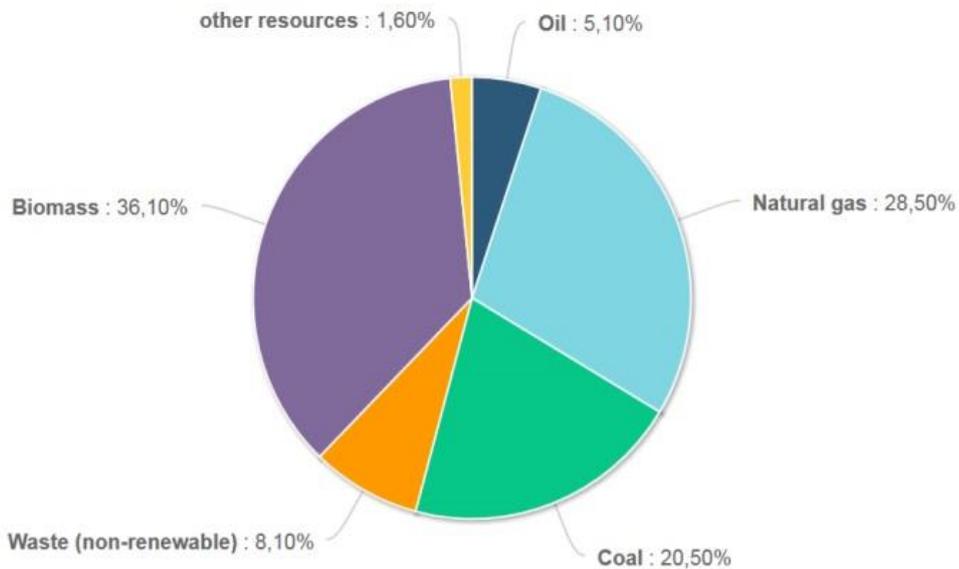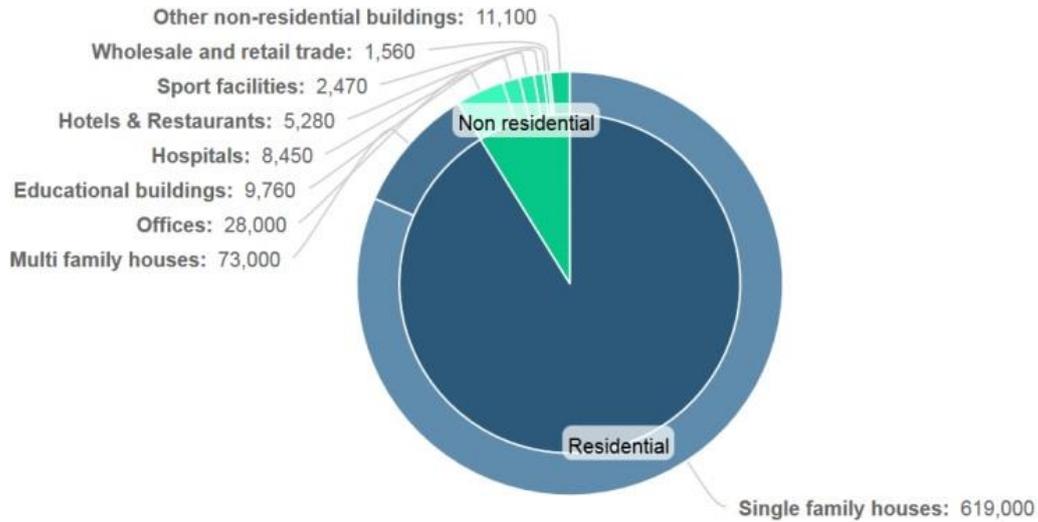
Figure 2-1: Upper: Danish buildings connected to a district heating system. Lower: Distribution of the Danish district heating production sources. (BPIE Data Hub, 2013).

The future goal of fossil-fuel-free societies requires long-term planning of the future energy supply on a societal level. Recent studies have investigated the potential in converting the existing energy system into a 100% renewable supply system in two local authorities in Denmark: Frederikshavn (Østergaard and Lund, 2011) and Aalborg (Østergaard et al., 2010). Both studies covered the heating, electricity and transport sectors and included energy-saving measures, but the focus was on the supply side and on production technologies. Both studies concluded that it is technically and economically possible to convert to a fossil-fuel-free society and that geothermal heat will play an important role in future district heating systems. A study from Sweden (Gustavsson et al., 2011) investigated how end-use heat savings in buildings will affect district heating production, including costs and primary energy savings, but included the use of fossil fuels. In the future, however, conversion to

renewable energy supply will be as important as end-use heat savings. The Heat Plan Copenhagen (VPH1, 2009; VPH2, 2011; VPH3, 2014) analyses various scenarios for future district heating production in Copenhagen aiming at CO_2-neutral production. However, the analyses make use of large shares of biomass, which will be a limited resource in the future (EEA, 2006; Ericsson and Nilsson, 2006), so it is important to focus on integrating other renewable energy resources in the future district heating system.

To meet our future goals of fossil-fuel-free societies, the supply systems need to be converted into renewable-based energy systems. This creates an option for designing the district heating systems in the most optimal way so that renewable energy sources can be used efficiently. This makes district heating a very important technology for realising the strategy of heating all buildings without the use of fossil fuels. Traditional district heating systems operate with a supply temperature of approximately 70 °C and a return temperature of 40 °C and most of them are supplied from combined power and heating plants based on biomass, natural gas, coal, solid waste incineration and oil (Figure 2-1).

If low-temperature operation is implemented (a supply temperature of 55 °C and a return temperature of 25 °C), the heat losses from the distribution pipes will be reduced, and heat supply from renewable sources becomes more appropriate and efficient (Dalla Rosa et al., 2011). It has been shown that district heating supply for low-energy buildings is competitive with the best alternatives, such as individual heat pumps (Lund et al., 2010; Dalla Rosa and Christensen, 2011). Low-temperature district heating is a cost-efficient and environmentally friendly way of supplying heat with linear heat densities down to 0.20 MWh/(m year) (Dalla Rosa and Christensen, 2011). These changes will increase the overall efficiency of district heating systems. The study made by Dalla Rosa and Christensen (2011) explains the design concept of low-temperature district heating. Theoretical investigations of low-temperature operation have been carried out in EFP (2007) and Olsen et al. (2008), and applied in Brand et al. (2010) and EUDP (2008). Low-temperature district heating operates with a supply temperature of 55 °C, which means that the legionella problems that can occur in district heating systems need to be considered. According to the German Standard (DVGW 1993) and research done in Germany (Rühling and Rothmann 2013), the risk of legionella growth is small as long as the water volume is less than three litres and the temperatures are above 50 °C or below 20–25 °C. If each home uses a local substation with an efficient heat exchanger containing only small amounts of water, the legionella problem will be avoided.

When end-use savings are implemented in buildings connected to a district heating system, the heat demand profiles for the individual buildings will change, which will affect the heat profile for the entire district heating system. Researchers in Sweden looked into how the end-use heat savings in buildings will affect district heating production, including costs and primary energy savings (Gustavsson et al. 2011). They found that a significant proportion of the primary energy savings were in the peak load capacity. In their study, the peak loads were supplied by light fuel oil boilers, but in the future such peak loads will have to be covered by renewable energy systems, which will be expensive. Therefore, after energy-saving measures have been implemented, the heat load duration profiles for the buildings are important, since they are the dimensioning factor for the future district heating system. To avoid oversized renewable energy based capacity, a long-term perspective needs to be taken.

Studies (Tol and Svendsen 2012a, 2012b) have investigated low-temperature district heating for buildings with existing radiators, focusing on the relationship between supply temperature, mass flow rate, and the dimensioning of the pipe distribution system based on future and current situations. Brand (2014) investigated low-temperature district heating mainly for new single family houses with a focus on finding the best heating system solution for both domestic hot water and space heating. He also did a small study on applying low-temperature district heating for an existing single family house, and found that it is possible to apply low-temperature district heating if either the house is renovated or the heating system is replaced with a new one.

Based on the literature review, no studies were found that combine the aspect of holistic energy renovation with basing future district heating supply on 100% renewable energy resources. It seems that there is a need for new knowledge in this field. Furthermore, the literature review also showed that there is a need for research on how to apply low-temperature district heating for existing multi-storey buildings.

2.3. Energy renovation of heritage multi-storey buildings – balancing energy savings and moisture safety when using internal insulation

A large proportion of the building stock consists of heritage buildings. Energy retrofitting of existing buildings is vital to achieve energy reductions, but challenges occur when it comes to retrofitting heritage buildings where the façade cannot be modified due to the architectural value of the building. Many buildings that have heritage value in Denmark are constructed with wooden floor beams and most were constructed in the period between 1850 and 1920. Approximately 20% of all homes in Denmark today were built in that period and represent a significant energy-saving potential (Engelmark, 1983; Rasmussen, 2011). Since the façade cannot be changed, external insulation cannot be applied and internal insulation is the only option.

One study (Morelli et al., 2011) investigated a holistic energy retrofitting of a multi-storey building with heritage value from 1930, which was constructed with solid brick façades and wooden beams. They found that it was theoretically possible to save 70% of the energy consumption without having to use external façade insulation. Funch and Graves (2013) carried out a retrofitting of a historical building with solid brick walls and a wooden beam construction and applied internal insulation to some of the façades. They found that it was possible to save 30% energy based on calculations, but no further analyses were made on the use of internal insulation with respect to the moisture risk. Another study (Rasmussen, 2011) investigated energy-saving measures for the improvement of the thermal insulation of a building with solid brick walls and a wooden beam construction. They concluded that it is possible to reduce heat losses by 62% by applying internal insulation on the external façades, insulating the roof, and replacing the windows. These three studies are all based solely on calculations, whereas the research presented in this PhD-study also includes comprehensive empirical measurements. Morelli et al. (2012) studied various energy-saving measures for heritage buildings and tested them in a test apartment. Measurements were made in the wooden beam ends and in the interfaces between the brick wall and insulation, and theoretical calculations of possible energy savings were carried out. They concluded that it was theoretically possible to save 68% of the energy consumption for the entire building and that the measurements showed no risk of mould growth or

wood decay. The research reported in this PhD-thesis presents a similar analysis, but for an entire building block instead of just one test apartment, and energy measurements are included, which was not the case for the research in Morelli et al. (2012).

Another study (Tommerup and Laustsen, 2012) carried out the retrofitting of a historical building, where internal insulation was planned. However, due to the risk of condensation, they decided not to apply internal insulation. When a façade is insulated from the inside, the outer brick wall becomes cold and its drying potential is reduced. In particular, the diffusion drying capacity of the masonry is reduced, and the surface evaporation can be slowed. Capillary flow, however, is unaffected by insulation and is a powerful moisture redistribution mechanism (Straube and Schumacher, 2007). Condensation can occur in the interface between the insulation and the brick wall if the temperature in the interface drops below the dew point, and this can lead to mould growth (Christensen and Bunch-Nielsen 2009; Munch-Andersen 2008; Kolaitis et al., 2013; Abuku et al., 2009). Furthermore the floor construction will not be insulated at the façade, which will lead to the occurrence of a thermal bridge between the floor beams and the load-bearing wooden beam construction. The moisture and temperature conditions in the wood are subject to change when internal insulation is applied, so attention needs to be given to the risk of mould growth on the wooden surfaces and the risk of the wood decay, which, in extremis, can lead to fatal structural damage. Krebs and Collet (1981) studied temperature and moisture content measurements in 30 wooden beam ends. Interior insulation was applied to some walls, and no insulation to others, in order to compare the results. They concluded that wind-driven rain did not have a significant influence and only a very limited risk of moisture problems in the beam ends was present. However, Morelli and Svendsen (2012) carried out a theoretical investigation on various intensities of wind-driven rain on façades using numerical simulation, and concluded that wind-driven rain has a great impact on the performance and durability of the wooden beam ends. They also concluded that if the internal insulation is stopped 200 mm above the floor, the risk of wood decay is minimised and heat losses can still be halved compared to a façade without insulation. Kehl et al. (2013) provided a literature review that also concludes that wind-driven rain has an important influence on the behaviour of moisture content and the risk of beam end decay. Ruisinger (2013) compares five different internal insulation systems in order to investigate the risk of damage to wooden beams, and found no hazard.

Various types of internal insulation product have been developed and are still being developed. Two main types can be identified: diffuse closed and diffuse open insulation products. Diffuse closed insulation requires a vapour-tight barrier, whereas diffuse open insulation relies on capillary-active materials, which have attracted a lot of attention in recent years (Grunewald et al., 2006; Pavlik and Cerny, 2008; Toman et al., 2009). Capillary-active insulation materials can absorb the condensation and transfer it to the inside where it can dry out. According to Scheffler and Grunewald (2003), this means that condensation in the interface can be avoided if capillary-active insulation systems are used. However, Vereecken and Roels (2014) compared different insulation systems in a laboratory and found that capillary-active insulation materials accumulated more moisture in the interface between the insulation and brick wall than the traditional system using vapour-tight barriers. The study only included steady-state conditions without wind-driven rain or solar radiation, both of which have significant impact on wall performance. Other new innovative insulation products showing promising properties are high-performance materials such as

aerogel and vacuum insulating materials. Baetens et al. (2011) and Cuce et al. (2014) carried out reviews on aerogel as a building insulation material and concluded that if aerogel can be manufactured for a fraction of its current economic and environmental cost, it may become an attractive alternative to the more traditional insulation systems currently used due to its extremely good thermal and acoustic properties. Johansson et al. (2014) applied vacuum insulating panels on the inside of a brick wall constructed with wooden beam ends and carried out laboratory tests and numerical simulations with various wind-driven rain exposures and temperatures. They found that vacuum insulation showed considerable potential for reducing energy use, but also that the temperatures in the wall decreased significantly, which can lead to the risk of condensation in the interface between wall and insulation as well as higher moisture content in the wooden beam end. Warren et al. (2003) installed a heating pipe just above the floor construction and below the internal insulation in order to provide increased temperature to heat up the wooden beam construction and consequently decrease the moisture content. They concluded that the relative humidity was 10-14% lower than without the heating pipe.

Another risk that occurs when applying internal insulation is freeze-thaw damage. This only occurs at temperatures well below freezing and when the brickwork is essentially saturated.

From the literature, it seems that the safety of applying internal insulation is still in doubt and so far no completely safe solutions have been identified. Focus in this area is therefore crucial if we are to develop robust solutions that can save energy but still be safe with regard to moisture in heritage buildings.

Based on the literature review, there is a lack of knowledge when it comes to ensuring robust solutions for energy savings in old heritage buildings. The solutions on the market today for heritage-valued buildings have still not been documented sufficiently for the building sector to take responsibility for applying them on a large scale. While old heritage buildings display similar constructional trends, each is unique in their specific design, so solutions are difficult to standardize. There is a need to find technically feasible standard solutions for the energy renovation of this segment of buildings. Instead of aiming at saving the most energy, solutions that pay regard to finding a balance between energy savings and durability in terms of reduced moisture risk need to be in focus.

2.4. Need for new knowledge and research

In the light of the literature review, this PhD thesis introduces new knowledge, which is presented in three topics.

2.4.1. Energy savings versus energy supply

No studies were found in the literature that take the approach of combining the aspect of holistic energy renovation with basing future district heating supply on renewable energy resources to the extent presented in this PhD-thesis. The research presented in this work focuses on the feasibility of saving energy in buildings supplied from a fossil-fuel free district heating system at the community level. It considers both end-use-savings and 100% RE-supply, but has a more detailed focus on when and to what extent it is worth implementing end-use savings in the building stock. The research aims at answering the research question: "To what extent should we save energy in the existing building stock and to what extent should we supply heat from district heating based on a 100% renewable supply?"

The research describes a method for making use of existing district heating systems in the future energy infrastructure with the aim of society being fossil-fuel-free in 2050. The scope is limited to the heating sector, excluding other sectors such as electricity generation and the transport sector. The electricity sector will also have to be fossil-fuel-free, and much of future electricity production will be based on fluctuating and vulnerable resources such as wind. If electricity is used for heating purposes, large, costly storage units may be required to meet peak loads. The use of district heating in appropriate areas will protect the electricity sector from increasing peaks in very cold periods. That is why electricity for heating purposes is not considered in this research work.

2.4.2. Low-temperature district heating for old existing buildings undergoing energy renovation

It was also found from the literature review that there is a need for research on how to supply low-temperature district heating for existing buildings. This subject is mostly covered for new buildings, but has not been covered to a degree that makes it possible to answer the research question "How much energy renovation is required in order to be able to supply low-temperature district heating to old multi-storey buildings, without compromising on thermal comfort and without replacing the existing heating system and district heating distribution network?"

The thesis describes a method for supplying low-temperature district heating to existing multi-storey buildings, focusing on the implementation of various levels of energy renovation and achieving good thermal indoor comfort. Furthermore, it describes a dynamic dimensioning method for the future district heating capacity based on renewable energy supply. Investigations are carried out on the extent to which it is possible to reduce the peak loads when supplying low-temperature district heating without compromising on the indoor thermal comfort.

2.4.3. Energy renovation of old multi-storey buildings – balancing energy savings and moisture safety when using internal insulation

From the literature review, it seems there is still no completely moisture-safe solution when it comes to the energy renovation of heritage building using internal insulation. The research work presented in this PhD project takes the approach of finding a balance between energy savings and moisture safety when applying internal insulation. New knowledge on full-scale tests of a multi-storey heritage residential building undergoing a deep and holistic energy renovation using internal insulation is presented together with detailed hygrothermal simulations of internal insulation on the façade. The assembly of the façade/floor construction is evaluated for the risk of mould growth. The research aims at answering the research questions: "Is it possible to save 50% of the energy consumption in an old heritage multi-storey building by energy renovation and still ensure moisture safety?" and "Is it possible to apply internal insulation in old heritage multi-storey buildings constructed with wooden beams and brick walls, without creating a risk of moisture problems between the insulation and brick wall and in the wooden beam construction?"

The thesis goes into the details of the energy renovation of a heritage multi-storey building because such buildings are a challenge to energy-renovate. Focus is placed on internal insulation. The aim of this part of the thesis was to focus on creating solutions that save energy but are also moisture safe. To ensure the moisture safety, investigations of the moisture and temperature conditions around the wooden beams embedded in the masonry wall and in the interface between the insulation and brick wall were carried out.

Since internal insulation is an energy-saving measure that could play an important role in the future energy renovations of heritage buildings, it is important to document its durability and robustness and find a compromise between reducing the heat losses through the wall and ensuring moisture-safe solutions.

3. Methods

This chapter includes a description of the research methods chosen to investigate the hypotheses and the corresponding research questions based on a discussion of possible methods. The chapter is divided in separate parts for each of the 3 main topics:

1. Energy savings versus energy supply
2. Low-temperature district heating for old existing buildings undergoing energy renovation
3. Energy renovation of old multi-storey buildings – balancing energy savings and moisture safety when using internal insulation

3.1. Energy savings versus energy supply

Methods for investigating the interaction and balance of the energy savings in all buildings in a community and the energy supply based on renewable district heating systems for the community are discussed and described.

The research question is whether it is feasible to save energy in existing buildings by carrying out energy renovation when the future energy supply system will have to be fossil-fuel-free (SH 1). Paper 1 focuses on the investigation of this topic.

The only applicable method to answer the research question is to perform theoretical analyses. The research question deals with an entire community and how to shape it in the future with regard to energy savings and supply. It is not possible to carry out experiments at the community-level because it would require that the community should undergo various scenarios of energy renovation and that the district heating supply system should be converted to renewable supply. This is not possible for many reasons and the best approach is to set up future scenarios and perform theoretical calculations. To be able to draw conclusions from the test of the hypothesis, a certain number of scenarios are needed so that all future options and their consequences are treated. However, it is difficult to cover all options and an evaluation of the most realistic scenarios has to be defined. Analyses that investigate conditions in the long-term future always involve rather large uncertainties. However, it is necessary to take a long-term perspective if we are to create a holistic picture of the consequences of a certain action plan. The assumptions made for future investments and future energy prices also involve a great deal of uncertainty, and best estimations are the only possible tool. However, one should be aware that different assumptions might lead to different results, and sensitivity analyses are a good tool to evaluate the credibility of the results.

The method used in this research topic was to compare the investment required for heat savings in existing buildings with that required for heat supply from district heating produced from renewable energy resources. The method is based on a theoretical comparison of scenarios of when and to what extent we should implement energy renovation. The demand and supply sides are compared, and the synergies between them are used to obtain optimal solutions at a societal level.

The investigation takes a long-term perspective and deals with a period up to 2070. The approach is that fossil fuels should be phased out before 2025 and replaced with renewable energy resources and waste incineration. Geothermal heat is used as a representative for a mix of renewables. Biomass is seen only as a temporary resource to be used until 2040 in the future district heating plants, since research shows that it

is a limited resource (EEA, 2006, Ericsson and Nilsson, 2006). Different solutions therefore need to be integrated.

The case study used to investigate this research topic is described in Chapter 4.

3.2. Low-temperature district heating for old existing buildings undergoing energy renovation

Methods are discussed and described for investigating the supply of low-temperature district heating to old buildings, so that heat losses in the district heating distribution network are reduced and the exploitation of renewable energy resources is more efficient.

The research question is to what level we should energy-renovate buildings in order to be able to supply low-temperature district heating to old multi-storey buildings without compromising on thermal comfort (SH2). Paper 2 focuses on the investigation of this topic.

To answer the research question, the optimal method would be to perform measurements on a large sample of buildings and to test the hypothesis empirically over a lengthy period. It would also require that the buildings should have low-temperature supply and undergo various levels of renovation, which is very costly and often not possible due to economic and time restrictions. Alternatively, a combination of both theoretical and practical investigations including measurements on a smaller number of buildings, would allow for validating the theoretical simulation models. However, carrying out measurements was not an option in this PhD-project due to economic and time restrictions, so only theoretical analyses were performed to test sub-hypothesis 2. The theoretical results are used to estimate what is theoretically possible and indicate where problems might occur before implementing it in real life on a large scale. The results can therefore be used as a first iteration before further and more detailed work.

The method applied was to make theoretical calculations using the whole-building energy simulation software IDA ICE 4.5. The method includes the implementation of various energy renovation strategies to clarify to what extent we should save energy in old multi-storey buildings in order to be able to supply low-temperature district heating without compromising on thermal comfort. The critical element is the control of radiator-operation to ensure the cooling of the district heating water. Since the results are based only on theoretical investigations, they assume an optimal operation of the heating system, which often is not the case in real life. It will therefore be necessary to confirm the test of the hypothesis by carrying out practical investigations afterwards. Unfortunately it was not possible to achieve this in this research work.

The case studies used to investigate this research topic are described in Chapter 4.

3.3. Energy renovation of old multi-storey buildings – balancing energy savings and moisture safety when using internal insulation

The third topic represents the biggest part of the PhD-project and tests three of the five sub-hypotheses. It focuses on the whole-building renovation of old heritage multi-storey buildings and the related energy savings when internal insulation is applied and moisture safety has to be ensured (SH3). A detailed and more general study of the moisture conditions in the façade and floor construction was also carried out to determine the effect of internal insulation (SH4 and SH5).

3.3.1. Whole-building renovation — balancing energy savings and moisture safety

To answer the research questions on whether it is possible to save 50% of the total building energy consumption and still ensure moisture-safe solutions, the optimal method would be to perform building energy renovations on a large sample of buildings and measure the energy performance before and after the renovation. To document whether using internal insulation is safe, comprehensive measurements would need to be performed in all the buildings/apartments undergoing the renovation. However, it is often impossible to carry out measurements and experiments on a large sample of buildings since it is too expensive and time-consuming. An alternative method is therefore to combine the experiments with theoretical calculations and to use the measurements from a single test building or apartment to validate a theoretical simulation model. The simulation model can then be used to simulate various parameter variations so that it is possible to cover a broader area and to draw conclusions on the hypotheses. However, even when the method is based on measurements on a real building, there are still many factors that are unknown, such as local weather conditions, occupant behaviour, etc., which all affect energy consumption and moisture conditions. This means that it can be difficult to validate the simulation model to an extent where we know with certainty that it is calculating correctly. However, carrying out measurements will give some indication of the credibility of the simulation model and is therefore preferred over analyses carried out using only theoretical models. Laboratory tests on individual energy-saving measures in order to estimate the total energy saving in a building is not an option, since there would be too many parameters and circumstances that are not included and it would lead to incorrect results.

The method applied to test sub-hypothesis 3 was to carry out measurements in a test building and use them to validate a theoretical whole-building simulation model. Carrying out a holistic energy renovation is very costly and only one test building was used in this research work. Measurements were made on the energy consumption (heating and electricity consumption for ventilation) before and after the renovation. Theoretical calculations were performed in IDA ICE 4.5 and the model was validated with the measurements. This is described in Paper 3. The focus was on finding a balance between energy savings and moisture safety. A solution where the insulation stops 200mm above the floor construction was investigated. This increases heat losses through the wall compared to a fully insulated wall, but might be a moisture-safe solution. This was implemented in IDA ICE by applying insulation on the interior side of the wall with a weighted average thermal transmittance taking the 200mm gap into account. IDA ICE does not allow for creating the actual gap over the floor

construction, and the heat losses through the exterior façade are therefore only approximated by this method. The effect of the 200mm gap on the entire building heat consumption was calculated by comparing the heat consumption calculated with IDA ICE (3D) with and without the gap in the insulation. The increased heat losses through the façade in percentage were also estimated using HEAT 2. HEAT 2 is a two dimensional transient and steady-state simulation software for thermal calculations. Four models were created and compared to evaluate the relative difference in heat transfer through the façade; a reference model of the original wall without insulation, a model with full insulation, a model with 200mm gap in the insulation above the floor construction, and a model with 200mm gap in the insulation above and below the floor/ceiling. The simulations were carried out with the floor beam (modelled as a slab) and without the floor beam, representing the section in between the floor beams. For more details about the specific method used and assumptions made, see Paper 3.

The case study used to investigate this research topic is described in Chapter 4.3.3.

3.3.2. Hygrothermal investigation for applying internal insulation

Methods are discussed and described for investigating the two research questions of whether it is possible to apply internal insulation without creating a risk of mould growth on the brick façade behind the insulation (RQ4) and on the surface of the wooden beam construction (RQ5).

To answer the research questions, the optimal method would be to perform measurements on a large sample of buildings and to test the hypotheses empirically over a lengthy period. However, it is often impossible to carry out measurements and experiments on a large sample of buildings because it is too expensive and time-consuming. An alternative method is therefore to combine the experiments with theoretical calculations and to use the measurements from a single test building or apartment to validate a theoretical simulation model. The simulation model can then be used to simulate various cases so that it is possible to cover a broader area and to draw conclusions on the hypotheses. However, even when the method is based on measurements on a real building, there are still many factors that are unknown, such as local weather conditions (sun, rain, etc.), which affect the amount of moisture in the wall. This means that it can be difficult to validate the simulation model to an extent where we know with certainty that it is calculating correctly. If experiments and measurements were performed in a laboratory, it would be easier to control all inputs and validate the model. However, laboratory tests do not represent reality completely and will contain other uncertainties. Sometimes it is not even possible to carry out measurements on either real buildings or in the laboratory due for instance to economic restrictions or a lack of willingness of the building owner to let it undergo experiments. The only method will then be theoretical calculations, with reservations as to its credibility, though the results can be compared with other similar analyses.

In this research, no laboratory experiments were included, but measurements in real test buildings and apartments were made alongside the theoretical calculations.

The method applied to investigate whether there is a risk of mould growth in the wooden beam ends was to install sensors in the beam ends in a test building and measure the relative humidity and temperature (Paper 3). The measurements were then used to validate a simulation model with the hygrothermal simulation software Delphin, so that the worst-case scenarios could be simulated and the risk of mould

growth could be estimated on the wooden beam construction and behind the insulation on the wall (Paper 4). The reason why the study uses the mould growth as the critical limit is due to more reasons. By using mould as the critical limit also wood decay funguses are avoided. It can be discussed whether mould in the wooden beam construction is critical since it is placed inside the floor and wall construction, but the old buildings are often very leaky through the floor construction and it can be expected that air can travel from the wooden construction to the room where it potentially can create a health risk. Therefore this study uses the mould growth as the critical limit, so that no mould growth is accepted.

Carrying out measurements always involves uncertainties with regard to the installation of equipment and the uncertainties of the measuring equipment itself. However, in this case the measurements were relative humidity and temperature, and the range of uncertainty of the equipment would not influence the result significantly. A variation of for instance ±2% relative humidity does not change the overall results, since the critical limits for mould growth are rather diffuse and other parameters such as duration and organic material are important factors as well. Another risk is that the sensors will not be installed at the exact location required or that they will be affected too much by the indoor air, for instance. However, the measurements will still give a rather good indication of the moisture conditions. The measurements carried out are installed inside the wooden beams. The evaluation of mould growth based on the measurement is therefore an approximation, since mould growth occurs at the surface and not inside the beam. However, mould growth happens over a longer period with critical moisture conditions and it is assumed that the wooden beam and the surface of the beam will be in state of equilibrium over time. The measurements are therefore used as indications of the moisture conditions and to evaluate if there is a risk of mould growth on the surface. However, detailed analyses with hygrothermal calculations are carried out to evaluate the risk of mould growth in more detail.

Validating the simulation model is a difficult task because models never reflect reality completely. Not all parameters and dynamics can be included, and there are many uncertainties related to the input parameters and to the geometry of the model. One uncertainty is the local weather, which is unknown unless comprehensive measurements are carried out on the building site. This was not possible in this research work, due to cost and to aesthetical reasons on the heritage building. The weather data used for validating the model was measured by the Danish Meteorological Institute (DMI), but local conditions, such as the actual amount of sun and wind-driven rain on the façade, are unknown parameters, which can be a problem for the validation process. Both the sun and driven rain are important parameters for the moisture conditions in the façade and will affect the results. It is therefore a difficult task to validate and quantify the model, but the results can be used as a first iteration that gives an approximate indication of what the consequences of applying internal insulation will be.

3.3.3. Method for evaluating the risk of mould growth
The method for evaluating whether there is a risk of mould growth is divided in two levels. A simple evaluation of the risk of mould growth based on the measurements was carried out based only on the relative humidity and temperatures, and then a more detailed evaluation was carried out using the VTT-model, which also includes the time-factor. This PhD-project aims at eliminating any risk of mould growth. This implies that the risk of wood decay will not exist as long as mould growth is avoided.

According to Viitanen et al. (2008), Viitanen (1997) and Viitanen et al. (2010) decay fungi can develop when the relative humidity is higher than 95% or the moisture content in the wood is higher than 25%, depending on the duration, temperatures, species and material.

Hukka and Viitanen et al. (1999) developed a mathematical model for evaluating the risk of mould growth on wood (the VTT-model), which has been further developed over the years and is described in several papers (Vereecken and Roels, 2012; Viitanen and Ojanen, 2007; Viitanen, 1997; Ojanen et al., 2010). The model was developed based on tests and includes critical limits for relative humidity, temperature and the time factor for conditions favourable and non-favourable for mould growth. A more recent study has further developed the model so that it also includes other materials such as concrete, cement, plastic-based materials, glass and metals (Ojanen et al., 2010). The model calculates the Mould Index (M), which describes the growth rate. The mould index can range from M=0-6 and is described in Table 3-1. The critical relative humidity in the model defines the minimum value for which mould growth can occur. The critical limit for mould growth on wood in the VTT-model is 80% and 85% for the interior surface of the exterior façade (Ojanen et al., 2010). For a detailed description of the model see Hukka and Viitanen et al. (1999), Viitanen H and Ojanen T (2007) and Ojanen et al. (2010).

Table 3-1: Description of Mould Index for the VTT-model (Viitanen H and Ojanen T, 2007).

Index (M)	Growth rate	Description
0	No growth	Spores not activated
1	Small amount of mould on surface (microscope)	Initial stage of growth
2	<10% coverage of mould on surface (microscope)	-
3	10-30% coverage of mould growth on surface (visual)	New spores produced
4	30-70% coverage of mould growth on surface (visual)	Moderate growth
5	>70% coverage of mould growth on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

3.4. Software tools
In the following, descriptions are presented of software tools for whole-building simulations and for hygrothermal simulations. First there is a general description and discussion of the various tools, after which the software tools used in this PhD-project are discussed.

3.4.1. Software for whole-building simulation
Energy Plus, ESP-r (Energy Simulation Software tool), IDA ICE (Indoor Climate Energy), IES-VE (Integrated Environmental Solutions – Virtual Environment), BSim, and TRNSYS are among the most recognized and complete building energy simulation software internationally (Woloszyn, 2008; Crawley, 2005; Sousa J, 2012). All of the programs mentioned are rather complex and require some expertise to use.

All these programs have some advantageous and disadvantageous features when compared against each other, but they all produce detailed models for building energy investigations at research level. The choice of software for the whole-building simulation for this PhD-project was IDA ICE for several reasons. IDA ICE is written in an object-oriented programing language, which offers a greater level of abstraction, customization and flexibility than procedure oriented language (Kalamees, 2004). The programming language used is Neutral Model Format (NMF), which is a program-independent language for modelling dynamic systems using differential algebraic equations. One great advantage with IDA ICE is that the equations for each object/component are publicly available. This allows for a better understanding of the physical models than with other programs, such as IES-VE or BSim. IES-VE and BSim do not offer this transparency and are characterized as a "black box". Another reason for choosing IDA ICE is that it provides a detailed model for analysing a building's energy system. It allows for simulating multiple zones with detailed options for user behaviour, variable set points for various energy systems and rooms. It also has the option of creating specific components and systems, such as ventilation systems with different control strategies. Furthermore, it is a very user-friendly tool that allows for detailed simulations, including the option of supplying and extracting various input and output files. IDA ICE does not include features like detailed analyses of daylight, as is the case for IES-VE (Radiance), but focus is not placed on daylight in this PhD project, and this feature is therefore less important.

HAMLab is a software tool that integrates the programs MatLab, SimuLink, and Comsol in one environment. It includes HAMBASE: HAM transport in multi zone building models; HAMSYS: building systems models; HAMDET: detailed building physics models (up to 3D); and HAMOP: optimal operation. It has integrated models for 3D heat and moisture transport in constructions, 2D airflow models, and it can calculate whole multi-zone building models. HAMLab therefore creates a strong simulation environment, but it requires MatLab, SimuLink, and FemLab and is not very user-friendly.

3.4.2. Software for detailed hygrothermal calculations in constructions

Hygrothermal performance is the coupled heat and moisture performance. Recently, a number of advanced hygrothermal simulation programs have been developed, and among the most popular and user-friendly of these are Delphin and WUFI. Both can simulate transient 1D and 2D models, whereas most other hygrothermal simulation programs are only capable of simulating 1D models. HAMLab allows for detailed 3D modelling for heat and moisture transport in construction, but it is a very detailed and complicated program that also includes the whole-building model and requires MatLab, SimuLink, and FemLab knowledge.

Both Delphin and WUFI are recognised programs that are used at research level.

Delphin has been validated several times with the focus on different aspects of the software. The implementation and the numerical solution method in the simulation program was tested and validated against HAMSTAD Benchmarks 1 to 5 (Adan, 2004), EN 15026:2007 (transient heat, air and moisture transport), EN 10211:2007 (Steady-state heat transport), and IBK Wetting and drying (Transient heat and moisture transport, with the focus on capillary transport in the middle and low moisture range) (Sontag et al., 2013). The validation of the transport model, and the

integrated material and climatic data models have been tested in several research projects, including (Scheffler, 2008). In this PhD-project, Delphin was chosen since it offers great flexibility and is user-friendly. It is a tool that is constantly being developed and updated for research purposes.

4. Case-studies

To test the sub-hypotheses four different case-studies were used and described:

Case study I: Copenhagen district heating system.
Case study II: Multi-storey building in Mønsgade 16 – Aarhus
Case study III: Multi-storey building in Ryesgade 25 – Copenhagen.
Case study IV: Multi-storey building in Ryesgade 30 – Copenhagen

How the case-studies are used is described on the basis of the structure presented in the methods section:

Topic 1: Energy savings versus energy supply
Case study I: Copenhagen district heating system.

Topic 2: Low-temperature district heating for old existing buildings undergoing energy renovation
Case study II: Energy renovation of the multi-storey building in Mønsgade 16 – Aarhus
Case study III: Energy renovation of the multi-storey building in Ryesgade 25 – Copenhagen.

Topic 3: Energy renovation of old multi-storey buildings – balancing energy savings and moisture safety when using internal insulation
Case study IV: Ryesgade 30 – Copenhagen

4.1. Energy saving versus energy supply

4.1.1. Case study I - Copenhagen district heating area

4.1.1.1. Scenarios

The scenarios used for testing the hypothesis (see also Figure 4-1) were:

i. *Reference Scenario—No energy renovation, but just natural replacement of existing buildings with new buildings.*
    In this scenario, no energy improvements are made in the building stock until 2070, except for replacements with new buildings. In this scenario focus is given fully to renewable energy supply.

ii. *Scenario 1 - Accelerated comprehensive energy renovation between 2030 and 2070.*
    Scenario 1 represents the case where no energy efficiency improvements are carried out in the buildings before 2030. The district heating supply will be converted from fossil fuels to biomass in the CHP-plants and prices will remain unchanged. When biomass is phased out between 2030 and 2040, geothermal heating plants are assumed to be established to cover the nearly unchanged heat load. The investment in geothermal energy will result in increased prices for district heating. Comprehensive energy renovations in buildings will be carried out as a consequence of the

increased heat prices. The coefficient of utilization of the geothermal heating plants will decrease and prices will rise further. Low-temperature district heating will be phased in from 2035, proportional to the energy renovations. The entire building stock will be subject to comprehensive renovation from 2030 phased in over 40 years. Assuming a lifetime of 60 years for such renovation measures, this share of the building stock will be replaced with new buildings from 2090.

iii. *Scenario 2 - Accelerated comprehensive energy renovations from 2013*
Scenario 2 represents the case where comprehensive energy renovations are implemented from 2013 to 2040. Biomass will be phased out between 2030 and 2040 and geothermal heating plants will be established. As a result of the energy efficiency improvements in the buildings, the investment in geothermal heating plants will decrease significantly. Low-temperature district heating will be phased in from 2013 proportional to the energy renovations. The entire building stock will undergo comprehensive renovation from 2013, phased in before 2040. Assuming a lifetime of 60 years for such renovation measures this part of the building stock will be replaced with new building from 2073.

iv. *Scenario 3 - Accelerated intermediate energy renovations from 2013*
Scenario 3 represents the case where intermediate energy renovations are considered and as for Scenario 2 the energy renovations are implemented from 2013 and phased in over 30 years. The lifetime for this kind of energy renovation is considered to be 30 years, resulting in a reinvestment after 30 years. Low-temperature district heating is phased in from 2013 proportional to the energy renovations.

The definition of comprehensive energy renovation in this research work is that energy consumption in the community will decrease by 65% and the renovation will consist of:
- Replacement of windows
- Insulation of the building envelope, and
- Installation of mechanical ventilation with heat recovery.

The definition of intermediate energy renovation in this research work is that the energy consumption in the community will decrease by 32% and the renovation will consist of:

- Replacement of windows, and
- Installation of mechanical ventilation with heat recovery.

Low-temperature district heating is phased in in all the scenarios except the Reference Scenario. All the scenarios assume existing buildings are replaced with new buildings at a rate of 1% per year (Barras, 2009). The Danish Building Research Institute (Kragh and Wittchen, 2010) has carried out an analysis that concludes that, if the energy consumption of the existing building stock is reduced by approximately 50% through energy renovations, the building stock will reach an energy level that corresponds to what the Danish Building Regulations 2010 (BR10, 2010) require for new buildings. The annual heat demand will then decrease by 0.5% per year in all the

scenarios. The study does not consider a possible increase in the building stock over time.

Reference Scenario
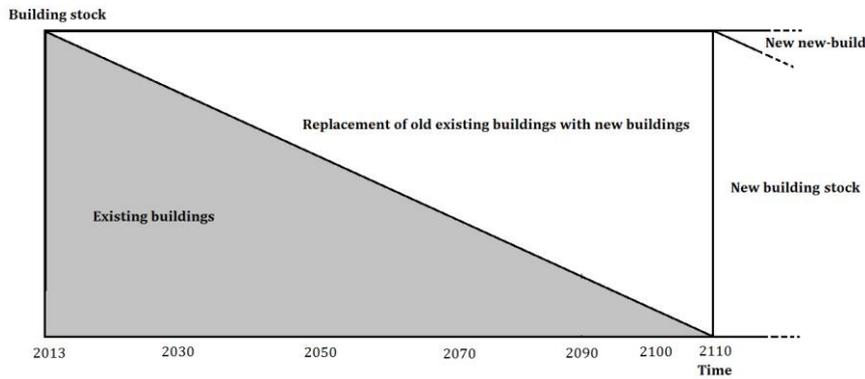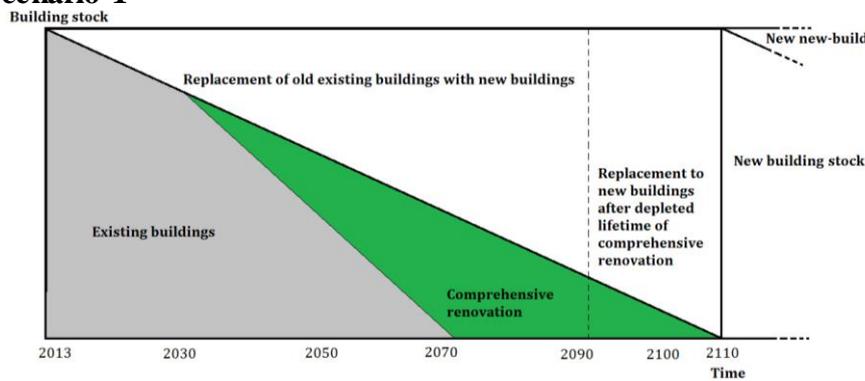

Scenario 1
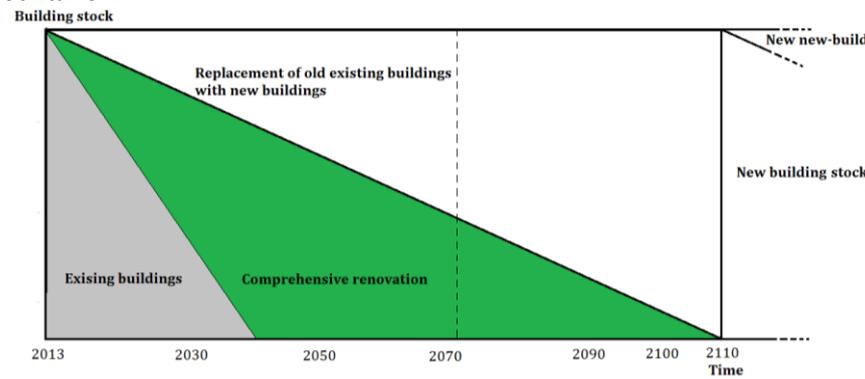
Scenario 2

Scenario 3
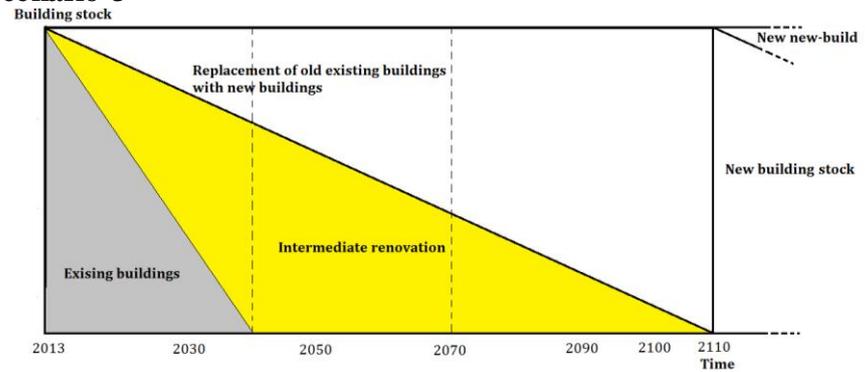
Figure 4-1: Scenarios used for testing sub-hypothesis 1.

4.1.1.2. Economics

To calculate the economic consequences for each of the scenarios, socioeconomic analyses were applied. Using the present value (PV) method, all future investments and costs were discounted to present levels and the scenario with the lowest costs was identified. This is in line with recommendations and guidelines from the Danish Finance Ministry and the Energy Saving Trust Association (ENS) (Danish Energy Agency, 2007a). A sensitivity analysis on the influence of the discount rate was carried out using discount rates of 0%, 1%, 3% and 5%. According to the Danish Finance Ministry and ENS, a discount rate of 5% should be used for present value calculations. The outcome from present value calculations is very sensitive to the discount rate, and it is debatable whether this is a reasonable value for energy-related projects in which the duration of the project is very long. Investments projected for many years from now will be discounted to smaller present values the higher the discount rate. This makes it appear more attractive to delay large investments, such as energy renovations (Ege and Appel, 2013; Atanasiu et al., 2013). Furthermore, (Stern, 2007) has elaborated this dilemma related to discounting in detail and states that if a project's costs and benefits are "allocated across generations and centuries, it is an ethical issue for which the arguments for low pure time discount rates are strong" and "if the ethical judgment is that future generations count very little regardless of their consumption level then investments with mainly long-run pay-offs would not be favoured. In other words, if you care little about future generations, you will care little about climate change. As we have argued, that is not a position which has much foundation in ethics".

Estimated costs of investment, maintenance and operation were included for the geothermal heating plants and for the district heating network. Energy prices for the fossil fuels and biomass were estimated from calculations carried out by (VEKS, 2012b). Waste for incineration was not priced due to the large uncertainties, but since the amount of waste is the same in all scenarios, this will not have any influence on their comparative costs. Moreover, the waste will have to be collected in all cases, and must either be incinerated or stored in a landfill lot, so the cost of waste is not included (Danish Energy Agency, 2007b).

All investments were included for the year they will take place, and salvage values of the investments beyond 2070 were subtracted. The costs for the Reference Scenario (no energy renovations) were calculated solely for the supply-side, whereas the costs for Scenario 1 (energy renovation later), Scenario 2 (comprehensive energy renovation now), and Scenario 3 (Intermediate energy renovation now) also include the investment in energy renovation.

For more details about the assumptions and argumentations made, see Paper 1.

4.1.1.3. Present heat demand and potential for conversion of individual natural gas heated buildings

The present district heating network in the Copenhagen area consists of three waste incineration plants and four CHP-plants distributed as shown in Figure 4-2. The supply area includes the supply companies VEKS, CTR, Vestforbrændingen and HOFOR. The total heat supply by district heating (2010) of the area shown in Figure 4-2 was 35 PJ/year with a peak load of 2500 MW (VPH2, 2011). This capacity was used as the starting point for the calculations in this study. The overall network heat losses are assumed to be 15% of the annual production with traditional district heating

and 8% with low-temperature district heating (VEKS, 2012a; HOFOR, 2012). It is assumed that the domestic hot water demand is 400 MW constantly over the year with the exception of the summer period when consumers are expected to use less domestic hot water due to vacations. In reality, the domestic hot water will vary over the year, but these variations have been left out of account to simplify the study. According to VPH1 (2009), a potential 10 PJ for heating individual homes can be converted from natural gas to district heating. The total heat consumption then adds up to 45 PJ/year with a peak load of about 3200 MW. It was assumed that the ratio between the space heating consumption and the domestic hot water consumption remains the same as the conversion takes place. The capacity of the district heating plants is distributed across small plants in the Copenhagen area.
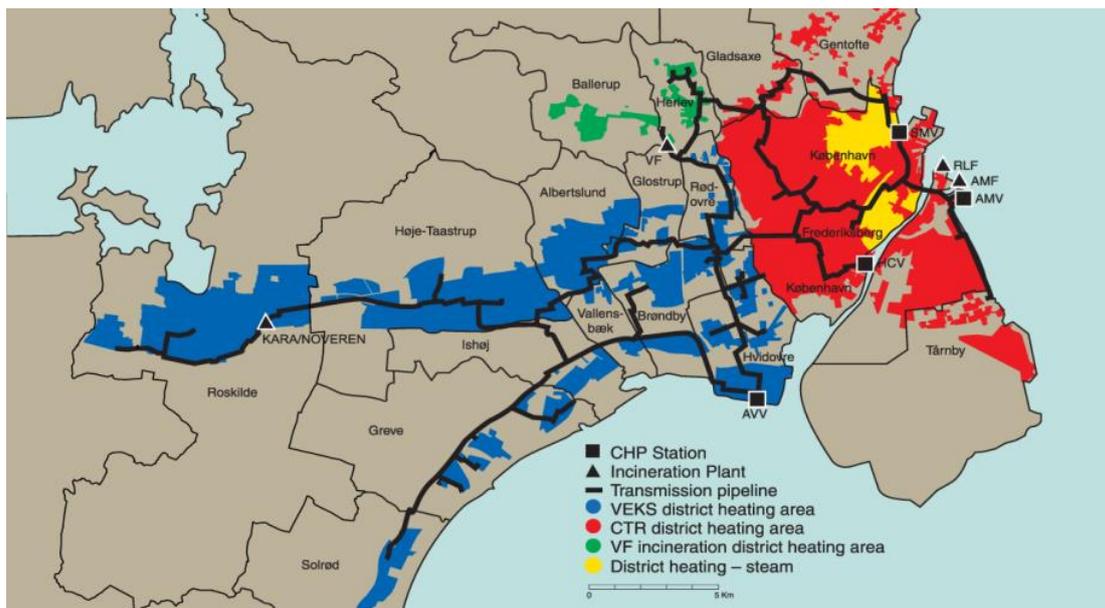

Figure 4-2: Map of the existing district heating network in Copenhagen area (VPH2, 2011).

As mentioned above, geothermal sources should be considered as a mix of various energy sources in the future heat supply infrastructure. Waste heat from industry could also be used in combination with either geothermal or solar heat, but the potential has been estimated to be low (3%) in the Copenhagen area, because the industrial sector is small (Danish Energy Agency, 2009). Geothermal water under Copenhagen can be tapped at temperatures of 73°C at a depth of 2000 m (Mahler and Magtengaard, 2010), so it is assumed that heat pumps are not needed to further elevate the temperature of the water. In Mahler and Magtengaard (2010) newly developed geothermal heating plants in Denmark are described. The priorities for the utilization of the resources in this study were:

1. Waste for incineration,
2. Geothermal energy,
3. Biomass, and
4. Fossil fuels.

Municipal solid waste for incineration has the first priority because plants have already been established and there is a certain ethical value in using heat produced from waste incineration instead of producing more geothermal heat. This may be

different in other countries that do not already have established plants. Furthermore, if the waste is not incinerated, the problem arises of how to treat the waste and what to do with it, so it seems reasonable to prioritize waste incineration. When the heating demand in buildings is reduced to low levels, low-temperature district heating becomes an option, because the need for space heating and the space heating peaks will decrease. This makes it possible to heat buildings with lower temperatures, which allows for the use of low-temperature district heating. This subject will be investigated under *Topic 2* of the thesis: *Low-temperature district heating for old existing buildings undergoing energy renovation*. Periods with very cold climate conditions require an increased supply temperature. It is assumed that this can be supplied from waste incineration plants.

4.2. Low-temperature district heating for old existing buildings undergoing energy renovation

4.2.1. General approach

Three different energy renovation strategies were investigated (*extensive*, *intermediate* and *minor* renovation) as presented in Table 4-1. It might be too optimistic a goal to carry out *extensive* energy renovation on all buildings within a short period, so it was important to investigate various levels of renovation to find out whether low-temperature district heating can provide acceptable comfort temperatures with a small degree of energy-saving renovation. It might also be too expensive to carry out *extensive* energy renovation on all buildings now (investigated in SH 1). Simply replacing windows is a relatively cheap and easy way of obtaining some immediate savings. Furthermore, a lot of buildings are protected, so the external façade must be preserved. Internal façade insulation needs to be applied, which is costly, takes up inside space, and can lead to problems with moisture and fungi (investigated later in the research work under Topic 3).

Table 4-1: Energy renovation levels.

	New windows (with solar shading)	Mechanical ventilation (heat recovery =85%, min. air change=$0.5h^{-1}$)	Basement insulation	Roof insulation	Façade insulation
Extensive renovation	X	X	X	X	X
Intermediate renovation	X	X	X	X	
Minor renovation	X	X			

When energy renovations are implemented, energy consumption decreases, but so do peak loads, and the changes in the heat load duration profile were investigated. The savings in annual heat demand were studied and compared to the savings at peak load. Since peak-load production is very costly, it is desirable to reduce peak loads as much as possible. Investigations were carried out into what lower limit it is possible to dimension peak-load production and still provide acceptable indoor thermal comfort when the building has been renovated. The savings and indoor comfort were studied for dimensioning peak-load production based on daily average values. Furthermore, investigations were carried out into whether it is possible to go one step further and dimension peak-load production based on an average of the five days with the highest daily average values without compromising on indoor thermal comfort (Figure 4-3).
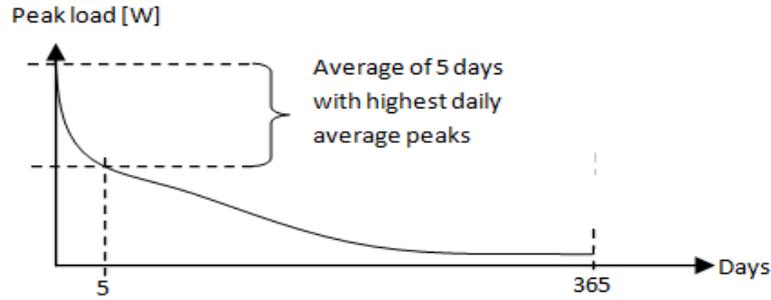
Figure 4-3: Sketch of duration curve for space heating – daily average

When low-temperature district heating is applied, it is crucial to have the same cooling of the district heating water in the system (ΔT) in order to achieve the same heat output (Q). The heat output is defined as:

$$Q = \dot{m} \cdot C_p \cdot (T_{supply} - T_{return}) = \dot{m} \cdot C_p \cdot \Delta T \qquad \text{Eq. 1}$$

Q	is the heat output [W]
$\dot{m}$	is the mass flow rate [kg/s]
C_p	is the specific heat capacity [J/kgK]
T_{supply}	is the supply temperature of the water [K]
T_{return}	is the return temperature of the water [K]
ΔT	is the cooling of the water [K]

Traditional district heating systems have a ΔT = 30K = (70–40°C), so the return temperature should be 25°C if the supply is 55°C at the building. If ΔT is decreased, the mass flow rate needs to be increased to achieve the same power output (i.e. Eq. 1). If the existing distribution pipes in the district heating network are to be used, the mass flow rate cannot be increased, since they are designed for a maximum flow rate, which implies that ΔT in the system needs to stay at 30 K.

Furthermore, when the temperature levels in the radiator are changed, the radiator performance also changes. This means that when low-temperature district heating is applied, radiator performance decreases. Eq. 2 describes the connection where 1 refers to the temperatures for traditional district heating and 2 refers to the temperatures for low-temperature district heating.

$$\frac{Q_1}{Q_2} = \left(\frac{\Delta m_1}{\Delta m_2}\right)^n \qquad \text{Eq. 2}$$

where

$$\Delta m_1 = \frac{T_{supply,1} - T_{return,1}}{\ln\left(\frac{T_{supply,1} - T_{room,1}}{T_{retur,1} - T_{room,1}}\right)} \qquad \text{Eq. 3}$$

$$\Delta m_2 = \frac{T_{supply,2} - T_{return,2}}{\ln\left(\frac{T_{supply,2} - T_{room,2}}{T_{return,2} - T_{room,2}}\right)} \qquad \text{Eq. 4}$$

Δm   is the logarithmic mean temperature difference
n   is the radiator exponent, which is set to 1.3.

The radiators were dimensioned using a temperature level of 70/40/20°C (supply temperature, return temperature, air temperature) based on DS418 to cope with an outdoor temperature of -12°C without any internal heat gains. As the supply temperature is decreased to 55°C, the temperature levels in the rooms are analysed to evaluate whether low-temperature operations is an option. The return water from the building to the district heating network was also logged and analysed. In cases where ΔT = 30K was not obtained, a weather-compensated curve was created so that the supply temperature was increased in colder periods.

4.2.2. Case study II: Energy renovation of the multi-storey building in Mønsgade 16 - Aarhus

The building in Mønsgade 16, Aarhus, Denmark, was built in 1910 and is located in a typical urban area. The building consists of five floors for residential living plus an unheated attic and basement. The overall heated area is $850m^2$. The load-bearing construction is made of wooden beams and brick walls. There is no façade insulation, but the building went through a renovation in 1989, upgrading some parts of the building envelope, so the roof had already been insulated with 200mm stone wool. However, no insulation was present in the floor construction over the unheated basement. The windows were replaced with double-glazing in 1989 and the ventilation was natural, coming from opening windows and leaks.

Only extensive and intermediate renovation were carried out, because the windows had already been changed in 1989, and the energy-saving potential in simply replacing the windows would be rather small compared with a building that has not yet been renovated. Only one floor was modelled in IDA-ICE as representative for the entire building. The U-values and infiltration rates before and after the renovation can be seen in Table 4-2. To include the heat loss from the roof and to the basement, these extra heat losses were included in the models as a weighted average in the U-value for the façade. The thickness of the façade varies, with the smallest thicknesses at the top and under the windows, so the façade U-value was based on a weighted average, representing the entire building façade. The radiators were dimensioned based on the heat losses from the zones in the existing building using an annual simulation with IDA-ICE. The radiators were dimensioned based on a supply temperature of 70°C and a return temperature of 40°C (Korado, 2013). For more details, see Paper 2.

Table 4-2: U-values and infiltration rate before and after the renovation for the building in Mønsgade 16

U-values and infiltration	Existing	Renovated
Façade [W/m2K]	1.34	0.16
Windows [W/m^{2}K]	2.90	1.28
Roof [W/m^{2}K]	0.20	0.13
Floor construction between ground floor and basement [W/m^{2}K]	1.50	0.30
Infiltration [h^{-1}]	0.5	0.05

4.2.3. Case study III: Energy renovation of the multi-storey building in Ryesgade 25 – Copenhagen

The building in Ryesgade 25, Copenhagen, Denmark, was built in 1906 and is located in a typical urban area. The building consists of five floors for residential living, plus an unheated attic and basement. The overall heated area is 3409m^2, spread out over 43 apartments. The bearing construction is made of wooden beams and brick walls. There is no insulation in the façade, roof or the floor construction between the ground floor and the basement. The windows were old one-layer inefficient windows. Fresh air was provided by natural ventilation from opening windows and leaks.

All three levels of energy renovation were carried out – the *extensive, intermediate* and *minor renovation*. Three apartments were modelled in IDA-ICE as representative for the entire building. The U-values and infiltration rates before and after the renovation can be seen in Table 4-3. To include the heat loss from the roof and to the basement, these extra heat losses were included in the models as a weighted average in the U-value for the façade. The thickness of the façade varies, with smallest thicknesses at the top and under the windows, so the façade U-value was based on a weighted average, representing the entire building façade. The radiators were dimensioned based on the heat losses from the zones in the existing building using an annual simulation with IDA-ICE. The radiators were dimensioned based on a supply temperature of 70°C and a return temperature of 40°C (Korado, 2013). For more details, see Paper 2.

Table 4-3: U-values and infiltration rate before and after the renovation for the building in Ryesgade 25.

U-values and infiltration	Existing	Renovated
Façade [W/m2K]	1.34	0.16
Windows [W/m^{2}K]	4.50	0.97
Roof [W/m^{2}K]	1.20	0.11
Floor construction between ground floor and basement [W/m^{2}K]	1.20	0.16
Infiltration [h^{-1}]	0.5	0.05

4.3. Energy renovation of old multi-storey buildings – balancing energy savings and moisture safety when using internal insulation

4.3.1. Whole-building renovation – balancing energy savings and moisture safety

The method applied to evaluate energy savings compared theoretical calculations with full-scale measurements, as described in the steps below. The method applied to evaluate the durability of using internal insulation was based solely on measurements in the wooden beam construction.

The first step was to document the energy consumption for the existing building before the renovation. The energy consumption for the existing building was calculated and validated with the actual measured energy consumption in the building. The calculations were carried out using the numerical building energy simulation software IDA ICE 4.5. The measurements for energy consumption before the renovation consisted of the average space heating and domestic hot water consumption over the period of 2007-2009.

The second step was to document the energy consumption for the renovated building. Heating consumption, including space heating and domestic hot water, and electricity consumption for ventilation were measured. The heating consumption was measured for the entire building and the relative use of space heating was measured by heat meters on the radiator in all rooms. The electricity consumption for the ventilation was measured using HOBO loggers. The energy consumption for the renovated building was also calculated with IDA ICE and validated with the measurements made after the renovation. Real weather data was used as input in the simulation model.

After validating the model for the energy-renovated building in IDA ICE, *the third step* was to calculate the normalised annual energy consumption using standard weather data (Design Reference Year – DRY) and user behaviour to evaluate the results. Based on the normalised model, the effectiveness of the various energy-saving measures implemented in the building was calculated to make it possible to evaluate the influence of the individual energy-saving measures.

The fourth step was to investigate the durability of the internal insulation and investigate whether it would lead to a risk of mould growth. Relative humidity and temperature measurements were carried out in the wooden beam ends embedded in

the masonry walls. A solution with 200mm gap in the insulation above the floor was implemented, which is described under case study IV, Section 4.3.3, and the reduced heat losses compared to the reduced heat losses of a fully internally insulated façade was estimated using Heat 2. Also the effect on the total building space heating consumption was estimated with IDA ICE.

This method was applied in the context of a specific case study (IV) described in section 4.3.3.

4.3.2. Hygrothermal investigation for applying internal insulation

Measurements and theoretical calculations were carried out to evaluate the risk of mould growth behind the insulation on the wall surface and on the wooden beam construction. Figure 4-4 shows the measuring point in the wooden beam ends together with the investigated areas in the construction (Position 1, 2 and 3) using Delphin simulation software. Since the measurements were only carried out in the wooden floor beams embedded in the masonry wall it is only that part of the construction that can be validated. To validate what happens in the brick wall behind the insulation, measurements would be needed and this research cannot validate that part of the model. Another model for simulating the wall construction was created as a 1D-model to evaluate the risk of mould growth behind the insulation.
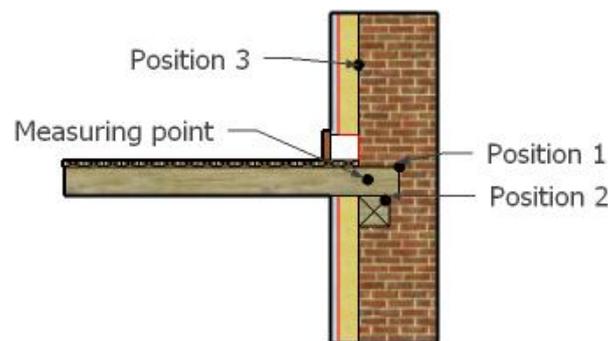

Figure 4-4: Internal insulation applied to a brick wall with indication of measuring point and investigated areas in the construction.

The sensors to measure temperature and relative humidity were installed in two apartments on the 4th and 5th floors with the façade facing south-west. There were no obstacles close to the façade and the wall was therefore highly exposed to the weather, such as wind-driven rain. The measuring points are described in section 4.3.3.2.2 under *Case study IV*. The indoor temperature and relative humidity were also measured in the two apartments to evaluate the indoor climate and to use them as input to the simulation model.

4.3.2.1. *Hygrothermal calculations*
The simulation models were created in Delphin software, which is a two-dimensional hygrothermal program. The fact that a two-dimensional program was used to analyse a three-dimensional problem implies great uncertainties regarding the simulated results. To try to reflect the three dimensional problem, two sets of simulations were carried out to simulate worst-case scenarios. A very simplified sketch of the assembly of the floor/exterior wall construction is shown in Figure 4-5(a). The wooden floor beams perpendicular to the exterior wall are approximately 1 metre apart and attached to the load-bearing beam embedded in the exterior brick wall parallel to the exterior

façade. One set of simulations was created with the wooden floor beams, representing the section at the beam (Figure 4-5(b)) (the beam is modelled as a slab in Delphin), and the other set was created without floor beams, representing the section in between the floor beams (Figure 4-5(c)). The specific parameters, such as material properties and boundary conditions, can be seen in Paper 4. The moisture around and in the wooden beam construction as well as the moisture conditions in the interface between the insulation and the masonry brick wall were investigated and worst-case scenarios were simulated. More details can be found in Paper 4
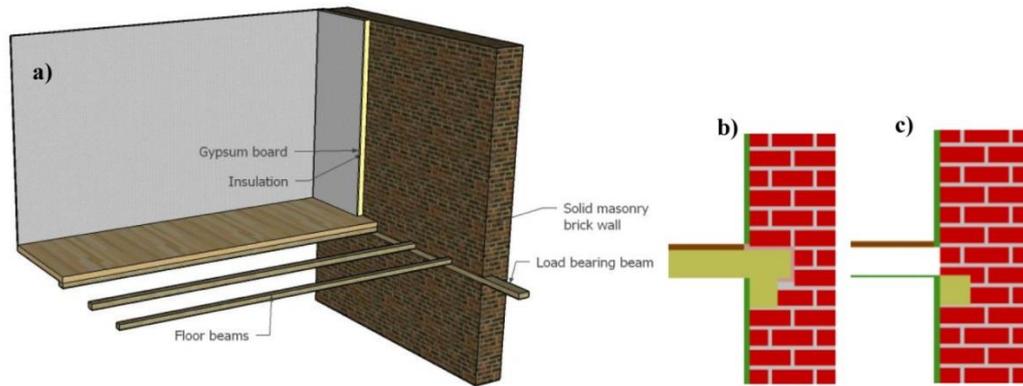

Figure 4-5: a) Assembly between exterior wall and floor construction. Wooden floor beams perpendicular to the façade are approximately 1 metre apart on top of a load-bearing continuous wooden beam in the brick wall. Two sets of models were created in Delphin: b) with floor beams and c) without floor beams.

4.3.2.1.1. Determination of the Catch Ratio (CR)

The rain striking the façade can be expressed by rain intensity vectors, which make up the catch ratio or the rain exposure coefficient, Eq. 5 (Nicolai and Grunewald, 2005-2006; Blocken and Carmeliet, 2002):

$$CR(t) = \frac{R_{dr}(t)}{R_h(t)} \qquad\qquad \text{Eq. 5}$$

$CR(t)$ Catch ratio
$R_{dr}(t)$ Driven rain intensity (integrated over all raindrop diameters)
$R_h(t)$ Unobstructed horizontal rainfall intensity (integrated over all raindrop diameters)

The rain exposure coefficient (catch ratio) is a constant value in Delphin and is difficult to estimate without any measurements because local conditions affect the actual amount of wind-driven rain on the façade. It is rather difficult to determine the catch ratio and there are many opinions and research results. A literature review and a discussion on the catch ratio can be found in Paper 4. But based on the literature review and the discussion, the catch ratio will most likely be 0.1 or less in urban areas, but simulations were carried out with catch ratios of CR=0.1, CR=0.3 and CR=0.5 in order to cover representative and worst-case scenarios.

4.3.2.1.2. Validation of the model of the wooden floor beams.

Two models were created with wall thicknesses of 2 bricks and 1.5 bricks to represent the façade on the 4th floor and the 5th floor respectively (see section 4.3.3).The model

was created with a 200mm gap in the insulation above the floor construction as was done in the test building (see Figure 4-4). The calculated temperature and relative humidity were compared to the measured data in the test apartments.

4.3.2.1.3. Worst case modelling

The worst-case scenarios were simulated over 4 years starting in September for the wooden beam end (2D-model) and over 10 years for the interface between the insulation and the brick wall (1D-model). After validating the model of the wooden beam, various scenarios were simulated to represent worst cases. Three scenarios of applying the insulation were modelled; Figure 4-6(a): insulation applied on the entire interior façade, Figure 4-6(b): a gap of 200 mm in the insulation above the floor, and Figure 4-6(c): a gap of 200 mm in the insulation both above the floor and below the ceiling. Reference models were also created representing the conditions before the retrofitting. The 1D-model for the wall is seen in Figure 4-6(d).

The models were simulated for the façade orientations towards west, north and south. The most dominant wind-direction in Denmark is from the west (Cappelen and Jørgensen, 1999), and west-orientated façades are therefore exposed to more wind-driven rain. But north-orientated façades will not have direct sun, which results in less drying of the wall. Also a south orientated façade was simulated for the insulation solution shown in Figure 4-6(c) and 4-6(d), since one could expect that when the sun heats up the façade the moisture might be pressed in towards the insulation and could potentially create moisture problems. Furthermore, simulations were carried out for wall thicknesses of 1.5 and 2 bricks with 40mm and 80mm insulation thicknesses corresponding to a thermal transmittance of roughly 0.4 W/m^2K and 0.2 W/m^2K respectively.
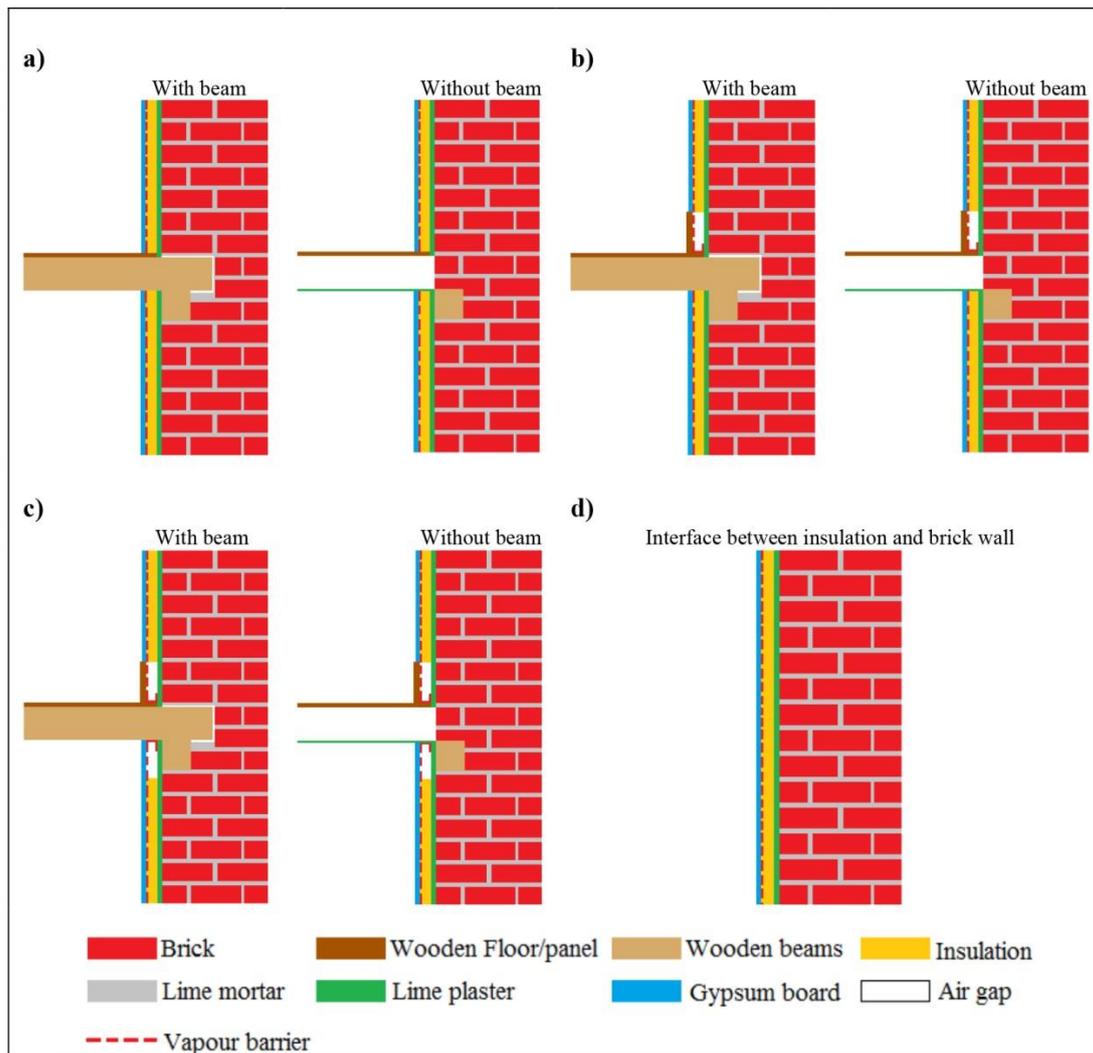
Figure 4-6: Different scenarios of internal insulation applied in the Delphin models – with and without the floor beam for: a) full insulation on the entire interior façade; b) 200mm gap in the insulation above the floor; c) 200mm gap in the insulation above and below the floor/ceiling; d) 1D model of the wall with internal insulation.

4.3.3. Case study IV: Multi-storey building in Ryesgade 30 – Copenhagen

The building is located in a typical urban area in Ryesgade 30, Copenhagen, Denmark, and was built in 1896. It is a multi-storey building with 6 floors with a heated area of 2717m^2 and an unheated basement. The building consists of 30 apartments located in three apartment blocks (Blocks A, B and C). The building can be seen in Figure 4-7 together with the floorplan and a 3D-view of the model built in IDA ICE 4.5. The building is constructed with solid masonry brick walls and wooden beams in the floor construction, which are embedded in the brick wall. The exterior walls had no insulation and the windows were old 1-layer inefficient windows. The building has a heritage value corresponding to Class 4 from the SAVE classification system in Denmark (SAVE, 2011), which means that the external façade must not be changed without permission from the municipality. The building is heated using district heating, and fresh air was provided by natural ventilation from opening

windows and infiltration. In the toilet/bathrooms and kitchens, an exhaust ventilation system had been installed, but in most apartments the ducts were blocked and did not work. Many of the apartments did not have a shower.

4.3.3.1. *Retrofitting approach*

4.3.3.1.1. General improvements
The building went through a deep retrofitting. In which energy-saving measures were in focus, but the interior comfort was also improved by installing new kitchens and bathrooms in all apartments. All surfaces were renovated and new electric wiring and plumbing were installed. The municipality granted permission to install penthouse flats with roof terraces and solar photovoltaic systems, increasing the total value of the building. The production from the solar photovoltaics was not included in the evaluation of the energy performance because the focus in this thesis was on energy-saving measures. It was decided to keep the existing heating system in the building based on district heating and radiators. The building can be seen in Figure 4-7(a) before the renovation and in Figure 4-7(b) after the renovation.

4.3.3.1.2. Building envelope
The municipality accepted that the windows were to be replaced with new windows, because the test apartment showed that this would be the most cost and energy-efficient choice. The new windows were constructed to be aesthetically like the old windows but with energy-efficient 3-layered glazing and wooden frames (Figure 4-7(d)). Due to the heritage value of the building, internal insulation was used (Figure 4-7(c)) except for the north-east façade (Block C). This façade faces a narrow passage and 250 mm external mineral wool was applied (thermal conductivity = 0.039 W/mK). The apartments in Blocks A and B were insulated with a mix of mineral wool and aerogel with a thermal conductivity of 0.019 W/mK. In the apartments in Block C, a rigid thermoset modified resin insulation was applied with a thermal conductivity of 0.020 W/mK with a thickness of 40mm and a gypsum plate of 10mm added to the inside. Under and around the windows only 20mm insulation was applied with a gypsum plate of 10mm.

4.3.3.1.3. Mechanical ventilation
Different mechanical ventilation systems with heat recovery were installed in the three apartment blocks. Table 4-4 shows a description of the three ventilation systems. In Blocks A and B, the air handling units (AHU) were located in the basement (Figure 4-7(e)) and the existing chimneys were used for the exhaust from bathrooms and kitchens. The air intake and exhaust are over the roof, but since there is no space in the attic for the AHU, the air was led down to the basement for heat recovery. The three different systems allowed for comparison of energy consumption and ease of installation. It can be a challenge to find space for the ducts in old building, especially for central ventilation systems, where the AHU is located in either the attic or the basement. The air flows met the requirements of the Danish Building Regulations (BR10, 2010) with exception of the system in Block B, where permission was given to operate with lower air flows during unoccupied hours. In Block C, the system was decentralised at apartment level (Figure 4-7(f))

Table 4-4: Description of the ventilation systems.

	Block A	Block B	Block C
Location of AHU	Central ventilation system with AHU in basement	Central ventilation system with AHU in basement	Decentralized ventilation system with AHU in each apartment
Operation control	Constant operation	Demand controlled operation based on: CO_2, relative humidity, temperature, user panel for specific needs	Constant operation
Air Flows	*Supply air flow:* 140 m³/h *Exhaust air flow from bathroom:* RH<55%: 20 m³/h RH> 55%: 54 m³/h *Exhaust air flow from kitchen:* Cooker hood off: 72 m³/h Cooker hood on: 144 m³/h	*Supply air flow:* 22 m³/h* – 144 m³/h *Exhaust air flow:* 22 m³/h* – 144 m³/h	*Supply air flow:* 140 m³/h *Exhaust air flow from bathroom:* RH<55%: 20 m³/h RH> 55%: 54 m³/h *Exhaust air flow from kitchen:* Cooker hood off: 72 m³/h Cooker hood on: 144 m³/h

The air flow of 22m³/h does not fulfil the Danish Building Regulations, but the municipality granted permission to ventilate with only 22m³/h during unoccupied hours.

Figure 4-7: a) The building before renovation. b) The building after the renovation. c) Internal insulation applied. d) New energy-efficient windows with 1+2 glazing reconstructed to be aesthetically like the old ones. e) Air handling unit in basement for central ventilation systems in Blocks A and B. f) Air handling unit for decentralized ventilation systems in Block C. g) Floorplan of the apartments. h) 3D-view of IDA ICE model.

4.3.3.2. Measurements carried out in the test building

4.3.3.2.1. Energy measurements

Measurements for the total heating consumption for the entire building and electricity consumption for ventilation for each block (A,B and C) were carried out. The measurements of heating consumption included space heating and domestic hot water. Since no separate measurements for domestic hot water were made, the heating consumption measured in the summer months (June and July) was used to estimate the domestic hot water consumption. The space heating consumption per apartment was found based on relative heat distribution data from Brunata. Brunata measures how many unit of heat each apartment consumes in order to calculate the heating consumption per apartment. The units of heat consumed where divided with the total heating consumption for the entire building resulting in a relative heat distribution per apartment. The measurements of electricity consumption for ventilation were taken centrally for each system (Blocks A, B and C) and represent the total electricity consumption for each ventilation system.

4.3.3.2.2. Moisture and temperature measurements

To evaluate the implementation of internal insulation and the effect on the beam ends with regard to moisture, wireless temperature and relative humidity sensors from BMT instruments were installed in the beam ends and measurements were made (Figure 4-8). Also the indoor temperature and relative humidity were measured. The measurements were logged every 30min. According to Blocken and Carmeliet (2006) and Kragh (1998), the effect of wind-driven rain is greatest at high positions on the

façade close to the corners of buildings. The dominant wind direction in Denmark is southwest-west (Cappelen and Jørgensen, 1999), so the measurements for this study were carried out in the two corner apartments facing southwest and west on the 4th and 5th floors. The measuring points and the section plane for the wall/floor construction are shown in Figure 4-8 together with pictures of the sensors. The insulation stopped 200mm above the floor (Figure 4-8, right) to create a thermal bridge around the wooden beams so that increased temperatures would reduce the moisture to a safe level. The heat losses through the wall will be higher compared to a solution with insulation applied on the entire façade, but the priority was firstly to ensure moisture safety and secondly to save energy. This solution is supported by investigations carried out by Morelli and Svendsen (2012), who concluded that if the insulation stops 200mm above the floor and below the ceiling, the risk of mould growth and wood decay in the wooden beam ends embedded in the masonry brick wall is significantly reduced. The red line in Figure 4-8 (right) demonstrates the vapour barrier installed.
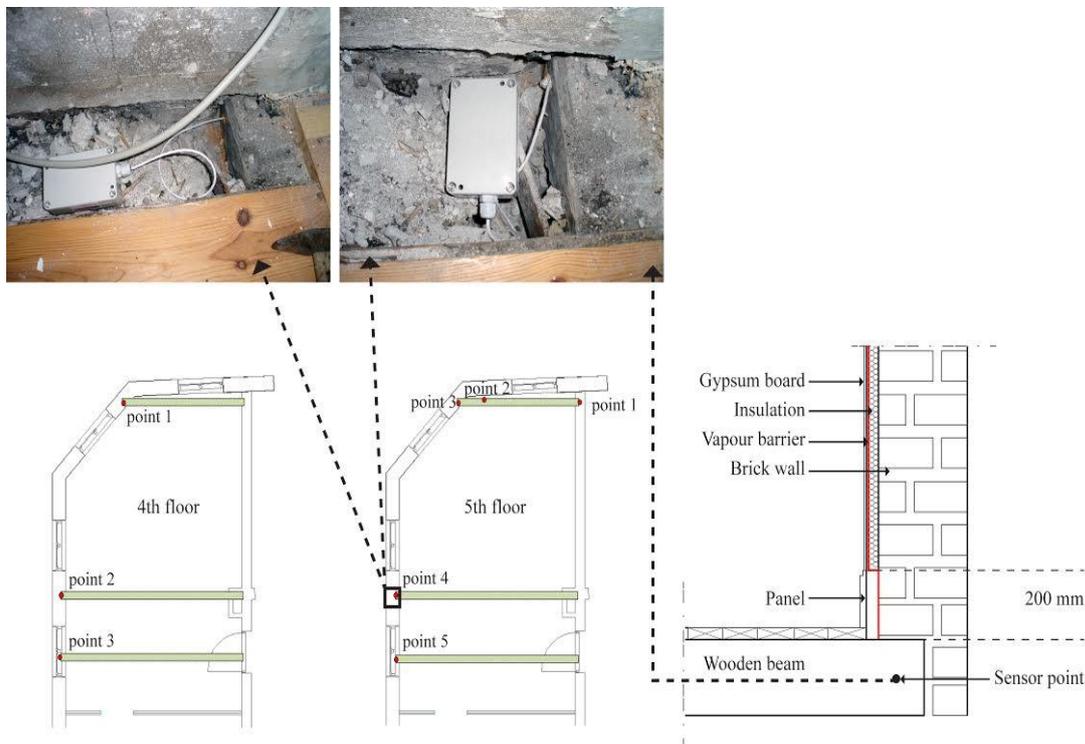

Figure 4-8: Left: Measurement points for temperature and relative humidity in the beam ends on the 4th and 5th floors. Right: Drawing showing how the internal insulation was mounted with an air gap behind the wooden panel.

5. Results and discussion

5.1. Energy savings versus energy supply

The result and discussion related to the case study of Copenhagen district heating area is presented below.

5.1.1. Reference scenario: No energy renovations

Figure 5-1(a) shows the peak load and the distribution of resources. The heat demand will increase until 2035, due to the conversion of natural gas areas into district heating. In the same period, the existing building stock will be replaced with new buildings, decreasing the heat demand by 0.5% per year. Figure 5-1(a) shows that with no accelerated heat savings an investment in geothermal heat corresponding to a capacity of 2800 MW will be required. Figure 5-2(a) shows the annual production of the different energy supply technologies until 2070. Geothermal heat production is expected to peak in 2040 at 32 PJ, after which it will decrease by 14% by 2070. The total geothermal production in the entire period is estimated to be 1100 PJ.

5.1.2. Scenario 1: Accelerated energy renovations later

Scenario 1 represents the case where accelerated comprehensive energy renovations are implemented from 2030. Figure 5-1(b) shows the peak load and the distribution of the supply technologies. The heat demand peaks in 2030, after which it decreases. The build-up in geothermal capacity is 2500 MW, which is slightly lower than in the Reference Scenario (no energy renovations) due to the accelerated energy renovations. Figure 5-2(b) shows the annual production of the different energy supply technologies between 2010 and 2070. Geothermal production peaks in 2040 at 28 PJ. The accelerated energy renovations imply a decrease in the heat demand from 2030 until 2070. The coefficient of utilization drops significantly because the investment in geothermal heat capacity has already taken place. The production of geothermal heat decreases by 61% by 2070. The total geothermal heat production for the entire period is 838 PJ.

5.1.3. Scenario 2: Accelerated comprehensive energy renovations now

Scenario 2 represents the case where investment in accelerated energy renovations begins in 2013. Figure 5-1(c) shows the peak load and distribution of the different supply technologies. The total heat demand decreases throughout the entire period. The investment in geothermal capacity is reduced to 1200 MW, corresponding to a reduction of 57% compared to the Reference Scenario (no energy renovation), and a reduction of 52% compared to Scenario 1 (energy renovations later). Figure 5-2(c) shows the annual heat production of the different supply technologies until 2070. Geothermal heat production peaks at 16 PJ, which is 50% less than in the Reference Scenario (no energy renovations) and 43% less than in Scenario 1 (energy renovations later). Geothermal production decreases by approximately 25% by 2070 compared to the peak value. The total geothermal heat production throughout the entire period is 543 PJ.

5.1.4. Scenario 3: Accelerated intermediate energy renovation now

Scenario 3 represents the case where accelerated intermediate energy renovations are carried out from 2013. Figure 5-1(d) shows the peak load and distribution of the

different supply technologies. The total heat demand decreases throughout the entire period. The investment in geothermal capacity is 2029 MW, corresponding to a reduction of 28% compared to the Reference Scenario (no energy renovation), 19% compared to Scenario 1 (energy renovation later), and an increase of 69% compared to Scenario 2 (comprehensive energy renovation now). Figure 5-2(d) shows the annual heat production of the different supply technologies until 2070. Geothermal heat production peaks at 25 PJ, which is 22% less than in the Reference Scenario (no energy renovations), 11% less than in Scenario 1 (energy renovations later), and 56% more than in Scenario 2 (comprehensive energy renovations now). Geothermal production decreases by approximately 20% by 2070 compared to the peak value. The total geothermal heat production throughout the entire period is 675 PJ.
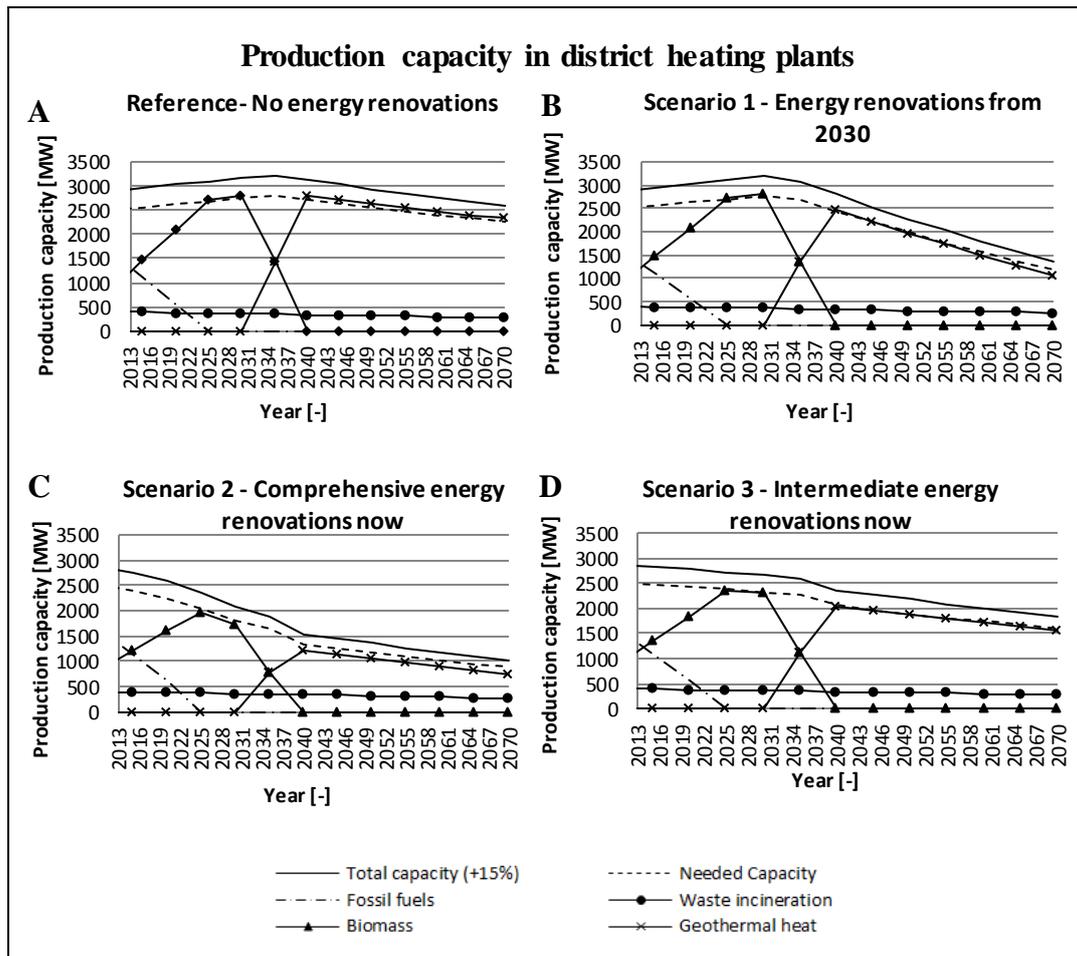

Figure 5-1. Production capacity for the different supply technologies for all the scenarios.
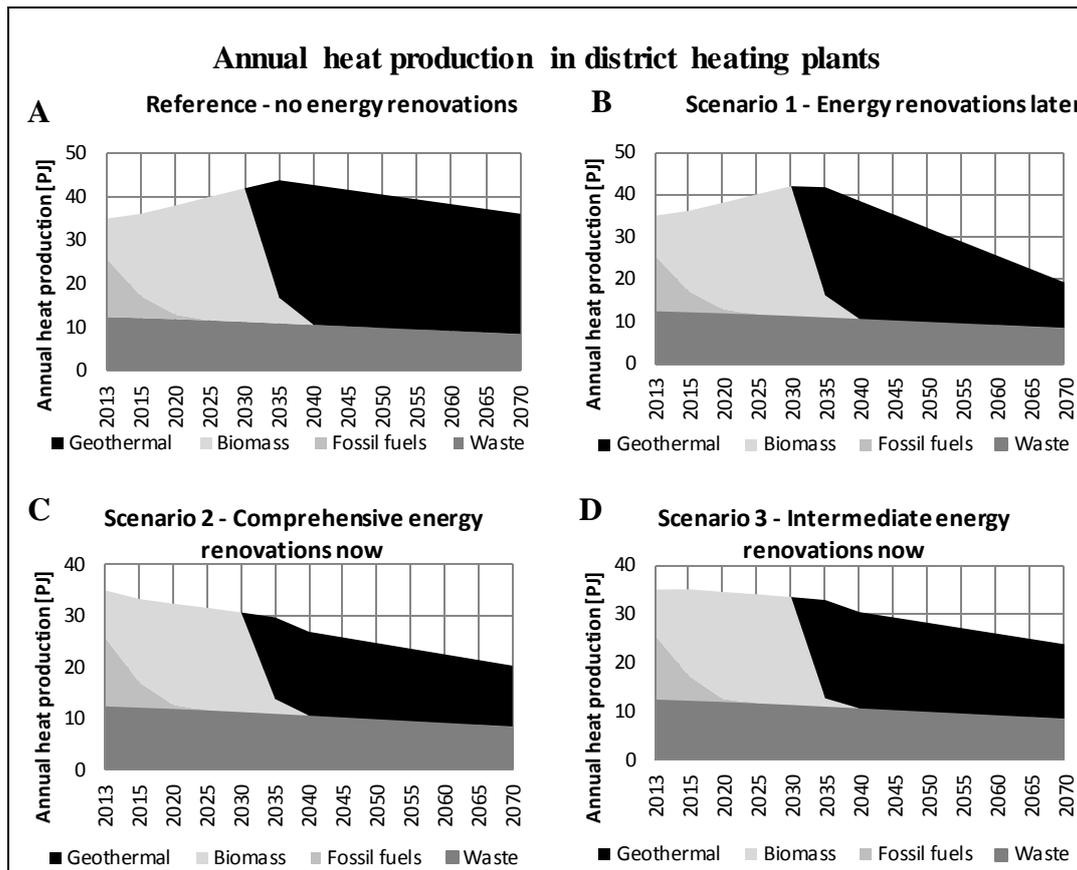
Figure 5-2. Annual heat production from the different supply technologies for all the scenarios.

5.1.5. Economics of the case study

Table 5-1 shows the result of the socioeconomic analysis. The total cost for the Reference Scenario (no energy renovations) is €833 M less than that of Scenario 1 (energy renovations later) if a discount rate of 0% is assumed. This is due to the large investments in energy renovations in Scenario 1 (energy renovations later) at the end of the period in question, and the effect on the investment in geothermal heating plants is therefore relatively small. When the discount rate is increased to 1%, 3%, and 5% the Reference Scenario (no energy renovations) will cost €1106 M, €938 M, and €616 M less than Scenario 1 (energy renovations later), respectively. Table 5-1 also shows that Scenario 2 (comprehensive energy renovations now) is less costly than the Reference Scenario (no energy renovations) by €509 M when a discount rate of 0% is assumed. However, if the discount rate is increased to 1% or more, Scenario 2 (comprehensive energy renovations now) is no longer beneficial compared to the reference, indicating the sensitivity of the cost estimates to the discount rate. The results of Scenario 3 (intermediate energy renovations now) are between Scenario 1 (energy renovations later) and Scenario 2 (comprehensive energy renovations now). Table 5-1 also shows that investing in comprehensive energy renovation from today rather than later will save approximately half the investment cost in geothermal heating plants, which is beneficial for the district heating companies. If investment in intermediate energy renovation (Scenario 3) takes place now, it will save approximately 16% of the investment cost in geothermal heating plants compared to postponing the investment in energy renovation (Scenario 1). However, Scenario 3 with less investment in energy renovation is more likely to be realized fast, since

replacing the windows and installing mechanical ventilation with heat recovery is an easier task than carrying out comprehensive energy renovation.

Table 5-2 shows the heat produced in the district heating plants and the heat delivered to the buildings, i.e. after the network heat losses. Since the Reference Scenario (no energy renovations) does not have low-temperature district heating, and Scenario 1 (energy renovations later) only implements low-temperature district heating from 2035 when the energy renovations are carried out, the network heat losses are higher than in the other scenarios where low-temperature district heating is implemented today proportional to the energy renovations. Taking the expenses for the district heating companies and dividing it by the heat delivered to the buildings, the cost per delivered heat unit is calculated. As can be seen, Scenario 2 (comprehensive energy renovations now) provides the lowest cost per delivered heat unit, followed by Scenario 3 (intermediate energy renovations now), which indicates a more competitive price for the district heating companies when energy renovations are carried out already from today.

Table 5-1: Present Value (PV) calculations for each scenario excl. waste for incineration. Discount rates of 0%, 1%, 3%, and 5% (DH=district heating).

PV 2013-2070	Reference No energy renovations [M €]	Scenario 1 Energy renovations later [M €]	Scenario 2 Comprehensive energy renovations now [M €]	Scenario 3 Intermediate energy renovations now [M €]
Discount rate 0%				
Investments				
Geothermal plants	8,736	7,644	3,744	6,396
DH-net expansion	187	187	187	187
Renovations	0	7,662	7,662	6,171
Salvage value				
Geothermal plants	-983	-860	-421	-720
DH-net expansion	-38	-38	-38	-38
Renovations	0	-5,044	-1,877	-3,514
Fuels	879	874	669	774
O&M	3,276	2,465	1,622	2,524
Total cost for DH companies	12,057	10,272	5,763	9,123
Total cost renovation	0	2618	5785	2657
Total discount rate 0%	12,057	12,890	11,548	11,780
Discount rate 1%				
Investments				
Geothermal plants	6,986	6,113	2,994	5,115
DH-net expansion	169	169	169	169
Renovations	0	5,311	6,776	4,758
Salvage value				
Geothermal plants	-552	-483	-237	-404
DH-net expansion	-22	-22	-22	-22
Renovations	0	-2,832	-1,421	-1,973
Fuels	780	776	601	690
O&M	2,295	1,730	1,141	1,763
Total cost for DH companies	9,656	8283	4,646	7,311
Total cost renovation	0	2479	5355	2785
Total discount rate 1%	9,656	10,762	10,001	10,096
Discount rate 3%				
Investments				
Geothermal plants	4,509	3,945	1,932	3,301
DH-net expansion	141	141	141	141
Renovations	0	2,679	5,425	3,092
Salvage value				
Geothermal plants	-177	-155	-76	-130
DH-net expansion	-7	-7	-7	-7
Renovations	0	-908	-821	-633
Fuels	731	728	578	655
O&M	1,192	904	600	915
Total cost for DH companies	6389	5556	3168	4,875
Total cost renovation	0	1771	4604	2459
Total discount rate 3%	6,389	7,327	7,772	7,334

Discount rate 5%				
Investments				
Geothermal plants	2943	2,575	1,261	2,155
DH-net expansion	119	119	119	119
Renovations	0	1,434	4,470	2,224
Salvage value				
Geothermal plants	-58	-51	-25	-42
DH-net expansion	-2	-2	-2	-2
Renovations	0	-298	-479	-207
Fuels	513	511	415	464
O&M	667	510	341	513
Total cost for DH companies	4182	3662	2109	3,207
Total cost renovation	0	1136	3991	2017
Total discount rate 5%	4,182	4,798	6,100	5,224

Table 5-2: Produced and delivered heat. Cost for delivered heat for the scenarios with different discount rates.

	Reference no energy renovations	Scenario 1 Accelerated energy renovations later	Scenario 2 Accelerated energy renovations now	Scenario 3 Intermediate energy renovations now
Delivered heat at buildings [PJ]	2,064	1,819	1,465	1,652
Produced heat [PJ]	2,379	2,098	1,640	1,827
Net losses [PJ]	315	279	175	175
Cost per delivered heat [€/PJ]				
Discount rate 0%	5.84	5.65	3.93	5.52
Discount rate 1%	4.68	4.55	3.17	4.43
Discount rate 3%	3.10	3.05	2.16	2.95
Discount rate 5%	2.03	2.01	1.43	1.94

5.1.6. Policy implications

In this investigation, biomass was viewed as a temporary resource that will disappear from the heating sector in the long term for use in other sectors. There are different opinions on this subject, but most agree that biomass is a limited energy source. Most sectors would like to make use of biomass, but this is not possible and other non-fossil fuel energy solutions must be found. The authors of (Østergaard and Lund, 2011; Østergaard et al., 2010) concluded that geothermal heating plants will play a significant role in future district heating systems, but they also made use of a small amount of biomass to cope with peak loads. Investing in sufficient geothermal heating plant to cover peak loads may in fact be unrealistic since the investment cost could be too high, and other technologies, such as energy storage, will probably be used to achieve peak-load production. For example, surplus electricity produced from wind could be used to produce hydrogen, which along with biomass would form a "synthetic natural gas". This gas could then be used in CHP plants and the heat production could be used to cover the peak loads. However, peak loads in the future will be much reduced by energy renovation in buildings, so peak-load production will have less importance. Considering that the main investments will be in geothermal heating plants, it may be advantageous to phase in geothermal heating plants at an earlier stage in order to develop the technology and cope with the problems that might occur during development. However, this would make no difference to the results

presented in this research work as long as the capacity needed in the different scenarios remains the same.

The assumption that the building stock is constant over the years might be slightly misleading since there will always be changes in the building stock over time. In history the building stock has generally increased in Copenhagen area, expect from a period from the 1950´ies to the 1980´ies where it decreased (Statistic Denmark, 2015b). It is expected that the population and the corresponding building stock will increase in the coming years (Statistic Denmark, 2015a), but for the sake of simplification and the large uncertainties related to this area it was not included in the study. However, if the building stock will increase this will only speak for the advantage for implementing the energy renovations from today so that the energy consumption can be decreased in the society before the investment in new production capacity takes place.

When estimating the costs for the energy renovation measures envisaged in the present study, it is assumed that energy renovation is only carried out when buildings need renovation anyway. This means that only the marginal cost for energy conservation was used. It is reasonable to assume that the existing building stock will need renovation within a period of 30–40 years because a majority of the buildings in Copenhagen are very old. This is also in accordance with visions for the building stock in Europe (Staniaszek et al., 2013).

The results from the economic calculations are very sensitive to the discount rate assumed. According to the Danish Finance Ministry and the ENS, a discount rate of 5% should be used in making cost estimates, but such high discount rates distort results when dealing with projects that have durations of many years because they affect future conditions significantly. Investments taking place in the future are discounted to low present values, making it attractive to delay any investments. The smaller the discount rate, the more importance is given to future conditions. To give full importance to future generations, the choice of discount rate for the conclusions drawn in this research work was therefore 0%.

The service lifetime of the building, the district heating network, and the geothermal heating plant are all important choices because they can affect the results. The time perspective is often discussed and there is a lot of literature and research on this subject. A wide range of lifetimes for buildings are used, ranging from 30 to 100 years (Mithraratne and Vale, 2004; Verbeeck and Hens 2010; Marteinsson, 2003; Scheuer et al. 2003; Kellenberger and Althaus, 2009, p. 819; Sartori and Hestnes, 2007; Ramesh et al., 2010; Grant and Ries, 2013; Aagaard et al., 2010). However, usually lifetimes of 50 years, 80 years and 100 years are used (Ramesh et al., 2010; Sartori and Hestnes, 2007; Grant and Ries, 2013) and it therefore seems reasonable to have a building lifetime of 60 years as was chosen for this study. The service lifetime of district heating pipes has also been discussed in the literature (Hallberg et al., 2012; Röse et al., 2002). One study (Hallberg et al., 2012) discusses the service lifetime for district heating pipes to be at least 30–50 years and states that future changes in operating conditions should be considered, since they may affect the service lifetime. When district heating systems are converted for low-temperature district heating, the operating temperatures will decrease, which according to (DS/EN 253, Annex A, 2009) will increase the service lifetime of the district heating pipes. If the operating temperature is T≤109°C, the service lifetime is expected to be 100 years. A study from Germany concludes that district heating pipes that had been in operation for 30 years had a remaining lifetime of 38 years, which gives a service lifetime of 68 years (Röse et al., 2002). So a lifetime of 60 years, as chosen for this research seems

reasonable. The lifetime of geothermal heating plants was assumed to be 40 years. In the literature, lifetimes in the range of 20–40 years are often used (Goldstein et al., 2011; Frank et al., 2012; Frick et al., 2010; Lako and Tosato, 2010; Guo et al., 2013). The choice of service lifetime for geothermal heating plants is in the higher end, but taking into account the development and the improvement of the technology over the years, longer lifetimes can be expected (Goldstein et al., 2011 – chapter 4.6), and it therefore seems a reasonable estimate for 2030 when they are assumed to be phased in. The importance of the choice of lifetime and how it affects the results should be investigated in future research. However, it lay beyond the scope of this research work.

The results of the present research are different from other studies dealing with the future of district heating in the EU27 countries. For instance, (Connolly et al., 2012a; 2012b) conclude that future supply from district heating is a more cost-effective energy efficiency measure than end-use savings. However, these studies included a large share of fossil fuels, so investment in renewable energy capacity was not critical for them, as it is for the study carried out in the present research. It should be noted though that the results presented here were based on prices for energy renovation estimated from Kragh and Wittchen (2010), which were later modified to more conservative estimates (Wittchen et al., 2014), making the investment in energy renovation higher. The range for how much we should energy-renovate our buildings is rather diffuse since there are many parameters affecting the outcome.

5.2. Low-temperature district heating for old existing buildings undergoing energy renovation

5.2.1. Annual energy consumption

5.2.1.1. The building in Mønsgade 16, Aarhus

As a result of the energy-saving measures, the total energy consumption decreased as shown in Table 5-3. If the building undergoes an *extensive* renovation, it is possible to achieve an annual heat reduction of about 70–80% and a total energy reduction of about 60–70%, which is in accordance with the findings in Kragh (2010), Kragh and Wittchen (2010), Lund et al. (2010), Rasmussen (2010) and Tommerup et al. (2010). The differences in the reduction in annual energy and annual space heating are due to the extra energy used for mechanical ventilation. An electricity consumption of 4–5 kWh/m^2 for mechanical ventilation is in accordance with the findings and suggestions in Tommerup and Svendsen (2006). When a building undergoes a renovation, it is often observed that the occupants discover an increased comfort level and therefore increase the room temperature from 20°C to 22°C. The increase of 2°C results in an increased space heating demand of about 30%, which indicates the importance of user behaviour for the energy savings achieved. If an intermediate renovation is carried out, it is possible to achieve a reduction in space heating demand of 20–30% if the set point for the room is kept at 20°C. If this is increased to 22°C, the energy savings are negligible, so in this case user behaviour is crucial for achieving savings. Low-temperature district heating with a supply temperature of 55°C was applied in both renovation levels, and it was possible to reach a minimum comfort temperature of 20°C in both cases without having to increase the supply temperature in cold periods.

Table 5-3: Annual energy demand and reduction compared to existing building. *CAV= Constant air flow. VAV=variable airflow. SH=space heating, DHW= domestic hot water*

[kWh/m^2]	Existing SH set point= 20 °C	Extensive renovation** SH set point= 20 °C		SH set point= 22 °C		Intermediate renovation** SH set point= 20 °C		SH set point= 22 °C	
		CAV	VAV	CAV	VAV	CAV	VAV	CAV	VAV
SH	133	38	29	55	43	106	95	136	124
DHW	13	13	13	13	13	13	13	13	13
Mechanical ventilation	-	5	5	5	4	5	4	5	4
Total	146	56	47	72	61	124	112	154	141
SH reduction* [%]	-	71	78	59	68	20	28	-3	6
Total energy reduction* [%]	-	62	68	51	58	15	23	-5	3

* Compared to existing building, ** Supply temperature 55 °C year round.

5.2.1.2. *The building in Ryesgade 25, Copenhagen.*

For the building in Copenhagen, Table 5-4 shows that an annual heat reduction of about 70–80% and a total energy reduction of about 60–70% can be achieved if the building undergoes an *extensive renovation*. This is similar to the building in Aarhus. The mechanical ventilation system in this building is based on CAV and the consumption is slightly higher than the building in Aarhus at 8 kWh/m^2, but still in accordance with Tommerup and Svendsen (2006). If an *intermediate renovation* is carried out, it is possible to reach a reduction in space heating demand of 30–50%, depending on the set-point temperature for the rooms. Occupant behavior has proportionately greater influence on the space heating savings when fewer energy-saving measures are implemented. *The minor renovation* on its own provides approximately 10% less savings than the *intermediate renovation*. The old windows were very inefficient, so a lot of the saved energy is due to the replacement of windows (20–40%). Low-temperature district heating is implemented with a building supply temperature of 55°C. It was possible to reach a minimum comfort temperature of 20°C for all three renovation levels without having to increase the supply temperature in cold periods.

Table 5-4: Annual energy demand and reduction compared to existing building

[kWh/m^2]	Existing 20° C	Extensive renovation 20° C	22° C	Intermediate renovation 20° C	22° C	Minor renovation 20° C	22° C
Space heating	128	22	34	66	86	80	103
Domestic hot water	13	13	13	13	13	13	13
Mechanical ventilation	-	8	8	8	8	8	8
Total	141	43	55	87	107	101	124
Space heating reduction* [%]	-	82	73	48	33	38	20
Total energy reduction* [%]	-	69	61	38	24	29	12

5.2.2. Changes in heat load profile

5.2.2.1. *The building in Mønsgade 16, Aarhus*

When energy-saving measures are implemented, the heat load profile for the individual building changes. Figure 5-3 shows the duration curve for daily average space heating loads, with the heat demand becoming more constant over the year as a result of the energy savings. If more energy-saving measures are implemented, the duration curve becomes lower (less loads) and the heat demand becomes more

constant. This means that the district heating plant will not have to invest in so much renewable supply capacity because the peak loads are lower. Furthermore, the demand will be more constant, which will also result in lower costs for the district heating plants. Table 5-5 shows the reduction in the peak load based on the hour with the highest load. As shown, the reduction is about 40–50% for the *extensive* renovation and between 15% and 20% for the *intermediate* renovation. It was also investigated whether it is possible to dimension the district heating capacity for the renovated building on the basis of an average of the five days with the highest daily average heat loads, without compromising on indoor thermal comfort. For this investigation, one scenario for each renovation level was chosen. For the *extensive* renovation, the investigation was based on a scenario with VAV and a set-point temperature of 22°C while, for the *intermediate* renovation, VAV and a set point of 20°C were chosen. Table 5-6 shows the peak loads and the peak-load reductions compared with the existing building, based on the different dimensioning scenarios for the *extensive* and *intermediate* renovations, respectively. Table 5-7 shows the thermal indoor comfort in terms of hours outside the desired temperature range. As shown, it is possible to achieve the same reduction in the peak loads as for the annual space heating (Table 5-3) when the dimensioning of the district heating capacity is based on the average of the five days with the highest daily average loads. With the *extensive* renovation, there are no hours below 20°C. With the *intermediate* renovation, a significant number of hours are below the limits with the lowest temperature being 17.4°C, which is not acceptable. However, if the set point for the room is raised to 22°C during cold periods, it is possible to avoid hours below 20°C for most of the year. This will increase the annual energy consumption, but the effect will be small, 2.4% over the year at the most. If the supply temperature is increased to 70°C in cold periods, the number of hours below 20°C slightly decreases, but it is not possible to completely avoid hours below 20°C. However, the number of hours below 20°C varies between 10 and 44, which is less than two days.
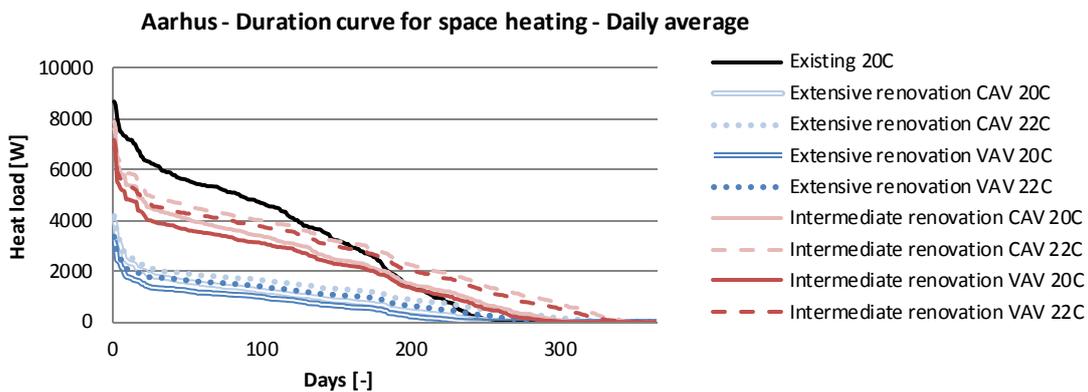

Figure 5-3: Aarhus: Duration curve for space heating – Daily average

Table 5-5: Reduction in peak load compared to the existing building based on hourly values

[%]	Extensive renovation				Intermediate renovation			
	Space heating set point=20°C		Space heating set point=22°C		Space heating set point=20°C		Space heating set point=22°C	
	CAV	VAV	CAV	VAV	CAV	VAV	CAV	VAV
Reduction in peak load (hourly values)	43	52	42	52	14	20	15	21

Table 5-6: Reduction in peak load compared to the existing building

	Extensive renovation		Intermediate renovation	
	Peak load (VAV– Space heating set point=22°C) [W]	Reduction [%]	Peak load (VAV– Space heating set point=20°C) [W]	Reduction [%]
Hour with highest load	4918	52[a]	8127	20[a]
Day with highest average load	3361	61[b]	6884	21[b]
Average of 5 days with highest daily average load	2853	67[b]	5958	31[b]

[a]Reduction compared to the existing building with highest hourly load,
[b]Reduction compared to the existing building with highest daily average load.

Table 5-7: Temperatures in the living zones and hours outside comfort limits

Average of 5 days with highest daily average load	Living room 1	Living room 2	Living room 3	Living room 4	Bed room 1	Bed room 2	Bed room 3	Bed room 4
Extensive renovation- space heating $T_{set\,point}=22°C$								
T_{i_max} [°C]	26.4	26.4	26.3	26.7	26.0	25.7	26.3	26.0
T_{i_min} [°C]	20.7	20.8	20.2	20.2	20.2	20.1	20.3	20.0
$T_i<20°C$	0	0	0	0	0	0	0	0
Intermediate renovation- space heating $T_{setpoint}=20°C$								
T_{i_max} [°C]	26.3	26.3	26.2	26.6	25.9	25.5	26.2	25.9
T_{i_min} [°C]	18.1	18.2	17.0	17.9	17.3	17.3	17.2	17.3
$T_i<20°C$	101	90	208	97	144	170	145	168
$T_i<19°C$	15	14	59	15	42	46	47	39
$T_i<18°C$	0	0	18	2	12	13	15	13
% hours below 20 °C	1.2	1.0	2,4	1.1	1.6	1.9	1.7	1.9
% hours below 19 °C	0.2	0.2	0.7	0.2	0.5	0.5	0.5	0.4
% hours below 18 °C	0	0	0.2	0	0.1	0.1	0.2	0.1
$T_i<20°C$ with *space heating* set point =22 °C	14	13	54	14	32	36	44	33
$T_i<20°C$ with increased supply temperature to 70°C in cold periods	13	10	44	13	23	26	34	25

5.2.2.2. The building in Ryesgade 25, Copenhagen

The same tendency of a reduction of the peak loads and a change in the duration curve is seen with the building in Copenhagen. Figure 5-4 shows the duration curve for space heating based on the daily average; the heat demand becomes more constant over the year as a result of the energy savings. The more energy-saving measures implemented, the lower the duration curve becomes (less loads). This is beneficial for the district heating companies in terms of initial capital investment costs and the degree of utilisation of the plants. Table 5-8 shows the reduction in the peak load based on the different dimensioning scenarios. As shown, the reduction for the *extensive* renovation is about 60% for the hour with the highest load, 65% for the day with the highest average load, and 70% for the average of the five days with the highest daily average loads. For the *intermediate* renovation, the reduction is about 30–35% for the hour and day with the highest loads, and about 40% for the average of five days. The *minor* renovation results in reductions of about 20–25% for the hour and day with the highest loads, and about 30% for the average of five days. Table 5-9

shows the hours outside the thermal indoor comfort range for the *extensive*, *intermediate* and *minor* renovations. The set point was 20°C and it was not possible to keep a minimum temperature of 20°C all year round. If the set-point room temperature is increased to 22°C in very cold periods, it is possible to avoid any hours below 20°C for all renovation levels. Furthermore, if the occupant wants to have an indoor room temperature of 22°C, the supply temperature from the district heating plant can be increased from 55°C to 70°C in cold periods.
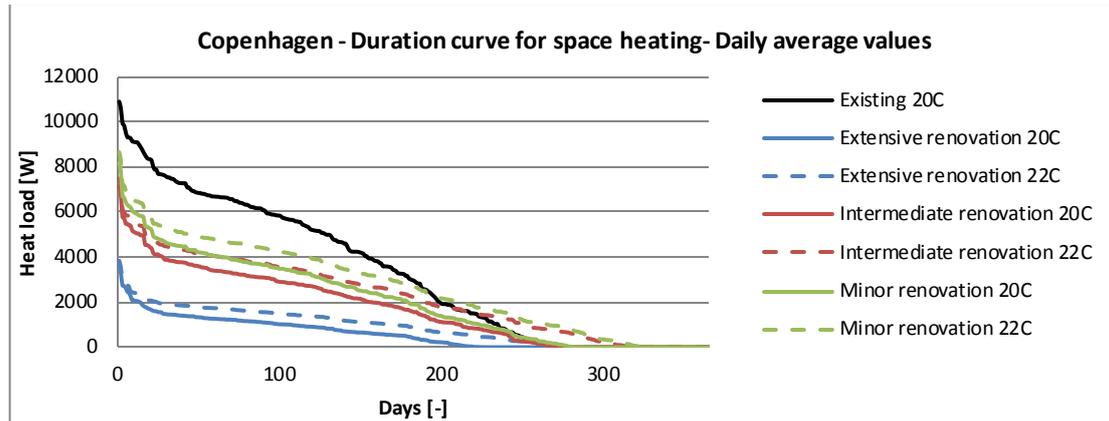
Figure 5-4: Copenhagen: Duration curve for space heating – Daily average values

Table 5-8: Reduction in peak load compared to the existing building

Reduction compared to existing building (Supply = 55 °C all year)	Extensive renovation		Intermediate renovation		Minor renovation	
[%]	20° C	22° C	20° C	22° C	20° C	22° C
Hour with highest load *	58	57	31	30	23	21
Day with highest average load **	67	65	34	31	25	21
Average of 5 days with highest daily average load **	72	70	43	40	34	30

* Reduction compared to the existing building with highest hourly load, ** Reduction compared to the existing building with highest daily average load.

Table 5-9: Temperatures in the living zones and hours outside comfort limits

Average of 5 days with highest daily average load	Living room 1	Living room 2	Living room 3	Bed room 1a	Bed room 2a	Bed room 2b	Bed room 3a	Bed room 3b
Extensive renovation 20°C								
$T_{i,max}$ [°C]	27.0	27.2	26.5	27.0	27.0	26.9	26.5	26.5
$T_{i,min}$ [°C]	18.8	19.3	18.8	18.9	19.4	19.2	18.7	18.2
T_i<20°C	35	16	35	28	13	27	41	35
T_i<19°C	5	0	4	4	0	0	6	4
% hours below 20 °C	0.4	0.2	0.4	0.3	0.2	0.3	0.5	0.4
% hours below 19 °C	0.1	0	0.1	0.1	0	0	0.1	0.1
T_i<20°C with space heating set point increased to 22C	0	0	0	0	0	0	0	0
Intermediate renovation 20°C								
$T_{i,max}$ [°C]	26.7	27.2	26.8	26.8	26.9	26.8	26.8	26.7
$T_{i,min}$ [°C]	18.3	18.6	18.3	19.0	19.2	18.8	18.3	18.6
T_i<20°C	56	38	55	17	23	40	55	44
T_i<19°C	14	9	12	1	0	5	4	8
% hours below 20 °C	0.6	0.4	0.6	0.2	0.3	0.5	0.6	0.5
% hours below 19 °C	0.2	0.1	0.1	0	0	0.1	0.1	0.1
T_i<20°C with space heating set point increased to 22°C	0	0	0	0	0	0	0	0
Minor renovation 20°C								
$T_{i,max}$ [°C]	26.9	27.4	27.2	26.9	27.2	27.1	27.1	27.0
$T_{i,min}$ [°C]	18.2	18.3	18.1	19.0	19.1	18.8	18.1	18.5
T_i<20°C	64	42	62	16	29	42	61	47
T_i<19°C	16	13	15	0	0	5	15	10
% hours below 20 °C	0.7	0.5	0.7	0.2	0.3	0.5	0.7	0.5
% hours below 19 °C	0.2	0.2	0.2	0	0	0.1	0.2	0.1
T_i<20°C with space heating set point increased to 22°C	0	0	0	0	0	0	0	0

5.2.3. Return temperature from the building to the district heating net

When low-temperature district heating is applied with an unchanged flow rate, the performance of the radiators decreases by a factor of 2.5. If the flow is increased, the performance will increase as well, but to obtain an acceptable cooling of the district heating water in the radiator (30 K), the flow cannot be increased (see Section 4.2.1), so the supply temperature may need to be increased in cold periods. The return temperatures from the buildings to the district heating network are presented in Figures 5-5 based on a supply temperature of 55°C all year. The figures are based on a set-point temperature for the room of 22°C. The return temperature will be higher for a set-point temperature of 22°C than for a set-point temperature of 20°C, and thus represents the worst-case scenario. In general, the lower the level of energy renovation implemented, the higher the return temperature. ΔT = 30K can only be achieved in the case of *extensive* renovation, whereas with *intermediate* and *minor* renovation it cannot be achieved the entire year. The solution is to increase the supply temperature when ΔT = 30K is not achieved. Figure 5-6(a) shows the return temperature and the ΔT for the building in Aarhus with *intermediate* renovation when the supply temperature is increased to 60°C in cold periods together with the weather compensated curve. Figures 5-6(b) and 6(c) show the return temperature and the ΔT for the building in Copenhagen when the supply temperature is increased to 60°C or 70°C in cold periods together with the weather-compensated curves.
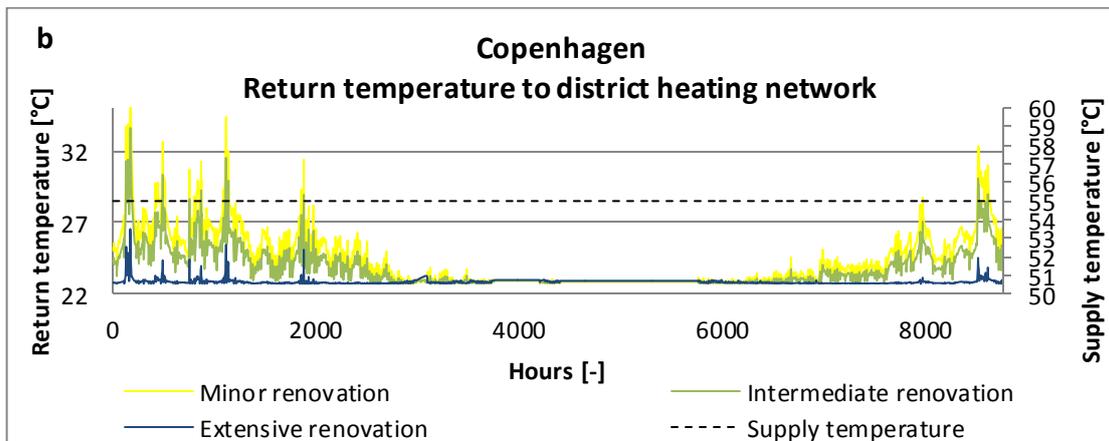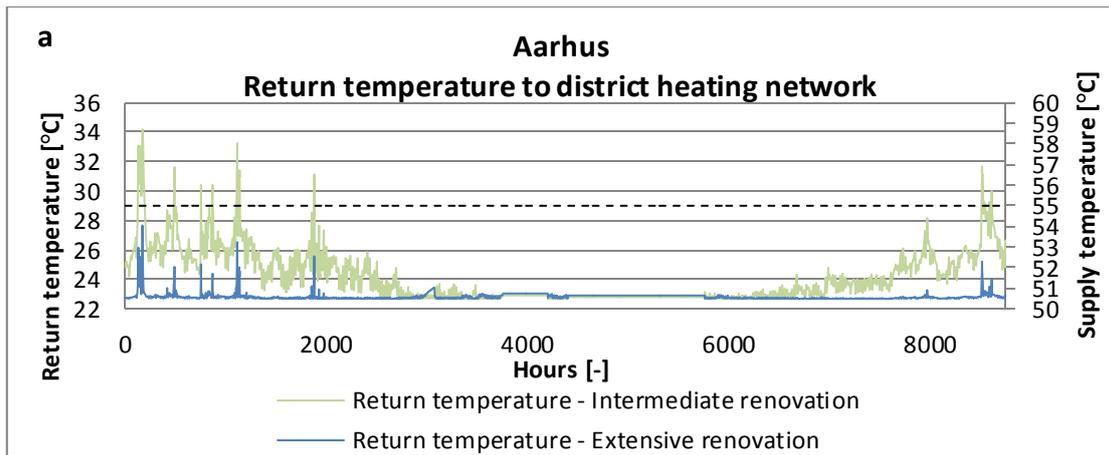
*Figure 5-5: Return temperature to district heating network for building in a) Aarhus and b) Copenhagen*
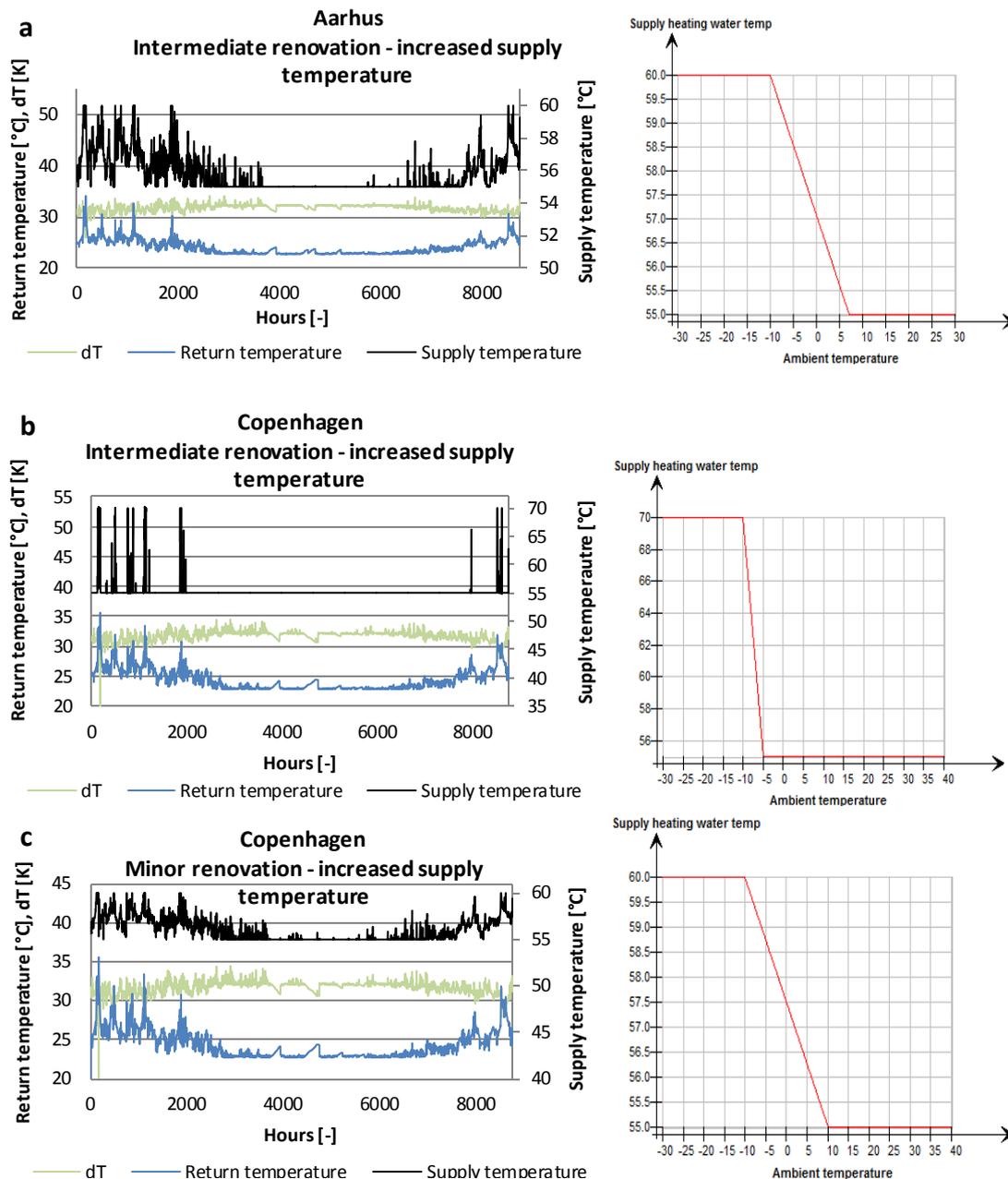
Figure 5-6: Left: Increased supply temperature, return temperature and ΔT for the building in Aarhus (intermediate renovation) and Copenhagen (intermediate and minor renovation). Right: Supply temperature as a function of the outdoor temperature.

5.2.4. Low-temperature district heating to old multi-storey buildings

From the investigation, it seems it is possible to supply low-temperature district heating most of the year. If the supply temperature is increased in cold periods, the comfort temperature is maintained in the buildings and the return temperatures from the building to the district heating plant are still cooled by 30K. However, it should be kept in mind that the investigation was only based on theoretical calculations, implying that the radiator operation was optimal. This is often not the case in real life, and the results found in this research might differ from reality. A further investigation including tests and measurements should therefore be carried out to support the results from the investigation. Nevertheless, the results from this investigation can be seen as

an indication and first iteration of how low temperatures can be supplied for different renovation levels. The higher the level of energy renovation is, the lower the acceptable supply temperature. This investigation did not cover the area of low-temperature district heating and domestic hot water but reference is made to Brand (2014).

5.3. Energy renovation of old multi-storey buildings – balancing energy savings and moisture safety when using internal insulation

5.3.1. Whole-building renovation - Energy consumption

5.3.1.1. Validation of IDA ICE model for the existing building with measured energy consumption

The annual measured energy consumption for the existing building was 156 kWh/m^2. The calculated annual energy consumption in each block before the renovation was found to be as follows: Block A: 129 kWh/m^2, Block B: 148 kWh/m^2, and Block C: 178 kWh/m^2. This gives a total weighted annual consumption of 152 kWh/m^2. The difference between the measured and the calculated annual heating and hot water consumption for the existing building was 2.6%, which is smaller than one could expect.

5.3.1.2. Validation of IDA ICE model for the renovated building with measured energy consumption

5.3.1.2.1. Space heating consumption after renovation

The measured heating consumption can be seen in Figure 5-7 and includes space heating and domestic hot water. The annual domestic hot water consumption is estimated to be 18 kWh/m^2, which is above the requirements for new buildings namely 13 kWh/m^2 according to the Danish building regulations 2010.
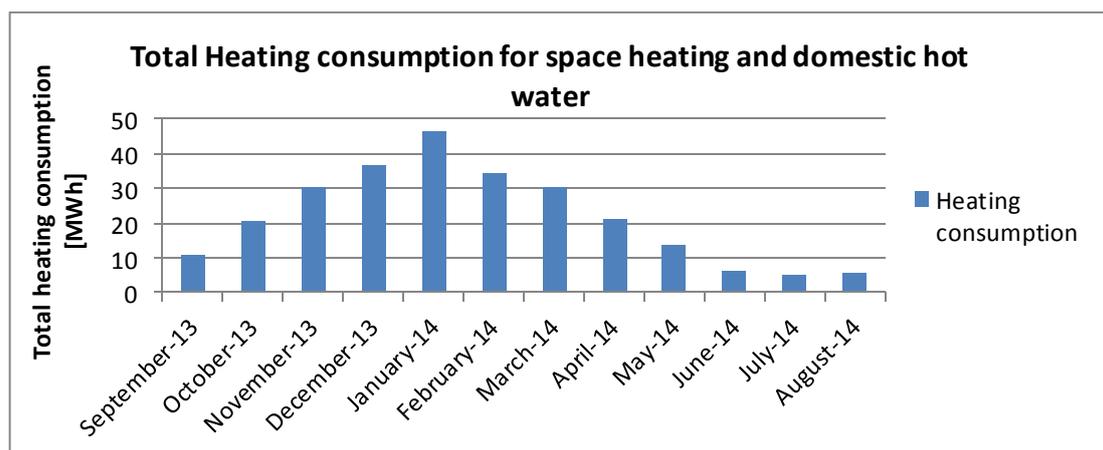
Figure 5-7: Measurements of heating consumption after the renovation incl. space heating and domestic hot water.

The annual space heating consumption was measured to be 60 kWh/m^2, which is above the expected consumption. A numerical simulation model was created in IDA ICE in order to evaluate the heating consumption and the reason for the higher space heating consumption. As shown in Figure 5-8(a), the calculated space heating

consumption deviated significantly from the measured consumption with ideal settings. Since the ventilation system had some operational problems, the heat recovery might be less than the assumed 85%. Moreover, an analysis carried out on occupant behaviour suggested that the infiltration rate could be higher than the ideal of 0.05 h^{-1}, which would increase the heat losses. The analysis showed that some people were smoking inside the apartments with the windows open, and that many of the occupants opened the windows in the bedroom and living room daily even though the mechanical ventilation system should be able to provide sufficient fresh air. Additionally, possible air leakages around the windows could be a reason for increased infiltration rates. As shown in Figures 5-8(b), 5-8(c), and 5-8(d), the simulated space heating consumption is similar to the measured when the heat recovery efficiency is 70%, the infiltration rates are increased to 0.1 h^{-1} - 0.2 h^{-1}, and when the room set-point temperature is approximately 22-24°C. This results in a relative deviation less than 5%. Figure 5-8 shows that the increased temperatures have a greater influence on the energy savings than the increased infiltration rates.
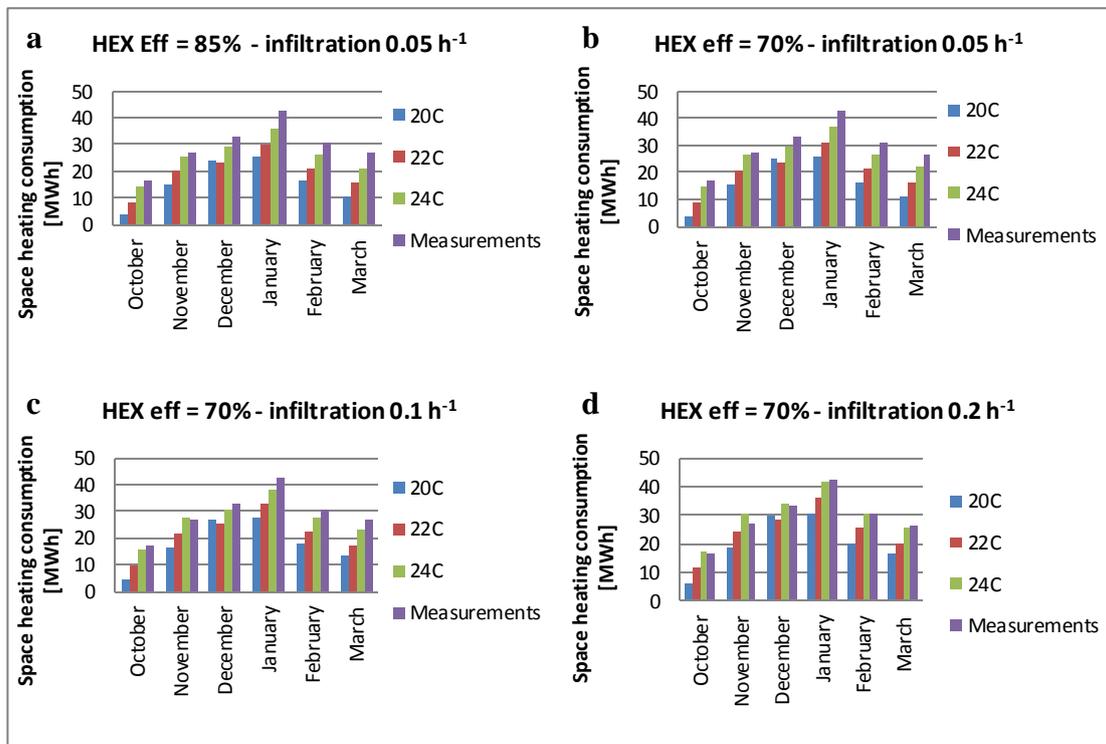
Figure 5-8. Validation and fitting of space heating consumption from October to March.

The temperature level in each apartment was measured and the average temperature level was approximately 22-23°C, which corresponds to the findings of the simulated results. Moreover, the temperature levels in some of the apartments were very low, i.e. down to 11°C, which could be due to habits of opening windows while smoking or to get fresh air. If the heating system is on, the result is increased heating consumption. It was measured that there were no overheating hours during the heating season as a result of the energy renovation, and therefore no related influence on the energy consumption.

To illustrate how much the energy savings were reduced as a result of the decreased heat recovery efficiency, increased infiltration rates, and increased temperature levels,

compared to the expected or ideal savings, Table 5-10 shows the difference between the simulated expected consumptions and the measured consumptions. The table shows an increased space heating consumption of 25 kWh/m^2 if the occupants have a room temperature of 20°C, and of 8 kWh/m^2 if they have a room temperature of 24°C. This is a considerable amount of energy lost due to occupant behaviour and operational failures.

Table 5-10: Difference between the expected and actual space heating consumption from October to March. Measured space heating consumption = 54 kWh/m^2.

[kWh/m^2]	At 20°C	At 22°C	At 24°C
Expected space heating consumption	29	36	46
Reduced space heat savings from October to March (expected savings minus actual savings)	25	18	8

5.3.1.2.2. Electricity consumption for ventilation

The electricity consumption for the three different ventilation systems was measured for one year from August 2013 (Figure 5-9). As can be seen, the systems did not have stable operation during the entire period, so the operation was only evaluated from January, when it was more stable. The non-optimal operation of the ventilation systems also confirms that the heat recovery efficiency might be lower than the 85% assumed and that the ventilation flow rates might not have been as expected, which could influence space heating consumption and indoor comfort. As shown in Figure 5-9, the ventilation system in Block A consumed up to 5 times as much electricity as the two other systems. The higher consumption compared to Block C could have been due to the longer duct run and increased pressure loss. However, Blocks A and B have similar duct runs, both being centralized systems, and the higher consumption in Block A can be explained by the constant air flow operation compared to the variable operation in Block B.
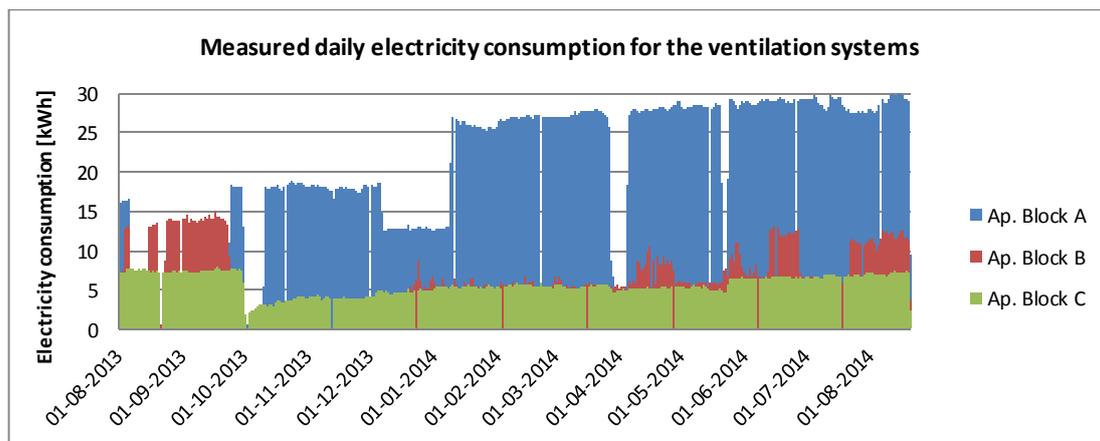
Figure 5-9: Measured electricity consumption for the three ventilation systems.

Table 5-11 shows the calculated and measured annual electricity consumption for the three different ventilation systems. The table shows that the measured and calculated electricity consumption differed by 1.9 kWh/m^2 for Block A, with the measured

consumption being the largest, whereas the difference for Blocks B and C was only 0.2-0.4 kWh/m^2, with the measured consumption being the smallest.

Table 5-11: Measured and calculated annual electricity consumption for the three ventilation systems

[kWh/m^2]	Block A Central constant ventilation		Block B Central demand controlled ventilation		Block C Decentralized ventilation room level	
	IDA ICE	Measured	IDA ICE	Measured	IDA ICE	Measured
Annual electricity consumption per m^2	8.0	9.9	2.8	2.4	2.5	2.3

5.3.1.2.3. Annual energy consumption – energy savings achieved

Table 5-12 shows the normalized annual energy consumption for the renovated building for three different temperature levels together with the measured energy consumption before and after the renovation. The calculated electricity consumption for ventilation was adjusted with the measured to provide more accurate results.

Table 5-12: Annual energy consumption for the existing and renovated building based on measurements and numerical simulations using the DRY weather file. SH is space heating, DWH is domestic hot water, and Fan is electricity use for the ventilation fans.

[kWh/m^2/yr]	Existing building Measured SH, DHW	Renovated building							
		Measured		Calculated 20°C		Calculated 22°C		Calculated 24°C	
		SH, DHW	Fan	SH, DHW	Fan	SH, DHW	Fan	SH, DHW	Fan
Block A	-	-	9.9	70.2	9.9	88.8	9.9	119.4	9.9
Block B	-	-	2.4	48.3	2.4	58.6	2.4	75.4	2.4
Block C	-	-	2.3	50.1	2.3	60.4	2.3	77.8	2.3
Weighted on source		78	4.8	56.2	4.8	69.2	4.8	90.8	4.8
Total weighted	**156**	**83**		**61**		**74**		**96**	
Savings [%]	**-**	**47**		**61**		**53**		**39**	

The measured annual energy consumption was found to be reduced to 83 kWh/m^2, corresponding to savings of 47% compared to the existing building. The calculated annual energy consumption for the renovated building was found to vary from 61-96 kWh/m^2 depending on the room set-point temperature, which corresponds to a reduction in the energy use of 39-61% compared to the energy use before the renovation. The investigation found that the room set-point temperature was between 22-24°C, implying that the expected savings were not obtained. However, if the occupants decrease the set-point temperature to 20°C, the building will consume 61

kWh/m^2/yr, which is close to the requirements for new buildings in the Danish Building Regulations 2010 (BR10, 2010). This implies that from a technical point of view the renovation carried out can decrease the energy consumption to the expected energy level, but in reality the consumption is higher, which underlines the significant impact that occupant behaviour has. The average temperature during the measured winter period was almost 3°C higher than the average normalized temperature (DRY).The heat consumption during a normal winter will be approximately 5 kWh/m^2 higher from October to March.

5.3.1.2.4. Distribution of the savings across the energy-saving measures based on calculations

To illustrate how much energy was saved by each of the different energy-saving measures installed in the building, Figure 5-10 shows the distribution of the savings achieved. The calculations were carried out based on ideal conditions with a set-point temperature of 20°C and the extra infiltration due to occupant behaviour, i.e. opening of windows, was ignored. Each energy-saving measure is shown as a percentage of the total savings. As shown in the figure, the new windows provided the highest savings, followed by the internal insulation and mechanical ventilation with heat recovery. If the extra infiltration was included, the distribution of the energy-saving measures would look different. However, it is complicated to investigate the influence of the extra infiltration because it is difficult to know whether it should be added to the windows or to the ventilation or shared by both due to the interaction between them. Moreover, it is preferable to find a solution to avoid the extra infiltration losses instead of trying to model the effect.
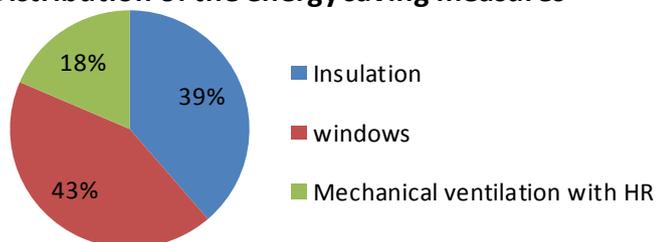
Figure 5-10: Savings from each specific energy-saving measure as a percentage of the total savings. HR=heat recovery.

5.3.1.2.5. Heat consumption distribution in the building

The distribution of the space heating consumption from November to March to each apartment is shown in Figure 5-11. It can be seen that *C-Apart 1* consumed more than five times the average space heating consumption of 24 kWh/m^2 from November to March. This particular apartment is used for commercial purposes, which may explain the higher consumption. The consumption in the remaining apartments varied a great deal: from close to 0 kWh/m^2 to almost 80 kWh/m^2.
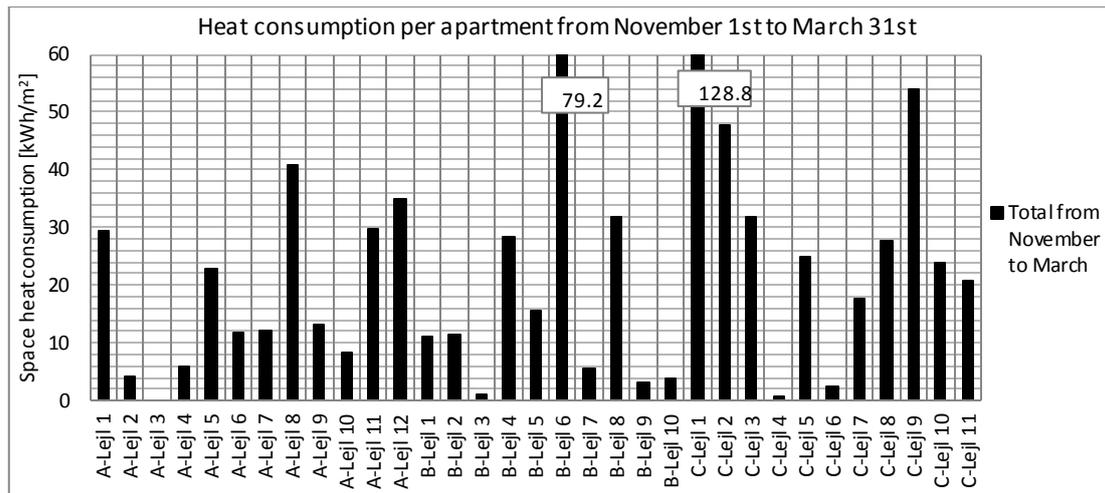
Figure 5-11: Space heating distribution across the apartments.

5.3.1.3. *Heat loss calculations of the solution with gap in the insulation*

The consequence of making a gap in the insulation above the floor construction is that the heat losses through the façade will be higher than if the entire façade was insulated. Figure 5-12 and Figure 5-13 show the temperature distribution and heat losses through the façade for four cases modelled with the floor beam (as a slab) and without the floor beam respectively. The four cases represents: one with no insulation, one with full internal insulation, one with a gap of 200mm in the internal insulation above the floor, and one with a gap of 200mm above and below the floor/ceiling. It can be seen that even with a gap of 200mm in the insulation above and below the floor/ceiling, the heat losses through the façade are still reduced by approximately 39-46% compared to the wall without any insulation. Furthermore, the temperature level in the wooden beam ends is higher than if the façade was fully insulated. One problem that might arise when leaving a gap in the insulation is that the temperatures at the brick wall behind the gap will be lower than before the renovation and condensation could potentially occur. However, the approach was to make the construction airtight so that the critical places are not in contact with the humid room air. In the test building, the vapour barrier was placed on the room side of the insulation and down along the brick wall in the gap. A more secure solution would be to continue the vapour barrier down along the wooden panel to the floor and along the floor to the brick wall to ensure that moisture diffusion is prevented. It is seen that the simulations without the floor beam result in an increased heat flow through the assembly compared to the model where the floor beam is modelled. However the increased heat flow is limited. Detailed hygrothermal calculations were carried out and the results are described in section 5.3.2. The effect on the total building heat consumption of leaving out 200mm insulation above the floor construction was calculated with the model created in IDA ICE, and a difference of approximately 3 kWh/m²/yr compared to a fully insulated wall was found.
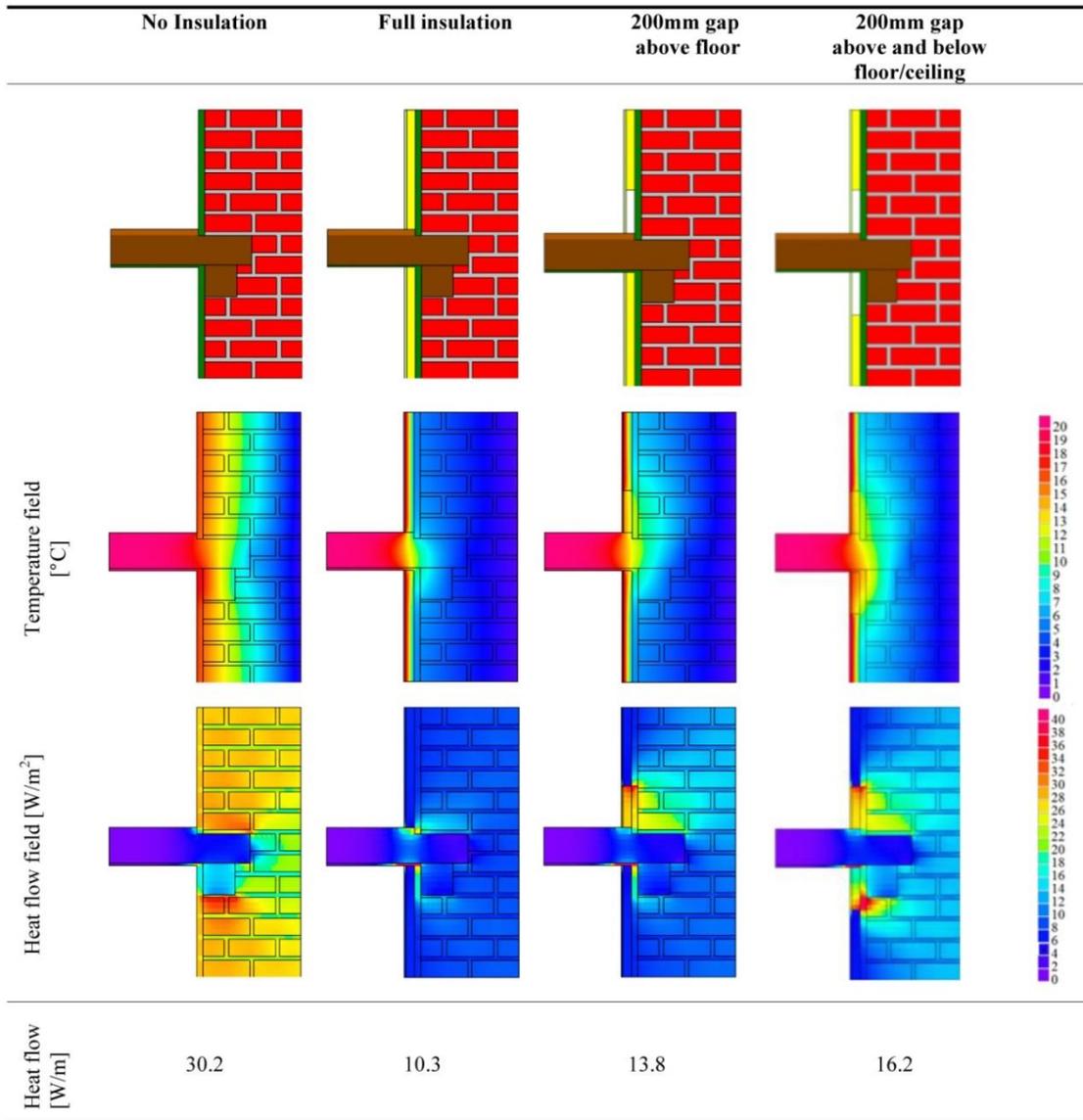
Figure 5-12: Detail of assembly of brick wall and floor beam. Temperature field and heat flow through the façade for the four cases: a) no insulation, b) full insulation applied to the internal side of the external façade, c) internal insulation applied to the internal side of the external façade with 200mm gap over the floor, and d) internal insulation applied to the internal side of the external façade with 200mm gap above and below the floor/ceiling. Under the floor beam end, there is a consistent beam that helps support the floor beams. Section at the floor beam.

	No insulation	Full insulation	200 gap above floor	200 gap above and below floor/ceiling
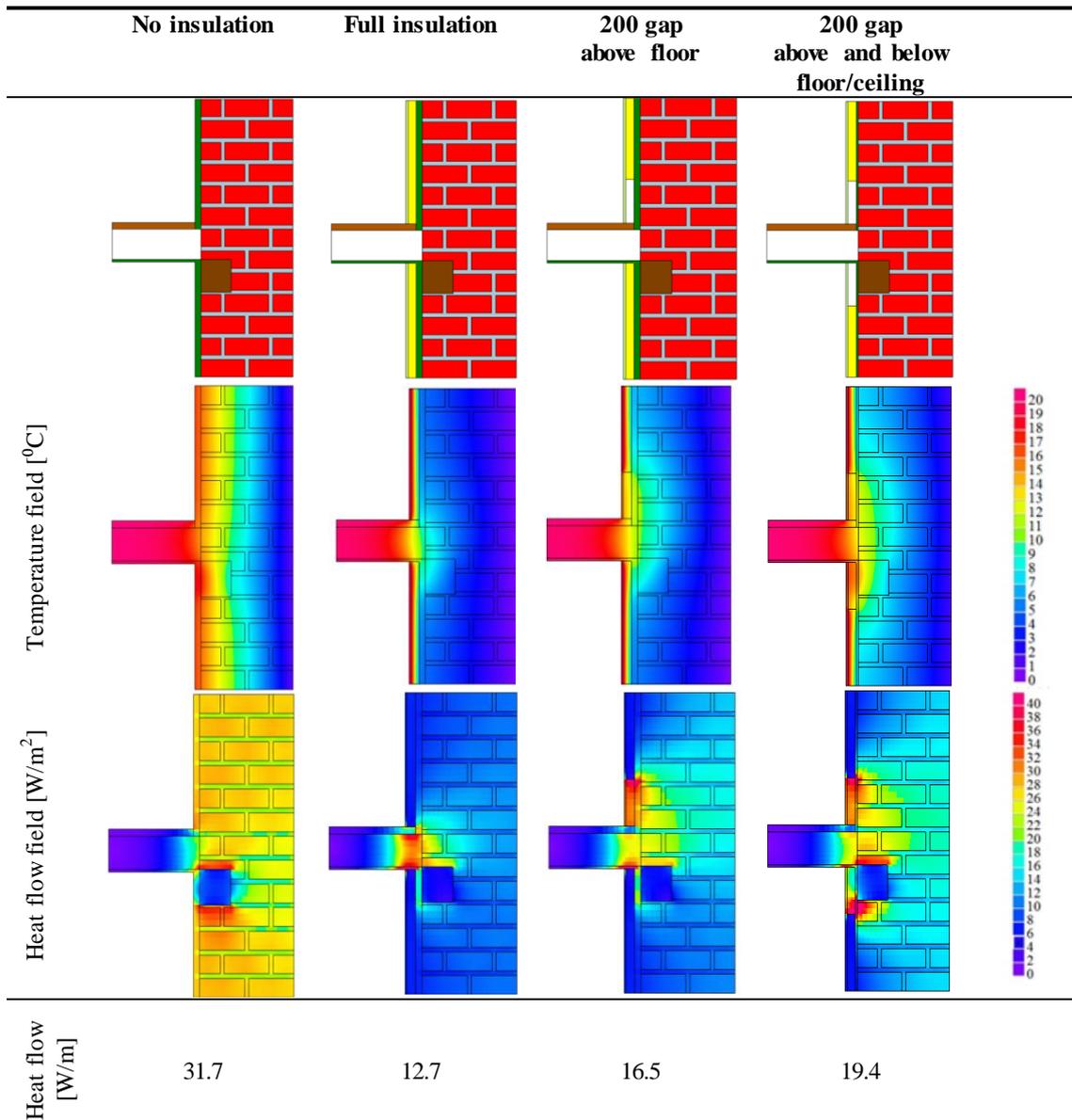
Figure 5-13: Detail of assembly of brick wall and floor beam. Temperature field and heat flow through the façade for the four cases: a) no insulation, b) full insulation applied to the internal side of the external façade, c) internal insulation applied to the internal side of the external façade with 200mm gap over the floor, and d) internal insulation applied to the internal side of the external façade with 200mm gap above and below the floor/ceiling. Under the floor beam end, there is a consistent beam that helps support the floor beams. Section between the floor beams.

5.3.2. Hygrothermal investigation for applying internal insulation

5.3.2.1. Measurements in the wooden beam ends

Figure 5-14 shows the daily average temperature and relative humidity measured in the beam ends on the 4th and 5th floor (with façade thicknesses of 2 and 1.5 bricks respectively). According to Viitanen et al. (2008), there is no risk of mould growth on a wooden surface that can create smell or health problems when the relative humidity is less than 75%. This is in agreement with a guideline for avoiding mould growth on

wooden surfaces in buildings developed by the Danish Building Research Institute (Valbjørn, 2003). They state that there is a risk of mould growth when RH>75%. Another guideline (Brandt, 2005) directed at the Danish building industry states that mould growth can take place if the relative humidity is above approximately 70%. This is in agreement with a study (Sedlbauer, 2001) that states that the lowest relative humidity where mould growth can happen is 70%. However, this is only at a temperature of 30°C. Other relevant literature (Johanson et al, 2012; Nielsen et al., 2004; Grant et al., 1989; Johanson et al, 2013) states that there is no risk of mould growth on building materials at room temperature when the RH<75-80%. Viitanen (1997) states that if the RH>80% for several weeks/months, there is a risk of mould growth in pine and sapwood when the temperature is between 5-50°C. Between 0-5°C, the mould growth is slow and only expected when RH>90%. Since the aim is to avoid mould growth the risk of wood decay is not present. Wood degradation can happen at relative humidity higher than 95% or a moisture content of 25% (Viitanen et al., 2008; Viitanen, 1997; Viitanen et al., 2010).

As shown in Figure 5-14, the relative humidity is less than 70% at all times (for both the 4th and the 5th floor) except for point 3 on the 5th floor, which has RH>70% during the first months and from November to the end of March, probably due to built-in moisture. Point 3 on the 5th floor has generally higher relative humidity and a lower temperature than the other points, since the façade is facing directly west and exposed to less sun. However, the temperature level reaches a maximum of 15°C during winter, which requires the relative humidity to be a minimum of 78% for 64 days before there is a risk of mould growth (Sedlbauer, 2001). This indicates that the proposed solution could be resistant to moisture problems.
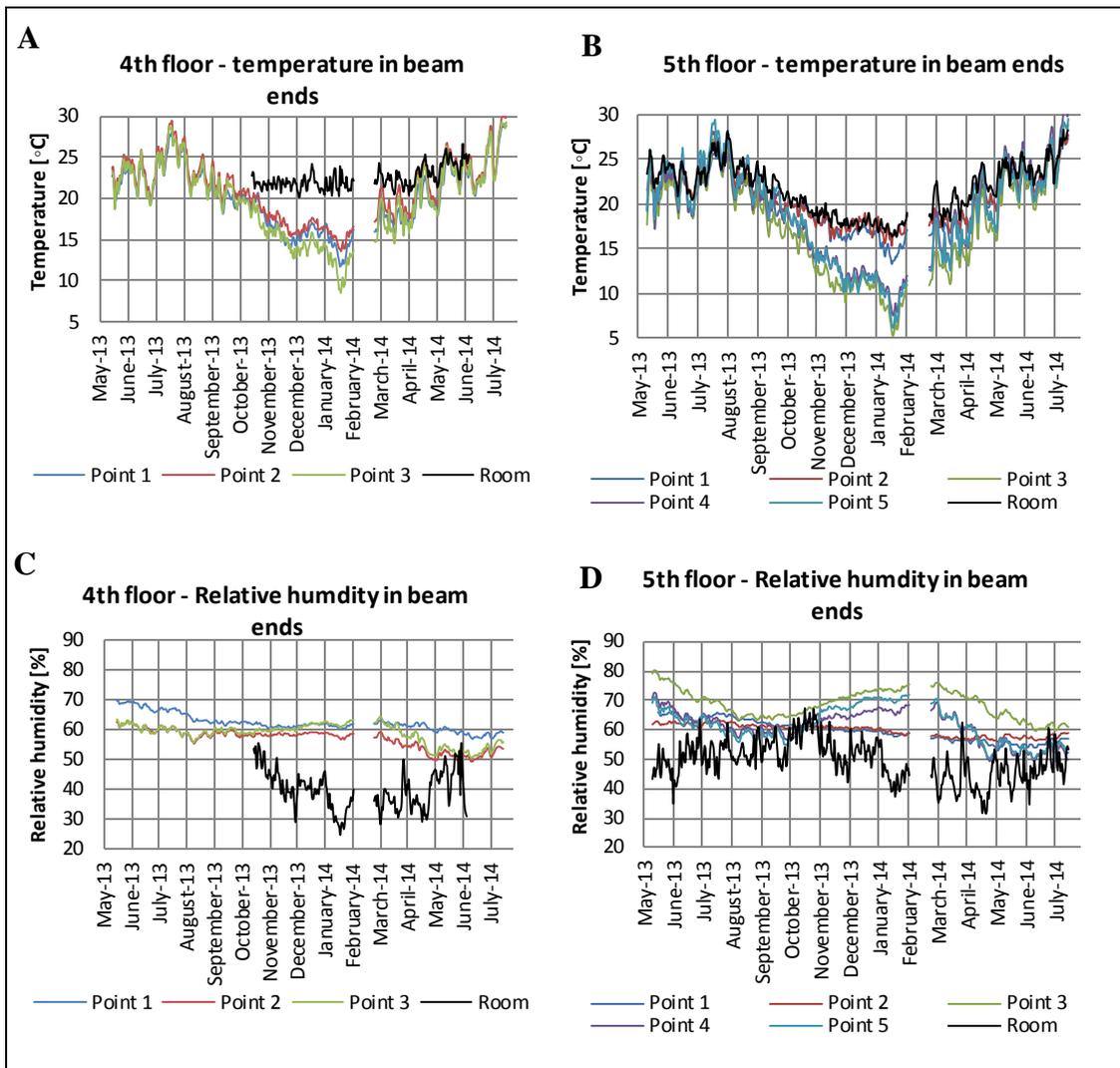
Figure 5-14: Daily average temperature and relative humidity measurements in the beam ends and room on the 4th and 5th floors.

5.3.2.2. *Validation of the simulation model of the wooden beam construction.*

Figure 5-15 shows the results from the Delphin simulation model with rain exposure coefficients (catch ratio) of CR=0.1, 0.3 and 0.5 together with the measured indoor temperatures and relative humidity in the respective rooms on the 4th and 5th floors (2 and 1.5 bricks respectively). The insulation thickness applied is 40mm corresponding to what was applied in the test-apartment. As can be seen, the room measurements for the 4th floor (2 bricks) are missing for large periods. To provide input data to the simulation model from the measured indoor conditions, the temperature and relative humidity were assumed to be an average value of the two measured points before and after the lack of data. The results from the simulation model are therefore incorrect during these periods, which also explains the rather large deviation in the temperatures in Figure 5-15(a). However, the deviation is only 1-2°C for the remaining period, when the actual measured data was used. Moreover, the effect of the thinner wall (1.5 bricks compared to 2 bricks) is expressed by the lower temperature levels during wintertime and there is a good agreement between the measurements and the calculations. Greater deviations can be seen between the measured and the calculated relative humidity. The variability is greater in the measurements than in the simulation results. This can be explained by the

mathematical model used in Delphin. Delphin only has a temperature-dependent sorption-isotherm for air, whereas for other materials it calculates the relative humidity based on the moisture content. The moisture content only changes based on moisture transport, which can be rather slow. Even though we have created a small air-space inside the wooden beam, it is still affected by the conditions in the wood, which might change slower than reality. However, the calculated relative humidity has the same levels as the measured, varying only by a few percentages. Another effect seen in Figures 5-15(c) and 5-15(d) is that the thinner the brick wall is, the more variation occurs in relative humidity, which results in greater deviation between the measured and the calculated results.

The simulation models were calculated with various rain exposure coefficients. As seen from Figure 5-15, the changes in the rain exposure coefficient has no effect on the calculated temperatures and very limited effect on the calculated relative humidity. The main reason for this is that an air space is modelled between the brick wall and the wooden beam heads, resulting in a limited moisture transport from the exterior to the measuring point. This confirms that it is not possible to validate the part of the model that includes the brick wall because the measurements are mostly affected by the indoor environment and the outdoor temperature and less by the outdoor wind-driven rain.

Based on comparison between the measurements and calculations in the wooden beam ends, the model seems to provide good results in the periods when the indoor temperature and relative humidity measurements were available.
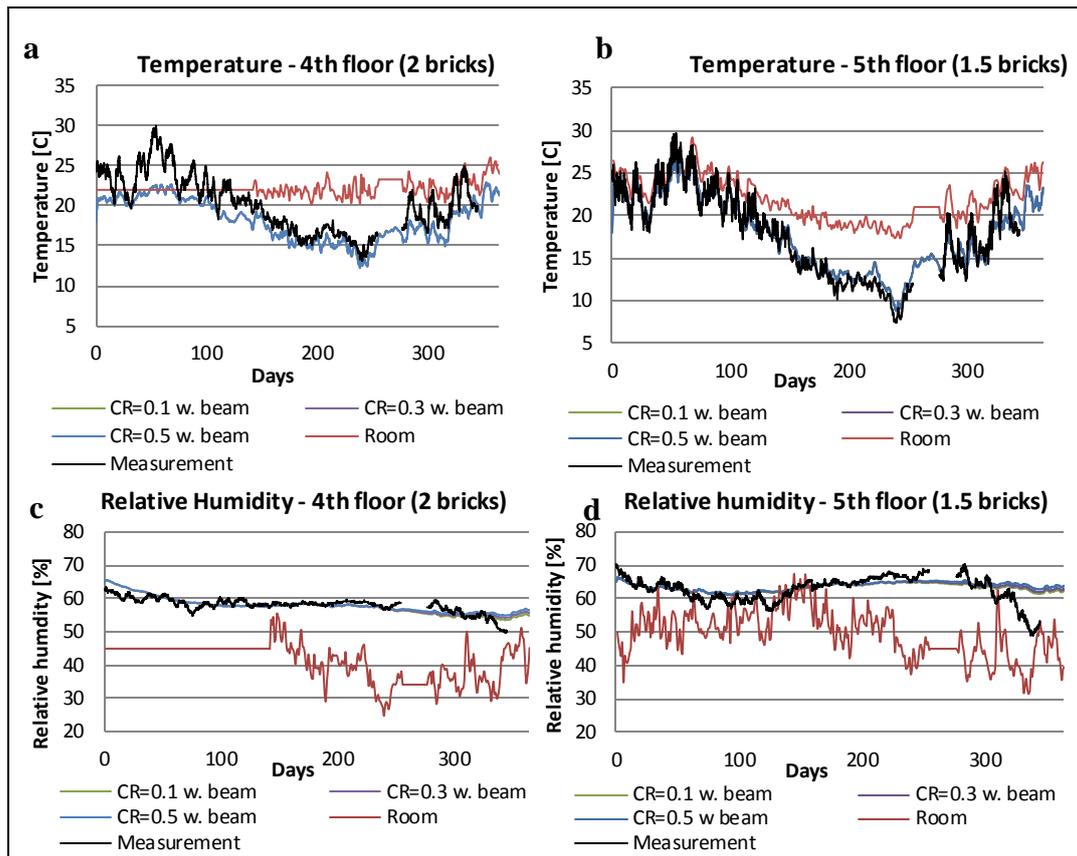
Figure 5-15: Temperatures and relative humidity in the wooden beam ends from measurements and simulations. The measured room temperature and relative humidity were used as input to the simulation model. Day 0 = June 1ˢᵗ.

5.3.2.3.   *Worst-case simulation with Delphin*

5.3.2.3.1.   **Wooden beams**

The models were simulated with a wall thickness of 2 bricks and for an orientation towards west and north for a period of 4 years. Figure 5-16(a) shows the mould growth index for a west-orientated façade and Figure 5-16(b) for a north-orientated façade in the wooden beam end (position 1). The simulations were carried out for rain exposure coefficients of CR=0.1, CR=0.3 and CR=0.5 (CR=0.5 only for the west-orientated wall) and for (i) no insulation (blue scale), (ii) 40mm insulation applied to the entire wall (red scale), (iii) 40mm insulation applied with a gap of 200mm above the floor (grey scale), and (iv) 40mm insulation applied with a gap of 200mm above and below the floor/ceiling (green scale). It is clear from Figure 5-16 that the north-orientated façade results in higher mould indexes than the west-orientated façade for low rain exposure coefficients. Most of the scenarios show an increasing trend, implying that there will be an accumulation of mould over the years even if the growth stops or decreases during summertime. All rain exposure coefficients greater than CR=0.1 result in a high mould index (between M=4 and M=6) indicating visual mould covering between 30-100% of the surface. Only the north-orientated façade without insulation and a rain exposure coefficient of CR=0.1 results in a mould index lower than 1. For the west-orientated wall, the mould index is kept below M=1 when a gap of 200mm is applied in the insulation above the floor and when it is applied both above and below the floor/ceiling. The last case results in more secure

conditions, since the mould index decreases to M=0 each year, whereas if a gap in the insulation is only applied above the floor, a small increasing trend is observed. However, it should be kept in mind that the floor beam is modelled as a slab, whereas in reality there is a beam only approximately every 1 metre. The results are therefore on the conservative side, since there will be a drying potential to each side of the beam in reality. Figure 5-16 shows that the gap in the insulation has a positive effect on the moisture conditions in the beam end and reduces the mould index in all cases. However, there is still a large risk of mould growth in the beam end.
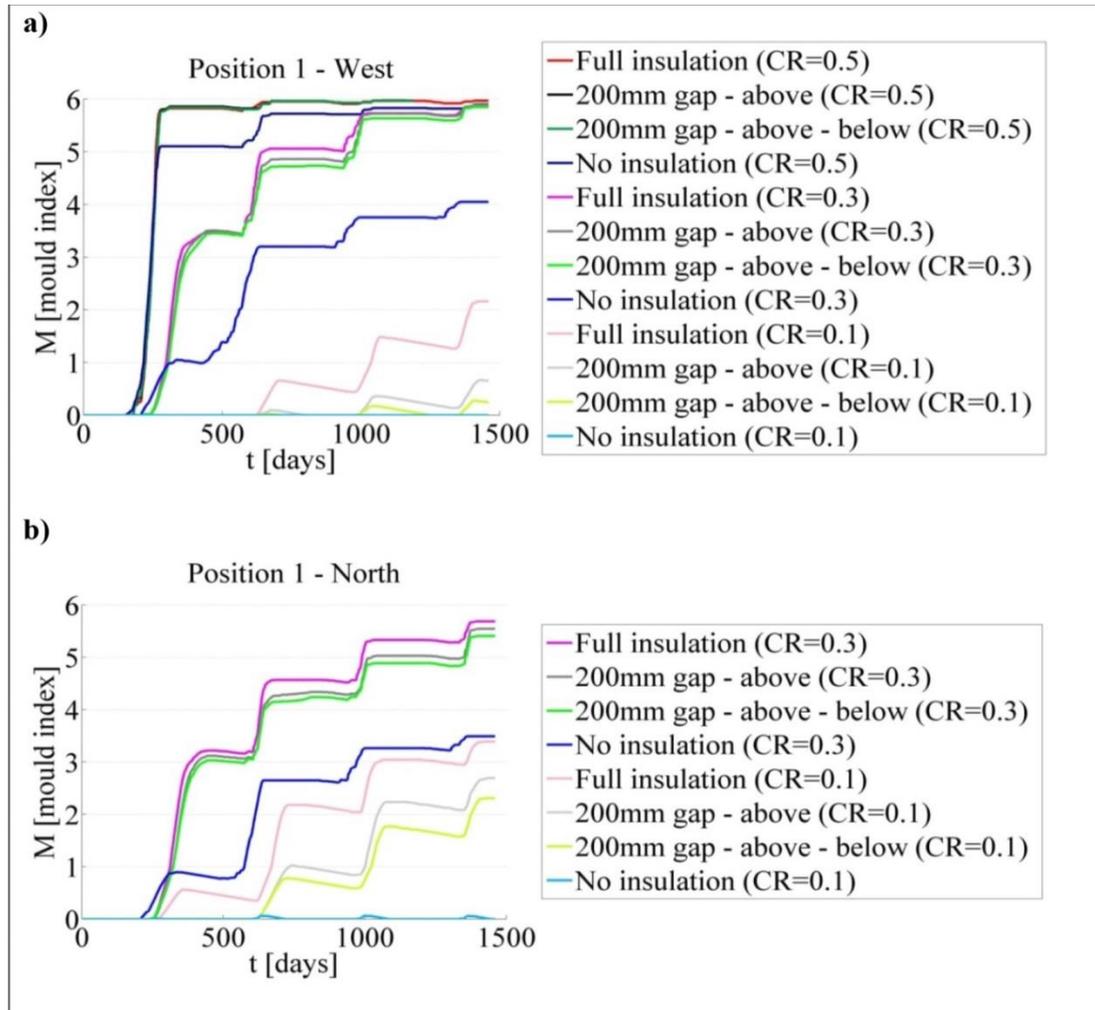
Figure 5-16: Mould index in position 1 for a) west- and b) north-orientated façades - 2 bricks thick, 40mm insulation. CR=0.1, 0.3, 0.5. No insulation; with internal insulation on the entire wall; with a gap of 200mm in the insulation above the floor; and with a gap of 200mm in the insulation above and below the floor/ceiling.

Figure 5-17 shows the mould index in position 2 for a west-orientated façade with 40mm insulation applied. The figure shows the sections at the beam end and between the beams referred to as (a) *with beam* and (b) *without beam* respectively. . The simulations without the floor beams result in lower mould indexes, due to a better drying possibility. As mentioned above, the simulations with the floor beams do not represent reality completely since they are modelled as a continuous beam due to the 2D model. Therefore the real results will be somewhere between the results from Figure 5-17(a) and (b). The results are similar in position 2 as in position 1 for the

west-orientated façade. When the rain exposure coefficient is CR=0.1, the mould index is below M=1 for the two insulation solutions with a 200mm gap applied. However, when the gap is only applied above the floor, an increasing trend is observed, which is not the case when the gap is applied both above and below the floor/ceiling. Figure 5-17(b) (without the beam) shows that there is no risk of mould growth for any case when the rain exposure coefficient is CR=0.1. The effect of the gap in the insulation is clear and gives lower mould indexes than a fully insulated wall. The figure 5-17 shows that when the rain exposure coefficient is CR=0.5 there is even a heavy mould growth for an uninsulated wall. It is known that many buildings have or have had mould problems even without internal insulation, and higher rain exposure coefficients may therefore be realistic in some cases. However, when the rain exposure coefficient is CR=0.5, the results show that the wooden surface should be completely covered with mould even without insulation, which is not the case. It is therefore believed that the rain exposure coefficient is less than CR=0.5.
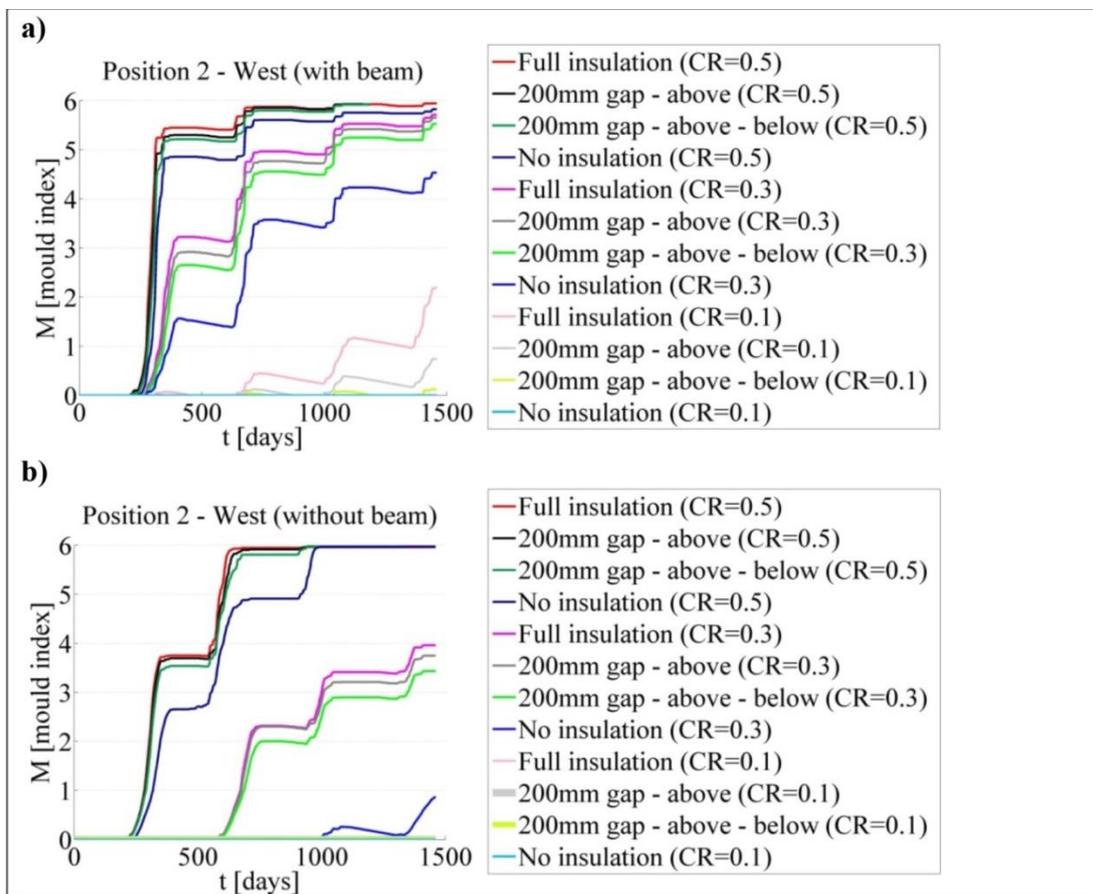

Figure 5-17: Mould index in position 2 for a west-orientated façade – 2 bricks thick, 40mm insulation a) with and b) without the floor beam for CR=0.1, 0.3, 0.5 and for no insulation; with internal insulation on the entire wall; with a gap of 200mm in the insulation above the floor; and with a gap of 200mm in the insulation above and below the floor/ceiling.

Figure 5-18 shows the mould index in position 2 for a north-orientated wall, 2 bricks thick and 40mm insulation applied (a) with and (b) without the floor beam. In general, the north-orientated façade has higher mould indexes than the west-orientated façade for low rain exposure coefficients and for the case where the beam is modelled. The

reason can be that the drying potential is significantly reduced. Figure 5-18(a) (with the floor beam) shows higher mould indexes than Figure 5-18(b) (without the floor beam) since the drying potential is reduced when the floor beam is modelled. As seen from Figure 5-18(a), none of the solutions seems to be safe. Even at low rain exposure coefficients and with a gap in the insulation both above and below the floor/ceiling, an increasing mould index reaches M=2 after 4 years. A mould index of 2 still represents a very limited mould growth at a microscopic level. However, the trend is strongly increasing and if the simulations were to be carried out for more years, they would probably result in much higher levels. In contrast, Figure 5-18(b) shows that there is no risk of mould growth for any case with a rain exposure coefficient of CR=0.1, even when the wall is fully insulated. For rain exposures of CR=0.3, the mould index reaches M=2.5-3 when there is a gap applied in the insulation, but a small increasing trend is observed. The mould indexes from Figure 5-18(a) will be lower in reality than the results shown here, since they will have the possibility to dry out between the floor beams. The case where a 200mm gap is applied in the insulation above and below the ceiling may therefore be a safe solution if there is enough drying potential to the sides of the beam.
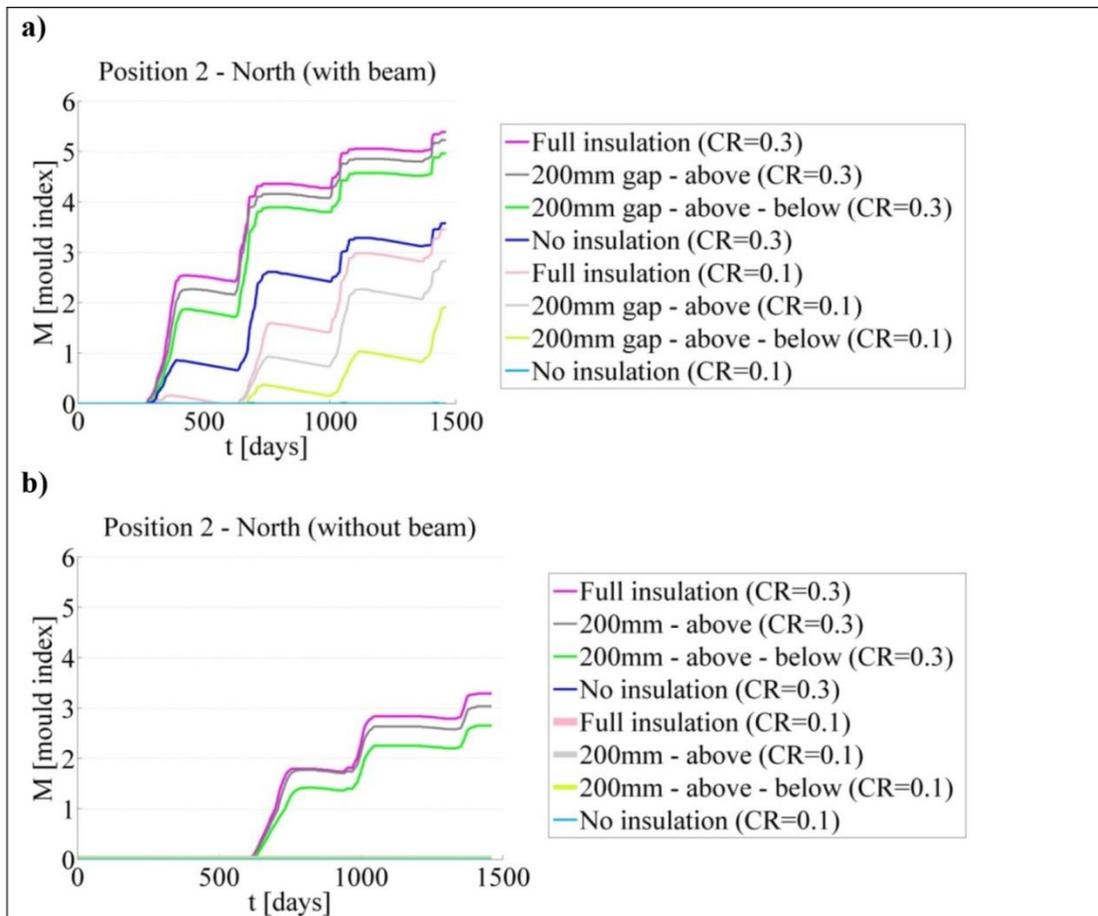
Figure 5-18: Mould index in position 2 for a north-orientated façade – 2 bricks thick, 40mm insulation a) with and b) without floor beam for CR=0.1, 0.3, 0.5 and for no insulation; with internal insulation on the entire wall; with a gap of 200mm in the insulation above the floor; and with a gap of 200mm in the insulation above and below the floor/ceiling.

Figure 5-19 shows the temperature and relative humidity fields for the construction with the different insulation solutions (40mm) and for an uninsulated wall. The figure shows the sections at the beam end and between the beams referred to as *with beam* and *without beam* respectively. The figure shows that higher temperatures around the wooden beams are seen as a result of the 200mm gap in the insulation, with the greatest effect when the gap in the insulation is both above and below the floor/ceiling. The higher temperatures result in lower relative humidity and therefore a decreased risk of mould growth. Temperatures are higher in the section plane between the beams than at the beam, resulting in lower relative humidity. The drying potential between the beams is therefore higher, which is in good agreement with the results from the mould risk analyses. The figure shows that when the internal wall is fully insulated the wooden construction has a relative humidity above 80-90% for at the outer part of the floor beam and at the load-bearing beam, whereas the relative humidity drops to below 80% for most of the wooden construction when there is a gap in insulation both above and below the floor/ceiling. A small part reaches just above 80% relative humidity and the risk of mould growth depends then amongst other things on the time and temperature, which were analysed using the mould growth index above. When there is a gap in the insulation, one might expect a risk of mould growth and condensation on the part of the wall that is uninsulated behind the panel. However, a vapour barrier was applied in accordance with Figure 4-6 which prevented the moist room air reaching the wall surface and condensing if the temperature is low enough. However, even though a vapour barrier is installed it is almost impossible to make it completely vapour tight at the assemblies due to the complex 3D construction in reality and there will be a risk of moisture traveling to the brick wall. The temperature on the uninsulated wall behind the panel is around 9-10°C for the section plane with the floor beam, and around 12-15°C for the section plane between the beams. For a room temperature of 20°C and a room relative humidity of 50%, the dew-point is 9°C and there will be a risk of condensation if the construction is not vapour tight. Therefore it is crucial that the vapour barrier is applied correctly. However, Figure 5-19 shows no risk of mould growth or condensation. Another issue that could arise when there are gaps in the insulation at some parts of the wall is the phenomenon of *ghosting marks*, which are dust particles trapped on the cold part of a surface. According to Christensen and Koch (2012), this can happen when the temperature difference on a surface is greater than 2-3°C. Figure 5-19 shows that the temperature difference between the panel and the insulated wall is around 3°C for the section plane with the beam and around 1-2°C for the section plane between the beams. A risk of *ghosting marks* is therefore present at the panel over the floor beams. However, again it should be kept in mind that the simulation model is a 2D model and the temperature difference is on the conservative side.
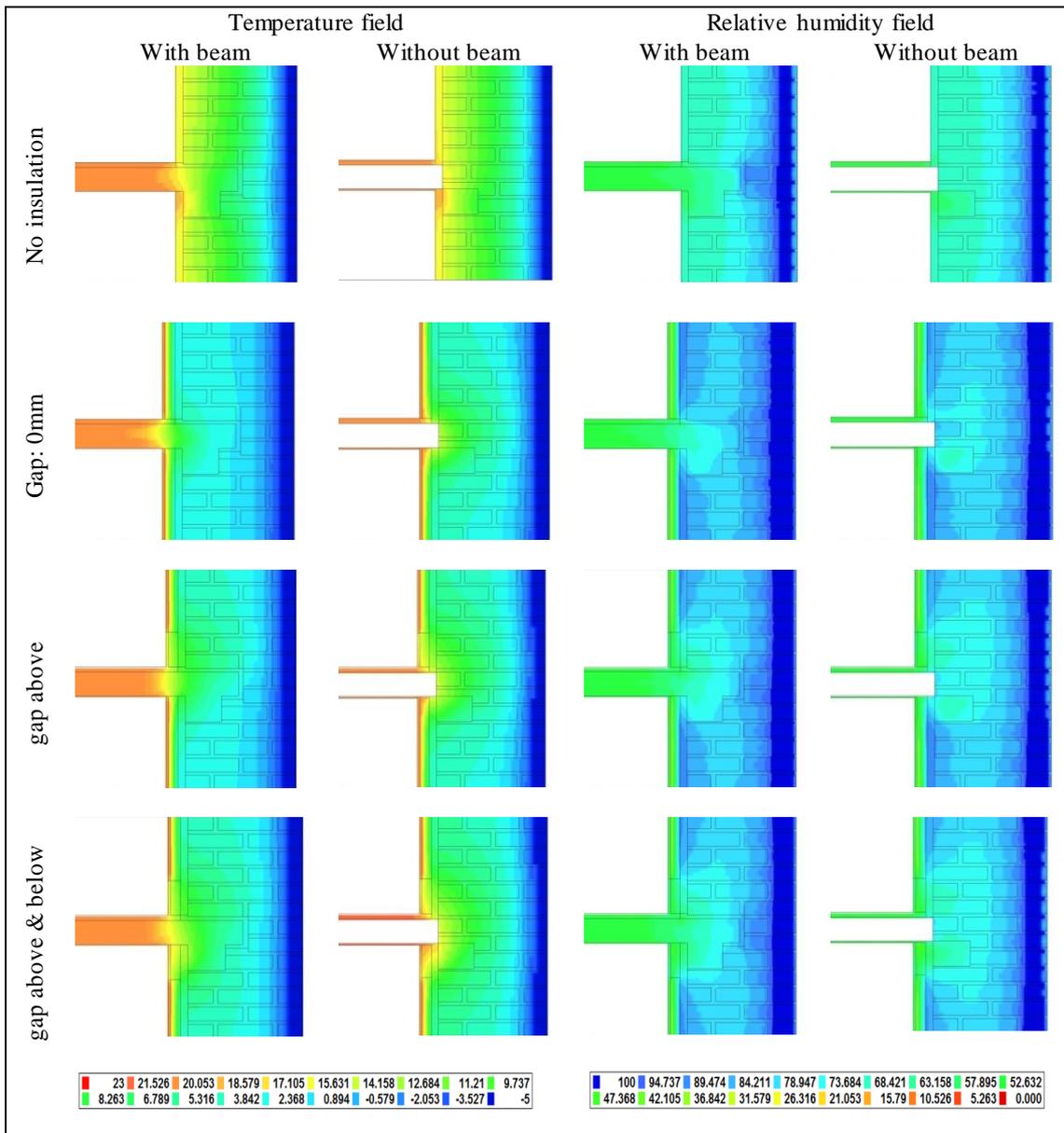
Figure 5-19: Temperature and relative humidity field for the models with and without the wooden floor beam and for the four cases with no insulation, 40mm insulation on the entire wall, 40mm insulation applied with a 200mm gap over the floor, and 40mm insulation applied with a gap of 200mm above and below the floor/ceiling.

Figure 5-20 shows the comparison in mould index between 40mm and 80mm of insulation applied, for the solution with a gap of 200mm above and below the floor/ceiling. The 40mm and 80mm insulation thicknesses applied on a wall with 2 bricks correspond to a thermal transmittance for the wall of 0.4 W/m^2K and 0.2 W/m^2K , respectively. As shown in Figure 5-20, the increased insulation thickness increases the mould growth index slightly. The effect of the extra insulation is not that significant since there is a gap in the insulation above and below the floor/ceiling and the beam construction is therefore less affected. However, the mould indexes are increased compared to 40mm insulation. Therefore, since even using 40mm insulation already shows debatable results, it cannot be recommended to apply more insulation on the wall.
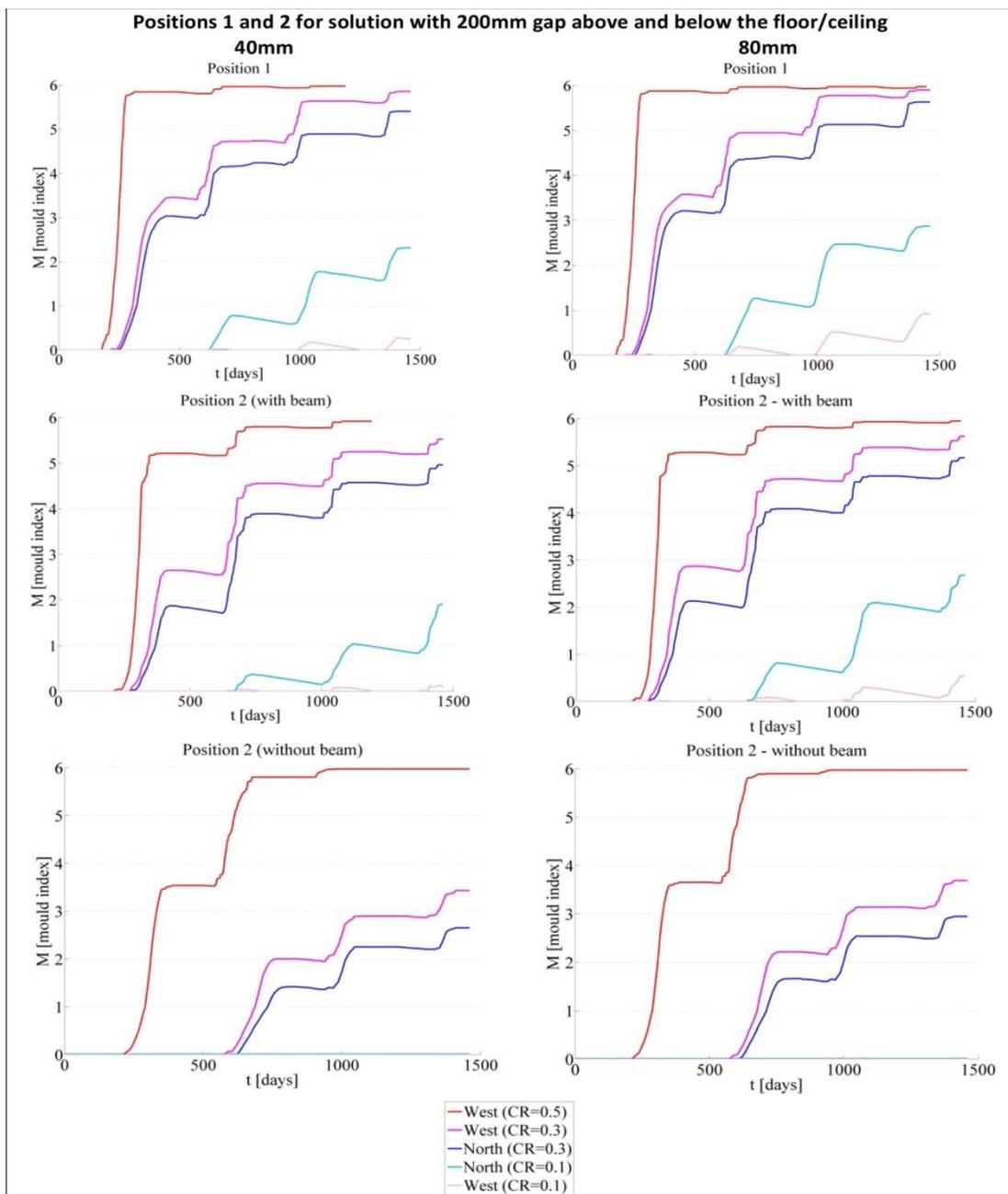
Figure 5-20: 40 mm and 80 mm insulation applied on the wall. Mould index in position 1 and 2 for the solution with a gap of 200mm above and below the floor/ceiling.

Figure 5-21 shows the comparison in mould index between a south and a west orientated façade for the insulation strategy with 200mm gap in the insulation above and below the floor/ceiling. The results are shown for position 1 and 2 (see Figure 4-4). As is seen from the calculations the south orientated wall results in lower mould indexes compared to the west orientated wall, indicating that the west orientating wall is more critical. It is seen that for the south orientated wall the mould index is below M=1 for rain exposure coefficients on CR=0.1 and CR=0.3, but reached too critical mould indexes for rain exposure coefficients of CR=0.5.

Position1 and 2 for solution with 200mm gap above and below the floor/ceiling
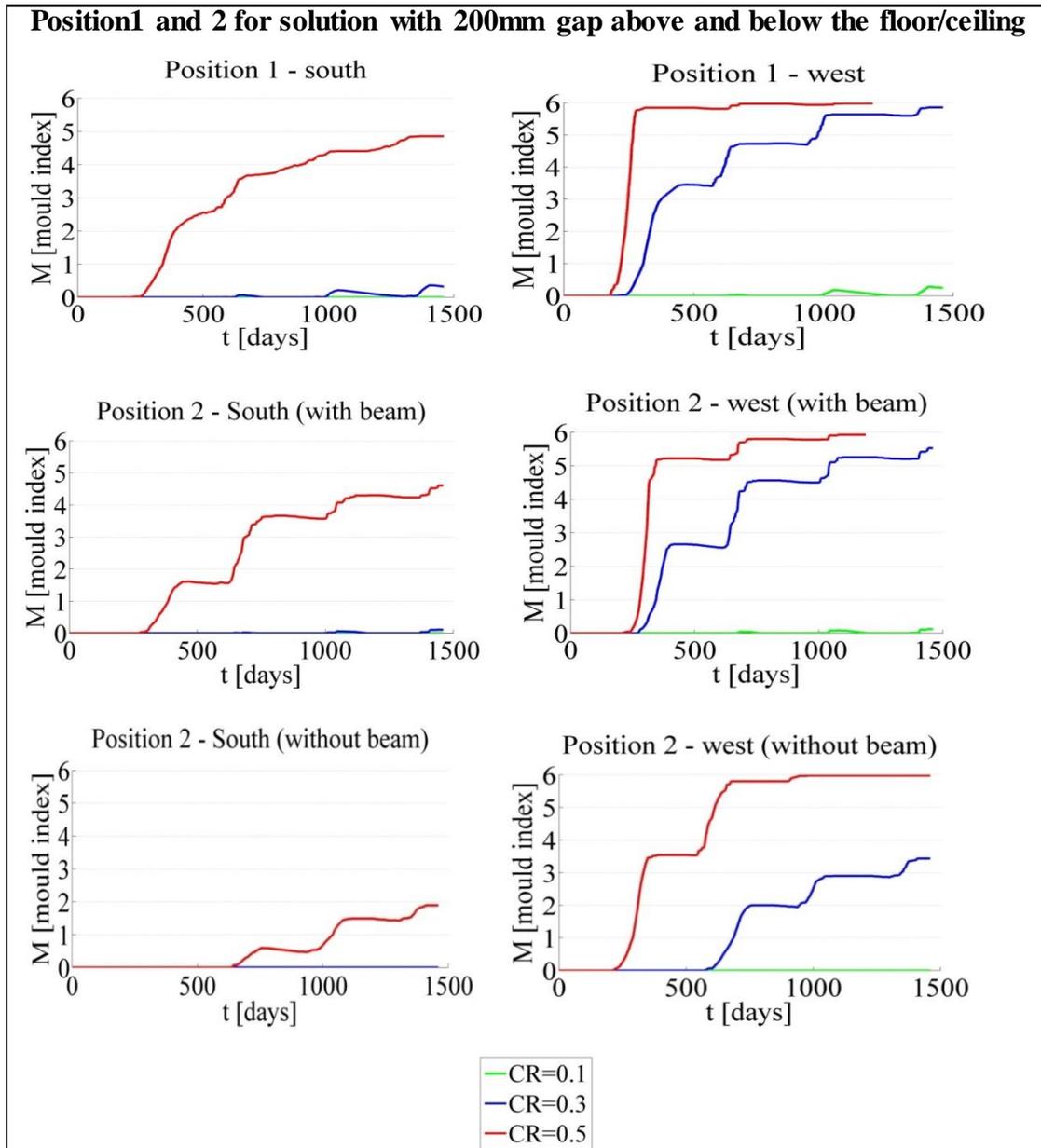
Figure 5-21: Mould index for position 1 and position 2 for a south and west orientated wall with a gap in the insulation 200mm above and below the floor/ceiling.

5.3.2.3.2.　　Interface between the insulation and the brick wall

Figure 5-22 shows the mould index in the interface between the insulation and the brick wall (position 3 – Figure 4-4) for 40mm and 80mm insulation applied. Simulations were performed for 10 years for fully insulated walls. The models were simulated for rain exposure coefficients of CR=0.1, CR=0.3 and CR=0.5. Simulations

were performed for four cases; west- and north-orientated walls and for thicknesses of 1.5 and 2 bricks in both cases. The maximum mould index reached in all cases was approximately 3.5, corresponding to a visual coverage of mould growth of 10-30% on the surface. It can be seen that for a north-orientated wall the mould index increases faster and for lower rain exposure coefficients the mould index reaches higher levels, due to the lack of sun on the façade and the drying process being reduced and slowed. Even for a rain exposure coefficient of CR=0.1, the mould index reaches approximately M=2.5, which is just below the visual mould growth state. Figure 5-22 also shows that a thinner wall has a slightly higher risk of mould growth since it is more affected by driven rain. When 80mm insulation is applied, corresponding to a thermal transmittance coefficient for the wall of 0.2 W/m^2K (corresponding to the requirements in the Danish Building Regulations 2010), it can be seen that even with low rain exposures (CR=0.1) there is a risk of mould growth (2<M<3). For walls insulated with 40mm insulation and with a low rain exposure coefficient (CR≤0.1), the west-orientated wall has no risk of mould growth, whereas the north-orientated wall has a significant risk of mould growth even at low rain exposure coefficients. Internal insulation might therefore be durable only with 40mm insulation applied for west-orientated walls. Extra caution needs to be taken if the wall is orientated towards the north and it is not recommended to apply more than 40mm insulation.
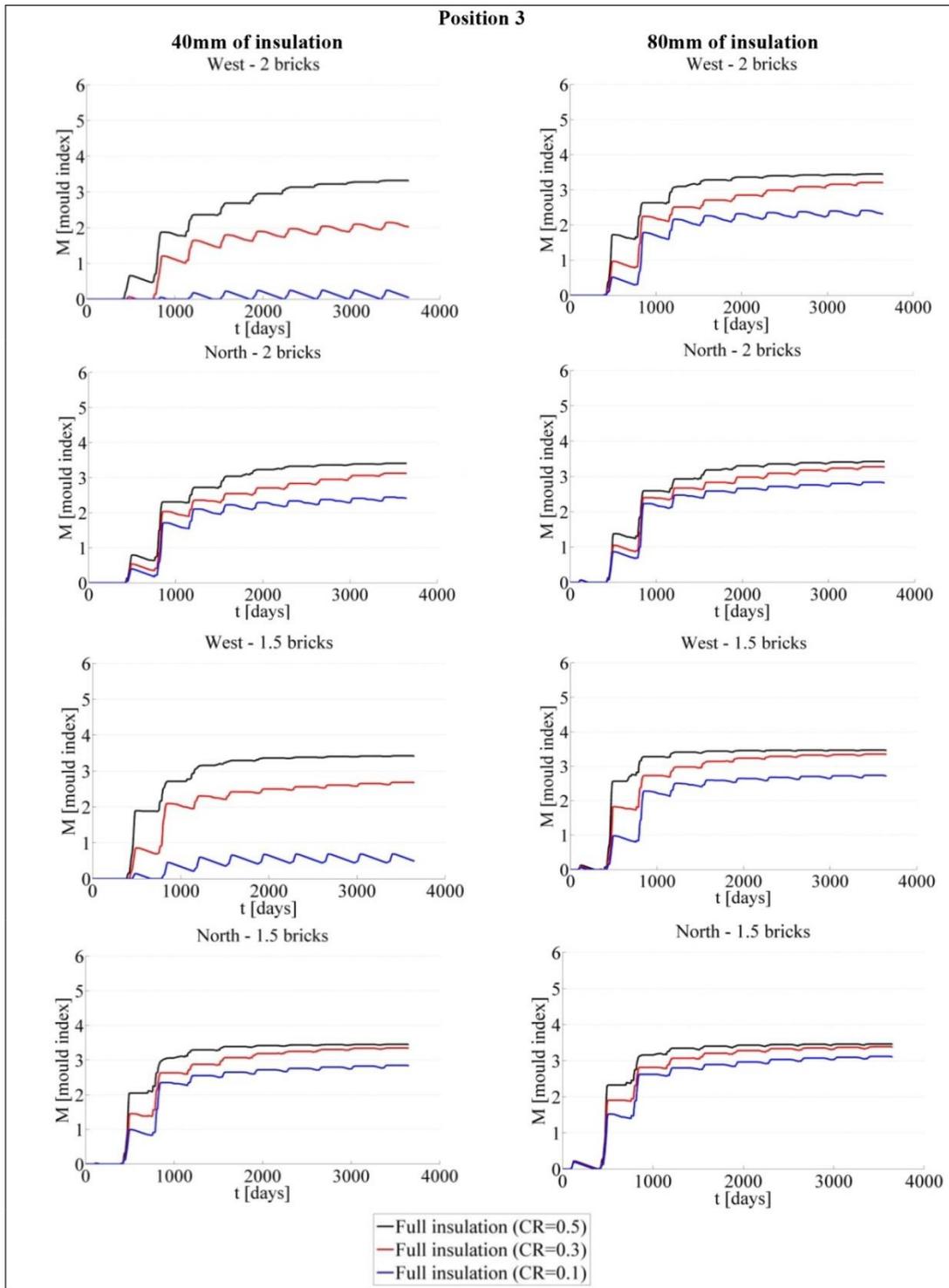
Figure 5-22: Mould index in position 3 for a west- and a north-orientated wall with a thickness of 1.5 and 2 bricks, with 40mm and 80mm insulation applied. RH_{crit}=85%.

Figure 5-23 shows a comparison between a south and a west orientated façade with 2 bricks thickness and 40mm insulation applied for position 3 (full insulated wall). As is seen from the figure the south orientated façade have lower mould indexes compared to the west orientated façade. However, only for low rain exposure coefficients of

CR=0.1 the mould index is below M=1 for the south orientated wall and the risk of mould growth is generally high.
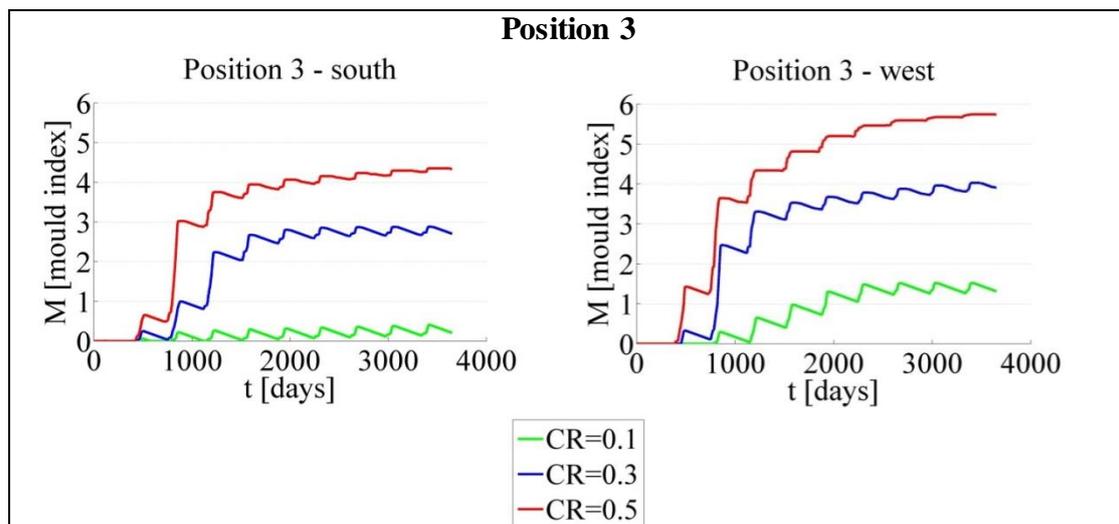
Figure 5-23: Mould index in position 3 for a south and west orientated façade with a thickness of 2 bricks with 40mm insulation applied. RH_{crit}=85%.

5.3.3. Standardization of the energy renovation solutions

To achieve lower energy consumption levels in old existing building stock, solutions and methods need to be found and developed, because there is a great energy-saving potential. Such energy-saving measures include the replacement of old leaky windows with new energy-efficient windows, the installation of mechanical ventilation with heat recovery, and insulation of the façades, roofs, and floor constructions. However, problems can arise during the process of a technical, economic or aesthetic character. The architectural expression of the façade of heritage buildings cannot be changed, which means that internal insulation is the only façade insulation that can be used. However, the use of internal insulation is still in a grey zone when it comes to safety and durability.

Moisture problems might occur, which can damage the building or create an unhealthy environment due to mould growth. Several studies have analysed this aspect but so far no safe conclusions can be drawn that would make it possible to standardize solutions. The conditions might differ significantly from building to building with different impacts of wind-driven rain, temperatures, sun, etc. Furthermore, user behaviour might have an impact on moisture conditions due to different levels of indoor relative humidity (ventilation rates, different habits of cooking, drying clothes, showering, etc.). To create moisture-safe solutions it may be necessary to compromise on energy savings. If a gap is made in the insulation, a thermal bridge is created resulting in increased temperatures around the wooden beam ends and decreased relative humidity. The measurements showed no risk of moisture problems, but this might differ for different buildings with different conditions. The measurements were carried out over a winter that was milder than normal, which may also be a reason that no risk was identified. The insulation was stopped 200mm above the floor construction in the measured building, which could be another reason that no risk of moisture problems was found. Applying this solution will reduce the possible heat savings, but calculations show that a 39-46% reduction of heat flows though the wall can still be obtained compared to a 60-66% reduction if the entire façade is

insulated internally. The consequent difference in the total building heat consumption is $3kWh/m^2$ floor area.

The worst-case simulations investigated the same solution as was applied in the building but also a solution where the insulation was stopped both above and below the floor/ceiling. A large risk of mould growth on the wooden beam construction and behind the insulation was found when internal insulating was applied. However, the internal insulation product investigated was a mix of mineral wool and aerogel with a vapour barrier applied, but other innovative materials, such as capillary active and diffuse open material without vapour barrier should be investigated in future research. The simulation model of the beam construction was created as a 2D model, but in reality it is a 3D problem so uncertainties are involved in the results. The investigation was carried out based on two model types; with and without the beam (modelled as a slab), with the implication that the reality will be somewhere between the results from these two models. The model did not include any cracks, which could potentially lead to higher moisture content in the wall and consequently a higher risk of mould growth. That should be another topic for future research. It might be possible to decrease the amount of rain absorbed by the façade by impregnating the façade with a waterproof but diffuse open coating, so that moisture will not get trapped inside the brick wall. Another issue that needs to be addressed and investigated is to what extent we could accept mould that does not create a health risk. According to Giuseppe (2013) mould cause great impact on human health and various health issues and diseases can be the consequence of mould inside buildings. It might be acceptable to have some small amounts of mould, but this is an area that needs more research. In Denmark the requirements are stricter than in other countries since it is required from the house owners that if mould if found, action should be taken to remove the mould (Ministry of Welfare, 2008). Therefore no mould growth is accepted in Denmark and the use of internal insulation is evaluated in accordance. In other countries, for instance Germany, the requirements are less strict and the critical limits are based on wood decay, which happens at higher relative humidity and moisture content. This is the reason that the use of internal insulation is more widespread and accepted in other countries compared to Denmark. The conclusions drawn in this research are based on the view that no mould growth is acceptable, but discussions on which mould type and the amount that could be acceptable should be subject for future research. One could argue that it is not critical to have mould growth on the wooden beam construction embedded in the masonry brick wall, but most of the old heritage multi-storey buildings have leaky floors and air might be able to travel from the construction to the indoor air. This might potentially create a health risk for the occupants if mould is present on the wood surface.

While not investigated in this PhD-project, experience shows that it is crucial to clean the brick wall of all organic material before applying the internal insulation to minimise the risk of mould (Morelli, 2014). The insulation is applied on a fully glued wall and if the glue is applied correctly, it will not be possible to have mould growth since there will not be any space for the mould. However, this is not the case in the wooden beam ends. Another crucial factor when applying internal insulation is the risk of freeze-thaw damage, which will increase due to the reduced temperatures in the wall. Furthermore, internal insulation takes up living space, which could stop users of the building investing in internal insulation.

6. Conclusions

This chapter concludes firstly on each of the 5 sub-hypotheses with argumentation on why the sub-hypothesis is either true or false. Based on the conclusions of the sub-hypotheses, conclusions are drawn about the main hypothesis. The conclusions are divided into the three main areas, which have been used throughout the PhD thesis.

6.1. Energy savings versus energy supply

Sub-hypothesis 1:
The socioeconomic cost of reducing heating consumption in buildings by 30-65% is similar to the socioeconomic cost of supplying the same amount of district heating using renewable energy sources.

Sub-hypothesis 1 is true: Calculations showed that the socioeconomic cost of reducing heating consumption in buildings by 30-65% is similar to the socioeconomic cost of supplying the same amount of district heating using renewable energy sources.

For the district heating system in the Copenhagen area, socioeconomic calculations indicate that it is slightly more cost-beneficial to invest in energy renovations from 2013, so that we can reduce the heat demand, before investing in new renewable energy supply technologies. However, the results from the socioeconomic calculations are very sensitive to the discount rate assumed. It does not make a great difference which scenario is chosen from a socioeconomic point of view. The costs for supplying heat and saving heat are at comparable levels.

However, investing in comprehensive energy renovations from today will reduce the investment cost for new supply technologies by 50%, or by 16% if only investments in intermediate renovation are made: replacement of old inefficient windows and installation of mechanical ventilation with heat recovery. The Danish government has already decided to aim at a fossil-fuel-free society by 2050, by saving energy in the building stock and by converting to renewable-based supply. Strategies with regard to energy renovation of existing building stock have already been implemented in the Danish action plan towards a fossil-fuel-free society. The Danish Building Regulations include an obligation to energy-upgrade buildings when they undergo improvements. Energy savings will therefore be implemented in the building stock sooner or later, and with this in mind, it will be more beneficial to carry them out from today.

Reducing heat demand by renovation also results in smaller peak loads and a more stable supply situation over the year, which is an advantage for future energy systems based on renewable energy resources and provides increased security of supply. Energy renovation also adds value to buildings in terms of increased indoor comfort and future-proofing.

Looking at the cost per heat unit delivered to the buildings, it is clear that carrying out energy renovations from today will result in more competitive conditions for the district heating companies than if energy renovations are carried out later on. This is also reflected in the fact that, when energy renovations have been carried out, low-temperature district heating can be implemented, which reduces heat losses from the distribution pipes and results in more heat delivered to the buildings.

6.2. Low-temperature district heating for old existing buildings undergoing energy renovation

Sub-hypothesis 2:
It is possible to supply low-temperature district heating to existing buildings if they are energy-renovated to moderate levels, without replacing the existing heating system in the buildings and without replacing the existing district heating distribution net.

Sub-hypothesis 2 is true: Simulations showed that low-temperature district heating can be supplied to existing buildings most of the year if they are energy-renovated to moderate levels, without replacing the existing heating system in the buildings and without replacing the existing district heating distribution net. The supply temperature will have to be increased to 60-70°C during cold periods corresponding to approximately 5% of the year.

A method for supplying low-temperature district heating to existing multi-storey buildings was presented. It is possible to supply buildings with low-temperature district heating for most hours of the year without compromising on indoor thermal comfort. In cold periods, it might be necessary to increase the supply temperature to either 60°C or 70°C because, with low-temperature district heating, the performance of the radiators decreases by a factor of 2.5 with an unchanged flow rate. If we are to keep the existing district heating distribution net, it is crucial that the cooling of the district heating water for low-temperature district heating application corresponds to a traditional system (30 K), so the return temperature is of great importance. It is possible to supply low-temperature district heating at all times if *extensive* renovation is carried out, but in the case of *intermediate* or *minor* renovations the supply temperature needs to be increased slightly when the outdoor temperature is lower than −5°C. Based on the Danish design reference year, this is less than 5% of the year. This indicates that low-temperature district heating operation is possible most hours of the year existing buildings that undergo renovation.

6.3. Energy renovation of old multi-storey buildings – balancing energy savings and moisture safety when using internal insulation

Sub-hypothesis 3:
It is possible to carry out moisture-safe energy renovation in old existing multi-storey buildings with heritage value and still save 50% of the building's energy consumption using existing technologies.

Sub-hypothesis 3 is false: Measurements and calculations indicate that it is not possible to carry out moisture-safe energy renovation in old existing multi-storey buildings with heritage value and still save 50% of the building's energy consumption using existing technologies.

However, it depends on the specific building since many parameters influence the results. User behaviour has a great impact on energy savings, and wind-driven rain and solar radiation on the walls strongly influence the moisture conditions in the

construction. Based on the case study, it was found that it was possible to save more than 50% if the room temperature is kept at 20°C after the renovation. The moisture safety of applying internal insulation is still debatable, and it depends on the specific building and weather conditions.

Sub-hypothesis 4:
It is possible to apply internal insulation on the solid masonry brick wall in old heritage multi-storey buildings and achieve a thermal transmittance of 0.2 W/m^{2}K for the exterior wall, corresponding to the requirements for renovation in the Danish Building regulations of 2010, without creating a risk of mould growth on masonry wall.

Sub-hypothesis 4 is false: Simulations indicates that it is not possible to apply internal insulation on the solid masonry brick wall in old heritage multi-storey buildings and achieve a thermal transmittance of 0.2 W/m^{2}K for the exterior wall (80mm insulation), without creating a risk of mould growth on the masonry wall.

However, the results showed that it was possible to apply 40mm internal insulation for a west-orientated wall with low rain exposure coefficients. The conclusions are based on worst-case simulations for 1.5 and 2 brick walls orientated towards the north, west and south. South was seen to be the least critical direction compared to west and north. Applying internal insulation on thicker brick walls and/or walls orientated towards the south and east could potentially be moisture-safe, but needs further investigation. The amount of wind-driven rain and the orientation of the walls strongly influence the moisture conditions in the construction, and each building should be carefully analysed before applying internal insulation. The use of internal insulation needs further research so that moisture-safe solutions can be developed and documented.

Sub-hypothesis 5:
It is possible to apply internal insulation on the solid masonry brick wall in old heritage multi-storey buildings and achieve a thermal transmittance of 0.2 W/m^{2}K for the exterior wall, corresponding to the requirements for renovation in the Danish Building regulations of 2010, without creating risk of mould growth on the wooden beams embedded in the masonry brick wall or the risk of wood degradation.

Sub-hypothesis 5 is false: Simulations indicate that it is not possible to apply internal insulation on the solid masonry brick wall in old heritage multi-storey buildings and achieve a thermal transmittance of 0.2 W/m^{2}K for the exterior wall (80mm insulation), without creating a risk of mould growth on the wooden beams embedded in the masonry brick wall.

However, the results showed that when a gap is made in the insulation the risk of mould growth is reduced. Furthermore, it was possible to apply 40mm internal insulation for a west-orientated wall with low rain exposure coefficients. The conclusions are based on worst-case simulations for 1.5 and 2 brick walls orientated towards the north, west and south. South was seen to be the least critical direction compared to west and north. Applying internal insulation on thicker brick walls and/or walls orientated towards the south and east could potentially be moisture-safe, but needs further investigation. The criterion for applying internal insulation is that no

mould growth is present and the risk of wood decay will therefore not be present since it requires higher relative humidity and moisture content. The use of internal insulation needs further research so that moisture-safe solutions can be developed and documented.

Main hypothesis:
Given that Denmark and Europe are aiming at fossil-fuel-free societies and that the architectural values of heritage buildings have to be preserved, it is technically possible and economically feasible to improve the energy performance of the old existing buildings by carrying out energy renovations.

The main hypothesis is true: Based on the sub-hypotheses, it is concluded that the main hypothesis is true. It is technically possible and economically feasible to improve the energy performance of old existing buildings by carrying out energy renovation, given that Denmark and Europe are aiming at fossil-fuel-free societies and that the architectural values of heritage buildings have to be preserved. However, the use of internal insulation is still debatable and extra caution should be exercised when internal insulation is applied. Sometimes, a better and more durable solution might be not to apply façade insulation, but only to energy upgrade the windows, install mechanical ventilation with heat recovery, and apply roof and basement insulation.

7. Perspectives and future work

This PhD project presents research on energy renovation of heritage multi-storey buildings divided into three sub-areas: (i) Energy savings versus energy supply, (ii) Low-temperature district heating for old existing buildings undergoing energy renovation, and (iii) Energy renovation of old multi-storey buildings – balancing energy savings and moisture safety when internal insulation is applied. The research was based on case-studies, and this chapter describes how the research can be applied in a wider and broader perspective and gives an overview of future work.

7.1. Energy savings versus energy supply

A method was presented for making use of the existing district heating system by carrying out long-term planning for energy supply, based on renewable energy sources and saving energy in buildings. The method was applied to a case study in the Copenhagen district heating area, and the long-term analysis can be the foundation for political decision-making and action in this area. Similar analyses can be carried out for other areas and used as a decision-making tool.

7.2. Low-temperature district heating for old existing buildings undergoing energy renovation

A method of supplying low-temperature district heating to old existing buildings was presented by suggesting various renovation strategies. The method was applied to two case-studies: a multi-storey building in Aarhus and a multi-storey building in Copenhagen. The conclusions drawn in this PhD study are based only on these two case-studies and cannot be generalised, but similar analyses can be conducted to evaluate how to supply low-temperature district heating to other buildings by using the suggested method.

Further work is needed since this research only was based on calculations. Tests and measurements are needed in real buildings to support the results from this PhD study. New research activities have already been established.

7.3. Energy renovation of old multi-storey buildings – balancing energy savings and moisture safety when internal insulation is applied

A method of energy-renovation was applied to an old multi-storey building with heritage value. Focus was on the application of internal insulation and moisture safety. A hygrothermal simulation model was validated using measurements and various scenarios were analysed. More research is needed to make generalized guidelines for how to apply internal insulation in old brick buildings with wooden beam construction, since the moisture and temperature conditions in a specific building are affected by many different parameters. However, similar analyses can be carried out for any other building where the application of internal insulation is planned.

New research activities have already been established in this field, and the use of internal insulation is the subject for future research work. A controlled ventilated air gap behind the insulation is being investigated as a new moisture-safe solution.

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Papers

Paper 1 – Appendix 1

M. Harrestrup, S. Svendsen, (2014).

Heat planning for fossil-fuel-free district heating areas with extensive end-use heat savings: A case study of the Copenhagen district heating area in Denmark.

Heat planning for fossil-fuel-free district heating areas with extensive end-use heat savings: A case study of the Copenhagen district heating area in Denmark

CrossMark

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H I G H L I G H T S

- We investigate how much heating consumption needs to be reduced in a district heating area.
- We examine fossil-fuel-free supply vs. energy conservations in the building stock.
- It is slightly cost-beneficial to invest in energy renovation from today for a societal point of view.
- It is economically beneficial for district heating companies to invest in energy renovations from today.
- The cost per delivered heat unit is lower when energy renovations are carried out from today.

A R T I C L E   I N F O

A B S T R A C T

The Danish government plans to make the Danish energy system to be completely free of fossil fuels by 2050 and that by 2035 the energy supply for buildings and electricity should be entirely based on renewable energy sources. To become independent from fossil fuels, it is necessary to reduce the energy consumption of the existing building stock, increase energy efficiency, and convert the present heat supply from fossil fuels to renewable energy sources. District heating is a sustainable way of providing space heating and domestic hot water to buildings in densely populated areas. This paper is a theoretical investigation of the district heating system in the Copenhagen area, in which heat conservation is related to the heat supply in buildings from an economic perspective. Supplying the existing building stock from low-temperature energy resources, e.g. geothermal heat, might lead to oversized heating plants that are too expensive to build in comparison with the potential energy savings in buildings. Long-term strategies for the existing building stock must ensure that costs are minimized and that investments in energy savings and new heating capacity are optimized and carried out at the right time.

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1. Introduction

1.1. Meeting future long-term objectives

The Danish government has a long-term goal of having no need to use fossil fuels by 2050. By 2035, the goal is that the energy supply mix for buildings (electricity and heating) should be based on Renewable Energy (RE) sources (Danish Ministry of Climate, Energy and Buildings, 2011; Danish Energy Agency, 2010a). The European building stock accounts for about 40% of all energy use (Lechtenböhmer and Schüring, 2011). To meet the future energy goal, the energy consumption of the existing building stock will have to be reduced by increasing energy efficiency and converting the present heat supply from fossil fuels to renewable energy sources.

Investigations have shown that the energy consumption of existing buildings can be reduced by approximately 50–75% (Kragh and Wittchen, 2010; Kragh, 2010; Lund et al., 2010; Rasmussen, 2010; Tommerup et al., 2010), but that it will take significant investments to reach such low levels (Kragh and Wittchen, 2010). The existing building stock will remain in existence for many years, so a focus on energy savings in this segment is unavoidable. Future energy systems will have to be based solely on renewable energy sources, which is a challenge for society.

1.2. Future district heating systems

District Heating (DH) is a sustainable way of providing Space Heating (SH) and Domestic Hot Water (DHW) to buildings in

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densely populated areas (Persson and Werner, 2011). DH systems are already established in many countries, but like the rest of the energy supply system, they face new challenges in the future. In Iceland and Turkey, a large share of the DH supply is based on geothermal heat, and some DH systems are also supplied from geothermal heat in China and the U.S.A. In countries like Denmark, Sweden, and Finland, the DH supply comes mainly from combined heat and power generation plants (CHP) (Gustafsson and Rönnqvist, 2008). The DH systems in Denmark will have to be converted from the present supply technologies based on fossil fuels to 100% renewable energy sources. Questions have been raised about whether there is a need for DH-systems in the future, since SH-demands will decrease to very low levels. The economic feasibility of future DH-systems has thus been questioned. A study of the DH-net in Malmö, Sweden, (Gustafsson, 1992) found the overall economic feasibility of DH systems to be problematic when end-use consumption in buildings is reduced. The overall costs strongly depend on the characteristics of the buildings and the district heating system (Gustavsson, 1994a, 1994b). However, a recent study in Denmark (Lund et al., 2010) has shown that even with a reduction of 75% in SH demand, it is beneficial to supply heat from DH. The study also shows that an expansion of the DH-network from the present 46% share of the total heat supply in Denmark to a 63–70% share would be beneficial. With low-temperature operation (a supply temperature of 55 °C and a return temperature of 25 °C), it has been shown that DH supply for low-energy buildings is competitive with the best alternatives, such as individual heat pumps (Lund et al., 2010; Dalla Rosa and Christensen, 2011). Low-Temperature District Heating (LTDH) is a cost-efficient and environmentally friendly way of supplying heat with linear heat densities down to 0.20 MWh/(m year) (Dalla Rosa and Christensen, 2011). LTDH reduces heat losses from the distribution pipes, and heat supply from renewable sources becomes more appropriate and efficient when low-temperature applications are implemented (Dalla Rosa et al., 2011).

1.3. The conversion to fossil-fuel-free societies with extensive end-use energy savings

Recent studies have investigated the potential in converting the existing energy system into a 100% renewable supply system in two local authorities in Denmark: Frederikshavn (Østergaard and Lund, 2011) and Aalborg (Østergaard et al., 2010). Both studies covered the heating, electricity and transport sectors and included energy-saving measures, but the focus was on the supply side and on production technologies. Both studies concluded that it is technically and economically possible to convert to a fossil-fuel-free society and that geothermal heat will play an important role in future district heating systems. A study from Sweden (Gustavsson et al., 2011) investigated how the end-use heat savings in buildings will affect district heating production, including costs and primary energy savings, but it included the use of fossil fuels. In the future, however, conversion to RE-supply will be as important as end-use heat savings.

The present paper considers both end-use-savings and 100% RE-supply, but has a more detailed focus on when and to what extent it is worth implementing end-use savings in the building stock. It describes a method for making use of the existing DH system in the future energy infrastructure of the Copenhagen area with the aim of society being fossil-fuel-free in 2050. The scope is limited to the heating sector, excluding other sectors such as electricity generation and the transport sector. The electricity sector will also have to be fossil-fuel-free, and much of the future electricity production will be based on fluctuating and vulnerable resources such as wind. If electricity is used for heating purposes, large, costly storage units may be required to meet peak loads.

The use of DH in appropriate areas will protect the electricity sector from increasing peaks in very cold periods. That is why electricity for heating purposes is not considered in this study.

The focus of this paper is on the implementation of geothermal heat sources for future DH-systems, as well as on heat produced from municipal solid waste incineration.

Socioeconomic calculations of various energy renovation strategies are carried out and discussed. The cost per delivered unit of heat in buildings is estimated for the various scenarios based on the energy renovation strategies.

We have taken a very general approach with the aim of providing an overall picture for planning future heat sourcing with regard to heat savings and supply in the existing building stock. The cost of new buildings is generally not included in any of the scenarios, since it is assumed that when a new building is constructed, it automatically fulfils the energy requirements of the Danish Building Regulations. This means that the cost will be incurred whichever renovation strategy is carried out.

2. Methods

2.1. Background and approach for the case study

The investigation takes a long-term perspective and deals with the period up to 2070. According to current energy policy, coal will be phased out by 2030 (Danish Ministry of Climate, Energy and Buildings, 2011), but according to the Heat Plan of Copenhagen (CTR et al. 2009) coal will already have been phased out by 2025. This study assumed that fossil fuels will be phased out before 2025 and replaced with waste for incineration, geothermal energy and biomass.

Some CHP plants have already been converted for biomass in Denmark, but according to research (EEA (European Environment Agency) 2006) the biomass potential in Europe will only account for approximately 15–16% of the total primary energy demand in 2030. Furthermore the study (Ericsson and Nilsson, 2006) concludes that the biomass resource is limited and with the slow implementation of RES-policy in Europe it is unlikely that the biomass targets will be reached. This study therefore assumed that the biomass resource will be seen as a temporary solution only available until 2040, after which it will relocate to other sectors, i.e. the transportation sector that will have to be fossil-fuel-free by 2050. This is in good agreement with recommendations and other similar case studies (Danish Energy Agency, 2010a; Dolman et al., 2012). So this study focused on other renewable energy resources. This is in good agreement with the considerations in (Østergaard and Lund, 2011; Østergaard et al., 2010), although those studies still assume that a small amount of the available biomass-resource for CHP will be exploited indirectly for heating purposes.

Geothermal sources should be considered as a mix of various energy sources in the future heat supply infrastructure. Waste heat from industry could also be used in combination with either geothermal or solar heat, but the potential has been estimated to be low (3%) in the Copenhagen area, because the industrial sector is small (Danish Energy Agency, 2009). Geothermal water under Copenhagen can be tapped at temperatures of 73 °C at a depth of 2000 m (Mahler and Magtengaard 2010), so heat pumps are assumed not to be needed to further elevate the temperature of the water. Mahler and Magtengaard (2010) can be mentioned among newly developed geothermal heating plants in Denmark.

The priority of the utilization of the resources in this study was:

1. Waste for incineration;
2. Geothermal energy;
3. Biomass; and
4. Fossil fuels.

Municipal solid waste for incineration has the first priority since there are already established plants and there is a certain ethic in using the waste heat produced from the incineration instead of producing more geothermal heat. This may be different in other countries that do not already have established plants. Furthermore if the waste is not incinerated the problem of how to treat the waste and what to do with it appears and therefore it seems reasonable to prioritize the waste incineration.

When the heating demand in buildings is reduced to low levels, LTDH becomes an option, because the need for SH and the SH-peaks will decrease. Therefore it is possible to heat the buildings with lower temperatures, which allows for the use of LTDH. It has been shown (Worm et al. 2011; Tol and Svendsen, 2012a, 2012b; Harrestrup and Svendsen, 2013) that LTDH is feasible in existing buildings for most hours of the year. Periods with very cold climate conditions require an increased supply temperature. It is assumed that this can come from waste incineration plants.

2.2. Present heat demand and potential for conversion of individual natural gas heated buildings

The present DH network in the Copenhagen area consists of three waste incineration plants and four CHP-plants distributed as shown in Fig. 1. The supply area includes the supply companies VEKS, CTR, Vestforbrændingen and HOFOR.

The total heat supply by DH (2010) of the area shown in Fig. 1 is 35 PJ/year with a peak load of 2500 MW (CTR et al., 2011). This capacity was used as the starting point for the calculations in this paper. The overall network heat losses are assumed to be 15% and 8% of the annual production with traditional DH and low-temperature DH respectively (VEKS, 2012a; HOFOR, 2012). It is assumed that the DHW demand is 400 MW constantly over the year with the exception of the summer period when consumers are expected to use less domestic hot water due to vacations.

In reality, the DHW will vary over the year, but these variations have been left out of account to simplify the study.

According to CTR et al. (2009), a potential of 10 PJ for heating individual homes can be converted from natural gas to DH. The total heat consumption then adds up to 45 PJ/year with a peak load of about 3200 MW. We have assumed that the ratio between the SH consumption and the DHW consumption remains the same as the conversion takes place. The capacity of the district heating plants is distributed across small plants in the Copenhagen area.

2.3. Energy renovation—annual heat demand and peak load

To calculate the investment cost in new RE-capacity when the building stock undergoes energy renovation, the study of Harrestrup and Svendsen (2013) has been used. The study investigated how the peak load changes when energy renovations are carried out on two old multi-storey buildings typical in Danish urban areas. The findings showed that, when 65% is saved on the annual heat demand, the peak load can also be reduced by 65% and the heating demand will have smaller variations over the year. Based on these findings the peak loads are reduced with the same percentage as the reduction in annual heat demand in the present study. The two buildings used for the investigation (Harrestrup and Svendsen, 2013) are from the beginning of the 20th century and are typical of a large proportion of the buildings in Copenhagen where energy renovations are needed to bring down the energy consumption. In the Building Regulations from 1977 the U-values were significantly tightened as a consequence of the energy crisis in the 1970s, implying that the thermal performance of the buildings constructed before the 1970s was significantly worse than the once constructed after. According to official statistics (Statistics, 2013), 83% of the buildings in Copenhagen are built before 1970, 72% before 1950 and 44% before 1930.
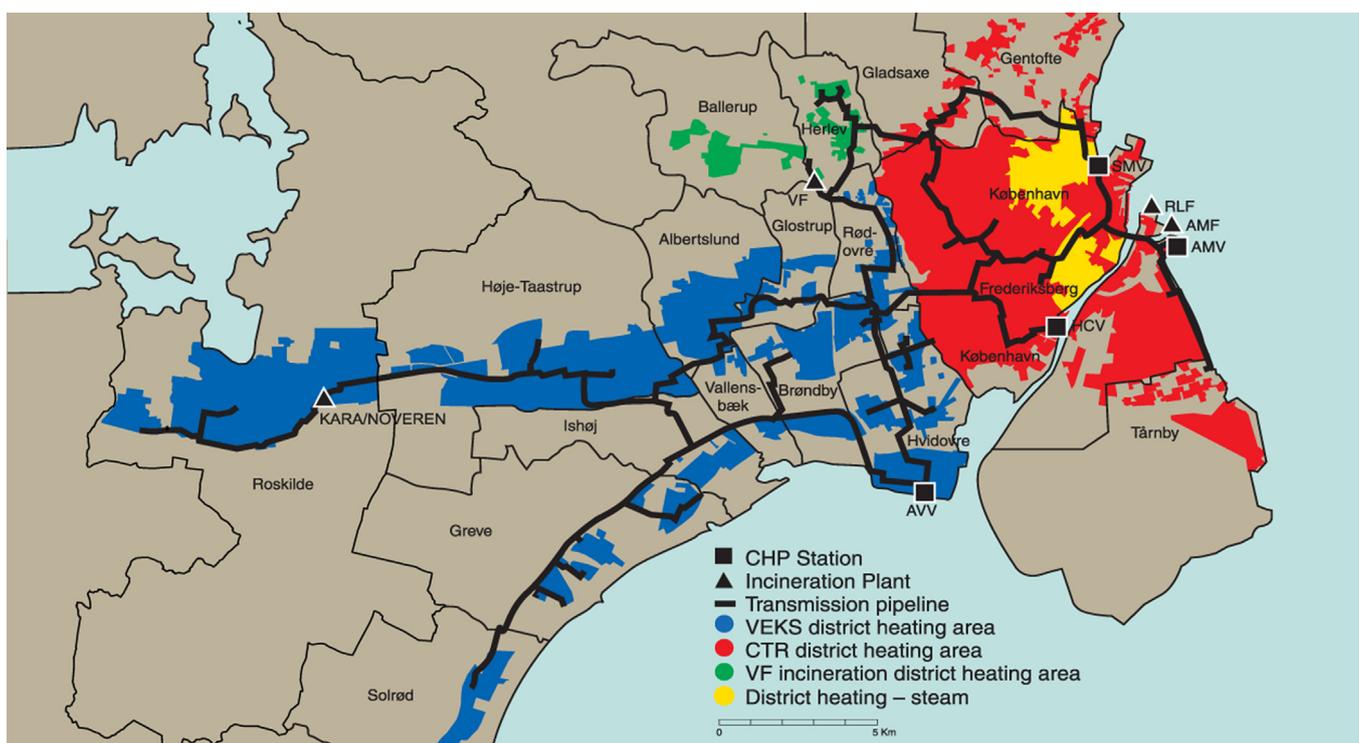
Fig. 1. Map of the existing DH network in Copenhagen area (CTR et al., 2011).

The annual energy consumption for space heating in the old building stock in Denmark is approximately (Kragh and Wittchen, 2010):

Before 1850:	520 MJ/m²
1851–1930:	540 MJ/m²
1931–1950:	610 MJ/m²
1951–1960:	580 MJ/m²
1961–1972:	470 MJ/m²

Obtaining 65% savings the annual space heating consumption will then range from 165–210 MJ/m², which is at comparable levels with new buildings from the Building Regulations 2010 (BR10 (Danish Building regulations) 2012). The minimum requirements for new buildings since 2010 are: $(189+5940/A)$ MJ/m²/yr including the energy usage for supplied energy for heating, ventilation, cooling and domestic hot water (with A being the heated area). Furthermore, the Building Regulations specifies the expected energy performance framework in 2015 to: $(108+3600/A)$ MJ/m²/yr and in 2020 to: 72 MJ/m²/yr.

2.4. Scenarios for the case study

Four different possible future scenarios with long-term approaches were examined. The calculations assumed a 1/3 decrease in the amount of domestic waste by 2070 compared to 2010 and that waste incineration will have higher priority than geothermal heat. This priority is assumed since there is an ethical value in using existing waste incineration plants before investing in new geothermal heating capacity. Furthermore, the municipal solid waste has to be treated in one way or another, either by incinerating it or storing it in land field lots. The priority is therefore to give it to the waste incinerating plants. According to the municipal solid waste plan of Copenhagen (Copenhagen Municipality, 2013) the prognosis is that waste for incineration will decrease by 8% in 2024 compared to 2010, as an average for household waste, waste from industry, and from construction due to more recycling. The assumption that the amount of municipal solid waste for incineration will fall by 33% before 2070 therefore seems reasonable (a rough estimation would be 70 years/14 years 8%=40%). Furthermore, the Danish government (Danish Ministry of the Environment, 2013) and the EU (European Commission, 2013) have a strategy of increasing recycling, which means less incineration of waste and therefore less heat produced from waste incineration.

The four scenarios are described below, and are referred to as the Reference Scenario, Scenario 1, Scenario 2, and Scenario 3. All scenarios assume existing buildings are replaced with new buildings at a rate of 1% per year (Barras, 2009). The Danish Building Research Institute (Kragh and Wittchen, 2010) has carried out an analysis that concludes that, if the energy consumption of the existing building stock is reduced by approximately 50% through energy renovation, the building stock will reach an energy level that corresponds to what is required for new buildings according to the Danish building regulations 2010 (BR10 (Danish Building regulations) 2012). The annual heat demand will then decrease by 0.5% per year in all the scenarios. The study does not consider a possible increase in the building stock over time.

LTDH is phased in all the scenarios except for the Reference Scenario. Two renovation levels are considered.

Comprehensive renovation will decrease the heat consumption by 65% and consists of (Kragh and Wittchen, 2010):

- Replacement of windows,
- Insulation of the building envelope, and
- Installation of mechanical ventilation with heat recovery.

Intermediate renovation will decrease the heat consumption by 32% and consists of (Kragh and Wittchen, 2010):

- Replacement of windows, and
- Installation of mechanical ventilation with heat recovery.

Reference Scenario—No energy renovation but only natural replacement of existing buildings with new buildings.

This scenario represents the scenario in which no energy improvements are made in the building stock until 2070, except for replacements with new buildings. The scenario therefore also represents a scenario in which focus is given fully to the RE-supply. A graphical sketch is shown in Fig. 2.

2.4.1. Scenario 1: Accelerated comprehensive energy renovation between 2030 and 2070

Scenario 1 represents the case where no energy efficiency improvements in the buildings are carried out before 2030. The DH supply will be converted from fossil fuels to biomass in the CHP-plants and prices will remain unchanged. When biomass is
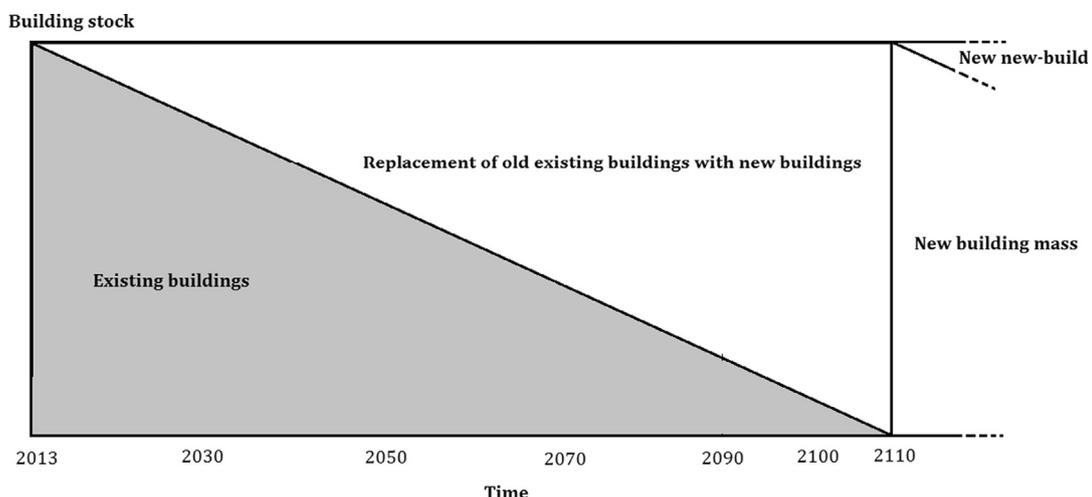
Fig. 2. Graphical sketch of the Reference Scenario—no energy renovations.

phased out between 2030 and 2040, geothermal heating plants are assumed to be established to cover the nearly unchanged heat load. The investment in geothermal energy will result in increased prices for DH. Comprehensive energy renovations in buildings will be carried out as a consequence of the increased heat prices. The coefficient of utilization of the geothermal heating plants will decrease and prices will rise further. LTDH will be phased in from 2035, proportional to the energy renovations.

A graphical sketch is presented in Fig. 3. As the figure shows, the entire building stock will undergo comprehensive renovation from 2030 phased in over 40 years. Assuming a lifetime of 60 years for such renovation measures, this share of the building mass will be replaced with new buildings from 2090.

2.4.2. Scenario 2: Accelerated comprehensive energy renovations from 2013

Scenario 2 represents the case where comprehensive energy renovations are implemented from 2013 to 2040. Biomass will be phased out between 2030 and 2040 and geothermal heating plants will be established. As a result of the energy efficiency improvements in the buildings, the investment in geothermal heating plants will decrease significantly. LTDH will be phased in from 2013 proportional to the energy renovations.

A graphical sketch is presented in Fig. 4. As the figure shows, the entire building stock will undergo comprehensive renovation from 2013, phased in before 2040. Assuming a lifetime of 60 years for such renovation measures this share of the building mass will be replaced with new building from 2073.

2.4.3. Scenario 3: Accelerated intermediate energy renovations from 2013

Scenario 3 represents the case where intermediate energy renovations are considered and as for Scenario 2 the energy renovations are implemented from 2013 (Fig. 5) and phased in over 30 years. The lifetime for this kind of energy renovation is considered to be 30 years, resulting in a reinvestment after 30 years. LTDH is phased in from 2013 proportional to the energy renovations.

2.5. Economic considerations

To calculate the economic consequences for each of the scenarios, socioeconomic analyses were applied. Using the present value (PV) method, all future investments and costs were discounted to present levels and the scenario with lowest costs was identified. This is in line with recommendations and guidelines
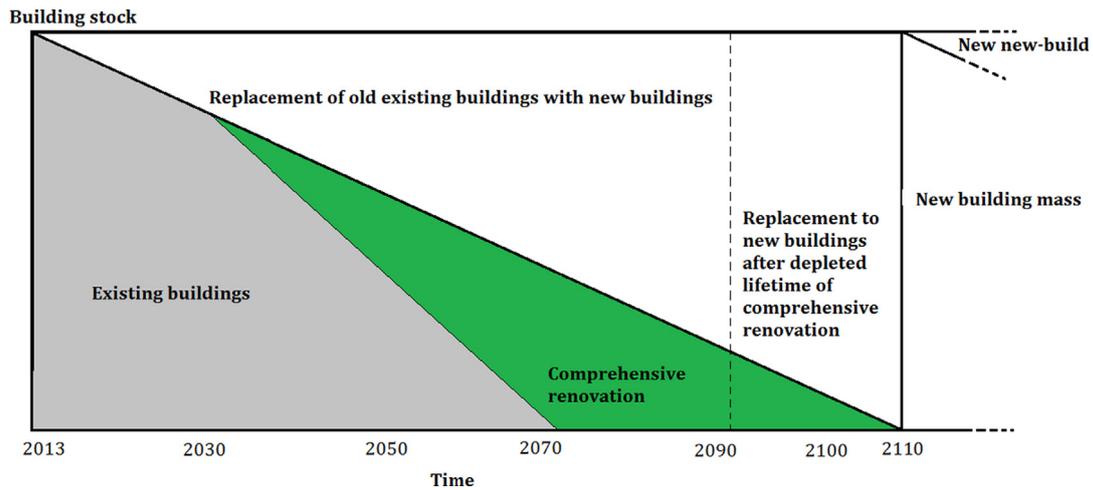
Fig. 3. Graphical sketch of Scenario 1—accelerated energy renovations later.
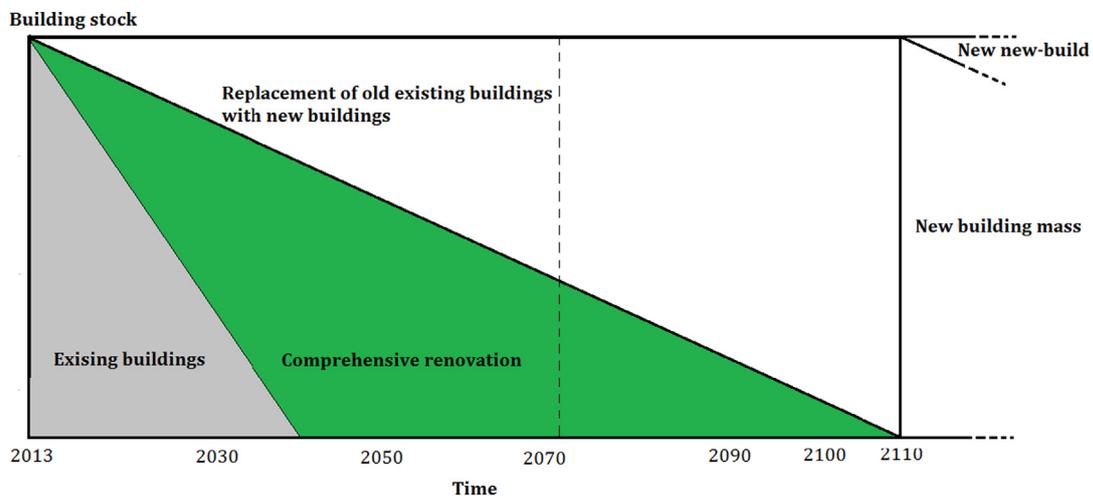
Fig. 4. Graphical sketch of Scenario 2—accelerated comprehensive energy renovations now.
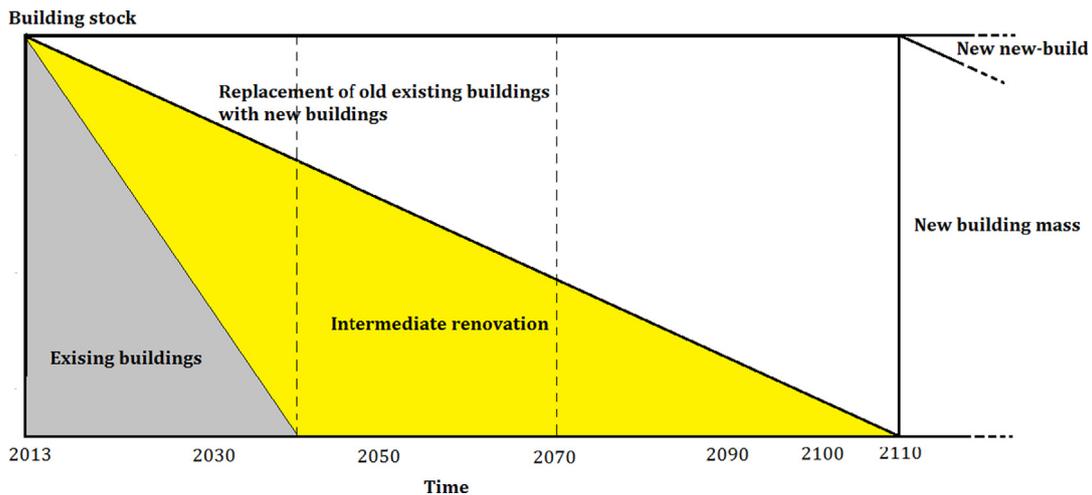
Fig. 5. Graphical sketch of Scenario 3—accelerated intermediate energy renovations now.

from the Danish Finance Ministry and the Energy Saving Trust Association (ENS) (Danish Energy Agency, 2007a). A sensitivity analysis on the influence of the discount rate was carried out using discount rates of 0%, 1%, 3% and 5%. According to the Danish Finance Minister and ENS a discount rate of 5% should be used for PV-calculations. The outcome from PV-calculations is very sensitive to the discount rate, and it is debatable whether this is a reasonable value for energy-related projects where the duration of the project is very long and affects long-term future conditions. Investments projected for many years from now will be discounted to smaller present values the higher the discount rate. This makes it appear more attractive to delay large investments, such as energy renovations (Ege and Appel, 2013; Atanasiu et al., 2013). Furthermore, (Stern, 2007) has elaborated this dilemma related to discounting in detail and states that if a project's costs and benefits are "allocated across generations and centuries, it is an ethical issue for which the arguments for low pure time discount rates are strong" and "if the ethical judgment is that future generations count very little regardless of their consumption level then investments with mainly long-run pay-offs would not be favoured. In other words, if you care little about future generations, you will care little about climate change. As we have argued that is not a position which has much foundation in ethics and which many would find unacceptable".

Estimated costs of investment, maintenance and operation were included for the geothermal heating plants and for the DH-net. The energy prices of the fossil fuels and biomass were estimated from calculations carried out by (VEKS, 2012b). They were based on an expected weighted distribution of the resources in the Copenhagen DH-system. Waste for incineration was not priced due to the large uncertainties, but since the amount of waste is the same in all scenarios, this will not have any influence on their comparative costs. Moreover, the waste will have to be collected in all cases, and must be either incinerated or stored in a landfill lot, so the cost of waste is not included (Danish Energy Agency, 2007b).

All investments were included for the year they will take place in, and salvage values of the investments beyond 2070 were subtracted. The costs for the Reference Scenario (no energy renovations) were calculated solely for the supply-side, whereas the costs for Scenario 1 (energy renovation later), Scenario 2 (comprehensive energy renovation now), and Scenario 3 (Intermediate energy renovation now) also include the investment in energy renovation.

2.5.1. Geothermal

The capital investment cost is estimated to be €1.6/W for a geothermal plant with a capacity of 135 MW where approximately half of the capacity is coming from geothermal heat and the half from heat pumps (CTR et al. 2009; CTR et al. 2011; COWI, 2012). With LTDH, there will be no need for heat pumps to boost the temperature since the underground water can be drawn at 73 °C. The capital investment cost for geothermal heat is assumed to be 5 times higher compared to the capital investment cost for heat pumps, which result in an estimated capital investment cost solely for geothermal heat on approximately €2.7/W (COWI, 2012).

Operation and maintenance costs (O&M) are difficult to estimate since they vary depending on various factors and conditions. The O&M-cost was assumed to be €1.75/GJ (COWI, 2012).

2.5.2. DH-network

According to (COWI, 2012), the cost in capital investment for expanding the DH-network can be assumed to be €84/GJ. The investment cost is estimated based on experience from (COWI, 2012), and represents a cost for expansion of the DH net to less populated areas, which increases the cost compared to densely populated areas.

The O&M cost was set at €0.56/GJ based on the Danish Energy Agency (2010b).

2.5.3. Energy renovation costs

According to (Kragh and Wittchen, 2010), which is based on the entire building stock in Denmark (homes), the marginal cost of saving 102 PJ/year, corresponding to energy savings of 65%, is €51,000 M/year. The comprehensive renovation then results in a unit price per saved petajoule of €8.3 M/PJ, based on savings over 60 years.

$$\text{Comprehensive renovation} = \frac{€51,000 \text{ M/year}}{(102 \text{ PJ/year} \times 60 \text{ years})} = €8.3 \text{ M/PJ}$$

According to Kragh and Wittchen (2010), the marginal energy-saving price for windows is €111 M/PJ, and for ventilation with heat recovery (intermediate renovation), it is on average €296 M/PJ. Assuming the same energy-saving efficiency for both measures and a lifetime of 30 years, the energy-saving price per year becomes

$$\text{Intermediate renovation} = \frac{€(111+296)\text{M/PJ}}{30 \text{ years}} = €13.6 \text{ M/PJ}$$

Assumed lifetimes	
Geothermal:	40 years (Lako and Tosato, 2010)
DH network:	60 years (Tang, 2010)
Renovations of dwellings:	60 years (Aagaard et al., 2010)

2.6. Cost of delivered heat

The cost of the delivered heat to the buildings for the different scenarios was calculated to evaluate the scenario with the lowest cost per heat unit delivered. The heat delivered to the buildings is calculated as the heat produced in the DH plant minus the net heat losses. To calculate the cost of the delivered heat, the expenses for the DH companies based on the socioeconomic calculations are divided by the delivered heat

$$\text{Cost of delivered heat} = \frac{\text{Expenses for DH companies}}{\text{Delivered heat to buildings}}$$

3. Results and discussion of the case study

3.1. Reference scenario: No energy renovations

Fig. 6(a) shows the peak load and the distribution of resources. The heat demand will increase until 2035, due to the conversion of natural gas areas into district heating. In the same period, the existing building mass will be replaced with new buildings, decreasing the heat demand by 0.5% per year. Fig. 6(a) shows that with no accelerated heat savings an investment in geothermal heat corresponding to a capacity of 2800 MW will be required.

Fig. 7(a) shows the annual production of the different energy supply technologies until 2070. The geothermal heat production is expected to peak in 2040 at 32 PJ, after which it will decrease by 14% by 2070. The total geothermal production in the entire period is estimated to be 1100 PJ.

3.2. Scenario 1: Accelerated energy renovations later

Scenario 1 represents the case where accelerated comprehensive energy renovations are implemented from 2030. Fig. 6(b) shows the peak load and the distribution of the supply technologies. The heat demand peaks in 2030, after which it decreases. The build-up in geothermal capacity is 2500 MW, which is slightly lower than in the Reference Scenario (no energy renovations) due to the accelerated energy renovations.

Fig. 7(b) shows the annual production of the different energy supply technologies between 2010 and 2070. The geothermal production peaks in 2040 at 28 PJ. The accelerated energy renovations imply a decrease in the heat demand from 2030 until 2070. The coefficient of utilization drops significantly because the investment in geothermal heat capacity has already taken place. The production of geothermal heat decreases by 61% by 2070. The total geothermal heat production for the entire period is 838 PJ.

3.3. Scenario 2: Accelerated comprehensive energy renovations now

Scenario 2 represents the case where investment in accelerated energy renovations begins in 2013. Fig. 6(c) shows the peak load and distribution of the different supply technologies. The total heat demand decreases throughout the entire period. The investment in geothermal capacity is reduced to 1200 MW, corresponding to a reduction of 57% compared to the Reference Scenario (no energy renovation), and a reduction of 52% compared to Scenario 1 (energy renovations later).

Fig. 7(c) shows the annual heat production of the different supply technologies until 2070. The geothermal heat production

Heat capacity in DH plants
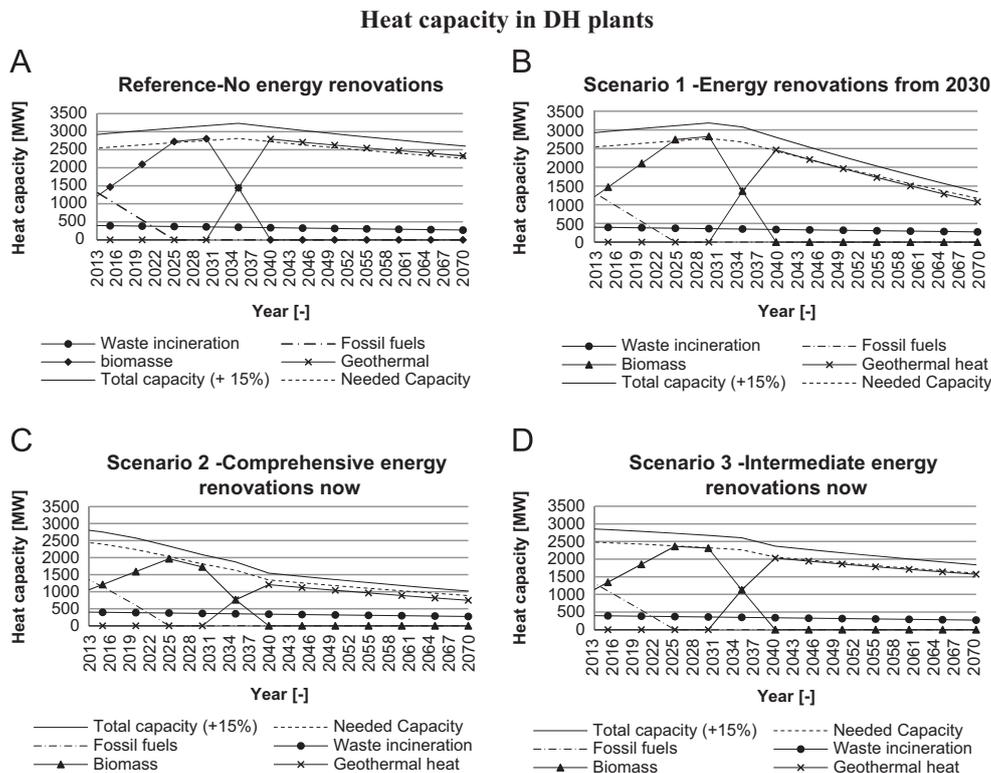
Fig. 6. Heat capacity for the different supply technologies for all the scenarios.

Annual heat production in DH plants
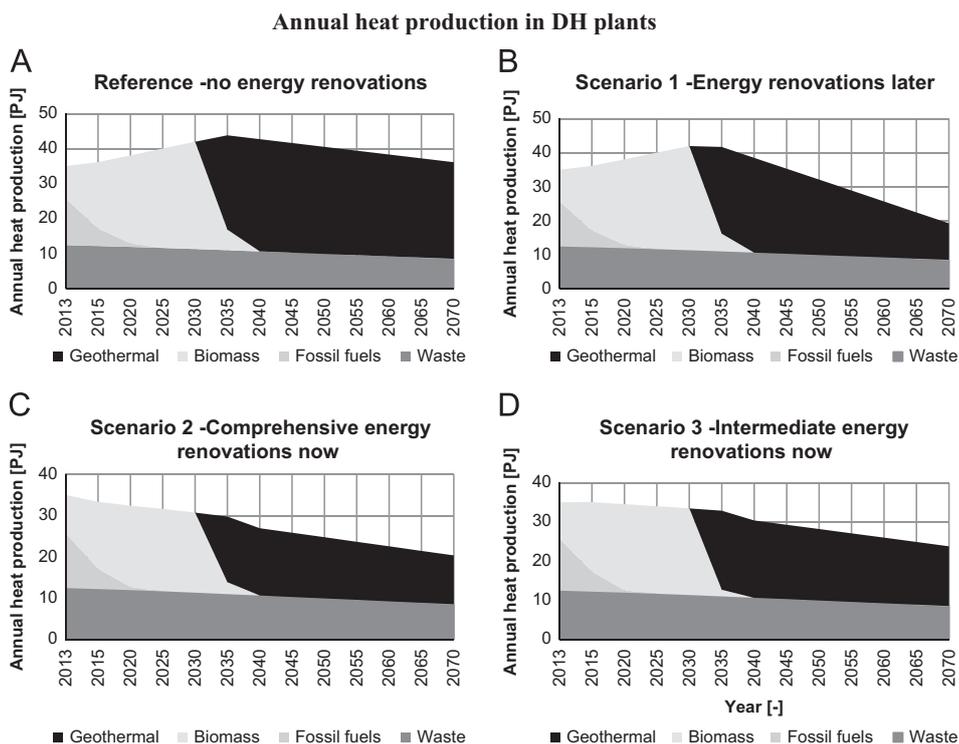
Fig. 7. Annual heat production for the different supply technologies for all the scenarios.

peaks at 16 PJ, which is 50% less than in the Reference Scenario (no energy renovations) and 43% less than in Scenario 1 (energy renovations later). The geothermal production decreases by approximately 25% by 2070 compared to the peak value. The total geothermal heat production throughout the entire period is 543 PJ.

3.4. Scenario 3: Accelerated intermediate energy renovation now

Scenario 3 represents the case where accelerated intermediate energy renovations are carried out from 2013. Fig. 6(d) shows the peak load and distribution of the different supply technologies. The total heat demand decreases throughout the entire period. The investment in geothermal capacity is 2029 MW, corresponding to a reduction of 28% compared to the Reference Scenario (no energy renovation), 19% compared to Scenario 1 (energy renovation later), and an increase of 69% compared to Scenario 2 (comprehensive energy renovation now).

Fig. 7(d) shows the annual heat production of the different supply technologies until 2070. The geothermal heat production peaks at 25 PJ, which is 22% less than in the Reference Scenario (no energy renovations), 11% less than in Scenario 1 (energy renovations later), and 56% more than in Scenario 2 (comprehensive energy renovations now). The geothermal production decreases by approximately 20% by 2070 compared to the peak value. The total geothermal heat production throughout the entire period is 675 PJ.

3.5. Economics of the case study

Table 1 shows the result of the socioeconomic analysis. The total cost for the Reference Scenario (no energy renovations) is €833 M less than that of Scenario 1 (energy renovations later) if a discount rate of 0% is assumed. This is due to the large investments in energy renovations in Scenario 1 (energy renovations later) at the end of the period in question, and the effect on the investment in geothermal heating plants is therefore relatively small. When the discount rate is increased to 1%, 3%, and 5% the Reference

Scenario (no energy renovations) will cost €1106 M, €938 M, and €616 M less than Scenario 1 (energy renovations later), respectively.

Table 1 also shows that Scenario 2 (comprehensive energy renovations now) is less costly than the Reference Scenario (no energy renovations) by €509 M when a discount rate of 0% is assumed. However, if the discount rate is increased to 1% or more, Scenario 2 (comprehensive energy renovations now) is no longer beneficial compared to the reference, indicating the sensitivity of the cost estimates to the discount rate. The results of Scenario 3 (intermediate energy renovations now) are in between Scenario 1 (energy renovations later) and Scenario 2 (comprehensive energy renovations now). Table 1 also shows that investing in comprehensive energy renovation from today rather than later will save approximately half the investment cost in geothermal heating plants, which is beneficial for the district heating companies. If investment in intermediate energy renovation (Scenario 3) takes place now, it will save approximately 16% of the investment cost in geothermal heating plants compared to postponing the investment in energy renovation (Scenario 1). However, Scenario 3 with less investment in energy renovation is more likely to be realized fast, since replacing the windows and installing mechanical ventilation with heat recovery is an easier task than carrying out comprehensive energy renovations.

Table 2 shows the heat produced in the DH plants and the heat delivered to the buildings, i.e. after the network heat losses. Since the Reference Scenario (no energy renovations) does not have LTDH and Scenario 1 (energy renovations later) only implements LTDH from 2035, when the energy renovations are carried out, the network heat losses are higher than in the other scenarios where LTDH is implemented today proportional to the energy renovations. Taking the expenses for the DH companies and dividing it by the heat delivered to the buildings, the cost per delivered heat unit is calculated. As can be seen, Scenario 2 (comprehensive energy renovations now) provides the lowest cost per delivered heat unit, followed by Scenario 3 (intermediate energy renovations now), which indicates a more competitive price for the district heating

Table 1
PV for each scenario excl. waste for incineration. Discount rates of 0%, 1%, 3%, and 5%.

PV 2013–2070	Reference. No energy renovations [M €]	Scenario 1 Energy renovations later [M €]	Scenario 2 Comprehensive energy renovations now [M €]	Scenario 3 Intermediate energy renovations now [M €]
Discount rate 0% Investments				
Geothermal plants	8736	7644	3744	6396
DH-net expansion	187	187	187	187
Renovations	0	7662	7662	6171
Salvage value				
Geothermal plants	−983	−860	−421	−720
DH-net expansion	−38	−38	−38	−38
Renovations	0	−5044	−1877	−3514
Fuels	879	874	669	774
O&M	3276	2465	1622	2524
Total cost for DH companies	12,057	10,272	5763	9123
Total cost renovation	0	2618	5785	2657
Total Discount rate 0%	**12,057**	**12,890**	**11,548**	**11,780**
Discount rate 1% Investments				
Geothermal plants	6986	6113	2994	5115
DH-net expansion	169	169	169	169
Renovations	0	5311	6776	4758
Salvage value				
Geothermal plants	−552	−483	−237	−404
DH-net expansion	−22	−22	−22	−22
Renovations	0	−2832	−1421	−1973
Fuels	780	776	601	690
O&M	2295	1730	1141	1763
Total cost for DH companies	9656	8283	4646	7311
Total cost renovation	0	2479	5355	2785
Total Discount rate 1%	**9656**	**10,762**	**10,001**	**10,096**
Discount rate 3% Investments				
Geothermal plants	4509	3945	1932	3301
DH-net expansion	141	141	141	141
Renovations	0	2679	5425	3092
Salvage value				
Geothermal plants	−177	−155	−76	−130
DH-net expansion	−7	−7	−7	−7
Renovations	0	−908	−821	−633
Fuels	731	728	578	655
O&M	1192	904	600	915
Total cost for DH companies	6389	5556	3168	4875
Total cost renovation	0	1771	4604	2459
Total Discount rate 3%	**6389**	**7327**	**7772**	**7334**
Discount rate 5% Investments				
Geothermal plants	2943	2575	1261	2155
DH-net expansion	119	119	119	119
Renovations	0	1434	4470	2224
Salvage value				
Geothermal plants	−58	−51	−25	−42
DH-net expansion	−2	−2	−2	−2
Renovations	0	−298	−479	−207
Fuels	513	511	415	464
O&M	667	510	341	513
Total cost for DH companies	4182	3662	2109	3207
Total cost renovation	0	1136	3991	2017
Total Discount rate 5%	**4182**	**4798**	**6100**	**5224**

companies when energy renovations are carried out already from today.

3.6. Policy implications

The approach to this investigation has been that biomass is a temporary resource that will disappear from the heating sector in the long-term for use in other sectors. There are different opinions on this subject, but most agree that biomass is a restricted resource that cannot be used as the primary resource for all future energy purposes. Most sectors would like to make use of biomass, but this is not possible and other non-fossil fuel energy solutions must be found. The authors of (Østergaard and Lund, 2011; Østergaard et al., 2010) concluded that the use of geothermal heating plants will play a significant role in future district heating systems, but they also made use of a small amount of biomass to cope with peak loads. Investing in sufficient geothermal heating plant to cover peak loads may in fact be unrealistic since the

Table 2
Produced and delivered heat. Cost for delivered heat for the scenarios with different discount rates.

	Reference No energy renovations	Scenario 1 Accelerated energy renovations later	Scenario 2 Accelerated energy renovations now	Scenario 3 Intermediate energy renovations now
Delivered heat at buildings [PJ]	2064	1819	1465	1652
Produced heat [PJ]	2379	2098	1640	1827
Net losses [PJ]	315	279	175	175
Cost per delivered heat [€/PJ]				
Discount rate 0%	5.84	5.65	3.93	5.52
Discount rate 1%	4.68	4.55	3.17	4.43
Discount rate 3%	3.10	3.05	2.16	2.95
Discount rate 5%	2.03	2.01	1.43	1.94

investment cost could be too high, and other technologies, such as energy storage, will probably be used to achieve peak load production. For example, surplus electricity produced from wind could be used to produce hydrogen, which along with biomass would form a "synthetic natural gas". This gas could then be used in CHP plants and the heat production could be used to cover the peak loads. However, peak loads in the future will be much reduced by energy renovations in buildings, so peak load production will have less importance.

Considering that the main investments will be in geothermal heating plants, it may be advantageous to phase in geothermal heating plants at an earlier stage in order to develop the technology and cope with the problems that might occur during development. However, this would not influence our results as long as the capacity needed in the different scenarios remains the same.

When estimating the costs for the energy renovation measures envisaged in the present study, we assumed that energy renovations are carried out only when buildings need renovation anyway. This means that only the marginal cost for energy conservation was used. It is reasonable to assume that the existing building mass will need renovation within a period of 30–40 years because a majority of the buildings in Copenhagen are very old. It is also in accordance with visions for the building stock in Europe (Staniaszek et al., 2013).

The results from the economic calculations are very sensitive to the discount rate assumed. According to the Danish Finance Ministry and the ENS, a discount rate of 5% should be used in making cost estimates, but such high discount rates distort results when dealing with projects that have durations of many years because they affect future conditions significantly. Investments taking place in the future are discounted to small present values, making it attractive to delay any investments. The smaller the discount rate, the more importance is given to future conditions. The choice of discount rate for the conclusions drawn in this paper was therefore 0%—in order to give full importance to future generations.

The choice of service lifetime of the building, district heating network and geothermal heating plant is important since it might affect the results of the paper. The time perspective is often discussed and lots of literature and research can be found here upon. Different literature uses a wide range of lifetimes for buildings ranging from 30 to 100 years (Mithraratne, Vale, 2004; Verbeeck and Hens 2010; Marteinsson 2003; Scheuer et al. 2003, Kellenberger and Althaus, 2009, p. 819, Sartori and Hestnes, 2007, Ramesh et al., 2010; Grant and Ries, 2013; Aagaard et al., 2010). However, often a lifetime on 50 years, 80 years and 100 years are used (Ramesh et al., 2010; Sartori and Hestnes, 2007; Grant and Ries, 2013) and it therefore seems reasonable to have a building lifetime on 60 years as was chosen for this study. The service life time of DH pipes have also been discussed in the literature (Hallberg et al., 2012; Tang, 2010; Röse et al., 2002; DFF, 2004).

The study (Hallberg et al., 2012) discusses the service life time for DH pipes to be at least 30–50 years and states that change of future operating conditions should be considered, since they may affect the service lifetime. Since the DH system is converted into LTDH the operating temperatures will decrease, which according to (DS/EN 253, Annex A, 2009) will increase the service lifetime of the DH pipes. If the operating temperature is $T \leq 109\ ^\circ C$ the service lifetime is expected to be 100 years. A study from Germany concludes that DH pipes that had been in operation for 30 years had a remaining lifetime on 38 years resulting in a service life time of 68 years (Röse et al., 2002, DFF, 2004). Therefore the chosen lifetime for the present paper of 60 years seems reasonable. The lifetime of the geothermal heating plants are set to 40 years. According to literature, lifetimes in the range of 20–40 years is often used (Goldstein et al., 2011; Frank et al., 2012; Frick et al., 2010; Lako and Tosato, 2010; Guo et al., 2013). The choice of service life for geothermal heating plant is in the higher end, but taking into account the development and the improvement of the technology over the years, longer lifetimes can be expected (Goldstein et al., 2011 – chapter 4.6), and it therefore seems as a reasonable number in 2030 when they are assumed to be phased in. The importance of the choice of lifetime and how it affects the results should be investigated in future research. However, it is beyond the scope of this paper.

The results of the present paper are different from other studies (Connolly et al., 2012a, 2012b) dealing with the future of district heating in the EU27 countries. They conclude that future supply from district heating is a more cost-effective energy efficiency measure than end-use savings. However, those studies include a large share of fossil fuels, so investment in renewable energy capacity is not critical for them, as it is for the study carried out in the present paper.

4. Conclusions

For the DH-system in the Copenhagen area, socioeconomic calculations indicate that it is slightly more cost-beneficial to invest in energy renovations from 2013, so that we can reduce the heat demand, before investing in new renewable energy supply technologies. However, the results are very sensitive to the discount rate assumed and the results from the socioeconomic calculations are very similar for all the scenarios. It does not make a great difference which scenario is chosen from a socioeconomic point of view. The costs for supplying heat and saving heat are at comparable levels.

However, investing in comprehensive energy renovations from today will reduce the investment cost for new supply technologies by 50%, or by 16% if investments in only intermediate renovation are made: replacement of old inefficient windows and installation of mechanical ventilation with heat recovery. The Danish

government has already decided to aim at a fossil-fuel-free society in 2050, by saving energy in the building stock and by converting to RE-based supply. Strategies with regard to energy renovation of existing building stock have already been implemented in the Danish action plan towards a fossil-fuel-free society. The Danish Building Regulations include obligations to energy-upgrade buildings when they undergo improvements. Energy savings will therefore be implemented in the building stock sooner or later, and with this in mind it will be more beneficial to carry them out from today. Reducing heat demand by renovation also results in smaller peak loads and a more stable supply situation over the year, which is an advantage for the future energy system based on renewable energy resources, and gives an increased security of supply. Energy renovations also provide added value to buildings, in terms of increased indoor comfort and future-proofing. When the building undergoes an energy renovation the energy standard of the building is upgraded and the building reaches comparable levels with new buildings. This results in more secured market values for future resale.

If we look at the cost per heat unit delivered to the buildings, it is clear that carrying out energy renovations from today will result in more competitive conditions for the district heating companies than if energy renovations are carried out later on. This is also reflected in the fact that, when energy renovations are carried out, low-temperature district heating can be implemented, which reduces heat losses from the distribution pipes and results in more heat delivered to the buildings.

Based on the aim of Denmark being a 100% fossil-fuel-free society, this paper has investigated various scenarios of how to achieve this aim for the Copenhagen district heating system. The conclusion drawn from the study is that the time at which energy savings are implemented in the building stock is crucial for the district heating companies from an economic point of view.

The paper also provides a method for making use of the existing district heating system in Copenhagen by carrying out long-term planning for energy supply based on renewable energy sources and saving energy in buildings. The long-term analysis can be the foundation for political decision making and action in both areas.

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Paper 2 – Appendix 2

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Changes in heat load profile of typical Danish multi-storey buildings when energy-renovated and supplied with low-temperature district heating

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Changes in heat load profile of typical Danish multi-storey buildings when energy-renovated and supplied with low-temperature district heating

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Denmark has a long-term objective of being free of fossil fuels by 2050, with the energy supply mix for buildings being fossil-free by 2035. Energy consumption for existing buildings needs to be decreased concurrent with the conversion from fossil-fuel supply to renewable-energy (RE) supply. When end-use savings are implemented in buildings concurrent with the application of low-temperature district heating (LTDH), the heat profiles of the buildings will change. Reducing peak loads is important, since this is the dimensioning foundation for future district heating systems. To avoid oversized RE-based capacity, a long-term perspective needs to be taken. Applying LTDH in existing buildings without changing the heating system implies reduced radiator performance, so it is of great importance that acceptable comfort temperatures can still be provided. The results indicate that it is possible to apply LTDH most of the year without compromising on thermal comfort if energy renovation is also implemented.

Keywords: energy renovation; end-use savings; space-heating demand; peak load; heat load profile; low-temperature district heating

1. Introduction

Europe has a vision of reducing energy consumption significantly. In Denmark, the government has a long-term objective of being completely independent of fossil fuels by the year 2050, with the energy supply mix for buildings already being free of fossil fuels by 2035 (Danish Minister of Climate 2011; Danish Energy Agency 2010). Urgent action is, therefore, needed to meet the requirements for the future energy system. The solution is to combine energy savings and renewable-energy (RE) supply in an optimal way. The building stock accounts for about 40% of overall energy use in Europe (Lechtenböhmer and Schüring 2011). This energy consumption needs to be reduced by carrying out energy renovations and increasing energy efficiency, and the present heat supply needs to be converted into RE sources.

The design of new low-energy buildings has been in focus in recent years and much research has been carried out to design buildings optimised from an energy perspective (Abel 1994; Chwieduk 2001; Karlsson and Moshfegh 2007; Thyholt and Hestnes 2008; Zhu et al. 2009). However, on average less than 1% of the building stock is replaced per year with new low-energy buildings in Europe (Hartless 2003), which underlines the importance of looking at the existing building

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stock, which will be around for many years. The potential for energy savings is large (Kragh 2010; Kragh and Wittchen 2010; Weiss, Dunkelberg, and Vogelpohl 2012) and several studies (Kragh 2010; Kragh and Wittchen 2010; Lund et al. 2010; Rasmussen 2010; Tommerup 2010) show that reductions on the scale of approximately 50–75% can be achieved.

One common way of providing space heating (SH) and domestic hot water (DHW) to buildings in densely populated areas is by using district heating (DH) (Reidhav and Werner 2008). In Denmark, about 60% of the total heat demand today is provided by DH (Grontmij 2013), and according to Dyrelund et al. (2010) that share will need to be increased to 70% by 2035. DH systems can be designed on the basis of the heat supply from RE sources, so DH is a very important technology for realising the strategy of heating all buildings without using fossil fuels.

Future DH systems using RE need to be planned on the basis of a long-term strategy to avoid oversized heating plants (Harrestrup and Svendsen 2012; Plan 2013). Reducing the heating demand of existing buildings before investing in changes in supply can save half the initial capital investment, which indicates the importance of carrying out energy savings now (Harrestrup and Svendsen 2012; Plan 2013). The marginal cost of saving one unit of energy by carrying out a renovation is about 45 €/MWh (Plan 2013), while the cost of supplying one unit of energy from DH in 2013 is 60 €/MWh (without taxes) and 93 €/MWh (with taxes) (Hofor 2013). According to Plan (2013), the cost of supplying one unit of energy based on geothermal heat could be around 69 €/MWh (without taxes) if accelerated energy renovations are carried out from today. This emphasises the importance of carrying out energy savings in buildings now and designing the district heat production based on a long-term perspective.

Traditional DH systems operate with a supply temperature of approximately 70°C and a return temperature of 40°C. Applying low-temperature DH, with a supply temperature of 55°C and a return temperature of 25°C, will give us an opportunity to exploit the low-temperature RE heat sources, i.e. geothermal heat, solar heat, etc. With lower operational temperatures in the DH net, the heat losses from the distribution pipes will decrease. These changes will increase the efficiency of DH systems. The study made by Dalla Rosa and Christensen (2011) explains the design concept of low-temperature district heating (LTDH). Theoretical investigations on low-temperature operation have been carried out in EFP (2007) and Olsen et al. (2008), and applied in Brand, Dalla Rosa, and Svendsen (2010) and EUDP (2008).

Low-temperature DH operates with a temperature of 55°C, which means that the legionella problems that can occur in DHW systems need to be considered. According to the German Standard (DVGW 1993) and research done in Germany (Rühling and Rothmann 2013), the risk of legionella growth is small as long as the water volume is less than 3 l and the temperatures are above 50°C or below 20–25°C. If each home uses a local substation that contains small amounts of water and is able to boost the water temperature this problem will be avoided. Moreover, recent research in Sweden has shown good results using UV-disinfection (Efsen 2012; Teknikmarknad 2011).

When end-use savings are implemented in buildings connected to a DH system, the heat demand profiles for the individual buildings will change, which will affect the heat profile for the entire DH system. Researchers in Sweden looked into how the end-use heat savings in buildings will affect DH production, including costs and primary energy savings (Gustavsson et al. 2011). They found that a significant amount of the primary energy savings was in the peak load units. In their study, the peak loads were supplied by light fuel oil boilers, but in the future, such peak loads will have to be covered by RE systems, which will be expensive. Therefore, after implementing energy-saving measures, the heat load duration profiles for the buildings are important, since they are the dimensioning foundation for the future DH systems. To avoid oversized RE-based capacity, a long-term perspective needs to be taken.

Studies (Tol and Svendsen 2012a, 2012b) have investigated low-temperature DH for buildings with existing radiators, focusing on the relationship between supply temperature, mass flow rate

and the dimensioning of the pipe distribution system based on future and current situations. One study (Brand et al. 2012) focused on finding the best heating system solution, while achieving good thermal indoor comfort, for new low-energy single-family houses based on LTDH. However, we found no research on LTDH for existing multi-storey buildings using the existing radiator system, which focuses on achieving good indoor thermal comfort as well as implementing end-use savings.

This study describes a method for supplying LTDH to existing multi-storey buildings, focusing on the implementation of various levels of energy renovation and achieving good thermal indoor comfort. Furthermore, it describes a dynamic dimensioning method for the future DH capacity based on the RE supply. The study investigates to what extent it is possible to reduce the peak loads when supplying low-temperature DH, without compromising on the indoor thermal comfort of the renovated building. We examined the relationship between the reduction in annual heat savings and changes in heat load profiles.

Two building blocks from the early 1900s located in typical urban areas in Denmark were investigated, and end-use savings were carried out concurrently with conversion to low-temperature DH supply.

2. Methods

Two building blocks, one in Aarhus and the other in Copenhagen, were used as case studies for this investigation. They are both located in typical urban areas and are from 1910 and 1906, respectively. Both of them are typical for a large share of the existing buildings in urban areas, which have large energy-saving potential. The existing state of the buildings was analysed, after which energy-saving measures were implemented to decrease energy consumption. Three levels of energy renovation were investigated (Table 1).

Three different energy renovation strategies were investigated, since it might be too optimistic a goal to carry out *extensive* energy renovations on all buildings within a short period. So it was important to investigate various levels of renovation in order to find out whether low-temperature DH can provide acceptable comfort temperatures with a small degree of energy-saving renovation. It might also be too expensive to carry out *extensive* energy renovation on all buildings now. It might be more reasonable to build new, instead of carrying out relatively expensive renovation measures. Simply replacing windows is a relatively cheap and easy way of obtaining some savings now. Furthermore, a number of buildings are protected, so the external façade must be preserved. The Internal façade insulation needs to be applied, which is costly and takes up the inside space, and can lead to problems with moisture and fungi (BYG-ERFA 2013; Morelli et al. 2012).

The building energy simulation software IDA-ICE 4 (EQUA 2013) was used for numerical simulations to determine the energy consumption before and after the implementation of energy-saving measures. The DRY weather file for Denmark was used for the simulations. According to the Köppen–Geiger Climate Classification, Denmark is indexed as belonging to the category Cfb (C: warm temperature, f: fully humid, b: warm summer) (Kottek et al. 2006), and according to the heating degree day (HDD) method, Denmark has an index of 3479 HDD (European Commission 2008).

Table 1. Energy renovation levels.

	New windows (with solar shading)	Mechanical ventilation (heat recovery = 85%, minimum air change $0.5\,h^{-1}$)	Basement insulation	Roof insulation	Façade insulation
Extensive renovation	X	X	X	X	X
Intermediate renovation	X	X	X	X	
Window renovation	X	X			

Figure 1.   (a) 3D-models of the buildings in Aarhus and (b) 3D-models of the buildings in Copenhagen.

2.1.   *Description of the buildings*

2.1.1.   *The building in Aarhus*

The building consists of five floors for residential living plus an unheated attic and basement. The overall heated area is $850\,m^2$. The load-bearing construction is made of wooden beams and brick walls. There is no façade insulation, but the building went through a renovation in 1989 upgrading some parts of the building envelope, so the roof is insulated with 200 mm stone wool. However, the horizontal division between the ground floor and the basement has no insulation. The windows were replaced with double-glazing. The ventilation is natural, coming from opening windows and leaks. Only *extensive* and *intermediate* renovation was carried out, because the windows had already been changed in 1989 and the energy-saving potential in simply replacing the windows would be rather small compared with a building that has not yet been renovated. Only one floor was modelled in IDA-ICE as representative for the entire building (Figure 1).

2.1.2.   *The building in Copenhagen*

The building in Copenhagen also consists of five floors for residential living, plus an unheated attic and basement. The overall heated area is $3409\,m^2$, spread out over 43 apartments. The bearing construction is made of wooden beams and brick walls. There is no insulation in the façade, roof or the horizontal division between the ground floor and the basement. The windows are old one-layer inefficient windows. Fresh air is provided by natural ventilation from opening windows and leaks. All three levels of energy renovation were carried out – the *extensive*, *intermediate* and *window* renovation. Three apartments were modelled in IDA-ICE as representative for the entire building (Figure 1).

   The U-values and infiltration for both buildings before and after the various renovation measures are presented in Table 2. To include the heat loss from the roof and to the basement, the extra heat losses from here have been included in the models as a weighted average in the U-value for the façade. The thickness of the façade varies, with smallest thicknesses at the top and under the windows, so the façade U-value was based on a weighted average, representing the entire building façade. The radiators were dimensioned based on the heat losses from the zones in the existing building using an annual simulation with IDA-ICE. The radiators were dimensioned based on a supply temperature of 70°C and a return temperature of 40°C (Korado 2013).

2.2.   *Annual heat demand and heat load profile*

The savings in annual heat demand were studied and compared with the savings at peak load. Since peak load production is very costly, it is desirable to reduce the peak load as much as possible. So

Table 2. *U*-values for the buildings before and after renovation.

U-values and infiltration	Copenhagen		Aarhus	
	Existing	Renovated	Existing	Renovated
Façade (W/m² K)	1.34	0.16	1.34	0.16
Windows (W/m² K)	4.50	0.97	2.90	1.28
Roof (W/m² K)	1.20	0.11	0.20	0.13
Horizontal division between ground floor and basement (W/m² K)	1.20	0.16	1.50	0.30
Infiltration (h⁻¹)	0.5	0.05	0.5	0.05

Figure 2. Sketch of duration curve for SH – daily average.

we investigated the lower limit to which it is possible to dimension peak load production and still provide an acceptable indoor thermal comfort when the building has been renovated. The savings and indoor comfort were studied for dimensioning peak load production based on daily average values. Furthermore, we investigated whether it is possible to go one step further and dimension peak load production based on an average of the five days with the highest daily average values without compromising on indoor thermal comfort (Figure 2).

2.3. *Return temperature from building to DH network with low-temperature DH*

With low-temperature DH, it is crucial to have the same cooling of the DH water in the system. Traditional DH systems have a $\Delta T = 30$ K (70–40°C), so the return temperature should be 25°C if the supply is 55°C. If ΔT is decreased, the mass flow rate needs to be increased to achieve the same power output. If the existing distribution pipes in the DH network are to be used, the mass flow rate cannot be increased, which implies that ΔT in the system needs to stay at 30 K. The return water from the building to the DH network was logged and analysed.

3. Results

3.1. *Annual energy consumption*

3.1.1. *The building in Aarhus*

As a result of the energy-saving measures, the total energy consumption decreased as shown in Table 3. If the building undergoes an *extensive* renovation, it is possible to achieve an annual heat reduction of about 70–80% and a total energy reduction of about 60–70%, which is in accordance with the findings in Kragh (2010), Kragh and Wittchen (2010), Lund et al. (2010), Rasmussen (2010) and Tommerup (2010). The differences in the reduction in annual energy and annual SH are due to the extra energy used for mechanical ventilation. A consumption of 4–5 kWh/m²

Table 3. Annual energy demand and reduction compared with existing building.

	Existing	Extensive renovation[a]				Intermediate renovation[a]			
	SH set point = 20°C	SH set point = 20°C		SH set point = 22°C		SH set point = 20°C		SH set point = 22°C	
		CAV	VAV	CAV	VAV	CAV	VAV	CAV	VAV
SH (kWh/m^2)	133	38	29	55	43	106	95	136	124
DHW (kWh/m^2)	13	13	13	13	13	13	13	13	13
Mechanical ventilation (kWh/m^2)	–	5	5	5	4	5	4	5	4
Total (kWh/m^2)	146	56	47	72	61	124	112	154	141
SH reduction[b] (%)	–	71	78	59	68	20	28	−3	6
Total energy reduction[b] (%)	–	62	68	51	58	15	23	−5	3

[a]Supply temperature: 55°C year round.
[b]Compared with existing building.

for mechanical ventilation is in accordance with the findings and suggestions in Tommerup and Svendsen (2006). When a building undergoes a renovation, it is often observed that the occupants discover an increased comfort level and, therefore, increase the room temperature from 20°C to 22°C. The increase of 2°C results in an increased SH demand of about 30%, which indicates the importance of user behaviour for the energy savings achieved. If an *intermediate* renovation is carried out, it is possible to achieve a reduction in SH demand of 20–30% if the set point for the room is kept at 20°C. If this is increased to 22°C, the energy savings are negligible, so in this case, user behaviour is crucial for achieving savings. Low-temperature DH with a supply temperature of 55°C was applied in both renovation levels, and it was possible to reach a minimum comfort temperature of 20°C in both cases without having to increase the supply temperature in cold periods.

Furthermore, Table 3 shows that the use of variable air volume (VAV) ventilation provides lower total energy consumption than constant air volume (CAV) ventilation. This is due to extra heat losses in cold periods with CAV. The Danish Building Regulations 2010 (Danish Energy Agency 2013) set a maximum energy consumption for residential buildings at $(52.5 + 1650/A) \, \text{kWh/m}^2 = 62 \, \text{kWh/m}^2$ including SH, DHW and energy for ventilation, with A being the heated area. An *extensive* renovation makes it possible to obtain an energy level in accordance with these requirements.

3.1.2. *The building in Copenhagen*

For the building in Copenhagen, Table 4 shows that an annual heat reduction of about 70–80% and a total energy reduction of about 60–70% can be achieved if the building undergoes an *extensive*

Table 4. Annual energy demand and reduction compared with existing building.

	Existing	Extensive renovation		Intermediate renovation		Window renovation	
	20°C	20°C	22°C	20°C	22°C	20°C	22°C
SH (kWh/m^2)	128	22	34	66	86	80	103
DHW (kWh/m^2)	13	13	13	13	13	13	13
Mechanical ventilation (kWh/m^2)	–	8	8	8	8	8	8
Total	141	43	55	87	107	101	124
SH reduction[a] (%)	–	82	73	48	33	38	20
Total energy reduction[a] (%)	–	69	61	38	24	29	12

[a]Compared to the existing building.

renovation. This is similar to the building in Aarhus. The mechanical ventilation system in this building is based on CAV and the consumption is slightly higher than the building in Aarhus at 8 kWh/m^2, but still in accordance with Tommerup and Svendsen (2006). If an *intermediate* renovation is carried out, it is possible to reach a reduction in SH demand of 30–50%, depending on the set-point temperature for the rooms. Occupant behaviour has proportionately greater influence on the SH savings when fewer energy-saving measures are implemented. *Window* renovation on its own provides approximately 10% less than the *intermediate* renovation. The old windows were very inefficient, so a lot of the saved energy is due to the replacement of windows (20–40%).

Low-temperature DH is implemented with a building supply temperature of 55°C. It was possible to reach a minimum comfort temperature of 20°C for all three renovation levels without having to increase the supply temperature in cold periods.

As for the building in Aarhus, it is possible to obtain an energy level that complies with the requirements for new buildings in the Danish Building Regulations 2010 (Danish Energy Agency 2013) if an *extensive* renovation is carried out.

3.2. *Changes in heat load profile*

3.2.1. *The building in Aarhus*

When energy-saving measures are implemented, the heat load profile for the individual building changes. Figure 3 shows the duration curve for daily average SH loads, with the heat demand becoming more constant over the year as a result of the energy savings. The more energy-saving measures are implemented, the lower the duration curve becomes (less loads) and more constant the heat demand is. This means that the DH plant will not have to invest in so much renewable supply capacity because the peak loads are lower. Furthermore, the demand will be more constant, which will also result in lower costs for the DH plants.

Table 5 shows the reduction in the peak load based on the hour with the highest load. As shown, the reduction is about 40–50% for the *extensive* renovation and between 15% and 20% for the *intermediate* renovation.

We also investigated whether it is possible to dimension the DH capacity for the renovated building, based on an average of the five days with the highest daily average heat loads, without compromising on indoor thermal comfort. For this investigation, one scenario for each renovation level was chosen. For the *extensive* renovation, the investigation was based on a scenario with VAV and a set-point temperature of 22°C while, for the *intermediate* renovation, we chose a scenario with VAV and a set point of 20°C. Table 6 shows the peak loads and the peak load reductions compared with the existing building, based on the different dimensioning scenarios for the *extensive* and *intermediate* renovations, respectively. Table 7 shows the thermal indoor comfort
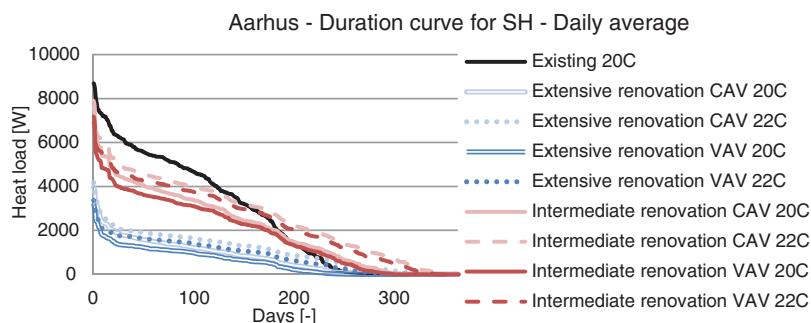
Figure 3. Duration curve for SH – daily average.

Table 5. Reduction in peak load compared with the existing building based on hourly values.

| | Extensive renovation | | | | Intermediate renovation | | | |
| | SH set point = 20°C | | SH set point = 22°C | | SH set point = 20°C | | SH set point = 22°C | |
Percentage	CAV	VAV	CAV	VAV	CAV	VAV	CAV	VAV
Reduction in peak load (hourly values)	43	52	42	52	14	20	15	21

Table 6. Reduction in peak load compared with the existing building.

| | Extensive renovation | | Intermediate renovation | |
	Peak load (VAV–SH set point = 22°C) (W)	Reduction (%)	Peak load (VAV–SH set point = 20°C) (W)	Reduction (%)
Hour with the highest load	4918	52[a]	8127	20[a]
Day with the highest average load	3361	61[b]	6884	21[b]
Average of five days with the highest daily average load	2853	67[b]	5958	31[b]

[a]Reduction compared with the existing building with the highest hourly load.
[b]Reduction compared with the existing building with the highest daily average load.

Table 7. Temperatures in the living zones and hours outside comfort limits.

Average of five days with the highest daily average load	Living room 1	Living room 2	Living room 3	Living room 4	Bedroom 1	Bedroom 2	Bedroom 3	Bedroom 4
Extensive renovation-SH $T_{set\ point}$ = 22°C								
$T_{i\_}$max (°C)	26.4	26.4	26.3	26.7	26.0	25.7	26.3	26.0
$T_{i\_}$min (°C)	20.7	20.8	20.2	20.2	20.2	20.1	20.3	20.0
T_i < 20°C	0	0	0	0	0	0	0	0
Intermediate renovation-SH $T_{set\ point}$ = 20°C								
$T_{i\_}$max (°C)	26.3	26.3	26.2	26.6	25.9	25.5	26.2	25.9
$T_{i\_}$min (°C)	18.1	18.2	17.0	17.9	17.3	17.3	17.2	17.3
T_i < 20°C	101	90	208	97	144	170	145	168
T_i < 19°C	15	14	59	15	42	46	47	39
T_i < 18°C	0	0	18	2	12	13	15	13
% Hours below 20°C	1.2	1.0	2,4	1.1	1.6	1.9	1.7	1.9
% Hours below 19°C	0.2	0.2	0.7	0.2	0.5	0.5	0.5	0.4
% Hours below 18°C	0	0	0.2	0	0.1	0.1	0.2	0.1
T_i < 20°C with SH set point = 22°C	14	13	54	14	32	36	44	33
T_i < 20°C with increased supply temperature to 70°C in cold periods	13	10	44	13	23	26	34	25

in terms of hours outside the desired temperature range. As shown, it is possible to reach the same reduction in the peak loads as for the annual SH reduction (Table 3) when the dimensioning of the DH capacity is based on the average of the five days with the highest daily average loads. With the *extensive* renovation, there are no hours below 20°C. With the *intermediate* renovation, a significant proportion of hours are below the limits with the lowest temperature being 17.4°C, which is not acceptable. If the set point for the room is raised to 22°C during cold periods, however, it is possible to avoid hours below 20°C for most of the year. This will increase the annual energy

consumption, but the effect will be small, 2.4% over the year at the most. If the supply temperature is increased to 70°C in cold periods, the number of hours below 20°C slightly decreases, but it is not possible to completely avoid hours below 20°C. However, the number of hours below 20°C varies between 10 and 44, which is less than two days.

3.2.2. *The building in Copenhagen*

The same tendency of a reduction of the peak loads and a change in the duration curve is seen with the building in Copenhagen. Figure 4 shows the duration curve for SH based on the daily average; the heat demand becomes more constant over the year as a result of the energy savings. The more energy-saving measures implemented, the lower the duration curve becomes (less loads). This is beneficial for the DH companies in terms of initial capital investment costs and the degree of utilisation of the plants.

Table 8 shows the reduction in the peak load based on the different dimensioning scenarios. As shown, the reduction for the *extensive* renovation is about 60% for the hour with the highest load, 65% for the day with the highest average load and 70% for an average of the five days with the highest daily average loads. For the *intermediate* renovation, the reduction is about 30–35% for the hour and day with the highest load, and about 40% for the average of five days. The *window* renovation results in reductions of about 20–25% for the hour and day with the highest load, and about 30% for the average of five days.

Table 9 shows the hours outside the thermal indoor comfort range for the *extensive*, *intermediate* and *window* renovations. The set point is 20°C and it was not possible to keep a minimum temperature of 20°C all year round. If the set-point room temperature is increased to 22°C in very cold periods, it is possible to avoid any hours below 20°C for all renovation levels. Furthermore,
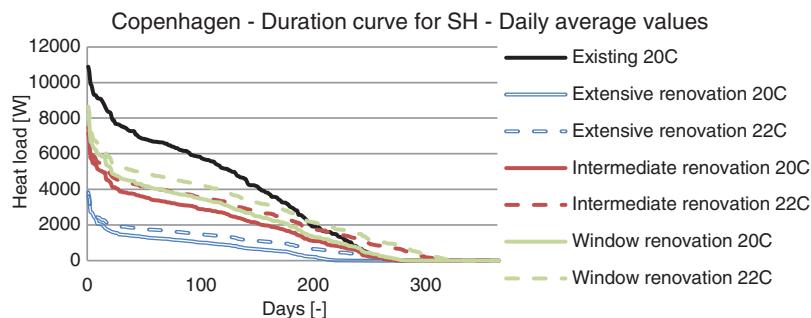
Figure 4. Copenhagen: duration curve for SH – daily average values.

Table 8. Reduction in peak load compared with the existing building.

Reduction compared with existing building (supply = 55°C all year)	Extensive renovation		Intermediate renovation		Window renovation	
	20°C	22°C	20°C	22°C	20°C	22°C
Hour with the highest load[a] (%)	58	57	31	30	23	21
Day with the highest average load[b] (%)	67	65	34	31	25	21
Average of five days with the highest daily average load[b] (%)	72	70	43	40	34	30

[a]Reduction compared with the existing building with the highest hourly load.
[b]Reduction compared with the existing building with the highest daily average load.

Table 9.   Temperatures in the living zones and hours outside comfort limits.

Average of five days with the highest daily average load	Living room 1	Living room 2	Living room 3	Bedroom 1a	Bedroom 2a	Bedroom 2b	Bedroom 3a	Bedroom 3b
Extensive renovation 20°C								
Ti_max (°C)	27.0	27.2	26.5	27.0	27.0	26.9	26.5	26.5
Ti_min (°C)	18.8	19.3	18.8	18.9	19.4	19.2	18.7	18.2
Ti < 20°C	35	16	35	28	13	27	41	35
Ti < 19°C	5	0	4	4	0	0	6	4
% Hours below 20°C	0.4	0.2	0.4	0.3	0.2	0.3	0.5	0.4
% Hours below 19°C	0.1	0	0.1	0.1	0	0	0.1	0.1
Ti < 20°C with SH set point increased to 22°C	0	0	0	0	0	0	0	0
Intermediate renovation 20°C								
Ti_max (°C)	26.7	27.2	26.8	26.8	26.9	26.8	26.8	26.7
Ti_min (°C)	18.3	18.6	18.3	19.0	19.2	18.8	18.3	18.6
Ti < 20°C	56	38	55	17	23	40	55	44
Ti < 19°C	14	9	12	1	0	5	4	8
% Hours below 20°C	0.6	0.4	0.6	0.2	0.3	0.5	0.6	0.5
% Hours below 19°C	0.2	0.1	0.1	0	0	0.1	0.1	0.1
Ti < 20°C with SH $T_{set\ point}$ increased to 22°C	0	0	0	0	0	0	0	0
Window renovation 20°C								
Ti_max (°C)	26.9	27.4	27.2	26.9	27.2	27.1	27.1	27.0
Ti_min (°C)	18.2	18.3	18.1	19.0	19.1	18.8	18.1	18.5
Ti < 20°C	64	42	62	16	29	42	61	47
Ti < 19°C	16	13	15	0	0	5	15	10
% Hours below 20°C	0.7	0.5	0.7	0.2	0.3	0.5	0.7	0.5
% Hours below 19°C	0.2	0.2	0.2	0	0	0.1	0.2	0.1
Ti < 20°C with SH $T_{set\ point}$ increased to 22°C	0	0	0	0	0	0	0	0

if the occupant wants to have an indoor room temperature of 22°C, the supply temperature from the DH plant can be increased from 55°C to 70°C in cold periods.

3.3.   *Return temperature from building to DH net*

When low-temperature DH is applied with an unchanged flow rate, the performance of the radiators decreases by a factor of 2.5. If the flow is increased, the performance will increase as well, but to
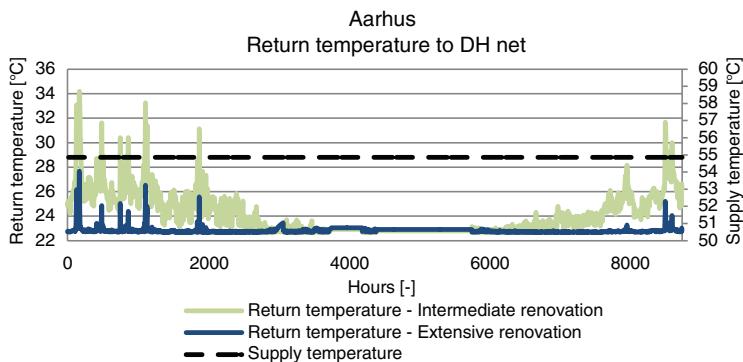
Figure 5.   Return temperature to DH network for building in Aarhus.

obtain an acceptable cooling of the DH water in the radiator (30 K), the flow cannot be increased (see Section 2.3), so the supply temperature may need to be increased in cold periods.

The return temperatures from the buildings to the DH network are presented in Figures 5 and 6 based on a supply temperature of 55°C all through the year. The figures are based on a set-point temperature for the room of 22°C. The return temperature will be higher for a set-point temperature of 22°C than for a set-point temperature of 20°C, and thus represents the worst-case scenario. In general, the lower the level of energy renovation implemented, the higher the return temperature is. $\Delta T = 30$ K can only be achieved in the case of *extensive* renovation, whereas with *intermediate* and *window* renovation, it cannot be achieved the entire year. The solution is to increase the supply temperature when $\Delta T = 30$ K is not achieved.

Figure 7 shows the return temperature and the ΔT for the building in Aarhus with *intermediate* renovation when the supply temperature is increased to 60°C in cold periods. The weather-compensated curve related to the supply temperature is shown in Figure 8.

Figures 9 and 11 show the return temperature and the ΔT for the building in Copenhagen for the *intermediate* and *window* renovations, respectively, when the supply temperature is increased to 60°C or 70°C in cold periods. The weather-compensated curves related to the supply temperature are shown in Figures 10 and 12.

4. Discussion and conclusions

Energy renovations were carried out on two typical Danish building blocks from the early 1900s in urban areas. It was found that the end-use energy consumption for both buildings can be reduced to the level the Building Regulations 2010 (BR10) require for new buildings – approximately 50–60 kWh/m^2 – when extensive energy renovation is implemented. This implies a combined solution where the façade, the roof and the basement are insulated, the windows are replaced with new energy-efficient windows with solar shading and mechanical ventilation with heat recovery installed. This is in agreement with what has been found in other studies (Kragh 2010; Kragh and Wittchen 2010; Lund et al. 2010; Rasmussen 2010; Tommerup 2010).

It was found that, if the expensive façade insulation is excluded, it is still possible to obtain end-use energy savings of 30–50% depending on whether the set-point temperature for the rooms is 20°C or 22°C. User behaviour has a significant impact on the energy savings achieved, and this impact is proportionately greater when fewer refurbishment measures are implemented.

Moreover, we found that the heat load profiles over the year generally decrease and become more constant as a result of the energy renovation, which is of great benefit to heating companies, since it provides a better utilisation of the heating capacity and, therefore, reduces the costs.

The dimensioning peak load was found to be reduced by the same percentage as the reduction in the annual SH, if the dimensioning is based on an average of the five days with the highest daily average loads. Furthermore, we found that it was possible to achieve an acceptable indoor thermal comfort with a minimum temperature of 20°C for the building in Copenhagen. For the building in Aarhus, a few hours corresponding to a total less than two days, were below 20°C with an *intermediate* renovation. This is generally not acceptable, and suggests that dimensioning criteria based on an average of five days with the highest daily average load might be too much for new DH capacity if an *intermediate* renovation is carried out. However, there were no problems for the building in Copenhagen or for the *extensive* renovation case in Aarhus. The conclusion we draw from this is that it depends on the savings achieved in the specific building and on the design of its existing heating systems. An average of five days with the highest daily average loads might be slightly too high in some cases, but acceptable in other cases.

The reduction in peak load leads to lower costs for investment in new RE supply capacity, which is beneficial to DH companies. Figure 13 shows our findings for possible reductions in the annual demands and in the peak loads.

The investigation indicated that it is possible to supply buildings with LTDH for most hours of the year without compromising on indoor thermal comfort. In cold periods, it might be necessary to increase the supply temperature to either 60°C or 70°C because, with LTDH, the performance
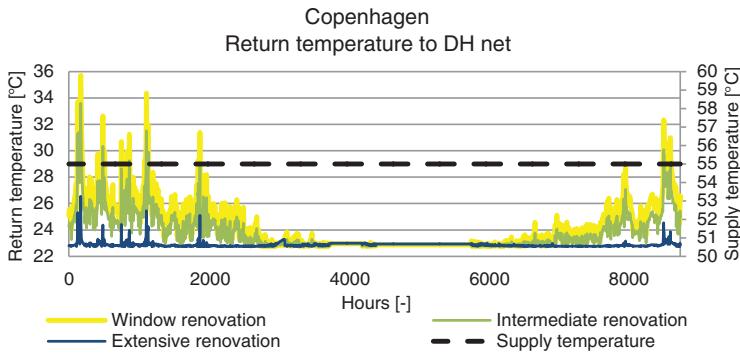
Figure 6.   Return temperature to DH network for building in Copenhagen.
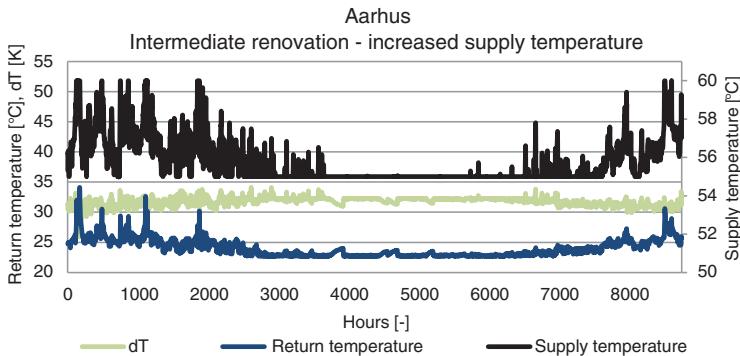
Figure 7.   Increased supply temperature, return temperature and ΔT for the building in Aarhus – intermediate renovation.
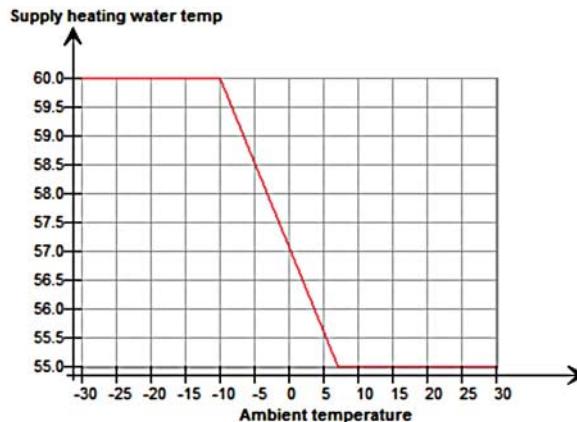
Figure 8.   Aarhus: intermediate renovation. Supply temperature as a function of the outdoor temperature.
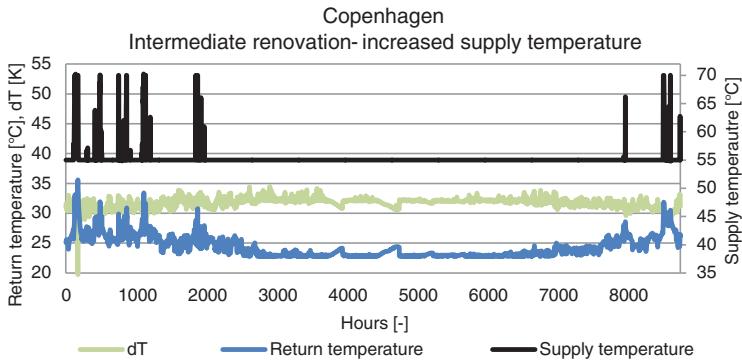
Figure 9. Increased supply temperature, return temperature and ΔT for the building in Copenhagen – intermediate.
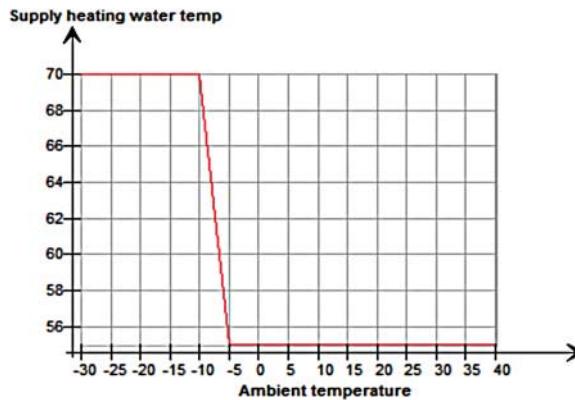
Figure 10. Copenhagen: intermediate renovation. Supply temperature as a function of the outdoor temperature.
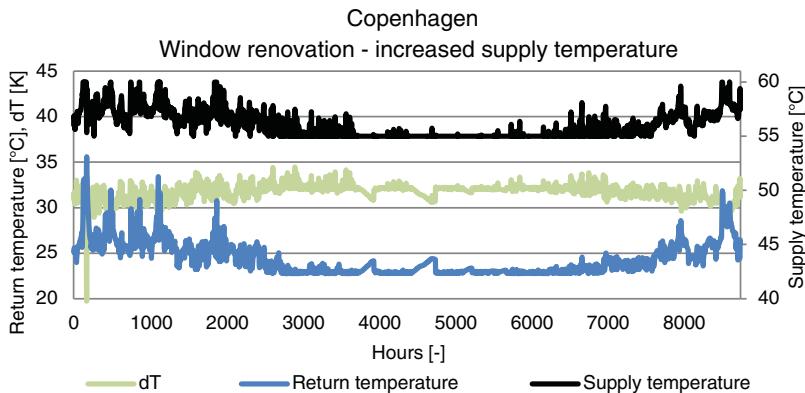
Figure 11. Increased supply temperature, return temperature and ΔT for the building in Copenhagen – window renovation.

of the radiators decreases by a factor of 2.5 with an unchanged flow rate. If the flow is increased, the performance will increase, but to obtain an acceptable cooling of DH water in the radiator (30 K), the flow cannot be increased. If we are to keep the existing DH distribution net, it is crucial that the cooling of the DH water for LTDH application corresponds to a traditional system (30 K), so the return temperature is of great importance. We found that it is possible to obtain a
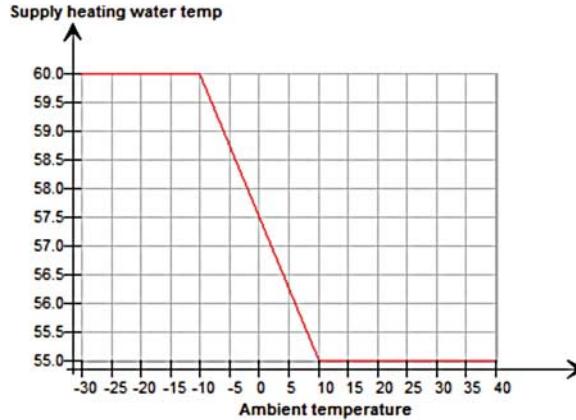
Figure 12.   Copenhagen: window renovation. Supply temperature as a function of the outdoor temperature.
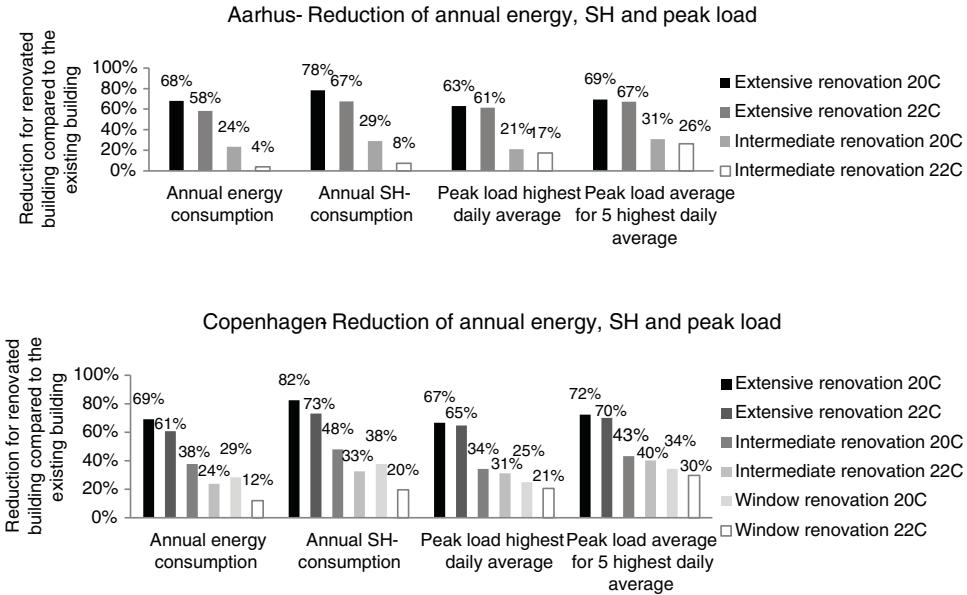
Figure 13.   (a) Reduced energy consumption and peak loads in Aarhus and (b) reduced energy consumption and peak loads in Copenhagen.

return temperature of 25°C in the case of *extensive* renovation, but that for the *intermediate* and *window* renovations the supply temperature needs to be increased slightly. If the increase is to 60°C, the period required will be longer than if the increase is to 70°C. However, increasing the supply temperature to 60°C can still be considered relatively low-temperature operation, and the supply temperature will reach a 60°C operation only when the outdoor temperature is lower than −10°C. Increasing the supply temperature to 70°C will be needed for a shorter period. In this case, the supply temperature starts increasing when the outdoor temperature is below −5°C and will increase proportionally until the outdoor temperature is −10°C. The period when the outdoor temperature is lower than −5°C is less than 5% of the year. This indicates that LTDH operation for existing buildings that undergo renovation is possible most hours of the year.

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Paper 3 – Appendix 3

Full-scale test of an old heritage multi-storey building undergoing energy retrofitting with focus on internal insulation and moisture

CrossMark

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ABSTRACT

The hypothesis investigated in this article is: it is possible to carry out moisture safe energy renovations in the old existing multi-storey buildings with heritage value and still save 50% of the building's energy consumption by use of existing technologies. A holistic energy renovation on an old multi-storey building with heritage value was carried out. Focus was given to energy-saving measures that would preserve the original architectural expression of the building, such as internal insulation. Comprehensive measurements were performed on the energy consumption before and after the renovation to document the obtained savings. Numerical simulations were validated with the measurements in order to explain the savings and to carry out parameter variations on the energy saving measures. Since internal insulation was applied the durability and robustness were investigated and measurements of the temperature and relative humidity were performed in the wooden beams-ends embedded in the masonry brick wall. A solution where the insulation was stopped 200 mm above the floor was investigated. This increased the heat flows through the wall compared to a fully insulated wall, and calculations showed that the difference in the space heating consumption was 3 kWh/m^2/yr. The measurements showed the proposed solution should have no risk of moisture problems. The measured energy consumption was reduced with 47% whereas the theoretical reduction could be reduced with 39–61% depending on the room set-point temperature (20–24 °C).

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1. Introduction

The EU roadmap aims at reducing greenhouse gas emissions and energy consumptions by 20% by 2020 and 80% in 2050 compared to 1990-levels [1] and Denmark has set an even more ambitious goal: being completely fossil-fuel-free by 2050 [2,3]. Energy retrofitting of existing buildings is vital for the achievement of reductions in energy use. However, challenges occur when it comes to retrofitting heritage buildings where the façade cannot be modified due to the architectural value of the building. Buildings with solid brick walls and wooden beam construction were constructed mainly in the period between 1850 and 1920. Approximately 20% of all dwellings in Denmark today are built within that period and represent a significant energy saving potential [4,5].

One study [6] investigated a holistic energy retrofitting of a multi-storey building with heritage value from 1930, which was constructed with solid brick façades and wooden beams. They found that it was theoretically possible to save 70% of the energy consumption without having to use external façade insulation. Funch and Graves [7] carried out a retrofitting of a historical building with solid brick walls and wooden beam construction and applied internal insulation at some facades. They found that it was possible to save 30% energy based on calculations but no further analyses were made on the use of internal insulation with respect to the moisture risk. Another study [5] investigated energy savings measures for the improvement of the thermal insulation of a building with solid brick walls and wooden beam construction. They concluded that it is possible to reduce the heat losses with 62% by applying internal insulation on the external facades, insulating the roof, and replacing the windows. These three studies are all based solely on calculations, whereas the research presented in this article also includes a comprehensive measuring program. Morelli et al. [8] studied different energy saving measures for heritage buildings and tested them in a test apartment. Measurements were

performed in the wooden beam-ends and in the interface between the brick wall and insulation and theoretical calculations of possible energy savings were carried out. They concluded that it was theoretically possible to save 68% of the energy consumption for the entire building and that the measurements showed no risk of mould growth or wood decay. The research reported here presents a similar analysis, but for an entire building block instead of only a test apartment. Also energy measurements are included, which was not the case for the research in Ref. [8].

Another study [9] carried out a retrofitting of a historical building, where internal insulation was planned. However, due to the risk of condensation they decided not to apply internal insulation. When the façade is insulated from the inside, the outer brick wall becomes cold and its drying potential is reduced. Condensation in the interface between the insulation and the brick wall can occur and can lead to mould growth [10]. Also the moisture and temperature conditions in the wooden beams are subject to change when internal insulation is applied so attention needs to be given to the risk of mould growth on the wooden surfaces and the risk of the wood decay, which, in extremis, can lead to fatal structural damage. Krebs and Collet [11] studied temperature and moisture content measurements in 30 wooden beam-ends. Insulation was applied at the interior at some walls and no insulation at others in order to compare the influence of the internal insulation. They concluded that wind driving rain did not have a significant influence and only a very limited risk for moisture problems in the beam-ends was present. Morelli and Svendsen [12] carried out a theoretical investigation on various intensities of wind-driven rain on façades using numerical simulation and [13] investigated the effect on the wooden beam-ends in a laboratory using vacuum insulating panels. Both studies concluded that wind driven rain has a great impact on the performance and durability of the wooden beam-ends. Kehl et al. [14] provided a literature review that also concludes that wind-driven rain has an important influence on the behaviour of moisture content and the risk of beam-end decay. The use of internal insulation is still in a grey zone when it comes to the safety with regards to possible moisture problems.

There is a need to find robust solutions for energy savings in the old heritage building stock. The solutions on the market today for heritage-valued buildings have still not been documented to the extent needed for the building sector to take responsibility for applying them on a large scale. While old heritage buildings have similar constructional trends, each is unique in their specific design, so solutions are difficult to standardize. There is a need to find standard solutions for the energy renovation of this segment of buildings that are technically feasible. Instead of aiming at saving the most energy, solutions that pay regard to finding a balance of energy savings and the durability in terms of reduced moisture risk needs to be in focus. Compared to the knowledge from the articles in the literature review this article presents new knowledge on full-scale tests of a multi-storey heritage residential building undergoing a deep and holistic energy renovation using internal insulation.

The aim of the research reported in the current paper was to set focus on creating solutions that save energy but also are moisture safe. The hypothesis is that it is possible to carry out moisture safe energy renovations in the old existing multi-storey buildings with heritage value and still save 50% of the building's energy consumption by use of existing technologies. A case study was used to test the hypothesis and an energy renovation was carried out in an old heritage multi-storey building. Internal insulation, new improved windows constructed to aesthetically match the old ones and mechanical ventilation with heat recovery was applied. Comprehensive full-scale measurements were carried out to demonstrate and document the obtained energy savings before and after the renovation and numerical simulations were compared with the measurements in order to evaluate the theoretical and actual savings against each other. Since internal insulation is an energy saving measure that could play an important role in the future energy renovations of heritage buildings, it is important to document the durability and robustness of it and find a compromise of reducing the heat losses through the wall and in the same time ensure moisture safe solutions. A comprehensive measuring program was established monitoring temperature and relative humidity (RH) in the wooden beam-ends embedded in the solid masonry wall in order to evaluate the risk of mould growth and woods decay.

2. Method

To evaluate energy savings the applied method compared theoretical calculations with full-scale measurements as described in the steps below. The applied method evaluated the durability of using internal insulation and was based solely on measurements in the wooden beam construction.

The first step was to document the energy consumption for the existing building before the renovation. The energy consumption for the existing building was calculated and validated with the actual measured energy consumption in the building. The calculations were carried out using the numerical building energy simulations software IDA ICE 4.5. The detailed simulation model is described under Section 3.2.1. The measurements for energy consumption before the renovation consisted of the average Space Heating (SH) and Domestic Hot Water (DHW) consumption over the period of 2007–2009.

The second step was to document the energy consumption for the renovated building. Heating consumption, including SH and DHW, and electricity consumption for ventilation were measured. The heating consumption was measured for the entire building and the relative use of SH was measured by heat meters on the radiator in all rooms. The electricity consumption for the ventilation was measured using HOBO loggers. The energy consumption for the renovated building was also calculated with IDA ICE and validated with the measurements monitored after the renovation. Real weather data was used as input in the simulation model.

After validating the model for the energy renovated building in IDA ICE *the third step* was to calculate the normalised annual energy consumption using standard weather data (Design Reference Year) (DRY) and user behaviour in order to be able to evaluate the results. Based on the normalised model the effectiveness of the various energy-saving measures implemented in the building were calculated in order to evaluate the influence of the individual energy saving measures.

The fourth step was to investigate the durability of the internal insulation and investigate whether it would lead to a risk of mould growth. Relative humidity and temperature measurements were carried out in the wooden beam-ends embedded in the masonry walls. A solution with 200 mm gap in the insulation above the floor was implemented, which is described under Section 3.3.2, and the reduced heat losses compared to the reduced heat losses of a fully internally insulated façade was estimated using Heat 2, which is a 2D heat transfer simulation software. Also the effect on the total building space heating consumption was estimated.

This method was applied in the context of a specific case study, as described below.

3. Case study – an old multi-storey building in Copenhagen with heritage value

The building is located in Copenhagen, Denmark, and was built in 1896. It is a multi-storey building with 6 floors with a heated area

of 2717 m^2 and an unheated basement. The building consists of 30 apartments located in three apartment blocks (Blocks A, B and C). The building can be seen in Fig. 1 and the plan view of the building together with a 3D-view of the model built in IDA ICE 4.5 can be seen in Fig. 2. The building is constructed with solid masonry brick walls and wooden beams in the floor construction, which are embedded in the brick wall. The exterior walls had no insulation and the windows were old 1-layer inefficient windows. The building has heritage value, which implies that the external façade cannot be changed. The building is heated using district heating, and fresh air was provided by natural ventilation from opening windows and infiltration. In the toilet/bathrooms and kitchens, an exhaust ventilation system had been installed, but in most apartments the ducts were blocked and did not work. Many of the apartments did not have a shower.

3.1. Retrofitting approach

3.1.1. General improvements

The building went through a deep retrofitting where energy-saving measures were in focus, but the interior comfort was also improved by installing new kitchens and bathrooms in all apartments. All surfaces were renovated and new electric wiring and plumbing were installed. The municipality granted permission to install penthouse flats with roof terraces and solar photovoltaic systems, increasing the total value of the building, but the production from the solar photovoltaics was not included in the evaluation of the energy performance because the focus in this paper was on energy-saving measures. It was decided to keep the existing heating system in the building based on district heating and radiators. The building can be seen in Fig. 1(a) before the renovation and in Fig. 1(b) after the renovation.

3.1.2. Building envelope

The municipality accepted that the windows were to be replaced with new windows because the test apartment showed that this would be the most cost and energy optimal choice. The new windows were constructed aesthetically as the old windows but with energy efficient 3 layered glazing and wooden frames (Fig. 1(d)). Due to the heritage value of the building, internal insulation was used (Fig. 1(c)) except for the north-east façade (Block C). This façade faces a narrow passage and 250 mm external

Fig. 1. a) The building before renovation. b) The building after the renovation. c) Internal insulation applied. d) New energy efficient windows with 3 layered glazing constructed aesthetically as the old once. e) AHU in basement for central ventilation systems in Block A and B. f) AHU for decentralised ventilation systems in Block C.
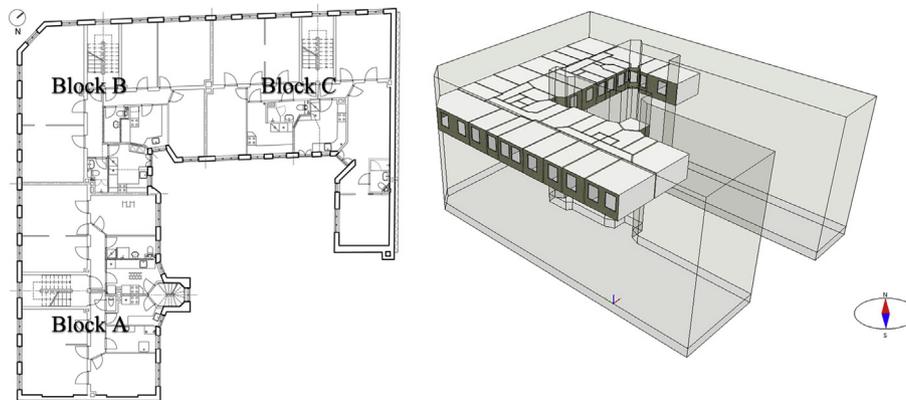
Fig. 2. Left: Plan drawing of the apartments. Right: 3D-view of IDA ICE model.

Table 1
Description of the ventilation systems.

	Block A	Block B	Block C
Location of AHU	Central ventilation system with AHU in basement	Central ventilation system with AHU in basement	Decentralized ventilation system with AHU in each apartment
Operation control	Constant operation	Demand controlled operation based on: - CO_2 - Relative humidity - Temperature - User panel for specific needs	Constant operation
Air flows	Supply air flow: • 140 m³/h Exhaust air flow from bathroom: • RH < 55%: 20 m³/h • RH > 55%: 54 m³/h Exhaust air flow from Kitchen: • Cooker hood off: 72 m³/h • Cooker hood on: 144 m³/h	Supply air flow: • 22 m³/h*–144m³/h Exhaust air flow: • 22 m³/h*–144m³/h	Supply air flow: • 140 m³/h Exhaust air flow from bathroom: • RH < 55%: 20 m³/h • RH > 55%: 54 m³/h Exhaust air flow from Kitchen: • Cooker hood off: 72 m³/h • Cooker hood on: 144 m³/h

* The air flow of 22 m³/h does not fulfil the Danish building regulations, but the municipality granted permission to ventilate with only 22 m³/h during unoccupied hours.

mineral wool was applied (Thermal conductivity = 0.039 W/mK). The apartments in Block A and B were insulated with a mix of mineral wool and aerogel with a thermal conductivity of 0.019 W/mK. In the apartments in Block C, a rigid thermoset modified resin insulation was applied with a thermal conductivity of 0.020 W/mK both with a thickness of 40 mm and a gypsum plate of 10 mm added to the inside. Under and around the windows only 20 mm insulation was applied with a gypsum plate of 10 mm.

3.1.3. Mechanical ventilation

Different mechanical ventilation systems with heat recovery were installed in the three apartment blocks. Table 1 shows a description of the three ventilation systems. In blocks A and B, the air handling units (AHU) are located in the basement (Fig. 1(e)) and the existing chimneys were used for the exhaust from bathrooms and kitchens. The air intake and exhaust are over the roof, but since there is no space in the attic for the AHU, the air is led down to the basement for heat recovery. The three different systems allows for comparison of energy consumption and ease of the installation. It can be a challenge to find space for the ducts in old building, especially for central ventilation systems, where the AHU is located either in the attic or in the basement. The air flows met the requirements of the Danish Building Regulations [15], with exception of the system in Block B, where permission was given to operate with lower air flows during unoccupied hours. In Block C the system was decentralised on apartment level (Fig. 1(f)).

3.2. Calculations with simulation tools

3.2.1. Energy calculations with IDA ICE

The model was created with the building energy simulation software IDA ICE only for one floor representing the entire building (Fig. 2). All rooms were modelled and calculated. To create a representative floor, a weighted average U-value for the façade was calculated including the heat losses through the entire façade and through the roof and basement. The thickness of the façade is thinnest at the top of the building and under the windows and thickest at ground level, which is taken into account in the weighted U-value. Furthermore, the total heat loss through the roof/floor is calculated based on the roof/floor area (W/K), after which the heat losses are distributed over the façade area (W/m²K) and then added to the weighted U-value for the façade in the simulation model (W/m²K).

The weighted U-value for the façade is calculated to be 2.01 W/(m²K) for the existing building and 1.01 W/(m²K) for the renovated building. The north-east façade was insulated with external insulation and the U-value is 0.14 W/(m²K). The U-value for the windows were 4.20 W/(m²K) before the renovation and 0.89 W/(m²K) after the renovation.

Infiltration was set to 0.5 h^{-1} (one half air change per hour) for the existing building and 0.05 h^{-1} (0.05 air change per hour) for the renovated building due to the air tightening of the building envelope (new windows and internal insulation). The heat exchanger efficiency was expected to be 85%. Internal heat gains were divided

Table 2
Occupant profile for the different rooms types.

	Bedroom		Living room		Dining room		Kitchen	
Occupants [−]	2		2		2		2	
Activity level [MET]	0.7		1		1		2	
Internal heat gain related to activity level [W]	72		108		108		108	
Schedule	Mon−Fri	Presence	Mon−Fri	Presence	Mon−Sun	Presence	Mon−Sun	Presence
	00:00−08:00	1.0	00:00−15:00	0.0	00:00−15:00	0.0	00:00−08:00	0.0
	08:00−23:00	0.0	15:00−19:00	0.5	15:00−24:00	0.5	08:00−09:00	1.0
	23:00−24:00	1.0	19:00−23:00	1.0			09:00−18:00	0.0
			23:00−24:00	0.0			18:00−20:00	1.0
	Saturday−Sun		Saturday−Sun					
	00:00−08:00	1.0	00:00−09:00	0.0				
	08:00−23:00	0.0	09:00−20:00	0.5				
			20:00−24:00	1.0				

into a) heat gains from occupants and b) heat gains from electrical appliances and lighting. The heat gains from occupants were described based on schedules for occupant presence in each room to create more realistic dynamics in the building. Four room profiles were made and are described in Table 2. The internal gains from electrical appliances and lighting were set to a daily average constant value of 3 W/m^2. Morelli et al. [6] chose to use a daily average internal heat gain value of 3.5 W/m^2 for equipment and lighting. Firlag and Zawada [16] found the average daily internal heat gain to be between 3.1 and 5 W/m^2 including heat flow from occupants and appliances in the living room and between 2.2 and 3 W/m^2 in the bedroom. The chosen value for internal heat gains from electrical appliances and lighting therefore seems reasonable. The simulations where carried out with measured weather data for validating the model, and with the DRY-weather for the normalised weather simulations. Room set-point temperatures of 20, 22, and 24 °C were simulated. A parameter study was carried out to determine the effect of the heat exchanger efficiency and of the infiltration rate and natural ventilation due to opening of windows. Simulations with heat exchanger efficiency of 70% and infiltration rates on 0.1−0.2 h^{-1} were performed.

3.2.2. Heat flow and temperature distribution calculated with heat 2

Transient heat flow and temperature distribution was calculated with Heat 2 using a sinus function for the outdoor climate and a constant indoor temperature on 20 °C accordingly to the Danish Standard DS418 [17]. The calculations were performed for three cases; a) no insulation, b) full insulation on the interior side of the external façade and c) internal insulation with a 200 mm gap over the floor allowing for an evaluation of the reduced energy savings when a gap of 200 mm is made.

3.3. Measurements carried out in the test building

3.3.1. Energy measurements

Measurements for heating consumption and electricity consumption for ventilation were performed. The measurements on heating consumption included SH and DHW. Since no separate measurements for DHW existed, the heating consumption measured in the summer month (June and July) was used to estimate the DHW consumption. The SH consumption per apartment was found based on relative heat distribution data. The measurements of electricity consumption for ventilation were taken centrally for each system (Block A, B and C) and represent the total electricity consumption for each ventilation system.

3.3.2. Moisture and temperature measurements

To evaluate the implementation of internal insulation and the effect on the beam-ends with regard to moisture, temperature and RH sensors were installed in the beam-ends and measurements were performed (Fig. 3). According to Blocken and Carmeliet [18]
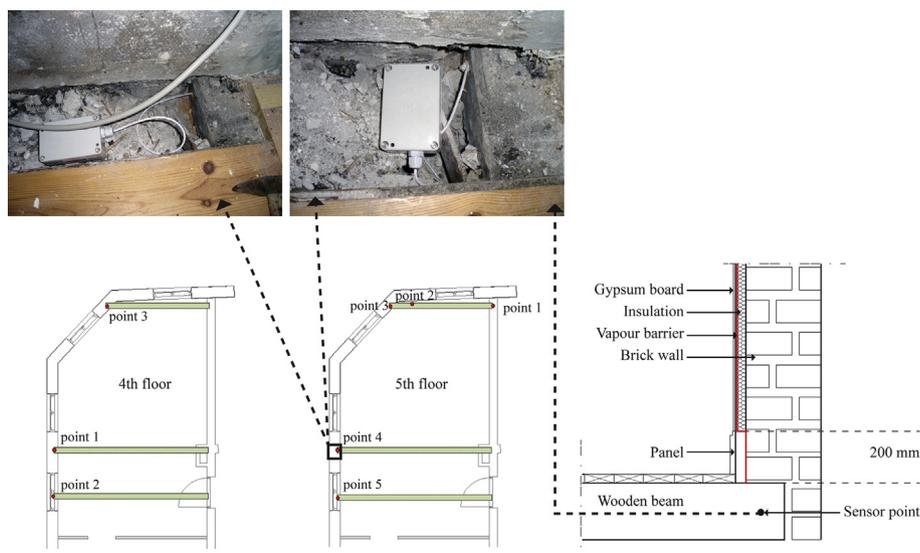
Fig. 3. Left: Measurement points for temperature and relative humidity in the beam-ends on 4th and 5th floors. Right: Drawing of how the internal insulation was mounted.

and Kragh [19], the effect of wind-driven rain is greatest at high positions on the façade close to the corners. The dominant wind direction in Denmark is southwest-west [20] so the measurements for this study were carried out in the two corner apartments facing southwest and west on the 4th and 5th floors. The measuring points and the section plane for the wall/floor construction are shown in Fig. 3 together with pictures of the sensors. The insulation was stopped 200 mm above the floor (Fig. 3, right), in order to create a thermal bridge around the wooden beams so that increased temperatures decreases the moisture to a safe level. The heat losses through the wall will be higher compared to a solution with insulation applied on the entire façade, but the priority is firstly to ensure moisture safety and secondly to save energy. This solution is supported by investigations carried out by Morelli and Svendsen [12], who concluded that if the insulation is stopped 200 mm above the floor and below the ceiling, the risk of mould growth and wood decay in the wooden beam-ends embedded in the masonry brick wall is significantly reduced. The red line in Fig. 3 (right) demonstrates the vapour barrier installed.

4. Results and discussion

4.1. Energy consumption

4.1.1. Validation of IDA ICE model for the existing building with measured energy consumption

The annual measured energy consumption for the existing building was 156 kWh/m^2. The calculated annual energy consumption before the renovation was found to be Block A: 129 kWh/m^2, Block B: 148 kWh/m^2 and Block C: 178 kWh/m^2, which results in a total weighted annual consumption of 152 kWh/m^2. The deviation between the measured and the calculated annual heating and hot water consumption for the existing building was 2.6%, which is smaller than one could expect.

4.1.2. Validation of IDA ICE model for the renovated building with measured energy consumption

4.1.2.1. Heating consumption after renovation. The measured heating consumption can be seen in Fig. 4 and includes SH and DHW. The annual DHW consumption is estimated to be 18 kWh/m^2, which is above the requirements for new buildings namely 13 kWh/m^2 according to the Danish building regulations 2010.

The annual SH consumption was measured to be 60 kWh/m^2, which is above the expected consumption. A numerical simulation model in IDA ICE was created in order to evaluate the heating consumption and the reason for the higher SH consumption. As shown in Fig. 5(A), the calculated SH consumption deviated significantly from the measured with the ideal settings. Since the ventilation system had some operational problems, the heat recovery might be less than the assumed 85%. Moreover, an analysis carried out on the occupant behaviour suggested that the infiltration rate could be higher than the ideal 0.05 h^{-1}, increasing the heat
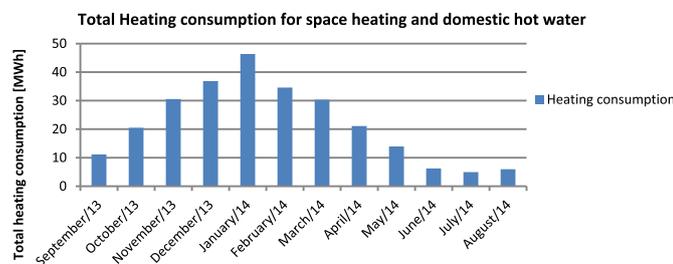
losses. The analysis showed that some people were smoking inside the apartments with the windows open, and that many of the occupants opened the windows in the bedroom and living room daily even though the mechanical ventilation system should be able to provide sufficient fresh air. Additionally, possible air leakages around the windows could be a reason for increased infiltration rates. As shown in Fig. 5B, C, and D, the simulated SH consumption is similar to the measured when the heat recovery efficiency is 70%, the infiltration rates are increased to 0.1 h^{-1}–0.2 h^{-1}, and when the room set point temperature is approximately 22–24 °C. This results in a relative deviation less than 5%. From Fig. 5 it is seen that the increased temperatures have larger influence on the energy savings than the increased infiltration rates.

The temperature level in each apartment was measured and the average temperature level was approximately 22–23 °C, which corresponds to the findings of the simulated results. Moreover, the temperature levels in some of the apartments was very low, i.e. down to 11 °C, which could be due to habits of opening windows while smoking or to get fresh air. If the heating system is on, the result is increased heating consumption. It was measured that there is no overheating hours during the heating season as a result of the energy renovation and thereby any related influence on the energy consumption.

To illustrate how much the energy savings were reduced by the decreased heat recovery efficiency, increased infiltration rates, and increased temperature levels, compared to the expected or ideal savings, Table 3 shows the difference between the simulated expected consumptions and the measured consumptions. The table shows an increased SH consumption of 25 kWh/m^2 if the occupants have a room temperature of 20 °C, and 8 kWh/m^2 if they have a room temperature of 24 °C. This is a considerable amount of energy lost due to occupant behaviour and operational failures.

4.1.2.2. Electricity consumption for ventilation. The electricity consumption for the three different ventilation systems was measured one year from August 2013 (Fig. 6). As can be seen, the systems did not have stable operation during the entire period, so the operation was only evaluated since January, when it was more stable. The non-optimal operation of the ventilation systems also confirms that the heat recovery efficiency might be lower than the 85% assumed and that the ventilation flow rates might not have been as expected, which could influence SH consumption and indoor comfort. As shown in Fig. 6, the ventilation system in Block A consumed up to 5 times as much electricity as the two other systems. The higher consumption compared to Block C can be due to the longer duct run and increased pressure loss. However, Block A and B have similar duct runs both being centralized system, and the explanation of the higher consumption in Block A is due to a constant air flow operation compared to a variable operation in Block B.

Table 4 shows the calculated and measured annual electricity consumption for the three different ventilation systems. The table shows that the measured and calculated electricity consumption differed with 1.9 kWh/m^2 for Block A with the measured consumption being the largest, whereas the difference for Block B and C was only 0.2–0.4 kWh/m^2 respectively, the measured consumption being the smallest.

4.1.3. Annual energy consumption − energy savings achieved

Table 5 shows the normalized annual energy consumption for the renovated building for three different temperature levels together with the measured energy consumption before and after the renovation. The calculated electricity consumption for ventilation was adjusted with the measured to provide more accurate better results.

Fig. 4. Measurements on heating consumption after the renovation incl. SH and DHW.
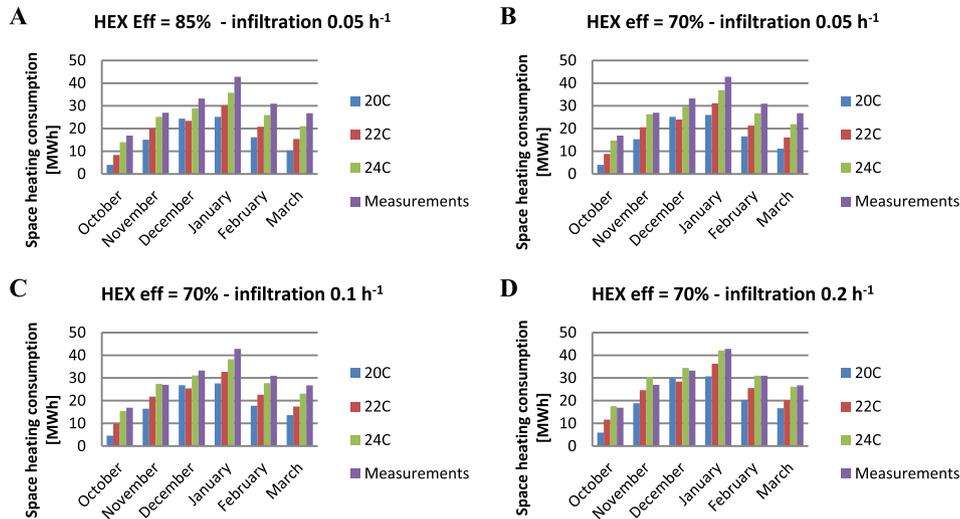
Fig. 5. Validation and fitting of SH consumption from October to March.

Table 3
Difference between the expected and actual SH consumption from October to March. Measured SH consumption = 54 kWh/m^2.

	At 20 °C	At 22 °C	At 24 °C
Expected SH consumption	29	36	46
Reduced space heat savings from October to March (expected savings minus actual savings) [kWh/m^2]	25	18	8

The measured annual energy consumption was found to be reduced to 82k Wh/m^2, corresponding to savings of 47% compared to the existing building. The calculated annual energy consumption for the renovated building was found to vary from 61 to 96k Wh/m^2 depending on the room set-point temperature, which corresponds to a reduction in the energy use of 39–61% compared to the energy use before the renovation. The investigation found that the room set-point temperature was between 22 and 24 °C, implying that the expected savings were not obtained. However, if the occupants decrease the set-point temperature to 20 °C, the building will consume 61 kWh/m^2/yr, which is close to the requirements for new buildings in the Danish Building regulations 2010 [15]. This implies that technically the renovation carried out can decrease the energy consumption to the expected energy level, but in reality the consumption is higher, which underlines the significant impact that occupant behaviour has. The temperature during the measured winter was in average almost 3 °C higher than the average normalized temperature (DRY), resulting in a higher heat consumption during a normal winter. It was found that the effect of the warmer winter resulted in a decreased heat consumption of approximately 5 kWh/m^2 from October to March.

4.1.4. Effect of the energy saving measures

To illustrate how much energy was saved by each of the different energy-saving measures installed in the building, Fig. 7 shows the distribution of the savings achieved. The calculations were carried out based on ideal conditions with a set-point temperature of 20 °C and the extra infiltration due to occupant behaviour, i.e. opening of windows, was ignored. Each energy-saving measure is shown as a percentage of the total savings. As shown in the figure, the new windows provided the highest savings, followed by the internal insulation and mechanical ventilation with heat recovery. If the extra infiltration was included the distribution of the energy saving measures would look different. However, it is complicated to investigate the influence since it is

difficult to know if they should be added to the windows or to the ventilation or as share on each due to the interaction between them. Additionally, it is preferable to find a solution to avoid the extra infiltration losses instead of trying to model the effect.

4.1.5. Heat consumption distribution in the building

The distribution of the SH consumption from November to March to each apartment can be seen in Fig. 8. It can be seen that *C-Apart 1* consumed more than five times the average SH consumption being 24 kWh/m^2 from November to March. This particular apartment is used for commercial purposes, which may explain the higher consumption. The remaining apartments consumed very differently: from close to 0 kWh/m^2 to almost 80 kWh/m^2.

4.2. Moisture and temperature measurements in the wooden beam-ends

Fig. 9 shows the daily average temperature and relative humidity measured in the beam-ends on the 4th and 5th floor. According to Viitanen et al. [21], there is no risk of mould growth that can create smell and health problems on a wooden surface when the RH is less than 75%. This is in agreement with a guideline for avoiding mould growth on wooden surfaces in the Danish buildings developed by the Danish Building Research Institute [22]. They state that there is a risk of mould growth when RH > 75%. Another guideline [23] from Denmark directed at the building industry states that if the RH is above approximately 70%, mould growth can take place. This is in agreement with a study [24] that states that the lowest RH where mould growth can happen is at 70%. This however, is only at a temperature of 30 °C. Other relevant literature [25–28] states that when the RH < 75–80% there is no risk of mould growth on building materials at room temperature. Viitanen [29] states that if the RH > 80% for several weeks/months, there is a risk of mould growth in pine and sapwood when the temperature is

Measured daily electricity consumption for the ventilation systems
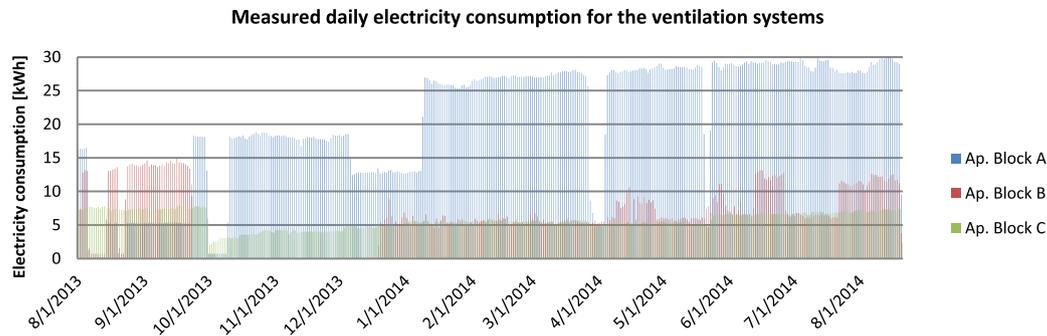
Fig. 6. Measured electricity consumption for the three ventilation systems.

Table 4
Measured and calculated annual electricity consumption for the three ventilation systems.

[kWh/m²]	Block A Central constant ventilation		Block B Central demand controlled ventilation		Block C Decentralized ventilation room level	
	IDA ICE	Measured	IDA ICE	Measured	IDA ICE	Measured
Annual electricity consumption per m²	8.0	9.9	2.8	2.4	2.5	2.3

Table 5
Annual energy consumption for the existing and renovated building based on measurements and numerical simulations using DRY weather file. SH is space heating, DWH is domestic hot water, ventilation is electricity use for the ventilation fans.

[kWh/m²/yr]	Existing building	Renovated building							
	Measured	Measured		Calculated 20 °C		Calculated 22 °C		Calculated 24 °C	
	SH, DWH	SH, DHW	Ventilation	SH, DHW	Ventilation	SH, DHW	Ventilation	SH, DHW	Ventilation
Block A	–	–	9.9	70.2	9.9	88.8	9.9	119.4	9.9
Block B	–	–	2.4	48.3	2.4	58.6	2.4	75.4	2.4
Block C	–	–	2.3	50.1	2.3	60.4	2.3	77.8	2.3
Weighted on source	–	78	4.8	56.2	4.8	69.2	4.8	90.8	4.8
Total weighted	156	83		61		74		96	
Savings [%]	–	47		61		53		39	

between 5 and 50 °C. Between 0 and 5 °C, the mould growth is slow and only expected when RH > 90%.

As shown in Fig. 9, the RH is less than 70% at all times (for both the 4th and 5th floor) except for point 3 on the 5th floor, which has RH > 70% during the first months, probably due to build-in moisture, and from November to end of March. Point 3 on the 5th floor has generally higher RH and a lower temperature than the other points, since the façade is facing directly west and exposed to less sun. However, the temperature level reaches maximum 15 °C during winter, which requires the RH to be minimum 78% in 64 days before there is a risk of mould growth [24]. This indicates that
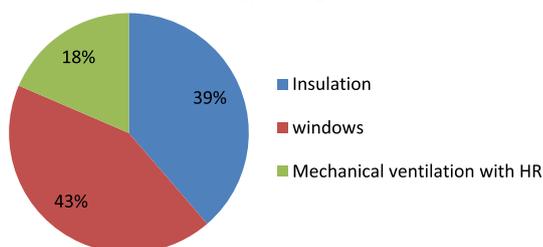
the proposed solution could be durable towards moisture problems.

As a consequence of making a gap in the insulation above the floor construction the heat losses through the façade will be higher than if the entire façade was insulated. Fig. 10 shows the temperature distribution and heat losses through the façade for three cases. One with no insulation, one with full internal insulation, and one with a gap of 200 mm in the internal insulation. It is seen that even when a gap of 200 mm is made the heat losses through the façade is still reduced with approximately 50% compared to the wall without any insulation. Also it is seen that the temperature level in the wooden beam-ends are higher than if the façade was fully insulated. An issue that might occur when leaving a gap in the insulation is that the temperatures behind the gap at the brick wall will be lower than before the renovation and condensation could potentially occur. However, the approach is that the construction is airtight and that the critical places are not in contact with the humid room air. The vapour barrier was placed at the room side of the insulation and down along the brick wall in the gap. A more secure solution would be to continue the vapour barrier down along the wooden panel to the floor and along the floor to the brick wall in order to ensure that moisture diffusion is prevented. Detailed hygrothermal calculations are to be carried out at a later state but are not within the scope of this paper. The effect on the total building energy consumption for leaving out the 200 mm was calculated and it was found that there is a difference of approximately 3 kWh/m²/yr compared to a fully insulated wall.

Distribution of the energy saving measures

Fig. 7. Savings from each specific energy-saving measure as a percentage of the total savings.
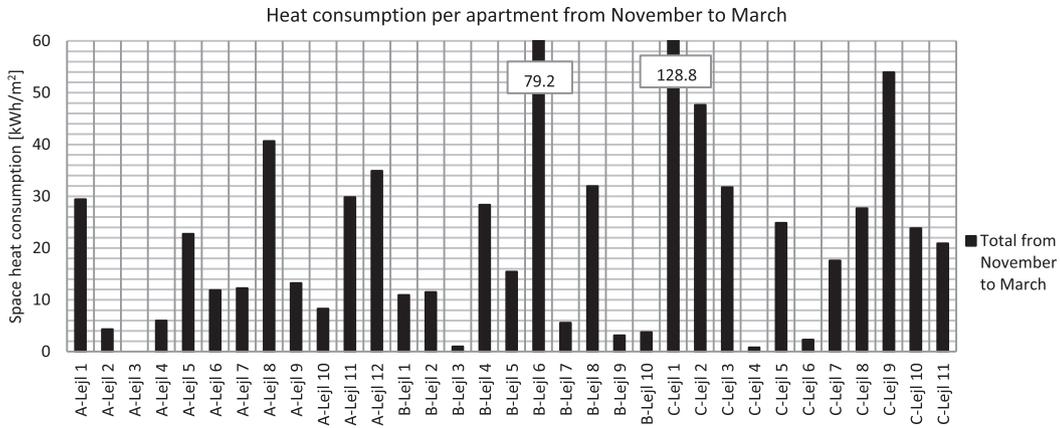
Fig. 8. SH distribution in the building.

4.3. Standardization of the energy renovation solutions

To achieve lower energy levels in the old existing building stock, solutions and methods need to be found and developed, since a great energy-saving potential is present. The energy-saving measures include the replacement of old leaky windows with new energy-efficient windows, the installation of mechanical ventilation with heat recovery, and insulation of the façades, roofs, and floor constructions. However, problems can arise during the process of technical, economical and aesthetical character. The

architectural expression of the façade of heritage buildings cannot be changed, implying that internal insulation is the only facade insulation to be used. However, the use of internal insulation is still in a grey zone when it comes to safety and durability.

Moisture problems might occur, which can damage the building or create an unhealthy environment due to mould growth. Several studies have analysed this aspect but so far no safe conclusions can be drawn that would make it possible to customize solutions. The conditions might differ significantly from building to building, implying different impacts of wind-driven rain, temperatures, sun
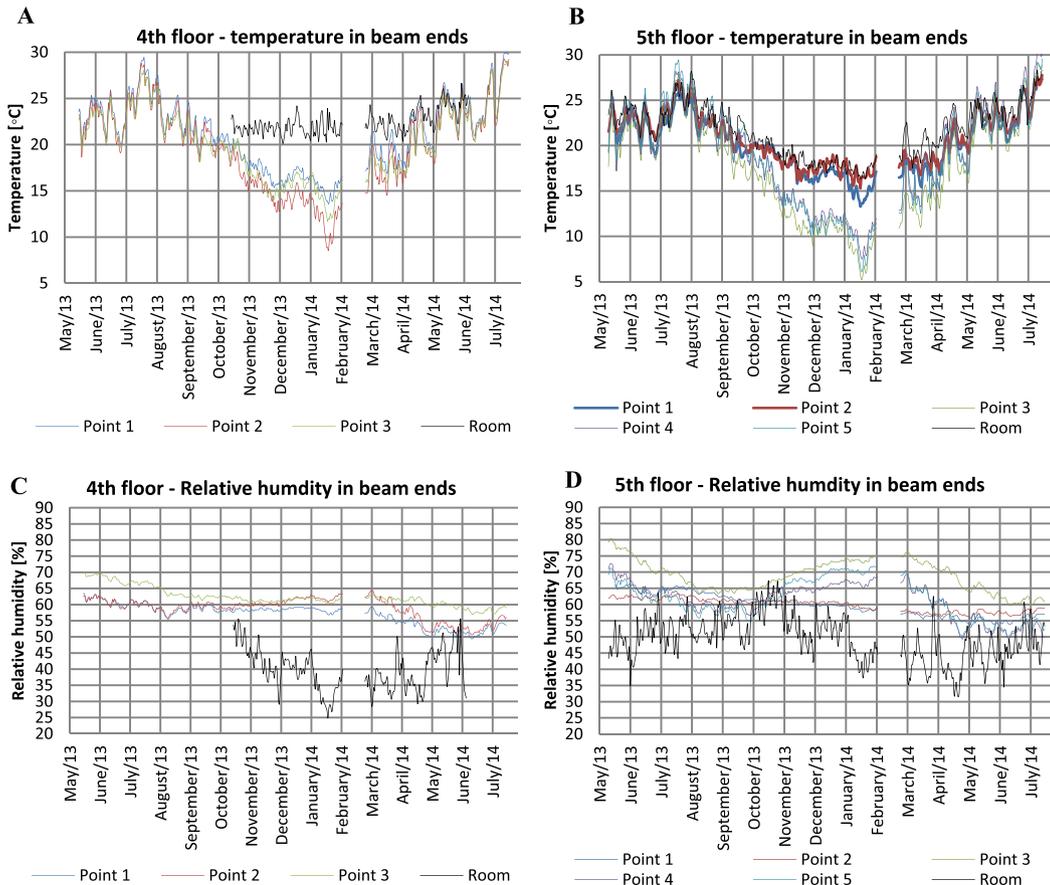
Fig. 9. Daily average temperature and relative humidity measurements in the beam-ends and room on the 4th and 5th floor.

	No Insulation	Full insulation	200mm gap in insulation
Heat flow q [W/m]	30.2	10.3	13.8
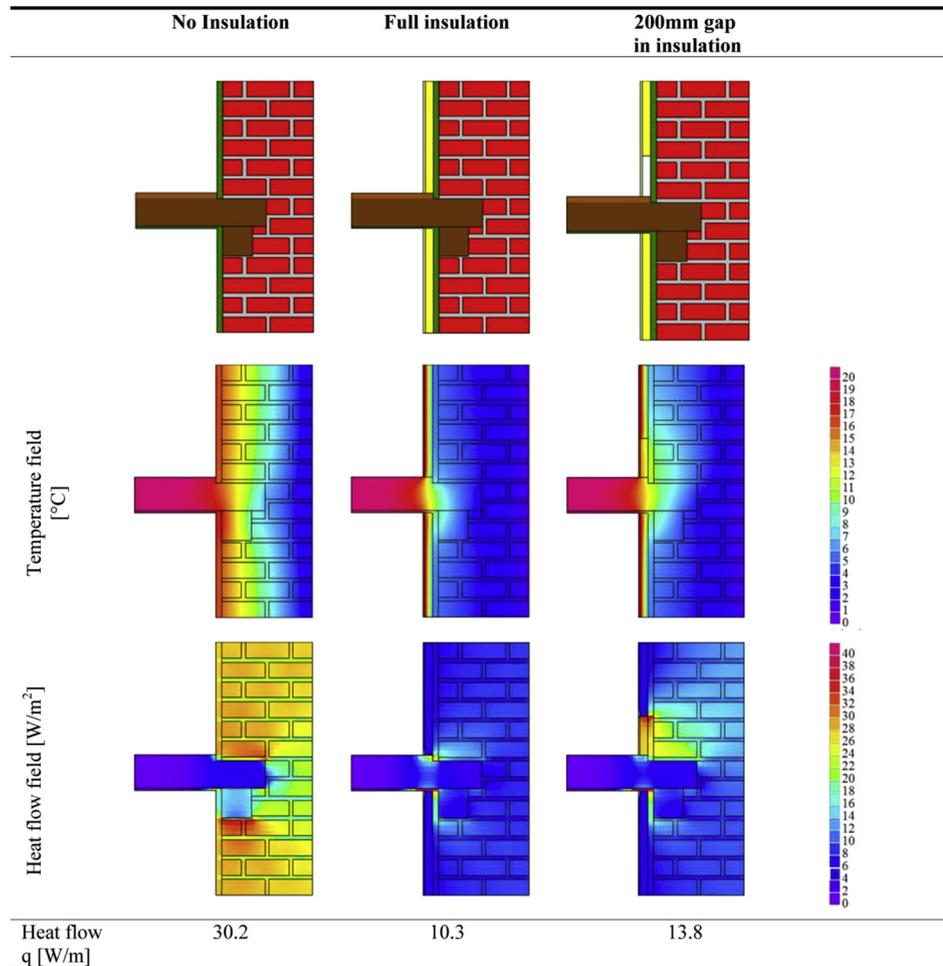
Fig. 10. Detail of assembly of brick wall and floor beam. Temperature field and heat flow through the façade for the three cases: a) no insulation, b) full insulation applied to the internal side of the external facade, and c) internal insulation applied to the internal side of the external facade with 200 mm gap over the floor. Under the floor beam-end there is placed a conductive beam that helps support the floor beams.

etc. Furthermore user behaviour might have an impact on moisture conditions due to different levels of indoor relative humidity (ventilation rates, different habits of cooking, drying clothes, showering, etc.). The hypothesis of this investigation was that it is possible to carry out moisture safe energy renovations in the old heritage buildings and still safe 50% of the energy consumption. In order to create moisture safe solutions it can be necessary to compromise with the energy savings. If the insulation is stopped 200 mm above the floor a thermal bridge is created resulting in increased temperatures around the wooden beam-ends and decreased RH. From this investigation the results showed no risk of moisture problems, and the suggested solution could be the reason, which is also supported in Ref. [12]. However, the measurements were carried out over a milder winter than normal, which also can be a reason that no risk was identified. Applying this solution will reduce the possible heat savings, but calculations show that a 54% reduction of heat flows though the wall can still be obtained compared to a 66% reduction if the entire façade was insulated internally, and consequently a difference in the total building heat consumption of 3 kWh/m^2. Even though more investigations are needed this solution could be durable and used in a wide range of buildings of this category.

The study [30] claims that the north façade could be subject to greater moisture problems since no sun reaches this façade and the wall might not dry out during summertime. The measurements in

this research were carried out on the south-west façade since it is exposed to more wind-driven rain and should be subject for future research. Risk of mould growth at the interface between the insulation and the brick wall is also present, because the temperatures at the interface will decrease. While not investigated in this paper, experience shows that it is crucial to clean the brick wall of all organic material before applying the internal insulation to minimise the risk [31]. Another crucial factor when applying internal insulation is that the risk of freeze-thaw damages, which will increase, since the temperatures in the wall will decrease. Furthermore it takes up living space, which could stop users of the building to invest in internal insulation.

When mechanical ventilation systems are installed in old buildings, it is a challenge to find space for the ducts for traditional central ventilation systems. The solution in this case-study was to take advantage of the staircase leading to the back-yard and install all the ducts there. This might not be an option in every case, which complicates the installation of central systems. The optimal solution might therefore be to install decentralized ventilation systems in each apartment.

5. Conclusions

This paper presents a method for energy renovation of old heritage multi-storey buildings, where moisture safety and energy

savings are balanced. Moisture safety is put prior to energy savings and a solution where the insulation is stopped 200 mm above the floor was investigated.

The energy consumption before and after the renovation was documented with measurements and calculations. Internal insulation and mechanical ventilation systems were installed and analysed, and the windows were replaced with new ones. It was found that the measured annual energy consumption was reduced to 83 kWh/m^2, which corresponds to savings of 47%. The calculated annual energy consumption for the renovated building varied from 61 to 96 kWh/m^2 depending on the room set-point temperature, which corresponds to a reduction in energy use of 39—61%. It was found that the room set-point temperature was around 22—23 °C and that the infiltration rate of the building was higher than expected, implying increased energy consumptions. If the occupants decrease the set-point temperature to 20 °C, the building will consume 61 kWh/m^2/yr (61% savings). Technically the renovation carried out can decrease the energy consumption to the expected savings of 50%, but in reality the consumption is higher. The space heating consumption was found to vary between the apartments by a factor 80, emphasising the importance of occupant behaviour. The replacement of windows and the insulation resulted in the largest energy savings.

The results from this paper documented a solution for internal insulation that could be durable with regards to moisture. A gap of 200 mm was applied in the insulation above the floor. This decreases the possible heat savings through the wall from 66% to 54% compared to the original wall, but no risk of moisture problem in the wooden beam-ends was identified, which is a crucial factor. The effect of the 200 mm gap resulted in a difference in total building heat saving of 3 kWh/m^2/yr. However, more investigations are needed. Additionally the milder winter can be a reason that no risk was identified.

The extent to which the method and solutions suggested in this paper can be generalized is still uncertain. More detailed investigation is needed before any final conclusions can be drawn. This paper solely investigated the technical aspects, which showed that it is possible to save more than half of the existing energy consumption, if user behaviour is taken into account, and still ensure the moisture safety of internal insulation.

Acknowledgements

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Paper 4 – Appendix 4

M. Harrestrup, S. Svendsen (2014).

Internal insulation applied in heritage multi-storey buildings with wooden beams embedded in solid masonry brick façades.

Internal insulation applied in heritage multi-storey buildings with wooden beams embedded in solid masonry brick façades

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Abstract

Internal insulation is investigated in a building with a wooden beam construction and masonry brick walls. Measurements were carried out and used to validate a hygrothermal simulation. The risk of mould growth in the wooden beams and in the interface between the insulation and the brick wall was evaluated. A solution with a 200mm area without insulation above and below the floor/ceiling was investigated. At low rain exposure coefficients (Catch Ratio, CR≤0.1) and with a wall orientation towards the west, this solution can be moisture-safe. However, it not recommended to apply internal insulation on a north-orientated wall, and caution should be exercised also with a west-orientated wall.

Keywords

Internal insulation, mould growth, hygrothermal simulations, moisture safety, wooden beam-ends

1. Introduction

Energy-retrofitting of existing buildings is vital to achieve energy reductions. Most old multi-storey buildings with solid brick walls and a wooden beam construction were built in the period between 1850 and 1920 (Engelmark, 1983). Approximately 20% of all homes in Denmark today were built in that period and they represent a significant energy-saving potential (Rasmussen, 2011), but challenges arise when it comes to retrofitting heritage buildings where the façade cannot be modified due to the architectural value of the building. One solution is to insulate the façade from the inside, but this will result in colder façades and the drying potential of the wall will be reduced. In particular, the diffusion drying capacity through the masonry is reduced, and the surface evaporation can be slowed. Capillary flow, however, is unaffected by insulation and is a powerful moisture redistribution mechanism (Straube and Schumacher, 2007). Condensation, which can lead to mould growth, can occur in the interface between the insulation and the brick wall if the temperature in the interface drops below the dew point (Christensen and Bunch-Nielsen, 2009; Munch-Andersen, 2008; Kolaitis et al., 2013; Abuku et al., 2009). Moreover, the moisture and temperature conditions in the wooden construction will change when internal insulation is applied and attention needs to be given to the risk of mould growth and wood decay here too. Krebs and Collet (1981) studied temperature and moisture content measurements in 30 wooden beam ends. Interior insulation was applied to some walls, and no insulation to others, and the results were compared. They concluded that wind-driven rain did not have a significant influence and that there was only a very limited risk of moisture problems in the beam ends. However, Kehl et al. (2013) provide a literature review that concluded that wind-driven rain has an important influence on the behaviour of moisture content and the risk of beam end decay. Ruisinger (2013) compared five different internal insulation systems in order to investigate the risk of damage to wooden beams, and found no hazard. Morelli and Svendsen (2012) carried out a theoretical investigation on various intensities of wind-driven rain on façades using numerical simulation, and concluded that wind-driven rain has a great impact on the

performance and durability of the wooden beam ends. They also concluded that if the internal insulation stops 200 mm above the floor, the risk of wood decay is minimised and heat losses can still be halved compared to a façade without insulation. However, it is important not only to look at the wood decay but also at the risk of mould growth. Several studies have tried to predict when there is a risk of mould growth on the wooden construction and in the interface between the insulation and the wall. According to Viitanen (1997), there is a risk of mould growth on pine and sapwood if the relative humidity is above 80% for several weeks/months and the temperature is between 5-50°C. At temperatures between 0-5°C, the mould growth is slow and only expected when the relative humidity is above 90%. Viitanen et al. (2008) state that there is no risk of mould growth that can create smell and health problems on a wooden surface when the relative humidity is less than 75%. Sedlbauer (2001) states that if the temperature is 30°C, mould growth can occur at a relative humidity of 70%. However, this is not so relevant since the critical places in the construction will have temperatures around 20°C and below, which require a relative humidity of more than 75-80% to initiate any risks (Johansson et al, 2012; Nielsen et al., 2004; Grant et al., 1989; Johansson et al., 2013). According to Sedlbauer (2002), the critical limit for mould growth on the façade is at a relative humidity higher than 80-90%, depending on the duration and temperature. Morelli (2014) found that to avoid mould growth in the interface it is very important to clean the wall of any organic materials.

Various types of internal insulation product have been developed and are still being developed. Two main types can be identified: diffuse closed and diffuse open insulation products. Diffuse closed insulation requires a vapour-tight barrier, whereas diffuse open insulation relies on capillary-active materials, which have attracted a lot of attention in recent years (Grunewald et al., 2006; Pavlik and Cerny, 2008; Toman et al., 2009). Capillary-active insulation materials can absorb the condensation and transfer it to the inside where it can dry out. According to Scheffler and Grunewald (2003), this means that condensation in the interface can be avoided if capillary-active insulation systems are used. However, Vereecken and Roels

(2014) compared different insulation systems in a laboratory and found that capillary-active insulation materials accumulated more moisture in the interface between the insulation and brick wall than the traditional system using vapour-tight barriers. Other new innovative insulation products showing promising properties are high-performance materials such as aerogel and vacuum-insulating materials. Baetens et al. (2011) and Cuce et al. (2014) carried out reviews on aerogel as a building insulation material and concluded that if aerogel can be manufactured for a fraction of its current economic and environmental cost, it may become an attractive alternative to the more traditional insulation systems currently used because it has extremely good thermal and acoustic properties. Johansson et al. (2014) applied vacuum-insulating panels on the inside of a brick wall constructed with wooden beam ends and carried out laboratory tests and numerical simulations with various wind-driven rain exposures and temperatures. They found that vacuum insulation showed considerable potential for reducing energy use, but also that the temperatures in the wall decreased significantly, which can lead to the risk of condensation in the interface between wall and insulation as well as higher moisture content in the wooden beam ends. Warren et al. (2003) installed a heating pipe just above the floor construction and below the internal insulation to provide increased temperature to heat up the wooden beam construction and consequently decrease the moisture content. They concluded that this reduced the relative humidity by 10-14%.

From the literature it seems that the safety of applying internal insulation is still uncertain and so far no completely safe solutions have been identified. Focus in this area is therefore crucial in order to develop robust solutions for heritage buildings that can save energy but still be moisture-safe.

The research presented in this paper was aimed at investigating in more detail how the brick wall and wooden beam construction embedded in the brick wall is affected when internal insulation is applied. The hypothesis tested was: It is possible to apply internal insulation on the solid masonry brick wall in old heritage multi-storey buildings and achieve a thermal transmittance of 0.2 W/m^{2}K for the exterior wall,

4

corresponding to the requirements for renovation in the Danish Building regulations of 2010, without creating a risk of mould growth on the masonry wall and in the wooden beam construction. Various insulation solutions were investigated, each of which aimed at eliminating the risk of mould growth in a) the wooden beam construction and b) the interface between the insulation and brick wall. The solution suggested in Morelli and Svendsen (2012) where the insulation stops 200mm above the floor and below the ceiling was investigated in more detail, together with a solution where the insulation stops only above the floor, for various wall orientations and rain exposures. The research presented in this article gained new knowledge on the use of internal insulation in brick buildings with wooden beam constructions. Hygrothermal simulations and measurements carried out in a renovated building in Copenhagen were used to evaluate the effect on the wooden beam construction. The risk of mould growth was evaluated with a mathematical mould growth model.

2. Methods

The method applied for this investigation was to carry out measurements in a test building to validate a hygrothermal simulation model created with Delphin Software 5.8. Since the measurements were only carried out in the wooden floor beams embedded in the masonry wall, only that part of the simulation could be validated. Another model for simulating the wall construction was created as a 1D-model to evaluate the risk of mould growth behind the insulation.

Measurements in the wooden beam ends

An old heritage multi-storey building from the beginning of the 20th century in Copenhagen was renovated and internal insulation was applied shown in Figure 1(c). Morelli and Svendsen (2012) suggest leaving a gap in the insulation 200 mm above the floor and below the ceiling to minimize moisture problems in the beam construction. For practical reasons, however, a gap in the insulation of 200 mm was

only applied above the floor construction and not below the ceiling as shown in Figure 1(a). 40mm of insulation with a thermal conductivity of 0.019 W/mK and a 10 mm gypsum board was applied to the façade. The insulation consists of a mixture of aerogel and mineral wool and was applied with an integrated vapour barrier; see the red line in Figure 1(a). The building is constructed with solid masonry bricks and wooden beams as the load-bearing construction. Temperature and relative humidity sensors were installed in the wooden beam ends and used to validate a simulation model (Figure 1(b)). The sensors were installed in two apartments on the 4th and 5th floor with the façade facing south-west. There are no obstacles close to the façade and the wall is therefore highly exposed to the weather, such as wind-driven rain. The measuring points can be seen in Figure 1(a). The indoor temperature and relative humidity were measured in the two apartments to evaluate the indoor climate and to use the data as input to the simulation model.
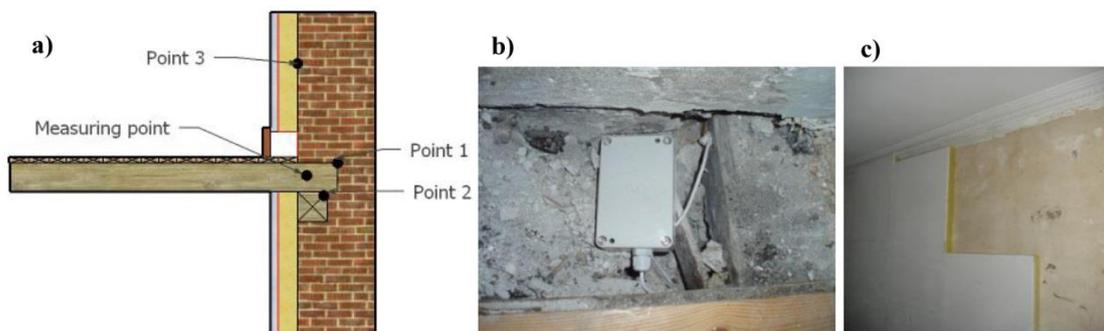
Figure 1: a): Internal insulation applied on the brick wall with an indication of measuring points and investigated areas in the construction, b) Temperature and RH sensors installed in the wooden floor beam ends, c) Internal insulation applied.

Simulation model in Delphin Software

The simulation models were created in Delphin software version 5.8, which is a hygrothermal two-dimensional program. Using a two-dimensional program to analyse a three-dimensional problem implies

great uncertainties with regard to the simulated results. In an attempt to reflect the three-dimensional problem, two sets of simulations were carried out to simulate worst-case scenarios. The assembly of the floor/exterior wall construction is shown in Figure 2(a). The wooden floor beams perpendicular to the exterior wall are spaced approximately 1 metre apart and supported by the load-bearing beam embedded in the exterior brick wall parallel to the exterior façade. One set of models were created with the wooden floor beam perpendicular to the exterior wall (Figure 2(b)), and the other set of models were created without the floor beam (Figure 2(c)).
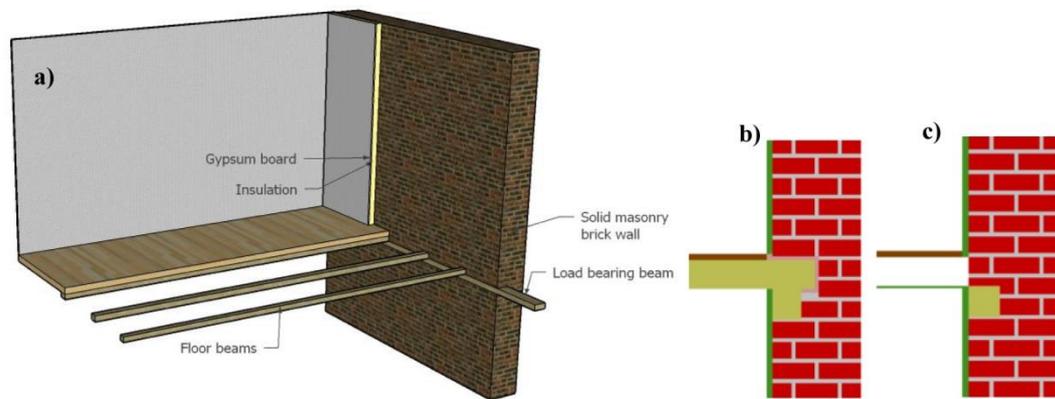
Figure 2: a) Assembly between the exterior wall and the floor construction. Wooden floor beams perpendicular to the façade are spaced approximately 1 metre apart on top of a load-bearing continuous wooden beam in the brick wall. Two sets of models were created in Delphin: b) with the floor beam and c) without the floor beam.

The exterior wall was constructed with bricks separated by lime mortar. The cross section area of the supporting beam is 150 mm x 150 mm and the height of the wooden beam in the floor construction is 140 mm. The floor was constructed as 30 mm wooden floor boards, and around the beam there is an air gap of 20 mm. 30 mm of lime plaster was applied to the façade on the inside. The material properties are shown

in Table 1. The liquid transfer resistance was modelled as a contact resistance at the interface between the bricks and the lime-cement mortar with a value of $5 \cdot 10^{10} \ (m^2 \cdot s \cdot Pa)/kg$. The vapour barrier was modelled as a contact resistance with a vapour diffusion resistance of $10.2 \cdot 10^9 \ (Pa \cdot s \cdot m^2)/kg$.

Table 1: Material properties for simulations in Delphin 5.8

Material properties	Unit	Brick	Lime mortar	Lime plaster	Insulation	Gypsum board	Spruce (wood)	Air gap
Density	kg/m^3	1788	1568	1800	30	850	528	1.3
Specific heat capacity	J/(kg·K)	868	1000	850	840	850	2000	1000
Thermal conductivity	W/(m·K)	0.91	0.70	0.82	0.019	0.20	0.13	0.27
Open porosity	m^3/m^3	0.35	0.41	0.30	0.92	0.65	0.70	-
Saturation moisture content	m^3/m^3	0.35	0.25	0.29	0.9	0.55	0.70	-
Capillary moisture content	m^3/m^3	0.26	0.25	0.25	0.9	0.40	0.55	-
Water absorption coefficient	kg/(m^{2}s$^{0.5}$)	0.227	0.300	0.127	-	0.277	0.058	-
Water vapour resistance factor	-	13.2	30	12	1	10	40	0.2
Liquid water conductivity at saturation moisture content	kg/(m·s·Pa)	1.4·10^{-8}	6.5·10^{-10}	2.8·10^{-9}	-	6.3·10^{-9}	4.0·10^{-9}	-

Boundary conditions. Interior and exterior boundary conditions were applied in the model. The measured indoor temperature and relative humidity were applied when validating the model, and a constant temperature of 20°C and a relative humidity of RH=50% were applied when simulating worst-case scenarios. The exterior environment was simulated with real weather data measured, provided by the Danish Meteorological Institute (DMI) when validating the model. The simulations performed for worst-

case scenarios were simulated with the Design Reference Year (DRY) for Denmark. The boundary

conditions for the interior and exterior environment are listed in Table 2. The thermal heat transfer

coefficients for surface heat flow were: inside: 10 W/(m^{2}K) (upwards), 6 W/(m^{2}K) (downwards), 8

W/(m^{2}K) (horizontal), and outside: 25 W/(m^{2}K). The vapour diffusion coefficients were $3 \cdot 10^{-8}$ kg/

(m$^2 \cdot$ s $\cdot$ Pa) for the interior and $8 \cdot 10^{-8}$ kg/(m$^2 \cdot$ s $\cdot$ Pa) for the exterior. The initial conditions for the

hygrothermal simulation consisted in a temperature of 15°C and a relative humidity of 65%.

Table 2: Boundary conditions for the interior and exterior environment for a) the validation of the model
and b) the worst-case modelling. (DMI=Danish Meteorological Institute, DRY= Design Reference Year).

Boundary conditions	Climate files	Source	
		Validation of model	Worst-case modelling
Inside			
Heat conduction	Air temperature [°C]	Measurements in test building: data points	Constant value: T=20°C
Vapour diffusion	Air temperature [°C] Relative Humidity [%]	Measurements: data points	Constant value: T=20°C, RH=50%
Outside			
Heat conduction	Air temperature [°C]	Measurements DMI: data points	DRY file for Denmark
Vapour diffusion	Air temperature [°C] Relative Humidity [%]	Measurements DMI: data points	DRY file for Denmark
Wind-driven rain	Horizontal Rain [l/(m^{2}h)] Wind direction [°] Wind velocity [m/s] Air temperature [°C] Relative Humidity [%]	Measurements DMI: data points	DRY file for Denmark
Short wave radiation	Direct solar radiation [W/m^2] Diffuse solar radiation [W/m^2]	Measurements DMI: data points	DRY file for Denmark
Long wave radiation	Sky radiation [W/m^2]	Measurements DMI: data points	DRY file for Denmark

Determination of Catch Ratio (CR). The rain striking the façade can be expressed by rain intensity

vectors, which are also described as the catch ratio or the rain exposure coefficient (Nicolai and

Grunewald, 2005-2006; Blocken and Carmeliet, 2002):

$$CR(t) = \frac{R_{dr}(t)}{R_h(t)}$$

$CR(t)$ Catch ratio

$R_{dr}(t)$ Driven rain intensity (integrated over all raindrop diameters)

$R_h(t)$ Unobstructed horizontal rainfall intensity (integrated over all raindrop diameters)

Kragh (1998, chapter 6) studied the microclimate on a building in Denmark and measured the catch ratio

for a west-orientated façade on a 3 storey building to be between 0.2–0.4 depending on the location. The

catch ratio was found to be higher for the corners and for the edges than for the middle of the building.

Furthermore, they found the average wind velocity to be approximately 6 m/s at a height of 10 m.

Blocken and Carmeliet, (2006) also studied the catch ratio for different building shapes using a CFD tool.

According to them, the catch ratio for a building with dimensions (height x width x length= 20m x 10m x

100m) was found to vary from 0.2 in the middle of the building to 1.45 at upper corner when the wind

velocity was 10 m/s. This shape and size could be comparable to the building shape of the multi storey

test building. On the basis of the Design Reference Year (DRY) for Denmark, the average wind velocity

is 4.36 m/s, which according to Blocken and Carmeliet, (2006) corresponds to a catch ratio of

approximately 0.5 based on CFD simulations. Blocken et al. (2011) compared CFD simulations with

measurements and the ISO-standard 15927-3:2009 (2009) for determining the catch ratio of a façade, and

they found that on average the catch ratio was 0.2-0.25 for two low-rise buildings. These studies,

however, represent the case with no obstacles to affect the catch ratio. Most multi-storey buildings,

including the test building, are located in an urban area and the surroundings will affect the wind-driven

rain. Coutu et al. (2012) investigated wind-driven rain on façades in urban areas. They found that in urban areas the wind-driven rain on the façade is significantly less than in open areas, resulting in catch ratios ranging from 0.01-0.09, all much lower than what other literature suggests. Based on this, the catch ratio will probably not reach 0.5 in urban areas, but will more likely be 0.1 or less. But simulations were carried out with catch ratios of CR=0.1, CR=0.3 and CR=0.5 in order to cover representative and worst-case scenarios.

Validation of the model of the wooden floor beams. Two models were created with wall thicknesses of 2 bricks and 1.5 bricks to represent the façade on the 4th and 5th floors respectively. The model was created with a gap in the insulation above the floor construction, as was done in the test building, to validate the simulation model of the beam construction with the measurements. The model was simulated for 1 year starting in June. The calculated temperature and relative humidity were compared with the measured data in the apartments in Copenhagen.

Worst-case modelling. The worst-case scenarios were simulated for 4 and 10 years starting in September for the wooden beam end and for the interface between the insulation and the brick wall, respectively. After validating the model of the wooden beam, various scenarios were simulated to find worst cases. Three scenarios of applying the insulation were modelled: Figure 3(a): insulation applied on the entire interior façade; Figure 3(b): a gap of 200 mm in the insulation above the floor; and Figure 3(c): a gap of 200 mm in the insulation both above the floor and below the ceiling. Reference models were also created to represent the conditions before the retrofitting. The 1D-model for the wall is shown in Figure 3(d). The models were simulated with the wall orientated towards the west and north. The most dominant wind-direction in Denmark is west (Cappelen and Jørgensen, 1999), and west-orientated façades are therefore exposed to more wind-driven rain. But north-orientated façades will not have direct sun, which results in reduced drying potential. Both orientations are therefore of interest. Furthermore simulations were carried

out for wall thicknesses of 1.5 and 2 bricks, and for insulation thicknesses of 40mm and 80mm, which correspond roughly to 0.4 W/m^{2}K and 0.2 W/m^{2}K, respectively.
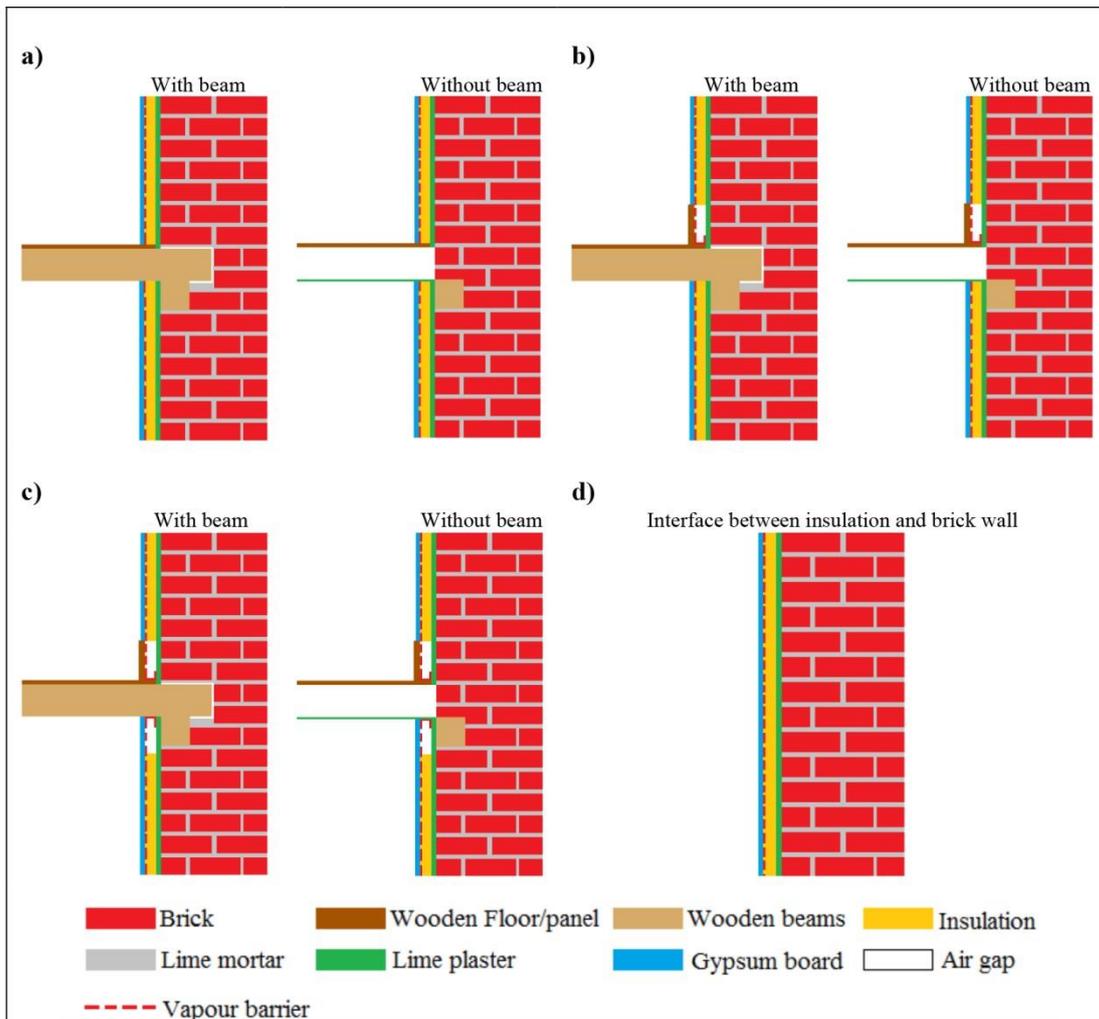
Figure 3: The various scenarios of internal insulation applied in the Delphin models - with and without the floor beam for a) full insulation on the entire interior façade; b) 200mm gap in the insulation above the floor; c) 200mm gap in the insulation above and below the floor/ceiling; d) 1D model of the wall with internal insulation.

Evaluation of mould growth. Hukka and Viitanen et al. (1999) developed a mathematical model for evaluating the risk of mould growth on wood (the VTT-model), which has been further developed over the years and is described in several papers (Vereecken and Roels, 2012; Viitanen H and Ojanen T, 2007; Viitanen HA, 1997; Ojanen et al., 2010). The model was developed based on tests and includes critical limits for relative humidity, temperature and the time factor, for conditions favourable and non-favourable for mould growth. A more recent study has further developed the model, so that it also includes other materials, such as concrete, cement, plastic-based materials, glass and metals (Ojanen et al., 2010). The model calculates the Mould Index (M), which describes the growth rate. The mould index can range from M=0-6 and is described in Table 3. The critical relative humidity in the model defines the minimum value at which mould growth can occur. The critical limit for mould growth on wood in the VTT-model is 80% and 85% for the interior surface of an exterior façade (Ojanen et al., 2010). For a detailed description of the model, see Hukka and Viitanen et al. (1999), Viitanen H and Ojanen T (2007) and Ojanen et al. (2010).

Table 3: Description of Mould Index (Viitanen H and Ojanen T, 2007).

Index	Growth rate	Description
0	No growth	Spores not activated
1	Small amount of mould on surface (microscope)	Initial stage of growth
2	<10% coverage of mould on surface (microscope)	-
3	10-30% coverage of mould growth on surface (visual)	New spores produced
4	30-70% coverage of mould growth on surface (visual)	Moderate growth
5	>70% coverage of mould growth on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

3. Results and discussion

Measurements in the wooden beam ends and validation of the simulation model of the wooden beam construction.

The measurements of temperature and relative humidity monitored in the wooden floor beam ends are shown in Figure 4 for the 4th floor (2 bricks) and the 5th floor (1.5 bricks). The results from the simulation model with rain exposure coefficients of CR=0.1, 0.3 and 0.5 are shown together with the measured indoor temperature and relative humidity. As can be seen, the room measurements are missing for large periods for the 4th floor (2 bricks). To provide input data to the simulation model from the measured indoor conditions, the temperature and relative humidity were assumed to be an average value of the two measured points before and after the lack of data. The results from the simulation model are therefore incorrect during these periods, which also explains the rather large deviation in the temperatures in Figure 4(a). However, the deviation is only 1-2°C for the remaining period, when the actual measured data was used. Moreover, the effect of the thinner wall is expressed by the lower temperature levels during wintertime, and there is good agreement between the measurements and the calculations. Greater deviations can be seen in the measured and the calculated relative humidity. The dynamics are greater in the measurements than in the simulation results. This can be explained by the mathematical model used in Delphin. Delphin only has a temperature-dependent sorption-isotherm for air, whereas for other materials it calculates the relative humidity based on the moisture content. The moisture content only changes based on moisture transport, which can be rather slow. Even though we have created a small air-space inside the wooden beam, it is still affected by the conditions in the wood, which might change slower than reality. However, the calculated relative humidity has the same levels as the measured, varying only by a few percentages. Another effect seen in Figures 4(c) and 4(d) is that the thinner the brick wall, the more

variation occurs in relative humidity, which results in greater deviation between the measured and the calculated results.

The simulation models were calculated with various rain exposure coefficients. As seen in Figure 4, the changes in the rain exposure coefficient have no effect on the calculated temperatures and very limited effect on the calculated relative humidity. The main reason for this is that an air space is modelled between the brick wall and the wooden beam heads, resulting in a limited moisture transport from the exterior to the measuring point. This confirms that it is not possible to validate the part of the model that includes the brick wall because the measurements are most affected by the indoor environment and the outdoor temperature and less by the outdoor wind-driven rain.

Based on comparison between the measurements and calculations in the wooden beam ends, the model seems to provide good results in the periods when the indoor temperature and relative humidity measurements were available.
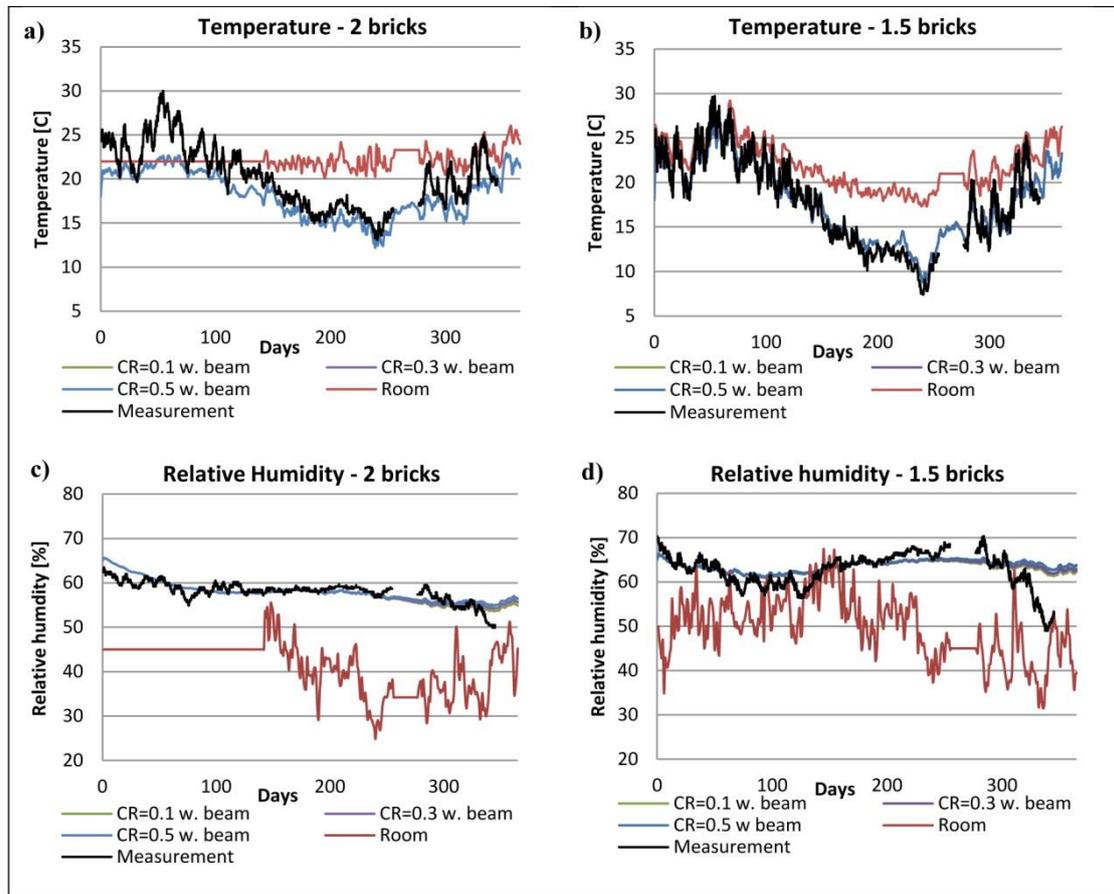
Figure 4: Temperatures and relative humidity in the wooden beam ends from measurements and simulations. The measured room temperature and relative humidity were used as input to the simulation model.

Worst-case simulation with Delphin

Wooden beams. The models were simulated with a wall thickness of 2 bricks and for orientations towards the west and the north for a period of 4 years. Figure 5(a) shows the mould growth index for a west-orientated façade and Figure 5(b) for a north-orientated façade in the wooden beam end (position 1). The simulations were carried out for rain exposure coefficients of CR=0.1, CR=0.3 and CR=0.5 (CR=0.5 only

for the west-orientated wall) and for (i) no insulation (blue scale), (ii) insulation applied to the entire wall (red scale), (iii) insulation applied with a gap of 200mm above the floor (grey scale), and (iv) insulation applied with a gap of 200mm above and below the floor/ceiling (green scale). It is clear from Figure 5 that the north-orientated façade results in higher mould indexes than the west-orientated façade for low rain exposure coefficients. Most of the scenarios show an increasing trend, implying that there will be an accumulation of mould growth over the years even if the growth stops or decreases during summertime. All rain exposure coefficients greater than CR=0.1 result in a high mould index (between M=4 and M=6) indicating visual mould covering between 30-100% of the surface. Only the north-orientated façade without insulation and a rain exposure coefficient of CR=0.1 results in a mould index lower than 1. For the west-orientated wall, the mould index is kept below M=1 when a gap of 200mm is applied in the insulation above the floor and when it is applied both above and below the floor/ceiling. The last case results in more secure conditions, since the mould index decreases to M=0 each year, whereas if a gap in the insulation is only applied above the floor, a small increasing trend is observed. However, it should be kept in mind that the floor beam is modelled as a continuous beam, whereas in reality there is a beam only approximately every 1 metre. The results are therefore on the conservative side. Figure 5 shows that the gap in the insulation has a positive effect on the moisture conditions in the beam end and reduces the mould index in all cases. However, there is still a large risk of mould growth in the beam end.
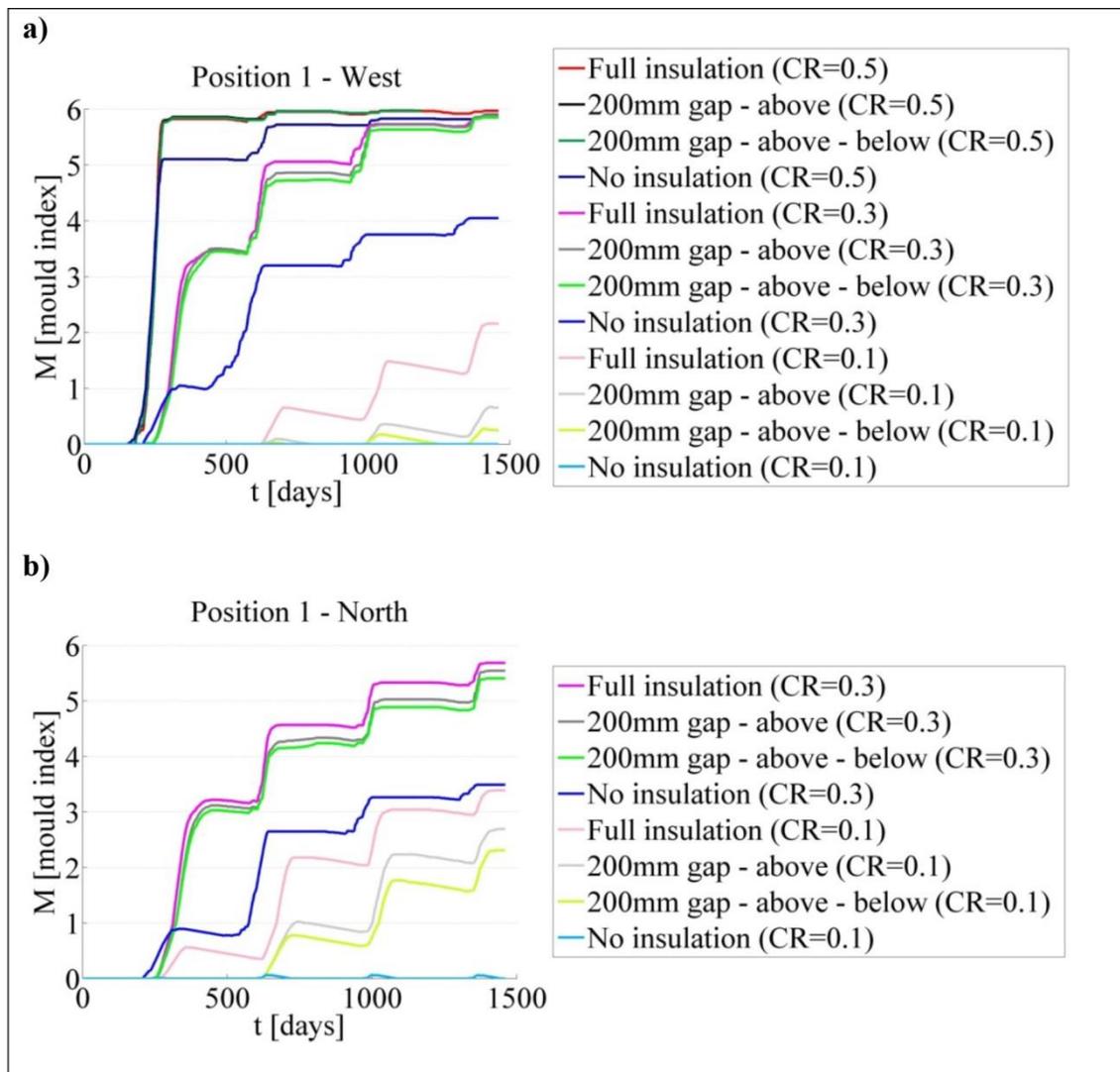
Figure 5: Mould index in position 1 for a) west- and b) north-orientated façades - 2 bricks thick. CR=0.1, 0.3, 0.5. No insulation; with internal insulation on the entire wall; with a gap of 200mm in the insulation above the floor; and with a gap of 200mm in the insulation above and below the floor/ceiling.

Figure 6 shows the mould index in position 2 for a west-orientated façade (a) with and (b) without the floor beam perpendicular to the façade. The simulations without the floor beams result in lower mould

indexes, due to a better drying possibility. As mentioned above, the simulations with the floor beams do not represent reality completely since they are modelled as a continuous beam due to the 2D model. Therefore the real results will be somewhere between the results from Figures 6(a) and (b). The results are similar in position 2 to those in position 1 for the west-orientated façade. When the rain exposure coefficient is CR=0.1, the mould index is below M=1 for the two insulation solutions with a 200mm gap applied. However, when the gap is only applied above the floor, an increasing trend is observed, which is not the case when the gap is applied both above and below the floor/ceiling. Figure 6(b) (without the beam) shows that there is no risk of mould growth for any case when the rain exposure coefficient is CR=0.1. The effect of the gap in the insulation is clear and gives lower mould indexes than a fully insulated wall. The figure shows that when the rain exposure coefficient is CR=0.5, there is even a heavy mould growth for an uninsulated wall. It is known that many buildings have or have had mould problems even without internal insulation, and higher rain exposure coefficients may therefore be realistic in some cases. However, when the rain exposure coefficient is CR=0.5, the results show that all wooden surfaces should be completely covered with mould even without insulation, which is not the case. It is therefore believed that the rain exposure coefficient is less than CR=0.5.
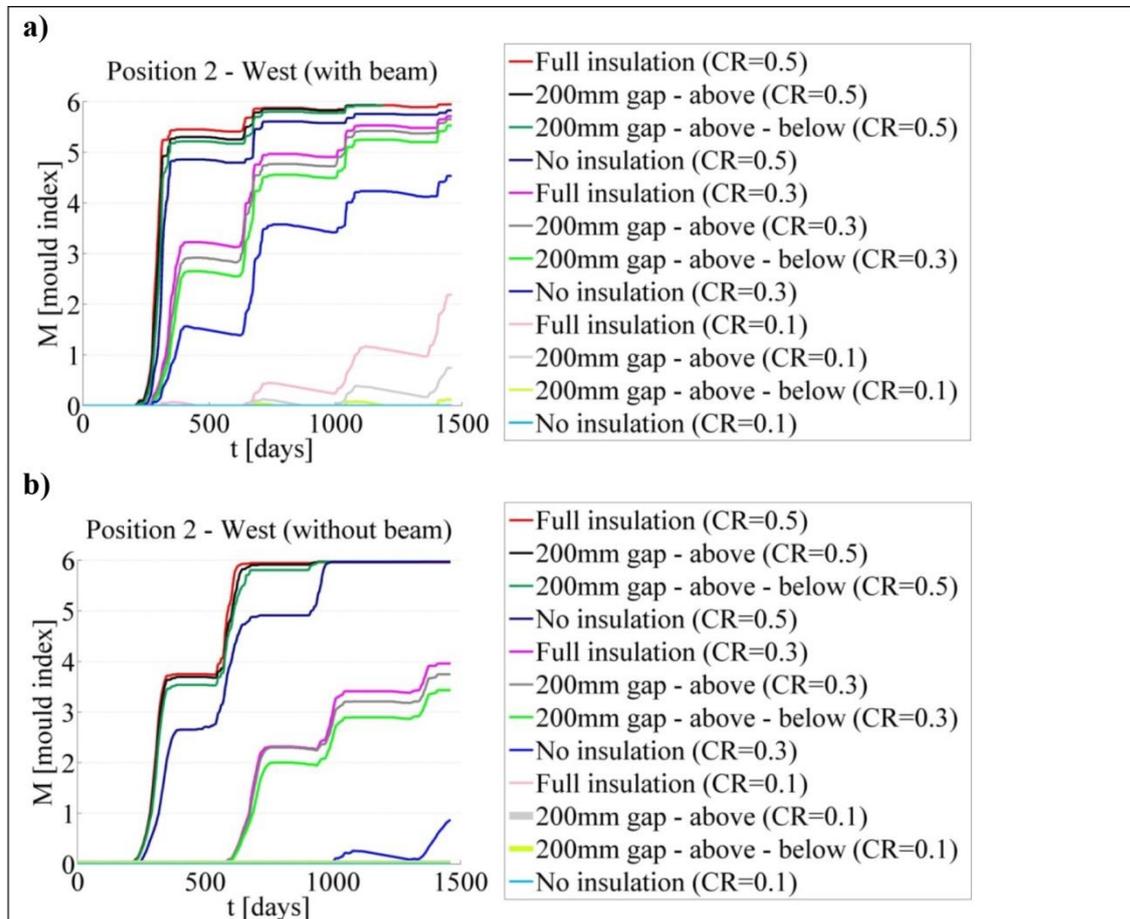
Figure 6: Mould index in position 2 for a west-orientated façade – 2 bricks thick, a) with and b) without the floor beam for CR=0.1, 0.3, 0.5 and for no insulation; with internal insulation on the entire wall; with a gap of 200mm in the insulation above the floor; and with a gap of 200mm in the insulation above and below the floor/ceiling.

Figure 7 shows the mould index in position 2 for a north-orientated wall 2 bricks thick (a) with and (b) without the floor beam. In general, the north-orientated façade has higher mould indexes than the west-orientated façade for low rain exposure coefficients and for the case where the beam is modelled. The reason can be that the drying potential is significantly reduced. Figure 7(a) (with the floor beam) shows

higher mould indexes than Figure 7(b) (without the floor beam) since the drying potential is reduced when the floor beam is modelled. As seen from Figure 7(a), none of the solutions seems to be safe. Even at low rain exposure coefficients and with a gap in the insulation both above and below the floor/ceiling, an increasing mould index reaches M=2 after 4 years. A mould index of 2 still represents a very limited mould growth at a microscopic level. However, the trend is strongly increasing and if the simulations were to be carried out for more years, they would probably result in much higher levels. In contrast, Figure 7(b) shows that there is no risk of mould growth for any case with a rain exposure coefficient of CR=0.1, even when the wall is fully insulated. For rain exposures of CR=0.3, the mould index reaches M=2.5-3 when there is a gap applied in the insulation, but a small increasing trend is observed. The mould indexes will be lower in reality than the results shown in Figure 7(a), since they will have the possibility to dry out between the floor beams. The case where a 200mm gap is applied in the insulation above and below the ceiling may therefore be a safe solution if there is enough drying potential to the sides of the beam.
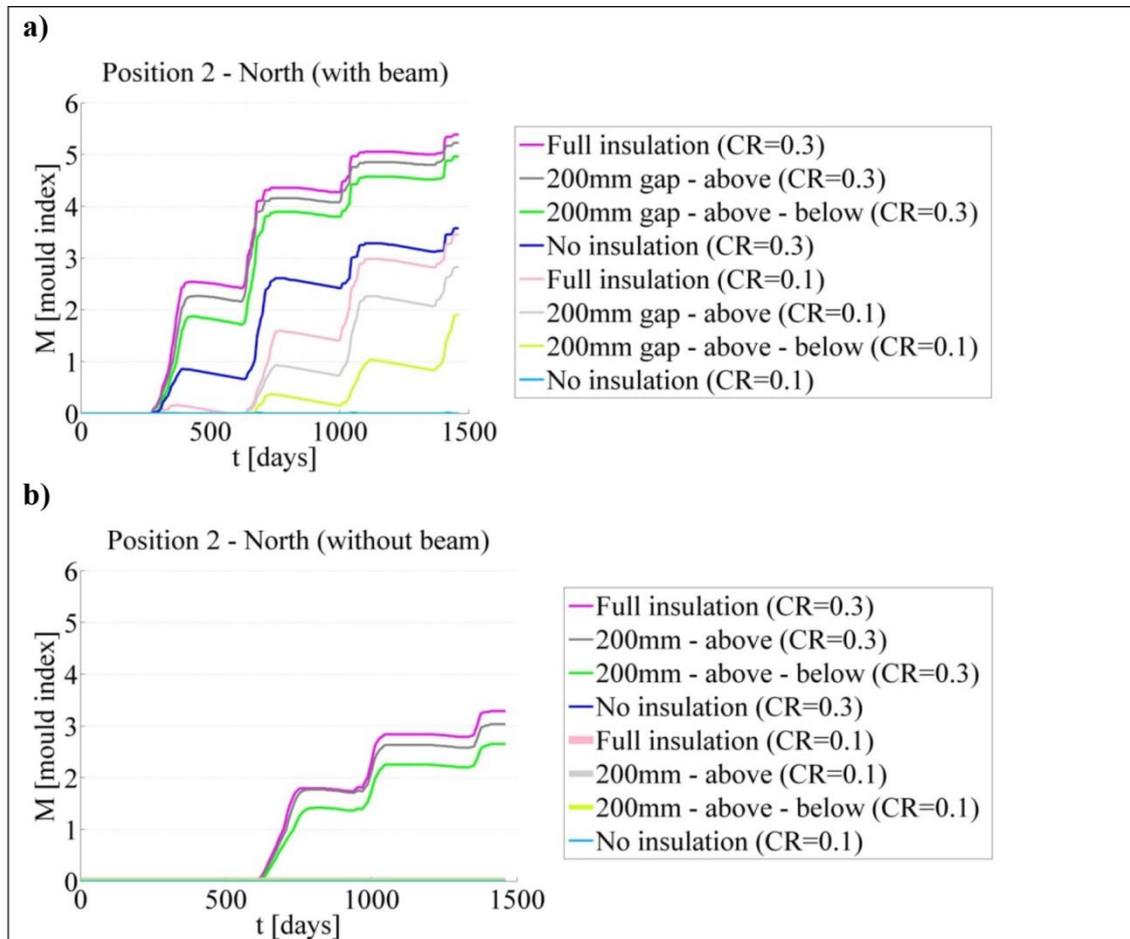
Figure 7: Mould index in position 2 for a north-orientated façade – 2 bricks thick, a) with and b) without the floor beam for CR=0.1, 0.3, 0.5 and for no insulation; with internal insulation on the entire wall; with a gap of 200mm in the insulation above the floor; and with a gap of 200mm in the insulation above and below the floor/ceiling.

Figure 8 shows the temperature and relative humidity fields for the construction with the different insulation solutions and for an uninsulated wall. The figure shows the sections at the beam end and between the beams, referred to as *with beam* and *without beam* respectively. The figure shows higher temperatures around the wooden beams are seen as a result of the 200mm gap in the insulation with the

greatest effect when gap in the insulation is both above and below the floor/ceiling. The higher temperatures result in lower relative humidity and therefore a decreased risk of mould growth. Temperatures are higher in the section plane between the beams (without the beam) than where the beam is located (with the beam), resulting in lower relative humidity. The drying potential between the beams is therefore higher, which is in good agreement with the results from the mould risk analyses. The figure shows that when the internal wall is fully insulated the wooden construction has a relative humidity above 80-90% in the outer part of the floor beam and at the load-bearing beam, whereas the relative humidity drops to below 80% for most of the wooden construction when there is a gap in the insulation both above and below the floor/ceiling. When there is a gap in the insulation, one might expect a risk of mould growth and condensation on the part of the wall that is uninsulated behind the panel. However, a vapour barrier was applied in accordance with Figure 3, which prevented the moist room air reaching the wall surface and condensing if the temperature is low enough. The temperature on the uninsulated wall behind the panel is around 9-10°C with the floor beam and 12-15°C without the beam. For a room temperature of 20°C and a relative humidity of 50%, the dew-point is 9°C and there would be a risk of condensation if the construction is not vapour tight. Therefore it is crucial that the vapour barrier is applied correctly. Another issue that could arise when there are gaps in the insulation in some parts of the wall is the phenomenon of *ghosting marks*, which are dust particles trapped on the cold part of a surface. According to Christensen and Koch (2012), this can happen when the temperature difference on a surface is greater than 2-3°C. Figure 8 shows that the temperature difference between the panel and the insulated wall is around 3°C for the section plane with the beam and around 1-2°C for the section plane between the beams. A risk of *ghosting marks* is therefore present at the panel over the floor beams. However, again it should be kept in mind that the simulation model is a 2D model and the temperature difference is on the conservative side.
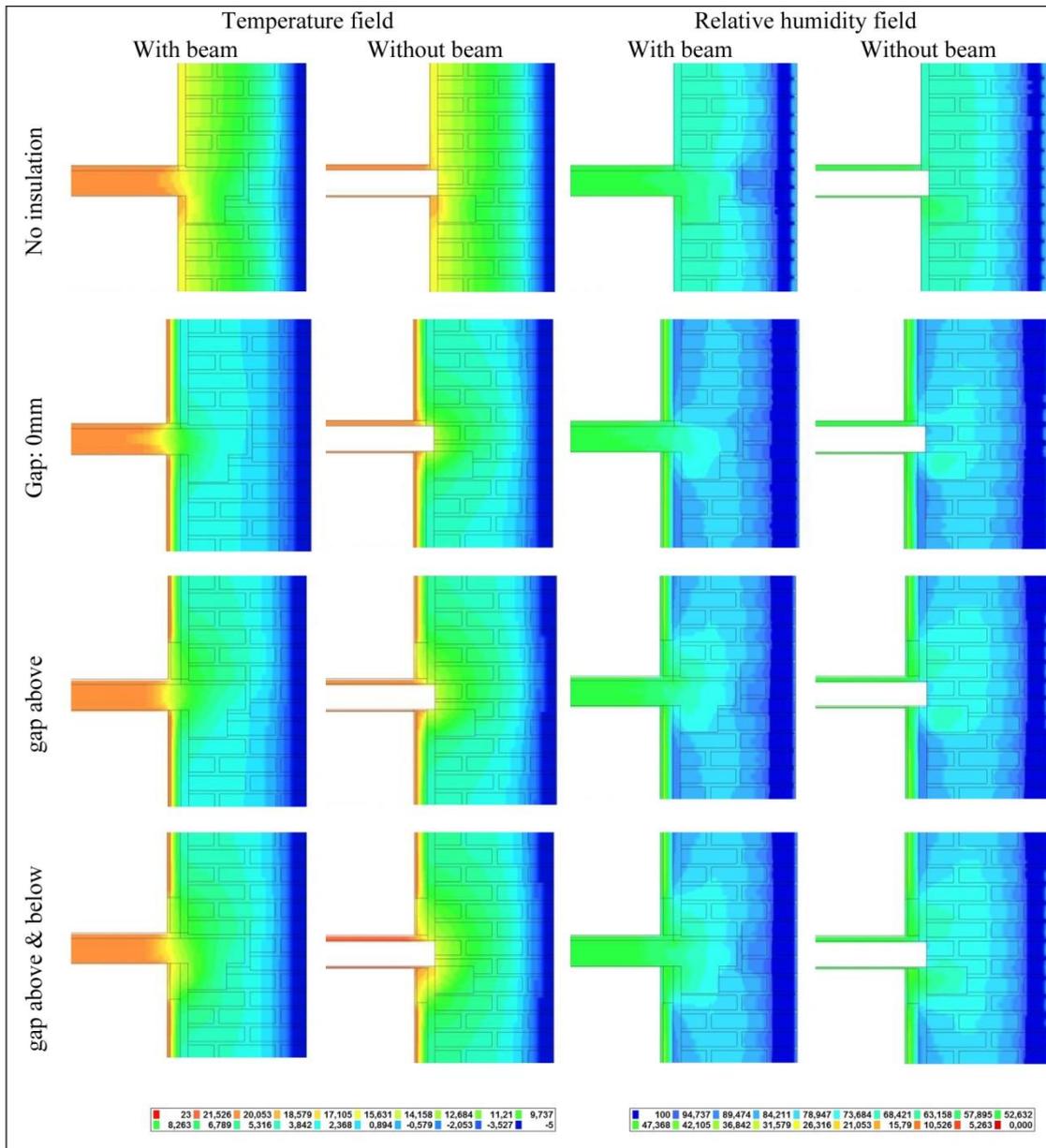
Figure 8: Temperature and relative humidity fields for the models with and without the wooden floor beam and for the four cases with no insulation, insulation on the entire wall, insulation applied with a

200mm gap over the floor, and insulation applied with a gap of 200mm above and below the

floor/ceiling.

Figure 9 shows the mould index for the solution with a gap of 200mm above and below the floor/ceiling with 40mm and 80mm of insulation, which correspond to a thermal transmittance for the wall of 0.4 W/m^2K and 0.2 W/m^2K, respectively. As shown in Figure 9, the increased insulation thickness increases the mould growth index slightly. The effect of the extra insulation is not that significant since there is a gap in the insulation above and below the floor/ceiling and the beam construction is therefore less affected. However, the mould indexes increased compared to 40mm insulation, and it seems to be safe to apply 80mm insulation only for low rain exposure coefficients for position 2 without the floor beam. Therefore, since even using 40mm insulation already shows debatable results, it cannot be recommended to apply more insulation and lower thermal transmittances of the wall.

Positions 1 and 2 for solution with 200mm gap above and below the floor/ceiling

40mm 80mm

Position 1

Position 1

Position 2 (with beam)

Position 2 - with beam

Position 2 (without beam)

Position 2 - without beam

West (CR=0.5)
West (CR=0.3)
North (CR=0.3)
North (CR=0.1)
West (CR=0.1)
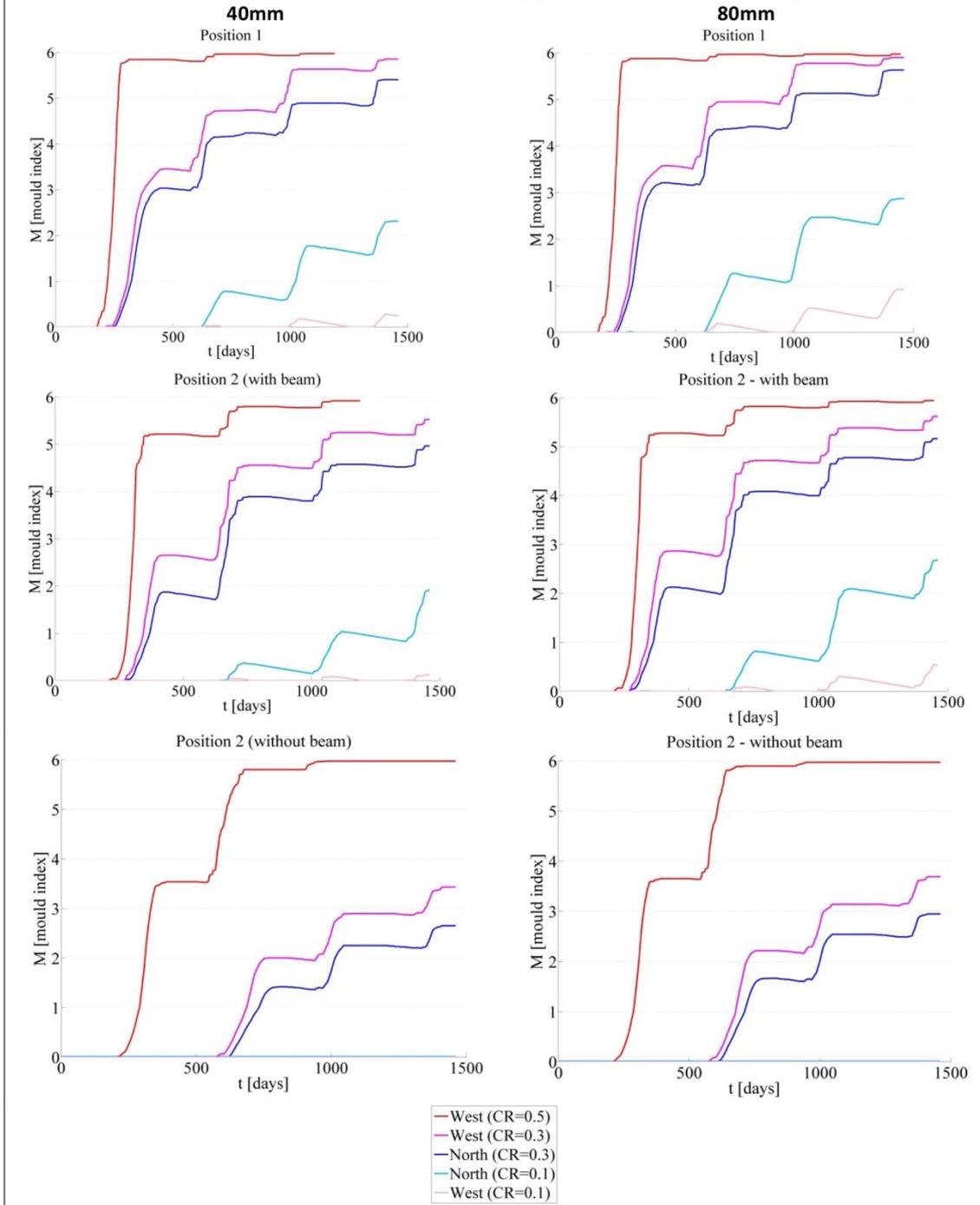
Figure 9: 40mm and 80mm insulation applied on the wall. Mould index in positions 1 and 2 for the solution with a gap of 200mm above and below the floor/ceiling.

Interface between the insulation and the brick wall. Figure 10 shows the mould index in the interface between the insulation and the brick wall (position 3) with 40mm and 80mm insulation applied. Simulations were performed for four cases; for west- and north-orientated walls and for wall thicknesses of 1.5 and 2 bricks in both cases. The maximum mould index in all cases was approximately 3.5, corresponding to a visual coverage of mould growth of 10-30% on the surface. It can be seen that for a north-orientated wall the mould index increases faster and that for lower rain exposure coefficients the mould index reaches higher levels. Even with a rain exposure coefficient of CR=0.1, the mould index reaches approximately M=2.5, which is just below the visual mould growth state. Figure 10 also shows that a thinner wall results in a slightly higher risk of mould growth since it is more affected by driven rain. When 80mm insulation is applied, corresponding to a thermal transmittance coefficient for the wall of 0.2 W/m^{2}K (corresponding to the requirements in the Danish Building Regulations 2010), it can be seen that even with low rain exposures (CR=0.1) there is a risk of mould growth (2<M<3). For walls insulated with 40mm insulation and with a low rain exposure coefficient (CR≤1), the west-orientated wall has no risk of mould growth, whereas the north-orientated wall has a significant risk of mould growth. Internal insulation might therefore be durable only with 40mm insulation applied and for west-orientated walls. Extra caution needs to be taken if the wall is orientated towards the north and it is not recommended to apply more than 40mm insulation.

Position 3

40mm of insulation
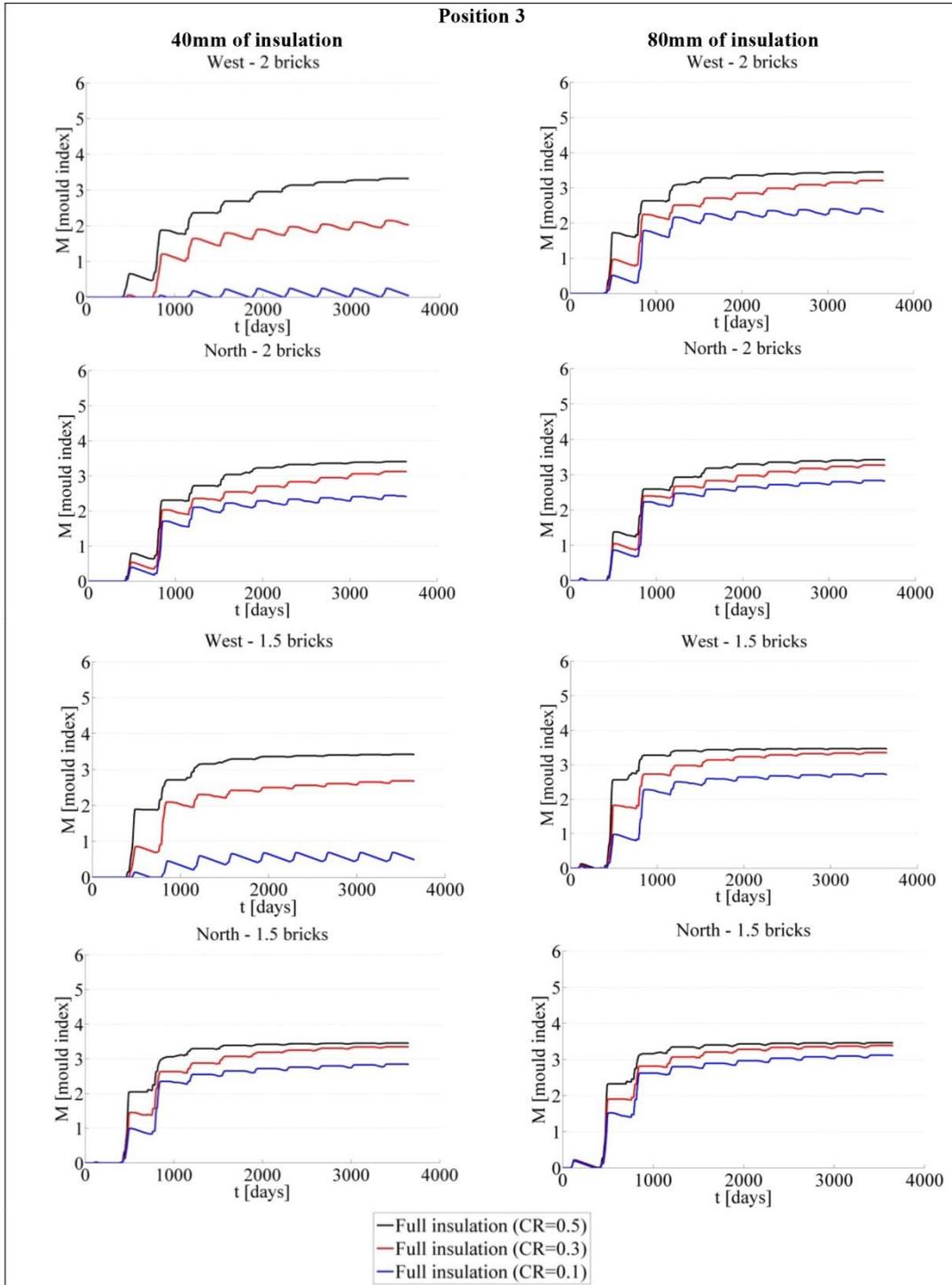
80mm of insulation

Figure 10: Mould index in position 3 for a west- and a north-orientated wall with a thickness of 1.5 and 2 bricks, and 40mm and 80mm insulation applied. RHcrit=85%.

Risk of mould growth. Based on these analyses, there is a large risk of mould growth on the wooden beam construction and behind the insulation when internal insulating is applied. However, the internal insulation product investigated was a mix of mineral wool and aerogel with a vapour barrier applied, and there is need for future research into using other innovative materials, such as capillary active and diffuse open material without vapour barrier. The simulation was created as a 2D model even though the real problem is a 3D problem, so uncertainties are involved in the results. The investigation was carried out based on two model types (with and without the beam), and the correct results will lie somewhere between the results from these two models. The models did not include any cracks, which could potentially lead to higher moisture content in the wall and consequently a higher risk of mould growth. This too needs future research. One possibility might be to reduce the amount of rain absorbed by the façade by impregnating the façade with a waterproof but diffuse open coating so moisture will not get trapped inside the brick wall. Another issue that needs to be addressed and investigated is to what extent we can accept mould that does not create a health risk. It might be acceptable to have some small amounts of mould, but this is an area that needs more investigation. The conclusions drawn in this paper are therefore based on the view that no mould growth is acceptable.

4. Conclusion

This paper presents an investigation of a method of applying internal insulation in a heritage multi-storey building. Measurements were carried out in the wooden beam ends in two test apartments on the 4th and 5th floors respectively. A hygrothermal 2D-simulation model created using Delphin was validated with measurements taken in the wooden floor beams of a test building to simulate worst-case scenarios with

wall orientations towards the west and north. Furthermore, a 1D-model was created to simulate worst-case scenarios for the interface between the insulation and the wall. Three different insulation strategies were investigated to evaluate the risk of mould growth in the wooden beam-ends. It was found that the risk of mould growth could be reduced by applying a gap in the insulation above and below the floor/ceiling. However, moisture safety depends on other parameters, such as the orientation and rain exposure of the façade. While no risk of mould growth was found for a west-orientated façade with low rain exposure coefficients (CR=0.1) for position 1 and 2, heavy mould growth were detected for rain exposure coefficients higher than CR=0.1. When the wall is orientated towards the north, the drying potential is reduced since no sun reaches the façade and the risk of mould growth increases significantly compared to the west-orientated wall.

The risk of mould growth in the interface between the insulation and wall was higher for a north-orientated wall and for the thinner wall (1.5 bricks compared to 2 bricks). The maximum mould index reached 3.5, which corresponds to visual growth covering between 10-30% of the surface. But for a west orientated façade with low rain exposure coefficients, there was no risk of mould growth.

It is crucial to apply the vapour barrier correctly to prevent the moist room air reaching the façade. The uninsulated part of the wall (behind the 200mm gaps in insulation) will risk condensation and mould growth if the moist air reaches the façade, since this part of the wall will be close to the dew-point temperature for room air. Moreover, the phenomena of ghosting marks can occur if the temperature difference between the interior surface of the insulated wall and the uninsulated wall is greater than 2-3°C, though this needs future research.

Due to the uncertainty of the actual rain exposure on the façade, further research is needed to draw final conclusions from the results. But when the coefficient is below CR≤0.1 and the wall is orientated towards the west, the solution with a gap above and below the floor/ceiling seems to be moisture-safe. It is not

recommended to apply 80mm insulation, but to keep it to a maximum of 40mm. However, based on the results from this investigation it not recommended to apply internal insulation to a north-orientated wall with a thickness of 1.5 or 2 bricks, and caution should be exercised when it is applied to a west-orientated wall. This paper only investigated 1.5 and 2 brick walls. Internal insulation applied on thicker walls (2.5-3.5 bricks) might show different results.

Acknowledgement

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Paper 5 – Appendix 5

M. Harrestrup, S. Svendsen (2012).

Planning of the district heating system in Copenhagen from an economic perspective comparing energy-savings versus fossil-free supply.

The 13th International Symposium on District Heating and Cooling, Copenhagen, September 3-4.

PLANNING OF THE DISTRICT HEATING SYSTEM IN COPENHAGEN FROM AN ECONOMIC PERSPECTIVE COMPARING ENERGY-SAVINGS VERSUS FOSSIL-FREE SUPPLY

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ABSTRACT

The Danish government has adopted a long-term energy policy of being independent of fossil fuels by 2050, and that the energy supply for buildings should be independent of fossil fuels by 2035. Therefore, urgent action is needed to meet the requirements for the future energy system. One way of becoming independent of fossil fuels is to energy upgrade the existing building stock and change the energy supply to renewable energy sources. A sustainable way of providing space heating (SH) and domestic hot water (DHW) to buildings in densely populated areas is through the use of district heating (DH). This paper is a theoretical investigation of the DH system in Copenhagen, where heat supply is compared to heat savings in buildings from an economic perspective. Supplying the existing building stock with heat from renewable energy supply technologies e.g. low temperature district heating (LTDH) from geothermal heating plants, may lead to oversized heating plants that are too expensive to build compared to implementing energy savings. Therefore reducing heat demand of existing buildings before investing in supply capacity will save society half the investment, indicating the importance of carrying out energy savings now.

INTRODUCTION

The Danish government has adopted a long-term energy policy of being independent of fossil fuels by 2050, and that the energy supply for buildings should be independent of fossil fuels by 2035. Therefore, urgent action is needed to meet the requirements for the future energy system. [1],[2]. The solution is to combine energy savings and renewable energy supply in an optimal way. The European building stock account for about 40 % of the overall energy use [3]. In order to reduce this energy use there is a need of reducing the energy use of the existing building stock, increase energy efficiency and converting the present heat supply from fossil fuels to renewable energy sources.

The design of new low energy buildings has been in focus throughout the recent years and much research has been carried out in order to design optimized buildings from an energy perspective [4]-[8]. However, only 1% of the building stock today is newly constructed as low-energy buildings, which underlines the importance of looking into the existing building stock, where the potential for energy savings is large [9]-[12]. Investigations have shown that the energy consumption can be reduced with about 50-75%[10]-

[14], but it takes significant investment costs to reach very low levels of energy consumption [10]. However, since the existing buildings will remain for many years yet to come, it is an unavoidable factor to deal with

The future energy system will have to be based solely on renewable energy sources, which is a huge challenge for the society. It will have to be based on well coordinated interacting energy supply systems where a list of different renewable energy technologies has to interact and balance in a way that will ensure a system with security of supply.

A sustainable way of providing SH and hot water to the buildings in dense populated areas is by the use of DH [15]. In many countries DH systems are already established, but they, as for the remaining energy supply system, face new challenges in the future. In countries like China, U.S.A, Iceland, and Turkey [16] a large share of the DH supply is based on geothermal, whereas in Denmark, Sweden, and Finland the DH supply mainly comes from combined heat and power generation plants (CHP) [16]. The DH systems will have to be converted from the present supply technologies based on fossil fuels into 100 % renewable energy sources. Different resources such as biomass, geothermal, sun, waste, heat pumps, and surplus heat from the industry and CHP etc. can be considered in regards to convert to a fossil free supply system. In Denmark some CHP plants have been converted into biomass and large solar and geothermal heating plants for DH have already been established. Among newly developed geothermal heating plants in Denmark can be mentioned, Dronninglund, Sønderborg, and Viborg [17].

The DH system currently operates with temperatures of 80°C/50°C. If the DH system is converted into low-temperature DH (60°C/30°C), the heat-losses from the network will be reduced and the heat supply from renewable sources will be more suitable for the system. The geothermal water under Copenhagen can be drawn at a temperature on 73°C [17], so heat pumps will not be needed to elevate the temperature of the water. This will save on electricity and avoid peak loads in the electrical supply system, which will be more fluctuating and vulnerable to peak loads since it will be based on renewable energy sources, mainly wind power.

This paper investigates different scenarios of the future DH system taken into account energy savings and the conversion of the fossil fuel supply technologies into renewable supply technologies. The approach to the

investigation is to state the economical consequences of different energy planning scenarios when it comes to the future DH system. The approach is very general and the objective is to give an overall picture of economical consequences by following different energy planning strategies. Details of the individual heating plants and locations of them are neglected and further detailed investigations will have to be carried out if a complete detailed picture has to be drawn. Furthermore simplified assumptions are made and there are details that will have to be investigated further.

Waste heat from the industry could be used in combination with either geothermal or solar heat, but from [20] the potential has been estimated to be low (3%) in the area of Copenhagen since the industry sector is small, and is therefore neglected in this investigation. This paper looks into the implementation of geothermal supply for the future DH system together with waste for incineration. Solar thermal plants with storage or heat pumps would be other possible future solutions, but are not the focus in this investigation.

THE MODEL

Approach

Due to the planned future energy policy, coal will have to be phased out in 2030 [1]. According to the Heat Plan of Copenhagen [18] coal will already have to be phased out in 2025, which have been the basis of this investigation. Additionally it is assumed that biomass will be available until 2040 after which it will descend to the transportation sector that will have to be fossil free in 2050 [1]. It is assumed that the transportation sector will be willing to pay more for the biomass resource in the future, implying that other renewable energy sources will have to be used. Furthermore research has found that Europe will have a biomass potential of only 15-16% of the total primary energy demand in 2030 [19]. This will result in that biomass will have to be imported from 3rd world's countries, which is not preferable and not considered a long term sustainable solution. The biomass is better used locally in order to develop sustainable energy sectors in 3rd world's countries, and to avoid dependency, which is one of the main concerns today regarding fossil fuels.

In order to use renewable energy sources in an efficient way, LTDH should be considered. LTDH has been object for investigation recently and are among others studied in [21]-[28]. When the heating demand in buildings are decreased to low levels the possibility of LTDH becomes an option, since the need of SH will decrease and the peak loads will to a larger extend be "cut off". It is found from [28] that low temperature DH is possible in most hours of the year in existing buildings. The period with very cold climate conditions require an increase in the temperatures, which is assumed to be possible in the waste incineration plants. Supplying water to the transmissions lines with high temperatures from the incineration plants and mixing it with the colder geothermal water in the local DH plants, it is assumed that the temperatures will be able to cope with the heating demand under cold climate conditions. When LTDH is implemented the problematic of legionella has to be considered regarding the DHW. Studies have shown that the

legionella problem can be avoided as long as the temperatures are above 50°C [21], which implies a local boosting of the water temperature in the buildings e.g. by the use of flat stations. Additionally, recent research in Sweden has shown good results by the use of UV-sterilization [29],[30].

Present heat demand and potential for conversion of individual natural gas heated buildings

The present DH network in Copenhagen area consists of three waste incineration plants plus four CHP-plants distributed in a geographical area as shown in Figure 1. The supply area includes the western CHP plants (VEKS) and the central CHP-plants (CTR) in the Copenhagen area. The fundamental basis of this investigation is based on the DH system as it is today, and does not include the entire Copenhagen area at the moment.
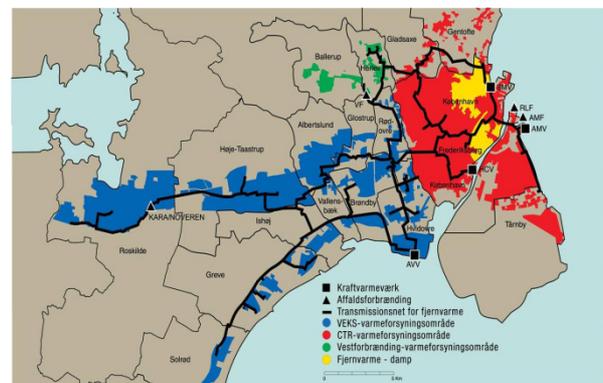
Fig. 1 Map of existing DH network in Copenhagen area. [31]

The total heat demand (2010) of the entire area is 35 PJ/year with a peak load on 2500 MW[31]. The overall net losses are assumed to be 15 % and 8 % of the yearly production with traditional DH and low temperature DH respectively [32],[33]. It is assumed that the DHW demand is 400MW constantly over the year with the exception of the summer period where buildings are expected to use less water due to vacations.

An analysis of the potential of converting individual natural gas users into DH has been carried out [31],[32],[33]. A potential on 10 PJ has been found as a realistic amount within a geographical possible area of conversion [33]. This implies a total yearly consumption on 45 PJ/year and a peak load of about 3200 MW assuming the same increase in percentage from present (2010). Furthermore it is assumed that the DHW-consumption increases with the same tendency as the conversion of the natural gas users into DH takes place.

Energy renovations

As a simplification it has been assumed that a decrease in yearly heat demand on 65%, correspond to a decrease in the power loads on 65%. This simplification is based on simulations made for a low-energy house and an existing building [28], and the ratio of total heat demand over the peak load has been

compared. This simplification contains certain errors and will have to be investigated further.

Scenarios

Calculations on three different possible future scenarios are carried out and sensitivity analyzes on the amount of waste for incineration in the future are done. The main calculations are carried out assuming a decrease in the amount of waste on 1/3 in 2070 compared to today.

Reference scenario – No energy renovation but only natural replacement of the existing building mass with new buildings.

This scenario represents a fundamental scenario of what will happen if nothing is done to reduce the heat consumption until 2070. In consequences of that no renovations are done in the existing building mass the buildings will over time dilapidate and be replaced with new buildings. According to [10] a heat reduction of around 50 % corresponds to that the existing buildings will reach an energy level corresponding to what is required from new buildings today in the Danish Building Regulations 2010 [34]. It is assumed that 1% of the existing building mass is replaced with new buildings a year, implying a yearly decrease in the heat demand on 0.5% of the building mass the year concerned.

Scenario 1 – Accelerated energy renovation from 2030-2070

Scenario 1 represents the case where no heat savings are carried out in the near future. The DH supply will be converted from fossil fuels to biomass on the CHP-plants and the prices will remain unchanged. No energy savings are carried out due to pour economy and no legislation or requirements here upon. Only the natural replacement of the building mass with new buildings on 1% per year is undertaken. The biomass will be phased out between 2030 and 2040 after which it will be moved to the transportation sector. Geothermal plants are established in order to cover the remaining nearly unchanged heat demand and the investment in geothermal energy will result in increased prices for DH. Deep energy renovation are carried out and the heat demand decreases with 65 % from 2030-2070, implying a decreased heat supply. The coefficient of utilization will decrease and the prices will rise further.

Scenario 2 – Accelerating energy renovations from today

Scenario 2 represents the case where heat savings are carried out from today. The DH will be converted to biomass and phased out between 2030 and 2040 as for the first scenario, but energy savings are carried out from today until 2040 implying a decrease in the heat demand. The investment in Geothermal heat supply plants are thereby decreased significant.

Economics

In order to calculate the economical consequences for the society for each of the scenarios, simple economical calculations have been carried out. The real interest rate is not considered, which in reality makes the costs higher than indicated here. Estimated costs of investment, maintenance and operating cost are included for geothermal heat and for the DH net. The costs related to the fossil fuels and biomasses are neglected since they are nearly the same in all scenarios. Furthermore it is assumed that the waste in the future will be considered a resource that will be priced, but since the price on heat will be based mainly on the investment in geothermal plants and the coefficient of utilization, the price on waste will be similar. The cost for the reference scenario will be based solely on supply whereas the costs for scenario 1 and 2 furthermore are based on the energy renovation, implying that they will be added to the supply price.

Geothermal investment cost

The investment cost for geothermal is estimated to be 1.6 mil €/MW for a geothermal plant on 135 MW [18],[31],[37]. Around half of the capacity (70MW) comes from geothermal heat. From other sources [35],[36] an investment cost on 1.7 mil €/MW is found. Assuming LTDH implying that there will be no need of heat pumps the investment in geothermal is assumed to be approximately $2.7 \ mil \ €/MW$. ($1.6 \ mil \ €/MW \cdot 2 = 3.2 \ mil \ DKK/MW$. The cost will be around the double, but due to economy of scale it is assumed to be slightly lower $\approx 2.7 \ mil \ DKK/MW$).

Operating and maintenance cost

The price for operation and maintenance cost (O&M) is difficult to estimate since it varies depending on various factors and conditions. The O&M-cost is assumed to be 6.3 €/MWh, based on [37].

DH network - Investment in new capacity

According to [37] the investment cost for installing new pipelines in a new DH area with a yearly heat demand on 38,000 MWh is about 10.7 mil €, resulting in a unit price on 282 €/MWh. This fixed asset investment is very sensitive to both the density and the accessibility of the area. Hence a unit price of 302€/MWh is assumed [37].

DH-network - Operating and maintenance cost

The O&M cost is assumed to be 2 €/MWh [36].

Energy renovation costs

According to [10] which is based on the entire building stock in Denmark (dwellings) the cost of saving 102 PJ/year corresponding to energy savings on 65% is 51 Mil €. This result in a unit price per saved petajoule of 8.3 Mil €/PJ, based on saving in 60 years.

Assumed lifetimes

Geothermal:	40 years
DH network:	60 years
Renovations of dwellings:	60 years

Costs

The investment cost for geothermal is found based on the needed capacity in the different scenarios, and O&M-costs are found based on the total geothermal heat production during the period in question (40 years). The investment cost for the DH network is based on the potential for converting natural gas costumers into DH corresponding to 10 PJ. O&M-cost is calculated based on the total heat production throughout the period in question (60 years). The total costs are:

$$Costs_{Total} = Invest_{Geo} + O\&M_{Geo} + Invest_{DH} + O\&M_{DH}$$

The unit price for supply energy is calculated as:

$$Unit\ Cost_{Supply} = \frac{Cost_{Total}}{Production_{Total\_Geo}}$$

The total costs for the supply throughout the entire period in question are:

$$Total\ Cost_{Supply} = Unit\ Cost_{Supply} \cdot Production_{Total\_DH}$$

In scenario 1 and 2 the total cost for supply is dependent on the decrease in heat demand, implying that the cost for carrying out energy renovation has to be added to the supply price:

$$Cost_{Savings} = US \cdot ES$$

US is cost of saving one unit of energy
ES is the energy savings in the period in question

Table 1 shows the economical calculations for each scenario.

RESULTS AND DISCUSSION

Reference scenario

The reference scenario represents the case where no accelerated energy renovations are carried out. Figure 2 shows the peak load and the distribution of resources. The priority of the utilization of the resources is 1. Waste for incineration; 2.Geothermal; 3. Biomass; 4. Fossil fuels. As seen from the figure the heat demand is increasing until 2035, due to the conversion of natural gas areas to DH. Simultaneously the existing building mass is replaced with new buildings decreasing the heat demand with 0.5% per year. The figure shows that it is needed to invest in a capacity of 2,800MW geothermal heat.
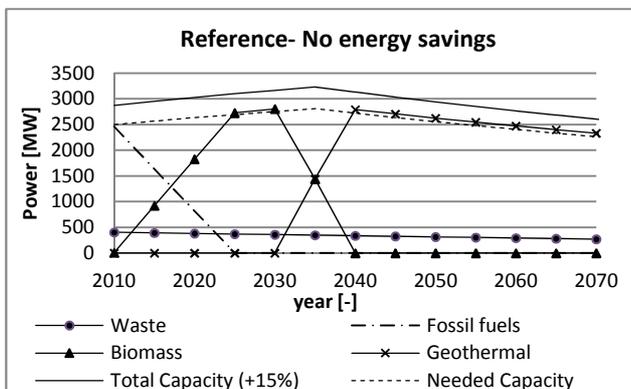
Fig. 2 Peak load for the reference scenario, where no accelerated energy renovations are carried out.

The yearly production of the different supply technologies until 2070 are seen in figure 3. As seen the geothermal heat production is peaking in 2040 with 32 PJ after which it decreases with 13% up until 2070. The total geothermal production in the entire period is 1100 PJ.
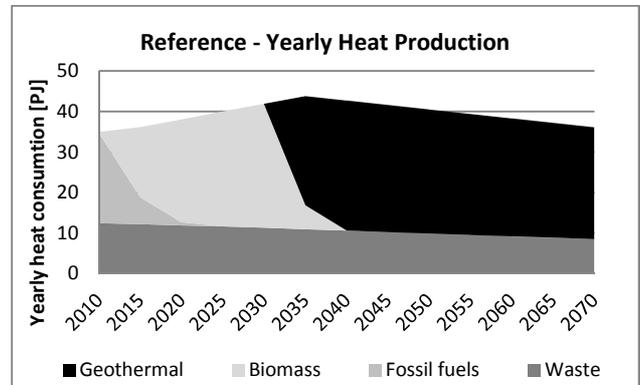
Fig. 3 Yearly heat production for the reference scenario, where no accelerated energy renovations are carried out.

Scenario 1

Scenario 1 represents the case where accelerated energy renovations are carried out from 2030. Figure 4 shows the peak load and the distribution of the supply technologies. As seen from the figure the heat demand is likewise the reference scenario peaking in 2030 after which it decreases. The investment in geothermal capacity is seen to be 2,500 MW, which is slightly lower compared to the reference scenario due to the accelerating energy renovations.
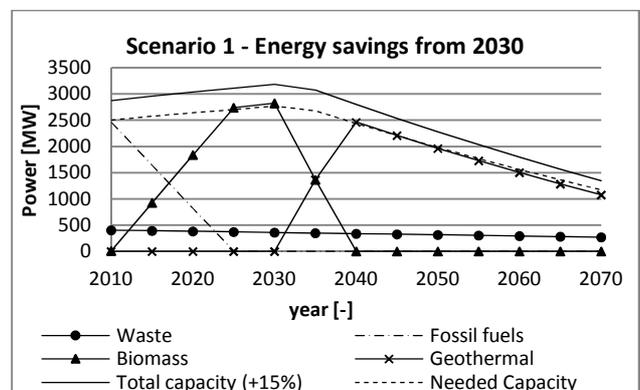
Fig. 4 Peak load for scenario 1 – accelerating energy renovations from 2030.

Figure 5 shows the yearly production of the different supply technologies from 2010-2070. The geothermal production peaks in 2040 with 28 PJ. Due to the accelerating energy renovations the heat demand decreases from 2030 up until 2070 resulting in the coefficient of utilization drops significantly. The production of geothermal heat decreases with 60 % up until 2070 and the total geothermal heat production within the entire period is 780 PJ.
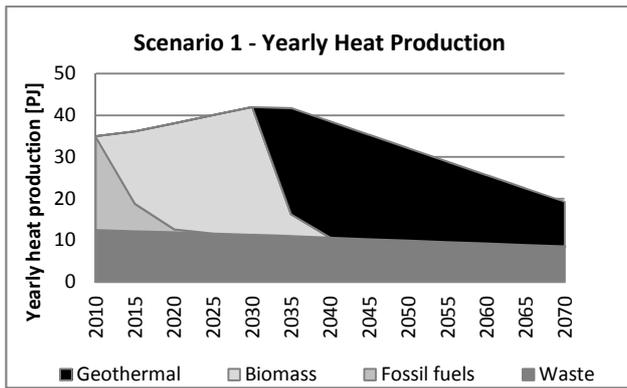
Fig. 5 Yearly heat production for scenario 1 - accelerating energy renovations from 2030.

Scenario 2

Scenario 2 represents the case where accelerated energy renovations are implemented already from today. Figure 6 shows the peak load and distribution of the different supply technologies. The total heat demand is decreasing throughout the entire period in question despite the conversion of the 10PJ. This implies that the investment in geothermal capacity is reduced to 1,200 MW corresponding to a reduction of 60% compared to the reference scenario, and 45% compared to scenario 1.
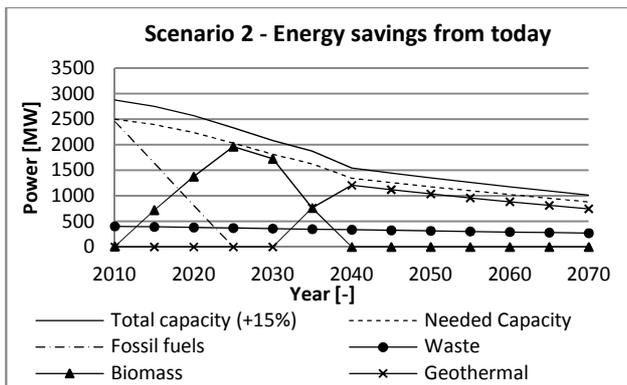
Fig. 6 Peak load for Scenario 2 – accelerated energy renovations from today.

Figure 7 shows the yearly heat production of the different supply technologies until 2070. As seen the geothermal heat production peaks with 16 PJ, which is 50% less compared to the reference scenario and 43% less compared to scenario 1. The geothermal production decreases with around 30% by 2070 compared to the year of peak. The total geothermal heat production throughout the entire period is 484 PJ.
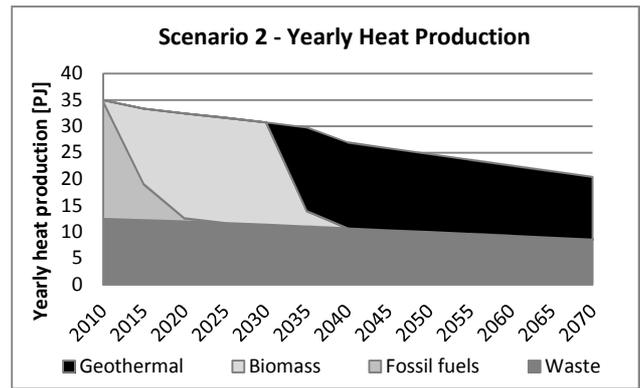
Fig. 7 Yearly heat production for Scenario 2– accelerated energy renovations from today.

ECONOMY

Table 1 shows the estimated costs for each of the scenarios. The total cost for the society is about 25 billion € if no accelerated energy renovations are carried out, but future investment exclusively focus on supplying heat in order to meet the future heat demand. If the accelerated energy renovations are implemented when investment in supply capacity already has taken place (scenario 1) it is seen that it is more costly for the society with about 3 billion € compared to the reference scenario, implying a total price on about 28 billion €. In this scenario the heat demand are reduced after the investment implying that the coefficient of utilization is decreased significant, which is very costly. On the other hand, it is seen that if accelerated energy renovations are implemented already from today (Scenario 2), resulting in a reduced heat demand when the investment in supply capacity takes place, it will save the society for about 1 billion € compared to the reference scenario and about 4 billion € compared to scenario 1.

This stresses the importance in carrying our energy renovation at the right time and thereby reducing the heat demand before investment in supply capacity takes place. As seen supplying heat to an unchanged heat demand compared to implementing energy renovations from today seems to not have significant different consequences. But reducing heat demand seems to be slightly more cost optimal for the society and furthermore, it should be taken into consideration that the peak load will be reduced, creating more stable supply conditions, which is very valuable in the future energy system. Furthermore it will ensure an added value of the building stock.

Table 1 The total cost for each scenarios

		Reference	Scenario 1	Scenario 2
Geothermal				
Unit price for fixed asset investment	[mil €/MW]	2.68	2.68	2.68
Capacity	[MW]	2793	2464	1207
Total price for fixed asset investment	[mil €]	7498	6614	3241
Unit price for O&M - costs	[mil €/MW]	2	2	2
Total O&M - costs	[mil €	1937	1463	947
DH-net				
Unit price for fixed asset investment	[€/MW]	302	302	302
Converted potential (10PJ)	[MWh]	2777778	2777778	2777778
Price for expansion of DH-net	[mil €]	839	839	839
Unit price for O&M - costs	[mil €/PJ]	0.56	0.56	0.56
Total O&M - costs	[mil DKK]	1341	1192	933
Heat production				
Total DH -production in 60 years	[PJ]	2379	2114	1656
Geothermal production in 40 years	[PJ]	1110	838	543
Total costs	[mil €]	11616	10108	5960
Unit price for supply	[mil €/PJ]	10.46	12.06	10.98
Total supply price in 60 years	[mil €]	24886	25487	18185
Renovation				
PJ saved by energy renovating (65%)	[PJ]	-	265	723
Unit price for savings	[mil €/PJ]	-	8	8
Price for energy renovation	[mil €]	-	2205	6021
Total price	[Bil €]	25	28	24

SENSITIVITY ANALYSIS

Waste for incineration

A sensitively analysis is carried out analyzing the consequences of increasing amounts of waste for incineration. All assumptions are unchanged except that the amount of waste is reduced with 1/3 up until 2070 compared to the initial conditions. This results in less investment in geothermal capacity. In reality this will require an investment cost in new incineration capacity, which has not been included in the calculations and reservations should be made here upon. The three scenarios already described are investigated. Figure 8 shows the cost for each scenario.

Geothermal heat as first priority

Furthermore a sensitivity analysis of the consequences for using geothermal heat as first priority compared to waste for incineration has been done. This implies that by 2040 there is no more waste utilized in the DH system and can likewise be seen as the scenario where the amount of waste is reduced, because the energy contained in the waste is utilized for other purposes resulting in a minimum contribution to the heat production. The three scenarios already described are investigated, and figure 8 shows the cost for each of the scenarios.
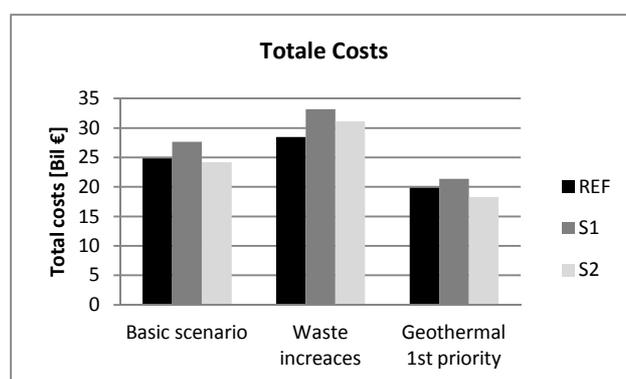
Fig. 8 Comparison between the three scenarios by different assumptions

Figure 8 shows a comparison between the different scenarios and the different sensitivity conditions. As seen scenario 2 represents the cheapest solution for both the basic analyses and the sensitivity analyses of geothermal heat as first priority. In the sensitivity analysis where the waste amounts are increased it is seen that the cheapest solution seems to be the supply-solution. It is expected that the amount of waste is decreased in the future, due to more efficient sorting and more efficient utilization of the energy content for other purposes, implying that either the basic scenario or the geothermal scenario most likely becomes more realistic. As seen from the figure the solution the

geothermal as first priority is generally cheaper than the others, due to the fact that the geothermal plants have a higher degree of utilization, which makes it more economically beneficial.

CONCLUSIONS

A simple and very general model analyzing different future energy planning scenarios regarding DH in Copenhagen has been carried out. Furthermore sensitivity analyses of what will happen if the amounts of waste for incineration changes have been done, using different preconditions. It is been found that from an overall economical perspective it is cost beneficial to invest in energy renovations in order to reduced the heat demand before investing in new renewable energy supply technologies for the future DH-system. This will save around half the investment cost in new supply technologies. If the heat demand is reduced after the supply-investment it will be very costly for the society since much capacity will not be utilized. The economical consequences of only focusing on supplying heat for an unchanged demand versus reducing heat demand through energy renovations starting from today, seems to be quite similar. From this investigation it seems to be slightly cheaper and more beneficial to carry out energy renovations, also taken into account the security of supply. Reducing the heat demand results in smaller peak loads and more stable conditions, which is an advantage for the future energy system based on renewable energy resources. This investigation is based on different assumptions that will have to be investigated further, implying certain uncertainties. Though, the conclusion drawn from this investigation indicates that it is important to reduce heat consumption before investing in new capacity.

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Paper 6 – Appendix 6

M. Harrestrup, S. Svendsen (2013).

Changes in heat load profile of typical Danish multi-storey buildings when energy-renovated and supplied with low-temperature district heating.

Paper 6 – Appendix 6

Change in heat load profile for typical Danish multi-storey buildings when energy-renovated and supplied with low-temperature district heating

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KEYWORDS – Energy renovation, End-use savings, Yearly energy demand, Peak load, Heat load profile, Low-temperature district heating.

ABSTRACT

Denmark has a long-term objective of being free of fossil fuels by 2050 with the energy-supply-mix for buildings being free of fossil fuels by 2035. Hence energy consumption from existing buildings needs to be decreased concurrent with the conversion from fossil-fuel supply into renewable-energy (RE) supply. When end-use-savings are implemented in buildings concurrent with the application of low-temperature district heating (DH) (supply=55°C, return=25°C) the heat demand profiles for the individual buildings will change. The reduction in peak load is important since it is the dimensioning foundation for the future DH-systems and in order to avoid oversized RE-based capacity, a long-term perspective needs to be taken. The results show that it is possible to design the DH-plants based on an average value of the 5 days with highest daily average loads without compromising with indoor thermal comfort. Applying low-temperature DH to existing buildings without changing the heating system imply reduced radiator performance, and it is of great importance that acceptable comfort temperatures can still be provided. The results indicate that it is possible to apply low-temperature DH for approximately 90% of the year without compromising thermal comfort when energy renovations are carried out.

1 INTRODUCTION

Europe has a vision of reducing energy consumption significantly. In Denmark the government has a long-term objective of being completely independent of fossil fuels by the year 2050 with the energy supply mix for buildings being free of fossil fuels already by 2035[1,2]. Therefore, urgent action is needed to meet the requirements for the future energy system. The solution is to combine energy savings and RE-supply in an optimal way. The European building stock accounts for about 40% of the overall energy use [3]. In order to reduce this energy use there is a need of reducing the energy consumption of the existing building stock, increasing energy efficiency and converting the present heat supply from fossil fuels to RE-sources.

The design of new low-energy buildings has been in focus throughout recent years and much research has been carried out in order to design optimized buildings from an energy perspective [4-8]. However, less than 1% of the building stock is in average replaced with new low-energy buildings in Europe [9], which underlines the importance of looking into the existing building stock, where the potential for energy savings is large [10-12]. Investigations have shown that the energy consumption can be reduced by about 50-75% [11-15], but it takes significant investment costs to reach very low levels of energy consumption [11]. Since existing buildings will remain for many years yet to come, it is an unavoidable factor to deal with. The future energy system will have to be based solely on renewable energy sources, which is a (mainly mental) challenge for the society. It will have to be based on different renewable energy technologies that have to interact and balance in order to ensure a system with security of supply.

DH is a sustainable way of providing space heating (SH) and domestic hot water (DHW) to buildings in dense populated areas [16]. In many countries DH systems are already established, but they face new challenges in the future. Around 60% of the heat demand is covered from DH in Denmark, which will have to be converted from the present supply technologies based on fossil fuels into 100% RE-sources, such as geothermal heat.

Supplying the existing building stock with heat from RE-supply technologies e.g. low-temperature DH from geothermal heating plants, may lead to oversized heating plants that are too expensive to build compared to implementing energy end-use savings [17,18]. Therefore reducing heat demand of existing buildings before investing in supply capacity will save half the initial capital investment, indicating the importance of carrying out energy savings now [17,18]. The marginal cost of saving one unit of energy when carrying out a renovation is about 45 €/MWh [18] and the cost of supplying one unit of heat from DH is 60 €/MWh in 2013 (w/o. taxes) and 93 €/MWh (w. taxes) [19]. According to [18] the cost of supplying one unit of heat based on geothermal heat has been estimated to be around 69 €/MWh (w/o. taxes) if accelerated energy renovations are carried out from today. This stresses the importance of carrying out energy savings in the buildings now and design the district heat production based on a long-term perspective.

Traditional DH-systems operate with a supply temperature of about 70°C and a return of 40°C. Applying low-temperature DH, with a supply temperature of about 55°C and a return temperature of 25°C, will give the opportunity to exploit the low-temperature RE heat sources i.e. geothermal heat, solar heat etc. Furthermore it will reduce the heat losses from the distribution pipes and increase the final efficiency of the system. The design concept of low-temperature DH is explained in [20], and theoretical analysis have been carried out in [21,22] and applied in [23,24]. When low-temperature DH is implemented the problem of legionella has to be considered with regards to DHW. According to the German Standards the legionella problem can be avoided as long as the water volume is less than 3 litres and the temperatures are above 50°C [25]. Using a local flat station that contains small amounts of water and is able to boost the water temperature will avoid this problem. Additionally, recent research in Sweden has shown good results by the use of UV-disinfection [26,27].

When end-use-savings are implemented in buildings connected to a DH-system the heat demand profiles for the individual buildings will change, which affects the heat profiles for the entire DH-system. A study from Sweden looks into how the end-use heat savings in buildings will affect district heating production including costs and primary energy savings [28]. They found that a significant amount of the primary energy savings was on the peak load units. In the study the peak loads are supplied from light fuel oil boilers, but in the future the peak loads will have to be covered from RE systems, which are costly. Therefore, after implementing energy-saving-measures the heat load duration profiles for the buildings are of importance since they are the dimensioning foundation for the future DH-systems. In order to avoid oversized RE-based capacity, a long-term perspective needs to be taken. The studies [29,30] investigated low-temperature DH for buildings with existing radiators focusing on the relation between supply temperature, mass flow rate, and the dimensioning on the pipe distribution system based on future and current situations.

Research dealing with a combination of low-temperature DH for existing buildings with focus on obtaining good indoor thermal comfort, concurrent with the implementation of end-use savings, is lacking. Implementing end-use-savings implies reductions in the peak loads, and investigations onto which extent it is possible to reduce the peak loads, when supplying with low-temperature DH and without compromising with the indoor thermal comfort is in focus. Furthermore the relationship between the reduction in yearly heat savings and the change in the heat load profiles is studied.

Two building blocks from the early 1900´s located in typical urban areas in Denmark are investigated, and end-use-savings are carried out concurrent with the conversion into low-temperature-DH supply.

2   METHODS

Two building blocks from Aarhus and Copenhagen have been used as case-studies for this investigation. They are both located in typical urban areas, and are from 1910 and 1906 respectively. Both of them represent a large share of the existing buildings in the urban areas with great energy-saving potentials. The existing state of the buildings is being analyzed after which energy saving measures are implemented in order to decrease energy consumptions. Three degrees of energy renovations are investigated (Table 1).

Table 1: Energy renovation levels

	New windows (w. solar shading)	Mechanical ventilation (heat recovery =85 %, min air change=$0.5h^{-1}$)	Basement insulation	Roof insulation	Facade insulation
Deep renovation	X	X	X	X	X
Light renovation	X	X	X	X	
Window renovation	X	X			

Three different energy renovation strategies are investigated since it might be an optimistic goal to carry out deep energy renovations on all buildings within a short term. Therefore it is important to investigate different levels in order to know whether the concept of low-temperature DH can provide acceptable comfort temperatures with lighter degrees of energy saving strategies. It might also be too expensive to carry out deep energy renovations on all buildings now, since they might as well fulfil the lifetime. Afterwards it might be more reasonable to build new instead of carrying out the relative expensive renovation measures. Therefore solely changing the windows will be a relatively cheap and easy way of obtaining some savings now. Furthermore, a large share is heritage buildings and the facade is protected. Internal facade insulation needs to be applied, which is costly, takes up space from the inside, and might create problems with moisture and fungi [31,32].

The building energy simulation software IDA-ICE 4 [33] has been used for numerical simulations of determining the energy consumption before and after energy-saving measures are implemented. The DRY-weather file for Denmark is used for the simulations.

2.1   Description of buildings

2.1.1 Building in Aarhus

The building consists of 5 floors for residential living plus an unheated attic and basement. The overall heated area is on 850 m^2. The carrying construction is made of wooden beams and brick walls. There is no facade insulation, but the building went through a renovation in 1989 upgrading some parts of the building envelope. Therefore the roof is insulated with 200 mm stone wool, but the horizontal division between the ground floor and the basement has no insulation. The windows were replaced to 2-layers windows. The ventilation comes from natural ventilation from opening windows and leaks. The *deep* and *light* renovations are carried out, since the windows were already changed in 1989 and the energy saving potential for solely replacing the windows will be rather small compared to a building that has not yet been renovated. Only one floor is modelled in IDA-ICE as representative for the entire building (Figure 1).

2.1.2 Building in Copenhagen

The building in Copenhagen also consists of 5 floors for residential living plus an unheated attic and basement. The overall heated area is on 3,409 m^2, spread out on 43 apartments. The carrying construction is made of wooden beams and brick walls. There is no insulation on the facade, roof or on the horizontal division between the ground floor and the basement. The windows are old 1-layer inefficient windows. Fresh air is provided by natural ventilation from opening windows and leaks. All three degrees of energy renovations are carried out - *the deep, light* and

window renovation. Only 3 apartments are modelled in IDA-ICE as representative for the entire building (Figure 1).

The U-values and infiltration for the constructions of both buildings before and after the different renovation measures are presented in Table 2. In order to include the heat loss from the roof and to the basement the extra heat losses from these constructions have in the models been included as a weighted average in the U-value for the facade. The thickness of the facade varies with smallest thicknesses at the top and under the windows. Hence the facade u-value is based on a weighted average representing the entire building facade. The radiators have been dimensioned based on the heat losses from the zones in the existing building by a yearly simulation with IDA-ICE. The radiators are dimensioned based on a supply temperature of 70°C and a return temperature of 40°C [34].

Table 2: U-values for the constructions before and after renovation

U-values and infiltration	Copenhagen		Aarhus	
	Existing	Renovated	Existing	Renovated
Facade [W/m²K]	1.34	0.16	1.34	0.16
Windows [W/m²K]	4.50	0.97	2.90	1.28
Roof [W/m²K]	1.20	0.11	0.20	0.13
Horizontal division between ground floor and basement [W/m²K]	1.20	0.16	1.50	0.30
Infiltration [h⁻¹]	0.5	0.05	0.5	0.05

Figure 1: 3D-model of the buildings in Aarhus (left) and Copenhagen (right)

2.2 Yearly heat demand and heat load profile.

The savings in yearly heat demand are studied and compared to the savings in the peak load. Since the peak load production is very costly, it is desirable to cut off as much of the peak load as possible. Hence it has been investigated until which lower limit it is possible to dimension the peak load production and still provide an acceptable indoor thermal comfort. The savings and indoor comfort has been studied for dimensioning the peak load production based on daily average values. Furthermore it has been investigated whether it is possible to go one step further by dimensioning the peak load production based on an average of the five days with highest daily average values without compromising with the indoor thermal comfort (Figure 2).
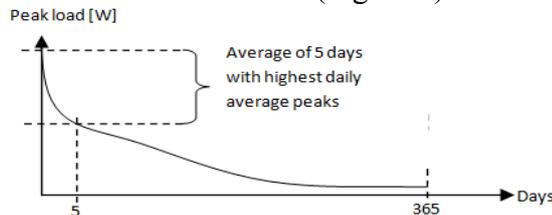
Figure 2: Sketch of duration curve for SH – daily average

2.3 Return temperature from building to DH-net with lowtemperature-DH application

When applying lowtemperature-DH it is crucial to have the same cooling of the DH-water in the system. Traditional DH-systems have a ΔT=30K (70°C to 40°C), and thus the return temperature should be 25°C when supplying with 55°C. If ΔT is decreased the mass flow rate will need to be increased in order to achieve the same power output. In order to be able to use the existing distribution pipes the mass flow rate cannot be increased, which implies that ΔT in the system needs to stay at 30K. The return water from the building to the DH-net has been logged and analysed.

3   RESULTS

3.1   Yearly energy consumption

3.1.1 Building in Aarhus

As a result of the energy saving measures, the total energy consumption has decreased as shown in Table 3. As seen, it is possible to obtain a yearly heat reduction of about 70-80% if the building undergoes a deep renovation and a total energy reduction of about 60-70%, which is in accordance with the findings in [11-15]. The differences in the reduction in yearly energy and yearly SH are due to the extra energy use for operating the mechanical ventilation. A consumption of 4-5 kWh/m^2 for the mechanical ventilation is in accordance with the findings and suggestions in [35]. When a building undergoes a renovation it is often observed that the occupants discover an increased comfort level and thereby increase the room temperature from 20°C to 22°C. The increase of 2°C results in an increased SH-demand of about 30%, which indicates the importance of the user behaviour for the obtained energy savings. When the light renovation is carried out it is seen that it is possible to reach a reduction in the SH-demand of 20-30% if the set point for the room is kept at 20 °C. If this is increased to 22 °C the energy savings are negligible, and the user behaviour is in this case crucial for the obtained savings. Low-temperature DH with a supply temperature of 55°C is applied in both renovation cases, but for the light renovation it was not possible to obtain a minimum comfort temperature of 20 °C all hours of the year. This is due to the fact that when low-temperature DH is applied the performance of the radiators are decreased with a factor 2.5 with an unchanged flow rate. If the flow is increased the performance will increase as well, but in order to obtain an acceptable cooling of the DH-water over the radiator (30K) the flow cannot be increased (see 2.3). Hence the supply temperature was raised to 70°C in cold periods. Figure 3 shows the weather-compensated supply curve, which was applied for the light renovation. Furthermore, Table 3 shows that the use of variable air volume (VAV) ventilation provides lower total energy consumptions compared to constant air volume (CAV) ventilation, which is due to extra heat losses in cold periods when using CAV. According to the requirements from the Danish Building Regulations 2010 [36] the energy consumption for residential buildings is (52.5+1650/A) kWh/m^2 = 62 kWh/m^2 including SH, DHW and energy for ventilation, with A being the heated area. By carrying out a deep renovation it is seen that it is possible to obtain an energy level in accordance with these requirements.

Table 3 Yearly energy demand and reduction compared to existing building

	Existing	Deep renovation**				Light renovation***			
	SH set point= 20 °C	SH set point= 20 °C		SH set point= 22 °C		SH set point= 20 °C		SH set point= 22 °C	
		CAV	VAV	CAV	VAV	CAV	VAV	CAV	VAV
Space heating [kWh/m^2]	133	38	29	55	43	105	94	135	123
Domestic hot water [kWh/m^2]	13	13	13	13	13	13	13	13	13
Mechanical ventilation [kWh/m^2]	-	5	5	5	4	5	4	5	4
Total [kWh/m^2]	146	56	47	72	61	123	112	153	140
SH-reduction* [%]	-	71	78	59	68	21	29	-2	8
Total energy reduction* [%]	-	62	68	51	58	16	23	-1	1

* Compared to existing building, ** Supply temperature 55 °C year round, ***Supply temperature most hours of the year, increased to 70 °C in very cold periods.
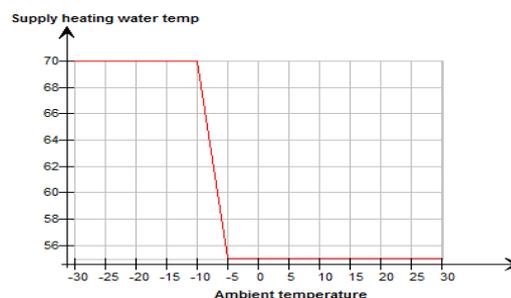

Figure 3: Weather compensated supply curve. Supply temperature as a function of the outdoor air temperature

3.1.2 Building in Copenhagen

For the building in Copenhagen it is seen from table 4 that it is possible to obtain a yearly heat reduction of about 70-80% if the building undergoes a *deep* renovation and a total energy reduction of about 60-70%, which is similar to the building in Aarhus. The mechanical ventilation system is in this building based on CAV and the consumption is seen to be slightly higher than 8 kWh/m^2, but still in accordance with [35]. When the *light* renovation and the *window* renovation are carried out it is seen that it is possible to reach a reduction in the SH-demand of 30-50% and 20-40% respectively, depending on the set point temperature for the rooms. The occupant behaviour has an increased influence on the saved SH when smaller degrees of energy saving measures are implemented. The *window* renovation only provides approximately 10% less than the light renovation, which is due to the very inefficient old windows. Hence a lot of the saved energy is due to the replacement of windows.

Low-temperature DH is implemented with a supply temperature to the building of 55 °C. It was possible to reach a minimum comfort temperature of 20 °C for all three renovation cases without having to increase the supply temperature in cold periods.

Table 4: Yearly energy demand and reduction compared to existing building

	Existing	Deep renovation		Light renovation		Window renovation	
	20° C	20° C	22° C	20° C	22° C	20° C	22° C
Space heating [kWh/m^2]	128	22	34	66	86	80	103
Domestic hot water [kWh/m^2]	13	13	13	13	13	13	13
Mechanical ventilation [kWh/m^2]	-	8	8	8	8	8	8
Total	141	43	55	87	107	101	124
SH-reduction* [%]	-	82	73	48	33	38	20
Total energy reduction* [%]	-	69	61	38	24	29	12

As for the building in Aarhus, it is possible to obtain an energy level that complies with the requirements for new buildings according to the Danish Building Regulations 2010 [36] when carrying out a *deep* renovation.

3.2 Change in heat load profile

3.2.1 Building in Aarhus

When energy savings measures are implemented in the buildings the heat load profile for the individual buildings changes. As seen from Figure 4, which shows the duration curve for daily average SH-loads, the heat demand will become more constant over the year as a result of the energy savings. The more energy-saving measures that are implemented the lower the duration curve becomes (less loads) and the more constant the heat demand is. This means that the DH-plant will have to invest in less renewable supply capacity since the peak loads are lower. Furthermore they are able to supply to a more constant demand, which results in a better economy for the DH-plants.
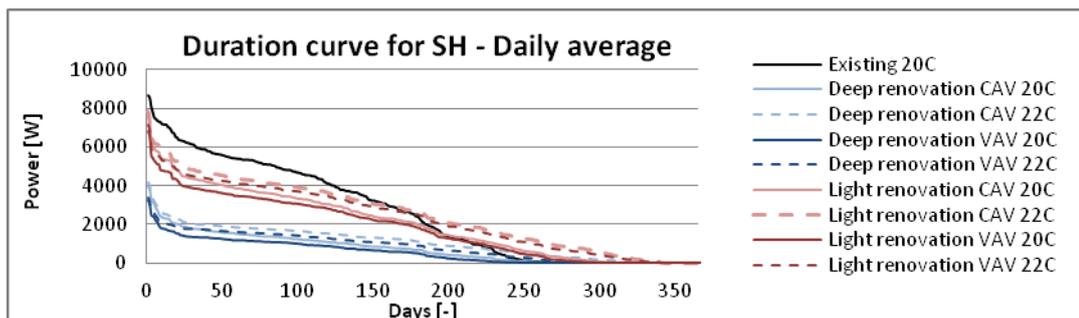

Figure 4: Duration curve for SH – Daily average

Table 5 shows the reduction in the peak load based on the hour with highest load. As seen the reduction is about 40-50% for the deep renoavation but only maximum 15 % for the light renovation.

Table 5: Reduction in peak load compared to the existing building based on hourly values

[%]	Deep renovation				Light renovation			
	SH set point=20°C		SH set point=22°C		SH set point=20°C		SH set point=22°C	
	CAV	VAV	CAV	VAV	CAV	VAV	CAV	VAV
Reduction in peak load (hourly values)	43	52	42	52	5	15	2	12

It has been investigatied whether it is possible to dimension the DH-capacity based on an average of the 5 days with the highest daily average heat loads without compromising with the indoor thermal comfort. For this investigation one scenario for each renovation-case has been chosen. For the deep renovation the investigation is based on the scenario with VAV and a set point temperature of 22 °C, and for the light renovation the scenario with VAV and a set point on 20 °C was chosen. Table 6 shows the peak loads plus the peak load reductions compared to the existing building based on the different dimensioning foundations for the *deep* and *light* renovation respectively. Table 7 shows the thermal indoor comfort with hours outside the desired temperature range. As seen, it is possible to reach the same reduction on the peak loads as for the yearly SH reduction (Table 3) when the dimensioning of the DH-capacity is based on the average of the 5 days with highest daily average loads. It is seen that there are no hours below 20 °C for the *deep* renovation. For the *light* renovation a significant amount of hours are below the limits with the lowest temperature being 17.4 °C, which is not acceptable. If the set point for the room is raised to 22 °C during cold periods it will be possible to avoid hours below 20 °C for most hours of the year. This will increase the yearly energy consumption, but the influence will be small since it will maximum be 1.4% of the year. In case the occupants want a room temperature on 22 °C all year round, it is possible to increase the supply temperature from the DH-plant in more hours of the year in order to meet the demand. This indicates that it is possible to convert into low-temperature DH for most hours of the year without compromising with the indoor thermal comfort.

Table 6: Reduction in peak load compared to the existing building

	Deep renovation		Light renovation	
	Peak load (VAV–SH set point=22°C) [W]	Reduction [%]	Peak load (VAV–SH set point=20°C) [W]	Reduction [%]
Hour with highest load	4918	52*	8670	15*
Day with highest average load	3361	61**	6862	22**
Average of 5 days with highest daily average load	2853	67**	6018	31**

*Reduction compared to the existing building with highest hourly load, **Reduction compared to the existing building with highest daily average load.

Table 7: Temperatures in the living zones and hours outside comfort limits

Average of 5 days with highest daily average load	Living room 1	Living room 2	Living room 3	Living room 4	Bedroom 1	Bedroom 2	Bedroom 3	Bedroom 4
Deep renovation-SH $T_{set\ point}=22°C$								
Ti_max [°C]	26,4	26,4	26,3	26,7	26,0	25,7	26,3	26,0
Ti_min [°C]	20,7	20,8	20,2	20,2	20,2	20,1	20,3	20,0
Ti<20°C	0	0	0	0	0	0	0	0
Light renovation-SH $T_{set\ point}=20°C$								
Ti_max [°C]	26,3	26,2	26,2	26,6	25,9	25,5	26,2	25,9
Ti_min [°C]	18,4	18,6	17,4	18,3	17,7	17,7	17,6	17,7
Ti<20°C	69	65	123	73	103	106	106	106
Ti<19°C	12	9	40	12	32	33	36	31
Ti<18°C	0	0	13	0	7	8	10	6
% hours below 20 °C	0,8	0,7	1,4	0,8	1,2	1,2	1,2	1,2
% hours below 19 °C	0,1	0,1	0,5	0,1	0,4	0,4	0,4	0,4
% hours below 18 °C	0	0	0,2	0	0,1	0,1	0,1	0,1
Ti<20°C with SH set point =22 °C	7	4	35	10	19	21	26	18

3.2.2 Building in Copenhagen

For the building in Copenhagen the same tendency is seen for the reduction of the peak loads and the change in the duration curve. Figure 5 shows the duration curve for SH based on daily average. As seen the heat demand becomes more constant over the year as a result of the energy savings. The more energy-saving-measures that are implemented the lower the duration curve becomes (less loads). This is beneficial for the DH-companies in terms of initial capital investment costs and degree of utilization of the plants.
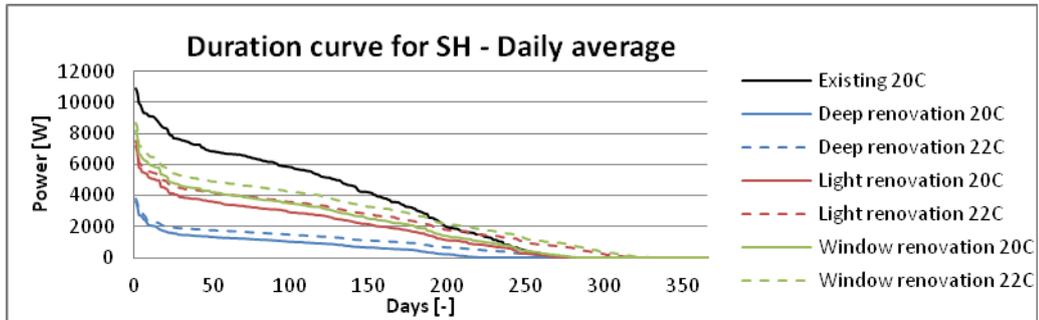

Figure 5: Duration curve for SH – Daily average

Table 8: Reduction in peak load compared to the existing building

Reduction compared to existing building (Supply = 55 °C all year)	Deep renovation		Light renovation		Window renovation	
	20° C	22° C	20° C	22° C	20° C	22° C
Hour with highest load * [%]	58	57	31	30	23	21
Day with highest average load ** [%]	67	65	34	31	25	21
Average of 5 days with highest daily average load ** [%]	72	70	43	40	34	30

*, Reduction compared to the existing building with highest hourly load, **Reduction compared to the existing building with highest daily average load.

Table 9: Temperatures in the living zones and hours outside comfort limits

	Average of 5 days with highest daily average load	Living room 1	Living room 2	Living room 3	Bedroom 1a	Bedroom 2a	Bedroom 2b	Bedroom 3a	Bedroom 3b
Deep renovation 20 °C	Ti_max [°C]	27,0	27,2	26,5	27,0	27,0	26,9	26,5	26,5
	Ti_min [°C]	18,8	19,3	18,8	18,9	19,4	19,2	18,7	18,2
	Ti<20°C	35	16	35	28	13	27	41	35
	Ti<19°C	5	0	4	4	0	0	6	4
	% hours below 20 °C	0,4	0,2	0,4	0,3	0,2	0,3	0,5	0,4
	% hours below 19 °C	0,1	0	0,1	0,1	0	0	0,1	0,1
	Ti<20°C with SH set point increased to 22C	0	0	0	0	0	0	0	0
Light renovation 20 °C	Ti_max [°C]	26,7	27,2	26,8	26,8	26,9	26,8	26,8	26,7
	Ti_min [°C]	18,3	18,6	18,3	19,0	19,2	18,8	18,3	18,6
	Ti<20°C	56	38	55	17	23	40	55	44
	Ti<19°C	14	9	12	1	0	5	4	8
	% hours below 20 °C	0,6	0,4	0,6	0,2	0,3	0,5	0,6	0,5
	% hours below 19 °C	0,2	0,1	0,1	0	0	0,1	0,1	0,1
	Ti<20°C with SH $T_{set\ point}$ increased to 22C	0	0	0	0	0	0	0	0
Window renovation 20 °C	Ti_max [°C]	26,9	27,4	27,2	26,9	27,2	27,1	27,1	27,0
	Ti_min [°C]	18,2	18,3	18,1	19,0	19,1	18,8	18,1	18,5
	Ti<20°C	64	42	62	16	29	42	61	47
	Ti<19°C	16	13	15	0	0	5	15	10
	% hours below 20 °C	0,7	0,5	0,7	0,2	0,3	0,5	0,7	0,5
	% hours below 19 °C	0,2	0,2	0,2	0	0	0,1	0,2	0,1
	Ti<20°C with SH $T_{set\ point}$ increased to 22C	0	0	0	0	0	0	0	0

Table 8 shows the reduction in the peak load based on different dimensioning foundations. As seen the reduction for the *deep* renovation is about 60 %, 65 % and 70 % for the hour with the

highest load, the day with the highest average load, and for an average of the 5 days with highest daily average loads respectively. For the *light* renovation the reduction is about 30-35 % for the hour and day with highest load and about 40 % for the average of 5 days. The *window* renovation results in reductions of about 20-25 % for the hour and day with highest load and about 30 % for the average of 5 days.

Table 9 shows the hours outside the thermal indoor comfort range for the *deep, light* and *window* renovation. The set point is 20 °C and as seen it is not possible to keep a minimum temperature on 20 °C all year round. If the set-point room temperature is increased to 22 °C in very cold periods it is possible to avoid any hours below 20 °C for all renovation cases. Furthermore if the occupant wants to have an indoor room temperature of 22 °C the supply temperature of the DH-plant can be increased from 55 °C to 70 °C in cold periods. From the investigation it indicates that it is possible to supply low-temperature DH most hours of the year without compromising the indoor thermal comfort.

3.3 Return temperature from building to DH-net

The return temperatures from the building to the DH-net are presented in figure 6 and 7 for the building in Aarhus and Copenhagen respectively. In general the lower the set point for the room temperature is, the lower the return temperature becomes. Furthermore, lower degrees of renovations result in an increased return temperature. It is seen that $\Delta T = 30K$ cannot be achieved the entire year for all renovation cases. The solution to that is to increase the supply temperature when $\Delta T = 30K$ is not achieved.
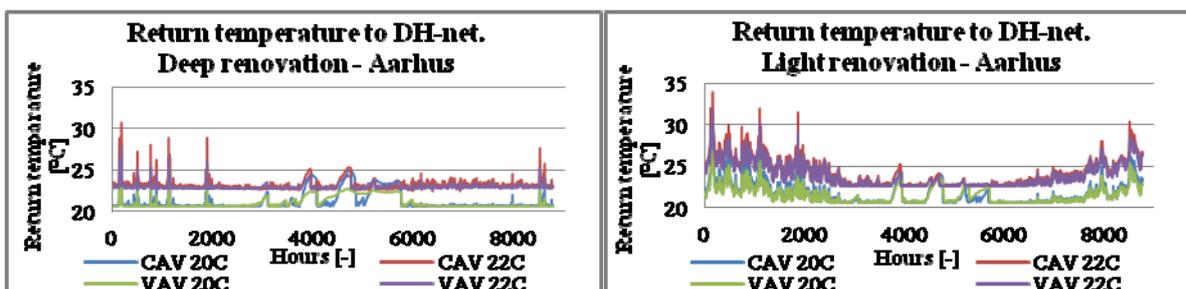
Figure 6: Return temperature to DH-net for building in Aarhus
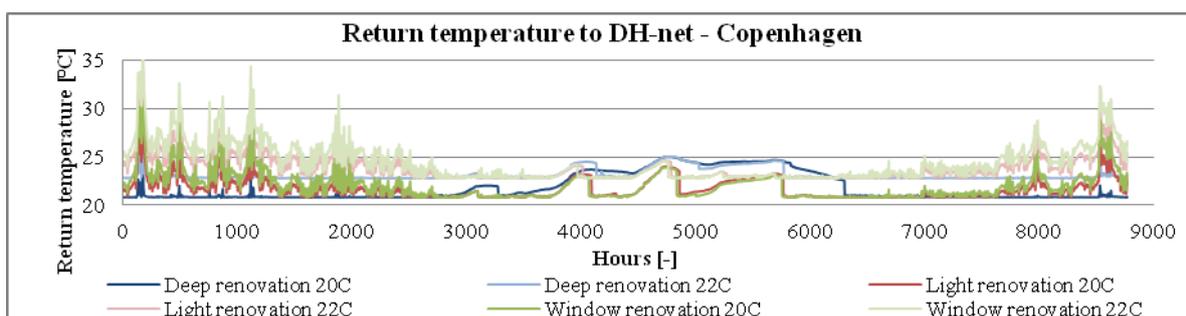
Figure 7: Return temperature to DH-net for building in Copenhagen

4 DISCUSSION AND CONSLUSIONS

Energy renovations have been carried out on two typical Danish building blocks placed in urban areas from the early 1900. It is found that the energy consumption for both buildings can be reduced to what is required for new buildings according to the Building Regulations 2010 (BR10) - approximately 50-60 kWh/m^2 when extensive energy renovation is implemented. This implies a combined solution where the facade, the roof and the basement will be insulated, the windows will

be replaced with new energy-efficient windows with solar shading and mechanical ventilation with heat recovery will be installed. This is in agreement with what was found in other studies [11-15].

It has been found that if the expensive facade insulation is excluded it is possible to obtain energy savings of 30-50 % depending on whether the set point temperature for the rooms is 20 °C or 22 °C. The user behavior has a significant impact on the energy savings achieved, which to a larger extend is reflected when fewer refurbishment measures are implemented.

It has moreover been found that the heat load profiles during the year is generally decreased and more constant as a result of the energy renovation, which is of great benefit to heating companies, since they will supply to a more constant need. It will provide a better utilization of the heat capacity and thereby a better economy.

The dimensioning peak load has been found to be reduced by the same percentage as the reduction in the annual space heating, if the dimensioning is based on an average of the 5 days with highest daily average loads. Furthermore it is found that it is possible to achieve an acceptable indoor thermal comfort, with a minimum temperature of 20 °C. The reduction in peak load leads to less investment in new RE supply capacity, which is beneficial for district heating companies. Figure 8 shows the findings for possible reductions in the yearly demands and in the peak loads.

The investigation indicates that it is possible to supply the buildings with low-temperature DH for most hours of the year without compromising the indoor thermal comfort. In very cold periods it might be necessary to increase the supply temperature to 70 °C in order to meet the demands. However this will only be around 5-10 % of the year. If the occupant wants a room temperature of 22 °C then the hours of supplying with 70 °C might increase. The reason why it is necessary to increase the supply temperature is that when low-temperature DH is applied the performance of the radiators is decreased by a factor of 2.5 with an unchanged flow rate. If the flow is increased the performance will increase as well, but in order to obtain an acceptable cooling of the DH-water over the radiator (30K) the flow cannot be increased. It is crucial that the cooling of the district heating water for low-temperature DH application corresponds to traditional system (30K) in order to keep the existing DH-distribution net. Therefore the return temperature is of great importance. It was found that it is possible to obtain a return temperature of 25 °C for most cases. In general the return temperature increases when lower degrees of energy renovations are carried out, and when the set point temperature for the rooms is increased. In these cases it might be necessary to increase the supply temperature from the DH-plants.
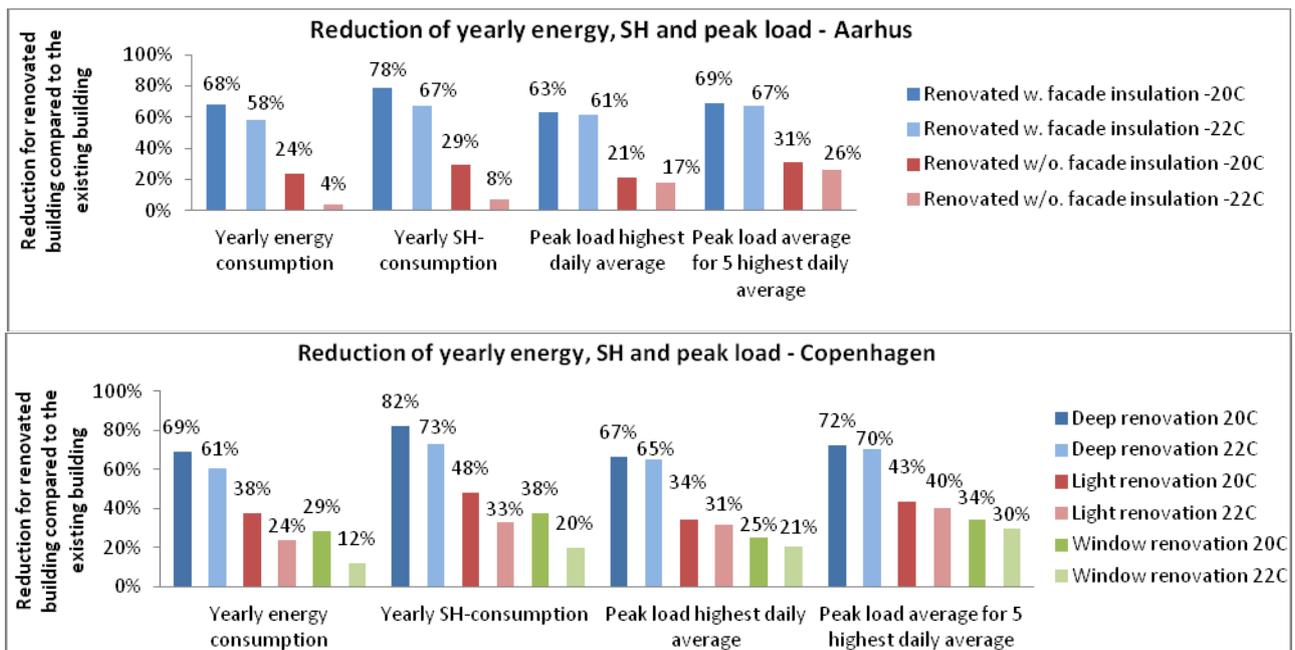

Figure 8: Reduced energy consumption and peak loads. Aarhus (upper), Copenhagen (lower)

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Paper 7 – Appendix 7

M. Harrestrup, S. Svendsen, A.M. Papadopoulos.

Energy retrofitting of an old multi-storey building with heritage value. A case study in Copenhagen with full-scale measurements.

Energy retrofitting of an old multi-storey building with heritage value. A case study in Copenhagen with full-scale measurements

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SUMMARY:
Europe has a vision of reducing energy consumption significantly and Denmark has set up an even more ambitious goal aiming at being completely fossil-free by 2050. But already in 2035 the energy-supply mix for buildings are aimed to be free of fossil fuels. Energy retrofitting of buildings is an important solution of securing energy reductions. But challenges occur when it comes to retrofitting of heritage buildings. A case study on a typical multi-storey building with heritage value in Copenhagen has been carried out. Theoretical investigations are validated with full-scale measurements on energy consumptions before and after the renovation. Energy-saving measures that pay regard to the heritage values of the building are in focus. This implies solutions such as internal insulation. When insulating the facade from the inside, the facade will become cold and condensation in the interface can occur. Furthermore the beam construction will not be insulated, which create a large thermal bridge and the moisture and temperature conditions in the wooden beams will change and attention needs to be given to risk of degradation of the wood. The investigation showed that the actual energy consumption was reduced by 42% whereas the calculated was reduced by 58%. The deviation might be due to altered occupant behaviour. Furthermore relative humidity and temperature measurements in the beam-ends showed no risk of wood decay.

1. Introduction

Europe has a vision of reducing greenhouse gas emissions and energy consumptions by 20 % by 2020 and 80% in 2050 compared to 1990-levels (European Commission 2010) and Denmark has set an even more ambitious goal, aiming at being completely fossil-fuel-free by 2050. Even more, the energy-supply mix for buildings is aimed to be free of fossil fuels as soon as 2035 (Danish Minister of Climate 2011; Danish Energy Agency 2010). Since the building sector is responsible for approximately 40% of the total energy consumption in EU today (Lechtenböhmer and Schüring, 2011) and less than 1% is replaced with new low-energy buildings (Hartless 2003), focus needs to be given to the old inefficient building stock. Different legislative frameworks have been introduced within the area of energy efficiency and buildings with the main legislative instrument in Europe to be the Energy Performance in Buildings Directive (EPBD) implemented in 2002 (EU 2002). In 2010 a recast of the directive was introduced stating that new and retrofitted buildings should consume 'nearly zero' energy (EU, 2010). Energy retrofitting of buildings is an important solution of securing energy reductions, but challenges occur when it comes to retrofitting of heritage buildings where the facade cannot be modified due to the architectural value of the building. The study (Morelli et al. 2011) investigated an energy retrofit of a multi-storey building with heritage value from 1930 constructed with brick facades and found that it was possible to save 70% of the energy consumption. In such cases internal insulation is the only solution for insulating the facade. When insulating the facade from the inside, the facade will become cold and the drying potential of the wall will be reduced. Condensation in the interface between the insulation and the brick wall can occur, which can lead to mould growth (Christensen and Bunch-Nielsen 2009; Munch-Andersen 2008). Furthermore the

horizontal division separating the floors will not be insulated, which will lead to the occurrence of a thermal bridge, where the load bearing beam construction is placed. Many buildings with heritage value are constructed with wooden beams as load bearing structural elements (Engelmark 1983). The moisture and temperature conditions in the wood will change and attention needs to be given to the risk of the wood's degradation, which can, in extremis, lead to a risk of fatal structural damage. Multiple studies have investigated the effect on the wooden beam constructions when applying internal insulation, including Krebs and Collet (1981), Chistensen and Bunch-Nielsen (2009), Munch-Andersen (2008) and Rasmussen (2010). These studies, however, do not include detailed investigation of the impact of Wind Driven Rain (WDR). Morelli & Svendsen (2012) investigated different intensities of WDR on the facade and concluded that the WRD has a great impact on the performance and durability of the wooden beam ends. Kehl et al. (2013a) provides a literature review that also concludes that WDR has an important influence on the behaviour of moisture content and the risk of decay of the beam ends. Other studies that investigate the impact of internal insulation are Ruisinger (2013) and Kehl et al (2013b).

This paper presents results from an energy retrofit of a typical multi-storey building in Copenhagen with heritage value. The aim of the project was to demonstrate a method of how to energy renovate a heritage building focusing on energy savings and to demonstrate the efficiency of different technologies and products. Theoretical investigations are validated with full-scale measurements of energy consumption before and after the renovation. Since the building is protected, energy-saving measures complying with its heritage value have been considered. Economic aspects are not discussed in this paper, since they had already been evaluated before the renovation took place in order to determine the most feasible energy saving measures. The results from that phase (the planning phase of this study) are described by Morelli et al (2012).

2. Methodological approach

2.1 Approach
Step 1: The existing energy consumption is calculated with the building simulations software IDA ICE 4.5 and validated with the measured energy consumption. The measured energy consumption consists of space heating and domestic hot water consumption and is an average consumption from the period 2007-2009. *Step 2:* The energy consumption of the renovated building is calculated with the retrofit measures implemented in the IDA ICE model and the reduction in energy consumption is evaluated based on the results. *Step 3:* The actual energy consumption of the renovated building is measured including heating consumption, domestic hot water consumption and electricity consumption for mechanical ventilation. The heating consumption was measured for the entire building including space heating and domestic hot water provided by HOFOR A/S. Three different mechanical ventilation systems were implemented in the building. A comparison between the electricity usages for each system was carried out. *Step 4*: Since the building is of heritage value, the use of internal insulation was used. The relative humidity and temperature conditions are measured in the wooden beam end embedded in the masonry wall. The measurements are carried out in the apartment that is more exposed to wind, rain, and sun. The measurements are used to evaluate the risk of moisture and degradation problems in the beam that may occur when implementing internal insulation.

2.2 Description of the existing building
The building is located in Copenhagen, Denmark, and was built in 1896. It is a multi-storey building with 6 floors with a heated area of 2717 m^2 and an unheated basement. The building consists of 30 apartments located in three apartment blocks (Block A, B and C). The plan view of the building together with a 3D-view of the model build in IDA ICE 4.5 can be seen in Figure 1. The load-bearing construction is made of wooden beams and brick walls. The thickness of the brick wall varies from 320-645mm. There is no insulation in the building envelope and the windows are old 1-layer inefficient windows. The building has a heritage value corresponding to Class 4 from the SAVE

classification system in Denmark (SAVE 2011), which imply that the building envelope cannot be changed. The U-values for the existing building can be seen in Table 1. The building is heated with district heating and fresh air is provided by natural ventilation from opening windows and leaks. In the toilet/bathrooms and kitchens an exhaust ventilation system was installed but in most apartments the ducts were blocked and did not work. Many of the apartments did not have a shower.
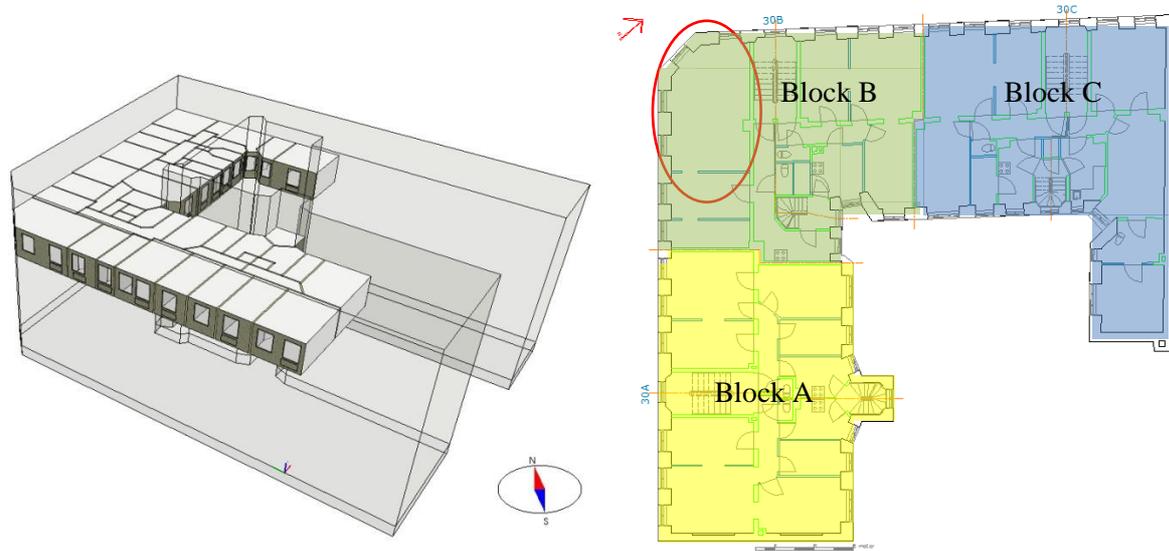

FIG 1. Left: 3D-view of IDA ICE model. Right: Plan drawing of the apartments. The red circle indicates the apartment for moisture and temperature measurements for evaluating the use of internal insulation.

TABLE 1. U-values for the existing building.

	U- values $W/(m^2 \cdot K)$
Average brick wall	1.40
Roof	0.52
Floor to basement	1.50
Windows 1 pane	4.20

2.3 Retrofitting approach

2.3.1 General improvements

The building went through a deep retrofitting where energy saving measures were in focus, but also the interior comfort was improved by installing bathrooms in all the apartments, which were lacking previously. Furthermore permission was given from the municipality to install penthouse flats with roof terraces and solar cells, increasing the total value of the building.

2.3.2 Building envelope

Before choosing which energy saving measures that should be used for the renovation, different energy saving measures were tested in a test apartment on the first floor in Block C. Different window-solutions and different internal insulation products were installed and tested with regards to costs, energy performance, and moisture and temperature conditions. The different solutions are described in Morelli et al. (2012). Since the building has heritage value, the facade cannot be changed. However, the municipality accepted that the windows were changed to new windows since it was proven from the test apartment that they are the most cost- and energy-optimal choice. The windows for the deep retrofitting were from Frovin Windows and Doors A/S and reconstructed as the old

windows. The frame is made of wood and the U-value for the window is U = 0.89 W/m^{2}K. Due to the heritage value of the building internal insulation was used except from the north-east facade (Block C). This facade is facing a narrow passage and 250mm external mineral wool from Rockwool was applied (U-value = 0.39 W/m^{2}K). The remaining facades were insulated with internal insulation. The apartments in Block A and B were insulated with Aerorock (a mix of Rockwool and Aerogel) with a U-value of 0.19 W/m^{2}K and in the apartments in Block C Kingspan (PUR) were applied with a U-value of 0.20 W/m^{2}K.

The installation of internal insulation can create a risk of mould growth at the interface between the insulation material and the brick-wall since the temperature at the interface will decrease when applying internal insulation. Experience from the test apartment showed that it is crucial to clean the brick wall from organic material before applying the internal insulation in order to minimise the risk.

2.3.3 Moisture and temperature measurements

In order to evaluate the implementation of internal insulation and the effect on the beam ends, temperature and relative humidity measurements are carried out in the beam ends. In the test apartment a similar investigation was done and showed no risk. However, the test apartment was orientated north-east facing a small passage and was located on the 1st floor, which implies a minimised amount of wind-driving rain. The measurements for this study are therefore implemented in the apartment that is exposed to the most extreme weather conditions (wind driven rain, sun, wind etc.). The apartment is facing south-west and is on the 5th floor where no shadow or shelter is present. The measuring points and a drawing of how the internal insulation was installed are seen in Figure 2. Due to wall socket and the cables for electricity the insulation was stopped 200 mm above the floor (see Figure 2). This solution is supported by investigations carried out by Morelli and Svendsen (2012) who concluded that if the insulation is stopped 200 mm above the floor, the risk of wood decay is decreased significantly.
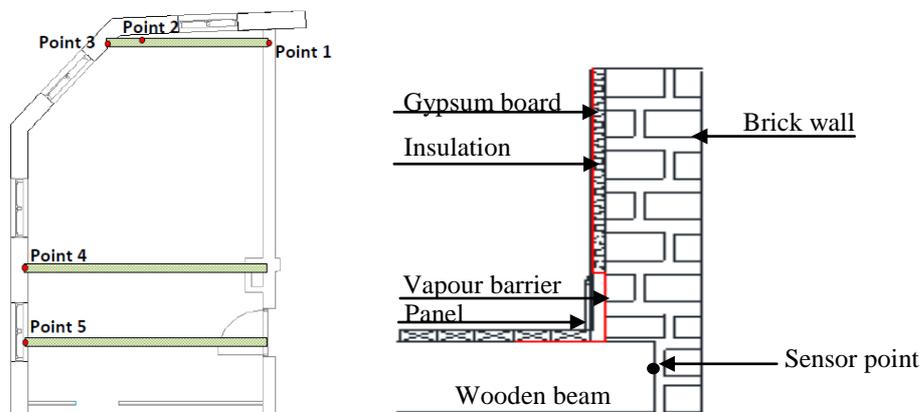
FIG 2. Left: Measurement points for temperature and relative humidity in the beam-ends. Right: Drawing of how the internal insulation was mounted.

2.3.4 Mechanical ventilation

Three different mechanical ventilation systems with heat recovery were installed in the three apartment blocks respectively. *Block A:* A traditional central mechanical ventilation system is installed. The air handling unit (AHU) is placed in the basement and the existing chimneys are used for the exhaust from the bathrooms and kitchens. The supply air to the living rooms is at a constant rate of 140 m^3/h. The exhaust air from the bathrooms is constant at 20 m^3/h when the relative humidity is below 55% and 54 m^3/h when it exceeds 55%. In the kitchen the exhaust rate is 72 m^3/h, but increases to 144 m^3/h when the cooker hood is activated. *Block B:* The ventilation system in Block B is a central ventilation system with the AHU placed in the basement. The ventilation system is operated as

demand controlled based on CO_2, relative humidity and temperature. Furthermore there is a user panel to regulate specific needs. During unoccupied hours a dispensation was given from the municipality to ventilate only with an air exchange rate of 22 m^3/h. *Block C*: The ventilation systems in Block C are decentralized systems on apartment level. This implies that each apartment has an AHU. The control for the ventilation system is demand controlled as for the system in Block B.

3. Results

3.1   Energy consumption

The annual energy consumption calculated and measured is shown in Table 2. The measured energy consumption for the existing building is an average from 2007-2009 and includes space heating and domestic hot water. The deviation between the measured and calculated annual heating and hot water consumption for the existing building is 2.5 % which is considered acceptable. The calculated energy consumption for the renovated building is 63.0 $kWh/m^2/yr$, which corresponds to a reduction in the energy use of 58% compared to the calculated energy use before the renovation. The biggest reduction is found in Block C (65 %) since the north/east facades with no sunlight were insulated with 250 mm external insulation reducing the heat loss dramatically. Morelli et al. (2012) calculated the energy consumption to be reduced by 68% with the building energy simulation software BE10 that is based on Danish standards. The software BE10 is however a simplified software and is working as a one-zone-model whereas IDA ICE software is a multi-zonal software providing more details. The calculated electricity consumption for ventilation is seen to be less for the demand controlled systems followed by the traditional central ventilation with constant airflow, but the calculated energy consumptions are very similar in all three cases.

TABLE 2. Calculated and measured energy consumption for existing building. Calculated energy consumption for the renovated building.

[kWh/m²/yr]	Existing building		Renovated building		
	Measured	**Calculated**	**Calculated**		
	Space heating and hot water	Space heating and hot water	Space heating and hot water	Mechanical ventilation	Total
Block A	-	127.5	78.4	7.0	85.4
Block B	-	134.6	37.1	6.9	57.0
Block C	-	191.1	60.4	6.8	67.2
Total weighted	**155.5**	**151.6**			**63.0**

3.2   Measured energy consumption in the renovated building

3.2.1   Heating consumption

The energy consumption was measured after the renovation was carried out. The total heating consumption for the entire building including space heating and domestic hot water was measured and is shown in Figure 3. Since the measured values include space heating and domestic hot water, the monthly hot water consumption is estimated based on an average value of the heat consumption from June, July and August. It is expected that there is no space heating consumption during these month and even though variations in the hot water consumption occurs over the year, it gives a reasonable estimate. The month November and December are estimated values in order to calculate the annual heating consumption per meter square. The total heated floor area after the renovation is 2892 m^2. This gives a total annual heat consumption of 88.8 kWh/m^2 (see Table 3). Considering weather data it was found that the monthly average temperature in 2013 was 1.5°C higher than that of the design reference year used in the simulation model.
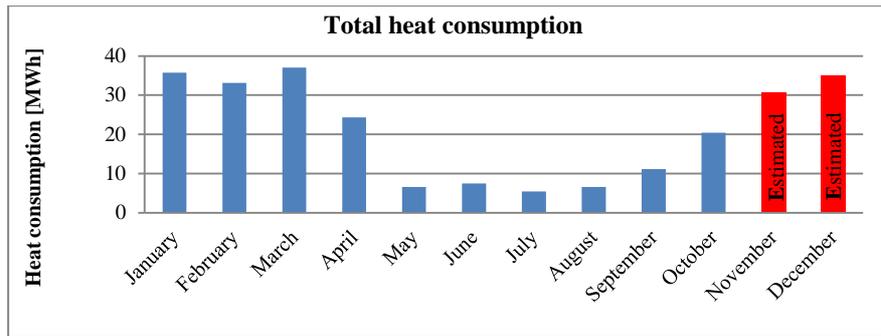
FIG 3. Total heat consumption for the entire building.

3.2.2 Electricity consumption for ventilation

The electricity consumption from the three different ventilation systems was measured and presented in Figure 4. Based on the measurements in Figure 4 the annual consumption per meter square was estimated for each system in order to compare them. As seen from Table 3 the ventilation system in Block B (Centralised demand controlled ventilation) is using the most electricity followed by Block C (Decentralised demand controlled ventilation) and A (Centralised constant ventilation). Table 3 shows that the measured annual energy consumption is 90.7 kWh/m^2, which is 28 % more than the calculated energy consumption.
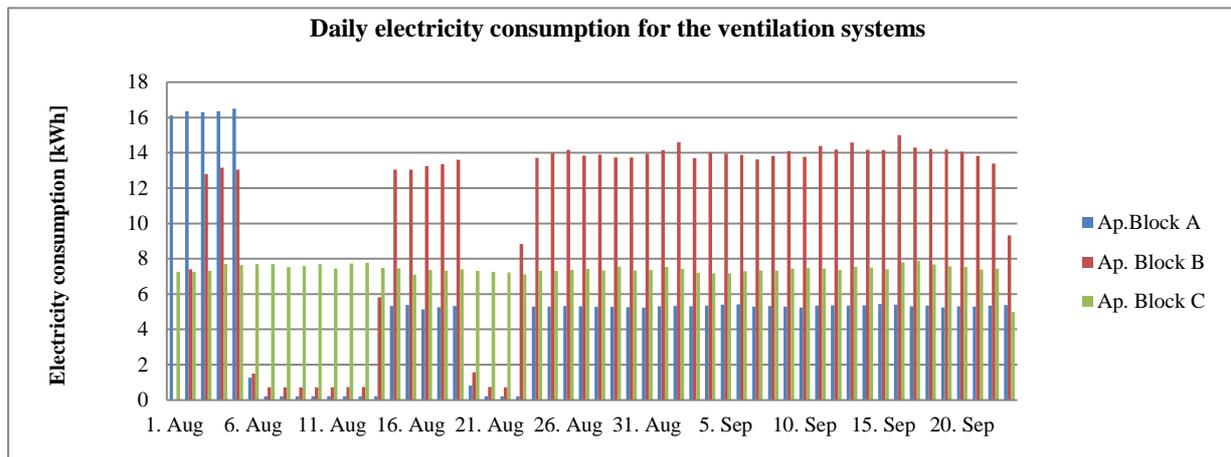
FIG 4. Daily measure electricity consumption for the ventilation systems

TABLE 3. Estimated annual energy consumption per meter square based on measurements

[kWh/m^2/year]	Energy consumption	Total
Heating		87.8
Hot water	27.0	
Space heating	60.8	
Ventilation (weighted)		2.9
Block A	1.9	
Block B	3.9	
Block C	2.9	
Total energy consumption		**90.7**

3.3 Moisture and temperature measurements

Figure 5 shows the measured temperature and relative humidity in the beam ends. According to Viitanen (1997) there is no risk of degradation of the beam when the RH is less than 75%. As seen

from Figure 5 the RH is less than 75% except from point 3 that has RH>75% during the first month. Point 3 has generally higher RH than the other points. The reason for that may be due to the orientation of this beam end, which is facing straight west and therefore exposed to less sun compared to point 4 and 5. Point 1 and 2 are not mounted in the facade and therefore these points are not as critical with regards to high relative humidity. This is also indicated in Figure 5 where the temperature in point 1 and 2 is higher in October/November.
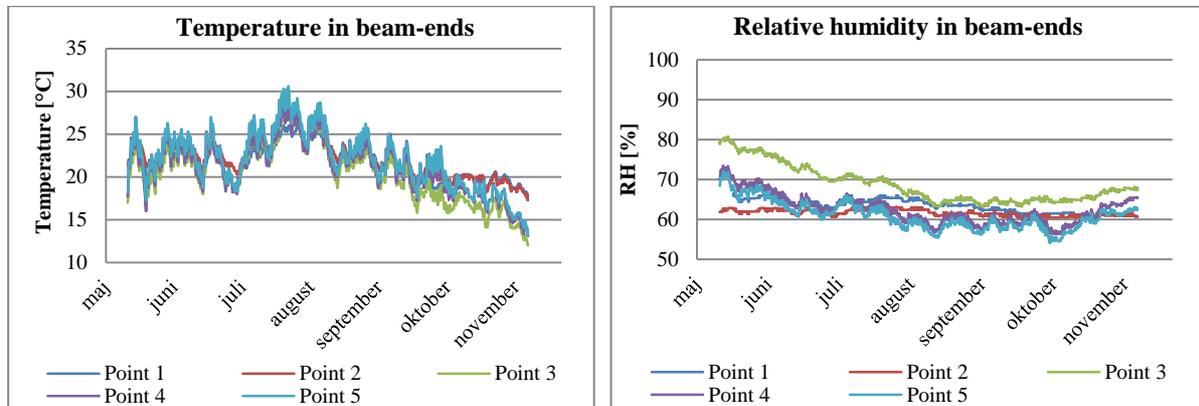

FIG 5. Left: Temperature in the beam ends. Right: Relative humidity in the beam ends.

4. Discussion

While the measured and calculated energy consumption before the renovation deviated with only 2.5%, the measured energy consumption of the renovated building was 28% higher than the calculated energy consumption for the renovated building. One reason for this can be the occupant behaviour. It is often seen that when a building undergo a renovation, the occupant feels an increased comfort and a tendency of an increased room temperature is often seen (Harrestrup and Svendsen 2013). Therefore the actual energy consumption is often higher than what has been calculated. The study showed that when the room set point temperature is increased with 2 °C, the space heating consumption increases by approximately 30 %. Since the monthly average temperature in 2013 in average is 1.5°C higher than the average temperature from the DRY used in the simulation, the increased consumption cannot be explained based on colder weather conditions in 2013 and therefore increased energy consumption. Another reason could be that when insulating from the inside the thermal capacity of the building is decreased, and therefore less heat might be stored during the day and released during night, which might increase the heating consumption. These reasons are to be investigated but are not within the scope of this paper. The measured and calculated electricity consumption for ventilation is seen to deviate with the actual consumptions being approximately 40-70% less than the calculated consumption. Furthermore the calculated results show that the demand controlled systems are more energy efficient than the traditional central system with constant airflow, whereas the actual consumptions show that the traditional central ventilation system with constant air flow is the most energy efficient system.

5. Conclusions

This paper presents a method on how to energy-renovate an old heritage multi-storey building in Copenhagen and document the energy use before and after the renovation. The calculated energy consumption was found to be reduced by 58% but the actual energy consumption was estimated to be reduced by 42% compared to the measured energy consumption before the renovation. A reason for this deviation can be due to altered occupant behaviour. Three different ventilation systems were installed in the building, one in each apartment block. The results from the simulations showed that the

decentralised systems were slightly more energy efficient compared to the traditional centralised system with constant airflow, whereas the measurements on the actual energy consumption showed the opposite. When applying internal insulation, as was done in the studied building, the risk of moisture problems and wood decay can be present. The temperature and relative humidity measurements carried out in the wooden beam ends showed no risk even in the facade of the apartment exposed to more wind driven rain. In this case study the internal insulation was stopped 200mm above the floor, which can be the reason that no risk of moisture problems seems to be present. This solution can therefore be a durable solution for insulating from the inside and still save a considerable amount of energy.

6. Acknowledgements

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Paper 8 – Appendix 8

M. Morelli, M. Harrestrup and S. Svendsen (2014).

Method for a component-based economic optimisation in design of whole building renovation versus demolishing and rebuilding.
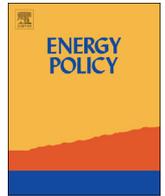
Method for a component-based economic optimisation in design of whole building renovation versus demolishing and rebuilding

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HIGHLIGHTS

- Development of a method for evaluation of renovation projects.
- Determination of an economic optimal combination of various energy saving measures.
- The method compared the renovation cost to those for demolishing and building new.
- Decision was highly influence by the investment cost and buildings market value.
- The results indicate that buildings should be renovated and not demolished.

ARTICLE INFO

ABSTRACT

Aim: This paper presents a two-fold evaluation method determining whether to renovate an existing building or to demolish it and thereafter erect a new building.

Scope: The method determines a combination of energy saving measures that have been optimised in regards to the future cost for energy. Subsequently, the method evaluates the cost of undertaking the retrofit measures as compared to the cost of demolishing the existing building and thereafter erecting a new one. Several economically beneficial combinations of energy saving measures can be determined. All of them are a trade-off between investing in retrofit measures and buying renewable energy. The overall cost of the renovation considers the market value of the property, the investment in the renovation, the operational and maintenance costs. A multi-family building is used as an example to clearly illustrate the application of the method from macroeconomic and private financial perspectives.

Conclusion: The example shows that the investment cost and future market value of the building are the dominant factors in deciding whether to renovate an existing building or to demolish it and thereafter erect a new building. Additionally, it is concluded in the example that multi-family buildings erected in the period 1850–1930 should be renovated.

1. Introduction

In the European Union (EU) the energy efficiency of the building sector has been regulated through the Energy Performance of Building Directive (EPBD) introduced in 2002 (EU, 2002). A revised EPBD was implemented in 2010 (EU, 2010) fostering the increased utilisation of renewable energy sources for energy use in buildings. Thereby, EU endeavours to liberate itself from the use of fossil fuels and, in turn, increases its energy security. Improving the energy efficiency of the building stock is expected to play a key role in

meeting the EU commitment to the Kyoto Protocol with respect to reducing CO_2 emissions. The energy use of the EU's building stock accounts for about 40% of the overall energy use including 25% to the households (EC, 2010). Thus improvements regarding energy usage in households account for a significant energy saving potential. Existing buildings represent about 99% of the building stock, where the replacement rate is less than 1%. This indicates that the energy savings must be realised through renovation of the existing building stock (EC, 2010; Hartless, 2003).

The Danish government has adopted a long-term policy regarding energy usage implying that Denmark should become independent of fossil fuels by the year 2050. One milestone in achieving this aim is the conversion from fossil fuels to renewable energy sources for heating buildings by 2035 (Danish Government, 2011). The conversion may be reached by investments in renewable energy supply technologies e.g., low temperature district heating plants,

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especially in district heating areas. The investments must be executed by ensuring a balance between energy supply and energy renovation of the existing building stock. This both counteracts oversized heating plants and ensures that energy renovation is not too extreme. Ideally, a balance must be found between the costs for improving energy efficiency in the existing building stock and the costs of buying energy from heating and power plants based on renewable energy sources. Another important aspect is the cost balance between retrofitting existing buildings or demolition of the building followed by the erection of a new building. The EU delegated regulation No. 244/2012 (EU, 2012), a supplementing directive to the EPBD, presents a framework for a comparative methodology for calculating cost-optimal levels of minimum energy performance requirements for new and existing buildings and building elements. The framework prescribes calculation of macroeconomic (society) and financial (private) viewpoints including sensitivity analyses regarding energy price, interest rate and other non-energy related costs.

This paper presents a component-based optimisation method to determine the combination of various energy saving measures in the design of whole building renovation. The design proposal balances the cost for renovation to the cost of buying energy from heating plants solely based on renewable energy. Furthermore, the method considers whether to retrofit the building or demolish it and thereafter erect a new building.

2. Existing methods for whole building retrofit

Building renovations undertaken to obtain energy savings are largely propelled by the potential economic benefits of the project. Often, the intent is to ensure the profitably of the retrofit project, regardless if a single energy saving measure is considered or a combination of several energy saving measures. However, several other parameters can be motivating factors for an energy renovation; for example, improved indoor environment, lower energy consumption, and better layout of the building. Jakob (2006) included these factors in a study for the Swiss residential sector even though these factors are difficult to quantify in economic terms. These kinds of improvements to buildings are generally achieved for new buildings but should also be considered in the renovation of buildings. This implies that a new building should be considered as an alternative to energy renovation if the overall costs of the new building and the energy renovation are of the same magnitude.

2.1. Simple payback time and net present value

The optimisation of building renovation proposals can be investigated by applying various economic evaluation techniques. Remer and Nieto (1995a, 1995b) identified 25 different techniques for project investment evaluation. The most commonly used techniques are simple payback time and net present value. Both techniques, as well as their limitations, are described by Martinaitis et al. (2004). Contrary to the method of simple payback time, the net present value (NPV) method includes consideration of both the service life of the renovation measures and the cost of borrowing money to complete the renovation. However, the dependency of an estimated future energy price is a disadvantage of both techniques. In renovation projects, the NPV method has been used for optimising retrofit measures (Gustafsson, 2000; Verbeeck and Hens, 2005) and for assessing energy-saving measures (Tommerup and Svendsen, 2006).

2.2. Cost of conserved energy

A more readily comprehensible method derived from the NPV method is the cost of conserved energy (CCE) (Meier, 1983), which gives the cost to save 1 kWh of energy. The CCE is directly comparable with the cost of supplied energy. Thus the CCE is a way to underscore the least expensive alternative; CCE helps determine whether to invest in energy saving measures or to purchase energy. This makes the CCE technique more transparent and practicable for understanding the cost-effectiveness of the measures as compared to the monetary result obtained using e.g., the NPV method. However, the method of CCE uses the estimated future energy price as the evaluation criterion.

Martinaitis et al. (2004) suggested a "two-fold benefit" method using CCE and a "project marginal cost" as described by Jakob (2006). In this method a coefficient of building rehabilitation is introduced for which the value of the coefficient captures renovation investments in respect to the cost of rehabilitation and those related to energy savings. By dividing the investment costs in this manner, it became apparent that more retrofit measures became profitable. Thereafter, Martinaitis et al. (2007) presented the "two-factor" method for appraising building renovation and energy efficiency improvement projects. Use of this method has permitted determining an investment ceiling for a project based on the difference between the market value of the existing building and market value of a new building. If the investment for energy renovation exceeded the investment ceiling, it was concluded that financing the construction of a new building would be a better choice. In this approach, the CCE method was used on the energy saving retrofit measures and the NPV method was used in respect to maintenance and operational costs. Neither the "two-fold benefit" method nor the "two-factor" method includes an optimisation of energy saving measures. Consequently, the selected retrofit measures are not necessarily the most economically beneficial to the investor.

The CCE method was also used in optimising the design of new buildings using a component-based optimisation approach (Petersen and Svendsen, 2012). This approach used the energy performance framework (i.e., buildings total energy consumption) as a constraint in the optimisation process. Thus the dependency of the estimated future energy price in the evaluation criterion was eliminated. The optimal combination of measures was obtained where the marginal values for the CCE were identical for the respective measures. However, the results from the study showed that for the different building components, identical marginal values of the CCE resulted in the selection of insulation having excessive thicknesses. This indicates that fulfilling the requirements set out in an energy performance framework might bring about measures that result in too much energy renovation of the building as compared to the cost of buying energy.

2.3. Other optimisation methods

Other methods, such as multi-objective optimisation methods (Asadi et al., 2012; Diakaki et al., 2008) can also be applied in renovation projects. The selection process in the use of these methods can become extremely lengthy if no predefined or pre-evaluated measures are chosen. Similar issues are evident using the NPV method due to the calculation of a NPV for each combination of energy saving measure.

Note that according to Verbeeck and Hens (2005), the economic optimum is assumed to be achieved if the total NPV is minimal. However, the economic optimum for energy saving measures in buildings is not one single combination of measures, but can be realised through a range of combinations of measures.

3. Background for proposed method

The proposed method originates from the method presented by Petersen and Svendsen (2012); using the marginal CCE given as follows:

$$CCE = [t^*a(n_r,d)^*I_{measure} + \Delta M_{year}]/[f_1{}^*\Delta E_{year} - f_2{}^*\Delta E_{operation,year}]$$
$$a(n_r,d) = d/[1-(1+d)^{\wedge} - n_r] \quad (1)$$

where t is a reference period that enables a comparison of measures with different service life and is defined as the ratio between the reference period, n_r (years), and the useful lifetime, n_u (years); $a(n_r,d)$ is the capital recovery rate, for which d is the real interest rate (absolute number); $I_{measure}$ is the marginal investment cost (€), where $a(n_r,d)^* I$ is the marginal annualised investment cost (€); ΔM_{year} is the change in annual maintenance cost (€); ΔE_{year} is the change in annual energy conserved by the measure (kWh); $\Delta E_{operation,year}$ is the change in energy consumption during operation of the measure (kWh); f_1 and f_2 are primary energy factors (EN 15603, 2008) that facilitate the comparison between different energy types (e.g., heat and electricity) in the energy performance framework.

The method described by Petersen and Svendsen (2012) and that includes the calculation of the marginal CCE, was developed for new buildings. However, the calculation of the marginal CCE must be adjusted to energy renovation projects based on the following differences that arise when considering the conditions for erecting new buildings, or those that occur when undertaking energy retrofits of existing buildings; these are:

- When designing new buildings all parameters, e.g., the structure of the building envelope, installations, and other building components that affect costs are adjustable. In contrast to that which occurs when designing new buildings, retrofit projects deal with several limitations regarding possible technical solutions due to the existing design of the building.
- The use of energy conversion factors in Eq. (1) is useful regarding new buildings. However, the use of the factors may not make sense in energy renovation projects. This is because of the factors probably not only reflect the ratio between the energy prices but also the energy type; e.g., whether the energy is delivered from fossil fuels or renewable energy sources.
- Regarding building renovation, it is presumed that some of the energy saving measures will not be profitable due to the existing building design; e.g., installation of mechanical ventilation. However, mechanical ventilation must be included for maintaining an acceptable indoor environment if the building envelope is tightened. Therefore, it might be difficult to fulfil an energy performance framework for energy renovation projects if only profitably energy saving measures must be implemented in the building.
- The calculation of marginal CCE in Eq. (1) excludes the energy use for operation, $\Delta E_{operation,year}$, because this is subsequently subtracted from the value of the annual energy use, ΔE_{year}. An example of this issue is evident if considering mechanical ventilation. The annual energy use for a mechanical ventilation system will consist of determining the heat loss through the heat exchanger and electricity to operate the fan. Subsequently, the operational energy will be subtracted from the annual energy use resulting in the heat loss as the annual energy use.

3.1. Marginal cost concept

In Eq. (1) the marginal cost concept is used in the calculation of the CCE. In essence, the marginal cost is the cost of the last produced unit or alternatively, the cost of producing an additional

Table 1
Conditions for profit development.

	Marginal profit	Total profit
MR > MC	Positive	Increasing
MR = MC	Zero	Maximum
MR < MC	Negative	Decreasing
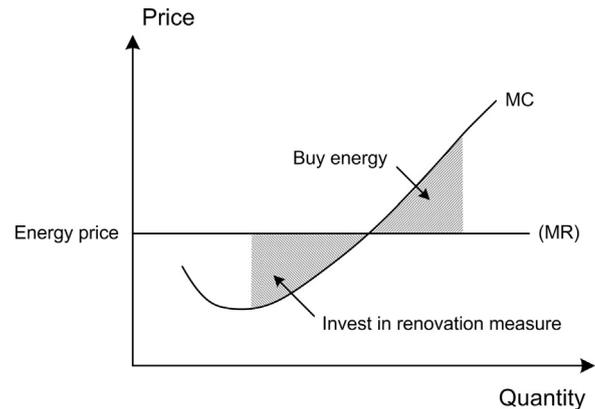
Fig. 1. Profit maximisation and optimisation of renovation measures using the marginal cost concept.

unit. In economics, total profit maximising occurs when the marginal revenue (MR) is equal to marginal cost (MC). The MR is defined as change in revenue per unit change in the number of units produced (Carbaugh, 2011). Table 1 illustrates the three scenarios with respect to the proportions of MR and MC.

This may be illustrated for example, as when the producer accumulates profit up until the intersection of the marginal revenue and the marginal cost (where zero profit is evident and any further production will result in negative marginal profit, because marginal cost will be larger than marginal revenue). The optimisation of renovation measures is analogous to the notion of profit maximising in economics, as shown in Fig. 1. Investing in energy savings is only profitable when the marginal cost for the energy savings is below the cost of energy, otherwise buying energy is economically reasonable.

4. Proposed method for determining whole building retrofit

The proposed method is divided into three general steps.

(1) Assessment of energy saving measures and determining the inter-relationship between the CCE_R for the different retrofit measures.
(2) Determination of the energy weighted average marginal CCE_R to equal the energy price based on renewable energy sources.
(3) Calculation of the economic profit from the project considering whether to renovate the building or demolish it and thereafter erect a new building.

Based on the value of CCE for new buildings as given in Eq. (1), a new approach is proposed for building renovation. The marginal cost of conserved energy for building renovation, CCE_R, is given in Eq. (2). Calculating the marginal CCE_R for different energy saving measures enables a direct comparison of their efficiency.

$$CCE_R = [t^*a(n_r,d)^*I_{measure} + \Delta M_{year} + \Delta E_{operation,year}{}^*P_{energytype}]/[\Delta E_{year}] \quad (2)$$

where I_{measure} is the marginal investment cost (€); $P_{\text{energy type}}$ is the energy price for the energy type used for operational energy (€/kWh); t, $a(n_r,d)$, ΔM_{year}, $\Delta E_{\text{operation,year}}$, and ΔE_{year} are the same as given for Eq. (1).

In the approach for CCE_R the marginal investment, maintenance and operational cost are added together (€) and divided by the marginal annual energy conserved by the measure (kWh). In this way it is possible to exclude the primary energy factors. Thus different energy types are not compared. Furthermore, only the substituted type of energy is considered in the annual energy saving.

4.1. Determining the combination of energy saving measures

To facilitate the optimisation process for determining the combination of energy saving measures, continuous CCE_R functions are developed. These functions express the marginal CCE_R of an energy saving measure as a function of its energy consumption.

The CCE_R-method is easily applicable to energy saving measures that can be expressed as continuous measures. These measures are recognised by having continuous energy properties; marginal increase in quantity, e.g., insulation thickness, results in a marginal increase in the CCE_R and a decrease in energy consumption. It is, however, more complex to apply the CCE_R-method to discrete measures such as windows (i.e., measures having discrete energy properties). Hence, a marginal increase of the quantity is not easily defined because of the individual components. Petersen and Svendsen (2012) presented a four step algorithm to determine a continuous CCE_R function for discrete energy saving measures. This process is construed to a five step algorithm in the following manner:

(1) A first reference is determined among a number of components based on their investment cost and annual energy use. The components are ranked according to investment cost, and the component with lowest cost is chosen as reference. If the investment cost is identical for two or more components, the component with lowest energy use should be chosen as reference, and the other components should be omitted due to the higher energy use. For existing components the investment cost will be the refurbishment cost, thus the component performs as when it was newly installed.

(2) The marginal CCE_R for each component is calculated applying Eq. (2) using the reference component determined in step 1. Components with negative values of CCE_R are omitted because they use more energy combined with a higher investment than the reference component determined in step 1.

(3) A new reference is determined based on the marginal CCE_R derived in step 2. The component with the smallest positive marginal CCE_R is chosen as a new reference to form a curve. From the remaining components, those with an energy use equal or higher than the new reference are omitted as they are not energy saving measures compared to the new reference.

(4) The marginal CCE_R for each component is calculated applying Eq. (2) using the reference component determined in step 3 and its respective investment cost and energy savings. Step 3 and 4 are repeated until there are no more components to consider.

(5) The reference component found in step 1 and those determined in step 3 are listed in the order they are determined. These discrete components are thereby transformed into a continuous CCE_R function by calculating the marginal CCE_R according to Eq. (2).

The proposed method suggests that the determination of a combination of energy saving measures for renovated buildings is

defined as the energy-weighted average marginal CCE_R of the measures ($CCE_{R,\text{average}}$) equal to the energy price, Eq. (3).

For discrete energy saving measures it is unlikely that one would obtain CCE_R values equal to the energy price. Thus the discrete measures must be chosen as close to the energy price as possible. This allows the energy-weighted average CCE_R to be adjusted by choosing the continuous measures reaching for the energy-weighted average marginal CCE_R to equal the energy price, as provided in Eq. (3).

$$CCE_{R,\text{average}} = \left[\Delta E_1 {}^*CCE_{R,1} + \Delta E_2 {}^*CCE_{R,2} + ... + \Delta E_n {}^*CCE_{R,n}\right]/[\textstyle\sum_1^n \Delta E_i] \leq P_{\text{heat}} \quad (3)$$

where E_n is the energy consumption for the energy saving measure n (kWh); $CCE_{R,n}$ is the cost of conserved energy for the energy saving measure n (€/kWh); $\sum_1^n \Delta E_i$ is the sum of the individual energy consumptions of all energy saving measures (kWh); and, P_{heat} is the energy price for heating (€/kWh).

Note that in Eq. (3) the interaction of different energy saving measures is not considered even though it influences the sum of saved energy (Chidiac et al., 2011). This may lead to an overstated average CCE, in case the interaction is taken into account in the sum of saved energy in the denominator. However, the interaction of the different energy saving measures is included in the calculation of profits given in Eq. (4).

A review of the $CCE_{R,\text{average}}$ suggests that a number of different combinations of energy saving measures can be chosen, where some will be cost efficient and others not. This is acceptable when the combination of energy saving measures is cost efficient. In the case where several combinations of energy saving measures can be chosen, one must consider the practical application of the measures and subsequently to maximise the energy savings and minimise the cost. For example, if the building envelope is tightened the need for mechanical ventilation might occur, and this energy saving measure might not be profitable. However, mechanical ventilation is needed for maintaining an acceptable indoor environment.

4.2. Renovated building versus new building

The decision whether to renovate a building is based on both the profitability of the energy saving measures and whether it is more prudent to erect a new building. Therefore, the cost of the proposed combination of energy saving retrofit measures once determined is then compared to the cost of demolishing the building and thereafter erecting a new one. Furthermore, the decision-making process also includes the cost of maintenance and operations considered over the expected service life of the building. The cost for building improvements such as new bath rooms and kitchens should also be included. It is, however, not a trivial question whether to renovate or demolish and rebuild as this might target different market segments. Furthermore, the ownership of building and apartments, e.g., a housing cooperative, private investor, tenants, or owner-occupied flats, can also influence the decision-making process. The proposed method can also be used to form the basis for decisions as to whether or not to implement the energy renovation of the building regardless of the ownership. The method can also be applied from a macroeconomic perspective for decisions about what to do with the existing building stock.

The profit of any given project is determined on the basis of the market value (MV) for the renovated building, or a newly erected building, minus the investment cost (which could also including the transaction costs) (I), and the discounted (1/capital recovery rate) maintenance and operational (M&R) costs, as given in Eq. (4). If a new building is erected at the exact same location as the

existing building, the cost for demolishing (D) the existing building must also be included. The building project that should be undertaken in economic terms will be the one having the highest profit.

$$\text{Profit} = MV - (I + D + M\&R/a(n_r, d)) \qquad (4)$$

4.3. Forecasted energy price

In Denmark, district heating is mainly derived from combined heat and power plants (Gustafsson and Rönnqvist, 2008) that use fossil fuels to produce energy. In accordance with the Danish government's energy policy, these heat and power plants must substitute their fossil fuels with other fuel sources, for example, this could be biomass, geothermal, sun, or waste heat. Thus they can eventually operate from a fossil-free fuel supply network for buildings. Some combined heat and power plants have already been converted to biomass, solar, or geothermal heating plants (Mahler and Magtengaard, 2010).

The forecasted energy price for district heating is based on a study by Harrestrup and Svendsen (2012). In this study it was assumed that the future combination of supply sources for district heating was based on geothermal sources and heat derived from the incineration of waste. The energy price of heat was determined based on the implementation of energy retrofit measures from 2010 up to 2040, thereby reducing the usage of heat from the existing building stock by 65%. This is a tolerable and transitional approach as suggested by Kragh and Wittchen (2010). In the study by Harrestrup and Svendsen (2012) the cost for the geothermal heating plant was calculated in which it was assumed that the geothermal heating plants had a service life of 40 years, and a 3% interest rate. The price of energy for geothermal heat was calculated as 45.42 €/MWh (excluding taxes and VAT) when taking into account the investment, operational and maintenance costs of the geothermal heating plants. Additionally, a connection cost was featured in the total price for heat; this cost was determined as 28.47 €/MWh. It was determined taking into account that the district heating company must cover the total fixed costs for which the fixed costs were converted into a representative value considering the amount of heat delivered over a period ranging between 2010 and 2070 (60 years) for the area of interest (Harrestrup and Svendsen, 2012). Subsequently, the price of heat was solely based on renewable energy sources and was calculated from the cost of supplying heat from geothermal heating plants including the connection cost, as provided in Table 2. The percentage of tax applied to the present price of heat was assumed representative of that to be applied to the future price of heat. Taxes in respect to CO_2 were neutralised with a distribution network solely based on renewable energy, however, other energy taxes may be introduced. The price of heat was thus determined as an average energy price of heat for the period between 2010 and 2070, hereafter referred to as 2040.

The forecasted price of heat was calculated as 148.70 €/MWh (including taxes and VAT) which is consistent with the findings given by Laustsen et al. (2000). Laustsen et al. (2000) calculated

the price for heat ranging between 0.13 and 0.16 €/kWh. In that study the heat supply was solely based on renewable energy sources in the form of an energy efficient district heating system and solar heating. Predictions for the price of energy are, however, associated with significant uncertainties. One reason being the long-term perspective and also, in the context of this study, the conversion in the energy supply system.

4.4. Life of mortgage, service life and interest rate

The reference period considered in the calculation is 30 years, corresponding to a typical loan period for building investments. The service life of most building components is in any case approximately 20-30 years and some components may even reach up to 100 years. For buildings, a lifetime beyond 100 years can be expected. Another argument for considering a 30 year period is that new and better products will certainly be available on the market within that time period. A period of 30 years is, however, associated with significant uncertainties in respect to the prediction of interest rates and energy prices. This indicates the need for completing a sensitivity analysis as was required in EU (2012).

The real interest rate is calculated as the amount by which the nominal interest rate is greater than the rate of inflation. Two real interest rates were considered, one corresponding to a house owner level (2.5%) and the other a sustainable level (0%). By house owner level it is understood that this corresponds to the real interest rate used in private financial affairs, whereas the sustainable level relates to macroeconomic considerations. If a real interest rate of 0 % is used instead of 2.5% then the society can compare present and future investment on the basis of a sustainable foundation for development. However, using the net present value method with a discount rate of 2.5% the value of future investments will decrease. Thereby it will be of greater benefit to wait for large investments such as those that are required for energy renovations. If the interest rate is greater than 0%, the payback time will be less than the current lifetime of the retrofit measure, thus the investment has to be earned over fewer years than the lifetime (Tommerup and Svendsen, 2006). In Table 3 values for the annuity factor are given for different values of lifetime and real interest rates. The annuity factor is synonymous with the payback time in years, hence, to an expense neutral investment.

5. Multi-family building—an example

This case study illustrates the application of the proposed method to evaluate whether to renovate the existing building or demolish the building and thereafter build a new one. In the case study two perspectives are used to determine the respective influence of either approach on the degree of energy retrofit measures: one to illustrate a macroeconomic point of view and the other a private financial viewpoint.

The building in the example is a typical multi-family building dated from the period of 1850–1930 and located in Copenhagen, Denmark. In this particular instance the six storey building of

Table 2
Present and forecasted price of heat.

	2012 (€/MWh)	Forecasted 2040 [a] (€/MWh)
Energy price	42.55	73.89
Taxes (CO_2, energy etc.)	26.00	45.07[b]
VAT (25%)	17.15	29.74
Total energy price	85.70	148.70

[a] Average price for the period 2010–2070; hereafter referred to as 2040.
[b] The tax rate in the forecasted price for heat is kept at the same order of magnitude as for 2012, that is, equal to 61% of the energy price.

Table 3
Annuity factor (1/capital recovery rate) in respect to lifetime and real interest rate.

Lifetime (years)	Real interest rate per year		
	0.0%	2.5%	5.0%
5	5.0	4.6	4.3
30	30.0	20.9	15.4
100	100.0	36.6	19.8

interest was actually built in 1896. The building has a floor to floor height of 2.6 m and a floor area at each storey of 453 m^2. The facades are made of solid masonry and have been deemed worthy of preservation. The windows constitute 27% of the overall facade area. The windows consist of a single layer of glazing. However, the windows on the street facade have had a secondary glazing installed. The floor divisions are constructed with wooden beams and clay pugging and they are un-insulated towards the unheated attic and basement. The building employs central heating which is produced from district heating. The 30 apartments are naturally ventilated by opening windows, infiltration and ventilations ducts located in the kitchen and bathroom. A more detailed description of the building can be found in (Morelli et al., 2012).

For simplicity, the optimisation of the building renovation was limited to walls, ceiling, basement floor division, windows, and mechanical ventilation. The energy usage of each of these elements is considered in turn as described in the respective sections. The interaction of the renovation measures was neglected in the calculation of the energy saving as a function of the marginal CCE$_R$ of the individual measures. Thus, the sum of the individual energy savings will be an overestimated value as compared to the energy saving based on their interaction of renovation measures (Chidiac et al., 2011). However, the interaction of the measures was included in the calculation of the buildings total energy use (energy performance framework) as described by Morelli et al. (2012) which also included detailed calculations of the linear heat loss transmittances. The CCE$_R$ calculations (Eq. (2)) were conducted for the private financial viewpoint with a real interest rate of 2.5% and energy prices of 0.09 €/kWh (present) and 0.15 €/kWh (2040). For the macroeconomic perspective a real interest rate of 0% was used combined with energy prices of 0.04 €/kWh (present) and 0.07 €/kWh (2040).

5.1. Opaque building envelope

The opaque portion of the envelope included the wall, roof, floor, and end wall. The energy use, Q_c (kWh/m^2 structure per year), for the structure, was calculated from equation (5) using the degree day method (ASHRAE, 2009):

$$Q_c = U_c * D_h \tag{5}$$

where U_c is the U-value for the structure (W/(m^2 K)) and D_h (kKh) is the number of degree hours in the heating season for the structure. The degree hours are 90 kKh for both the wall and the roof and 45 kKh for the floor to the unheated basement according to the Danish design reference year (DRY) (Jensen and Lund, 1995) with a base temperature of 20 °C. During the heating season, which occurs from September 24 to May 13, the heating system is active 24 h a day. For highly insulated buildings the heating season is shorter than for poorly insulated buildings because of reduced heat loss from the building. Alternatively the heating season can be determined according to EN ISO 13790 (2008).

Fig. 2 shows the energy use as a function of the CCE$_R$ based on the data given in Table 4. The costs provided in Table 4 include installation and material cost (V&S, 2012).

Table 4
Data assumption for mineral wool insulation of walls, roof, and floor.

Building element	Thermal conductivity (W/(m K))	Cost (€/mm/m^2)	Service life (years)
Wall	0.037	0.15	100
Roof	0.037	1.30	100
Floor	0.037	0.81	100
End wall	0.037	3.03	100
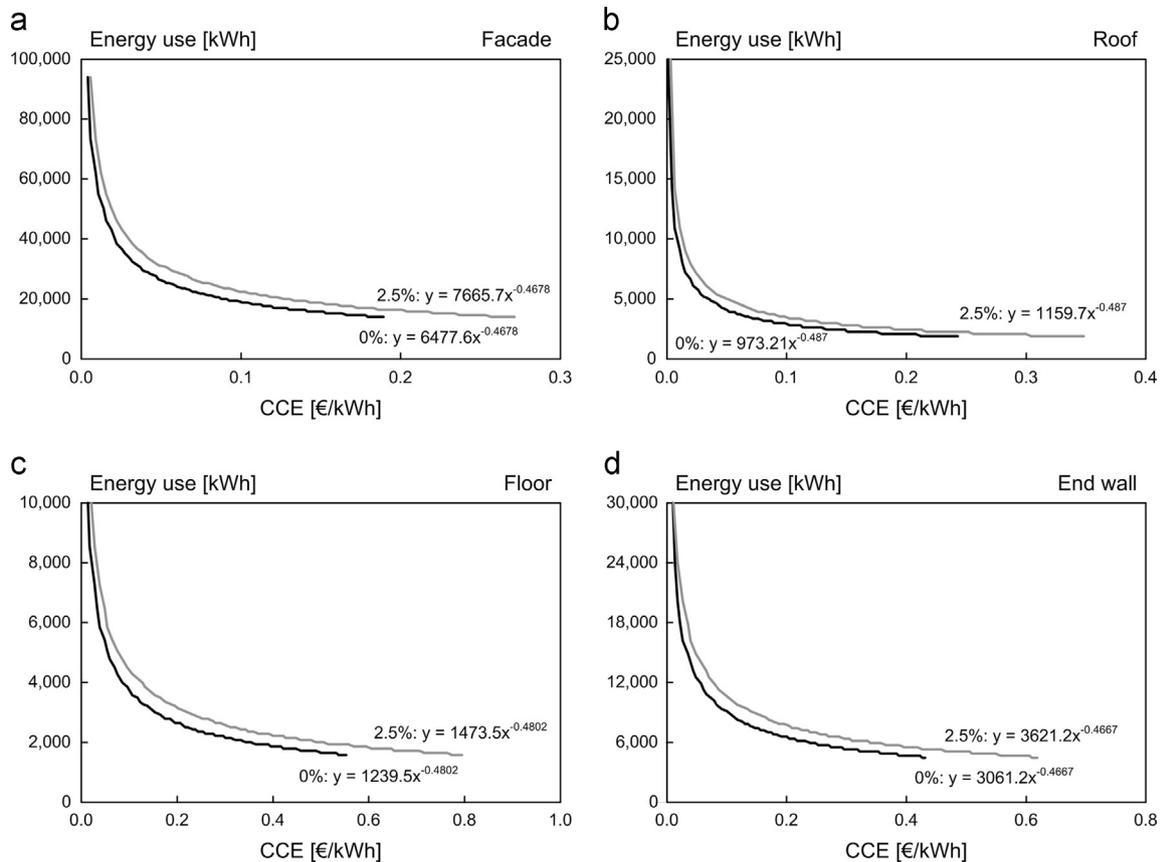
Fig. 2. Energy use as a function of CCE$_R$ for insulation of (a) interior facade, (b) roof, (c) floor, and (d) exterior end wall for interest rates of 0% and 2.5%.

- *Wall*: steel framework, mineral wool, vapour barrier and two gypsum boards.
- *Roof*: mineral wool placed in attic.
- *Floor*: clay pugging exchanged with mineral wool, vapour barrier, new floor boards and removal of materials.
- *End wall*: new base, mineral wool and mortar as external surface.

The maintenance costs for each step of the energy saving measure of, e.g., mineral wool, are identical and therefore set to zero. The energy calculation is performed for the entire structure, e.g., wall with a reference of the existing structure and to approximate a continuous function, in steps of 10 mm insulation.

Table 5
Data for window retrofit measures. *U*-value and *g*-value are given for a window size of 1.1 m × 1.6 m; values for costs include VAT.

Window type	U-value (W/(m^2K))	g-Value (–)	Cost (€/m^2)	Service life (years)
Reference with 1 layer normal pane	4.05	0.51	439	20
Reference with secondary pane (2 panes)	2.20	0.45	531	20
Retrofitted with secondary glazing (3 panes)	1.09	0.38	641	20
Retrofitted with secondary pane (2 panes)	1.62	0.44	723	20
Retrofitted with sash on casement (2 panes)	1.76	0.44	783	20
New with coupled frames (3 panes)	0.96	0.33	815	20
New with coupled frames (2 panes)	1.74	0.46	888	20

Fig. 3. Energy use as a function of CCE_R for two reference windows: (1) single pane and (2) single pane with secondary pane.

5.2. Windows

The energy use for windows, E_w (kWh/m^2 window per year), is calculated as the net energy gain. The energy use for windows is the difference between the solar gain and heat loss as given in Eq. (6) as described in Nielsen et al. (2000).

$$E_w = 196.4^*g - 90^*U \tag{6}$$

where g is the total solar energy transmittance for the window, and U is the thermal transmittance for the window (W/(m^2 K)). The number 90 is the degree hours, as described at Eq. (5). The number 196.4 is the orientation-weighted solar radiation for vertical windows for a well-defined window percentage and orientation of typical Danish single family buildings. The two constants in Eq. (6) depend on both the climate and the reference building. The net energy gain method is used for an easy comparison of several window measures.

For the case-study building, 5 window retrofit measures were considered and the data for the windows are shown in Table 5. The values were obtained from the project described by Morelli et al. (2012).

The installation cost of the window is included in the given prices. Contrary to insulation materials, a continuous function in relation to the CCE_R cannot easily be approximated for windows because windows are individual components. Therefore, the CCE_R for windows was approximated using a marginal approach as previously described in Section 4.1. The CCE_R for windows are shown in Fig. 3. Note that after the continuous function was approximated based on the marginal approach, only one new window was available for the entire building retrofit. This is due to the higher energy use of the other window retrofit measures as compared to the one proposed.

5.3. Mechanical ventilation

The energy use caused by the heat loss from the mechanical ventilation with heat recovery is calculated from Eq. (7) whereas electricity consumption to operate the fan of the ventilation system is given in Eq. (8).

$$Q_{v,energy} = \rho^*c^*(1-\eta)^*D_v^*q \tag{7}$$

$$Q_{v,operational} = SFP^*\tau^*q \tag{8}$$

where ρ is the density of air (kg/m^3), c is the specific heat capacity of air (J/(kg K)), η is the heat recovery efficiency, and D_v is the number of degree hours in the heating season for the ventilation (90 kKh), q is the air volume (m^3/s), SFP is the specific fan power (W/(m^3/s)) and, τ is the ventilation time in use (8.76 kh for residential buildings).

Data for the three mechanical ventilation systems investigated in this study are shown in Table 6 as well as the existing natural ventilation in the building. Apart from this, two central mechanical ventilations units to be installed in the basement were investigated. Furthermore, decentralised mechanical ventilation units

Table 6
Data for natural ventilation and the three mechanical ventilation systems.

Ventilation	Average SFP[a] (J/m^3)	Heat recovery (–)	Investment cost (€pr. m^3/s installed)	Maintenance cost (€/year)	Air volume (m^3/h (m^3/s))	Service life (years)
Natural (ref)	0	0	0	0	3260 (0.91)	30
Central no DCV[b]	1160	0.86	179,200	5200	4655 (1.29)	30
Central DCV	1120	0.85	315,300	5200	2795 (0.78)	30
Decentral DCV	1000	0.85	240,400	9000	2795 (0.78)	30

[a] SFP is the specific fan power.
[b] DCV is Demand Controlled Ventilation.

were also investigated. These were, however, to be installed in the individual apartments. One of the centralised ventilations systems as well as all decentralised units included demand controlled ventilation (DCV). The use of DCV allowed a lower ventilation rate as compared to the mechanical ventilation units not having DCV since the occupant could control the ventilation rate. The lower resulting ventilation rates in turn, reduced the specific fan power (SFP) of the units.

The investment and maintenance cost for the ventilation given in Table 6 were obtained from the project described by Morelli et al. (2012). The investment cost includes ventilation units, ducts and related components, electrical work, and control. However, the cost does not include roof cap, fire exhaust fan, and exhaust hood.

The central installed mechanical DCV was chosen based on the CCE_R calculation for mechanical ventilation. The decentralised ventilation had the same energy use (Eq. (7)) but a higher total cost. Thus, it would be more expensive to install the decentralised DCV than the centralised mechanical DCV. The CCE_R was calculated to 0.18 €/kWh and 0.22 €/kWh for a real interest rate of 0% and 2.5%, respectively.

5.4. Determine the overall renovation costs

The intent is to reach the energy price of a fossil fuel distribution network by choosing the energy saving measures implying that the energy-weighted average marginal CCE_R equals the energy price. The optimising process was performed for both a macroeconomic and a private financial perspective. The optimisation was performed by, in the first instance, choosing the discrete retrofit measures (windows and ventilation) and thereafter, by choosing the continuous retrofit measures. The results from the optimisation process including the renovation costs are shown in Table 7.

Based on the results given in Table 7 the yearly energy consumption per heated floor area for the building is calculated as shown in Fig. 4 with detailed calculations for the linear heat loss transmittances. The electricity use before renovation was 0.9 kWh/(m^2 year) and 3.7 kWh/(m^2 year) after the renovation. The increase is due to the mechanical ventilation system.

5.5. Evaluation of renovation or new building

The market value of the building before renovation, which was based on the 2011 public valuations, is 1550 €/m^2 and it is presumed that after renovation the value would increase two-fold to 3100 €/m^2. This is based on the 2011 public valuations of other buildings located in the same area (OIS, 2012). A similar new building is presumed to have a market value of 4000 €/m^2. In connection with the renovation of the building it is expected that new bathrooms and kitchens would be established, which

would amount to 435 €/m^2 heated floor area of the building. In Table 8 the profit is shown in relation to market values and related renovation costs. It is apparent from the information provided in Table 8 that under the given assumptions previously described; the renovation of the building is the preferred option. The cost of maintenance is neglected because new windows as well as a new mechanical ventilation system were installed in both the renovated and new buildings. Thus the maintenance costs are assumed to be similar for both buildings.

6. Discussion

The proposed method can be used by the decision-maker to determine whether to renovate the building or demolish it and thereafter erect a new building. The method can be applied early in the project to obtain an idea of what to do with the building. However, it can also be applied later in the design process, when more detailed information about prices and energy savings are
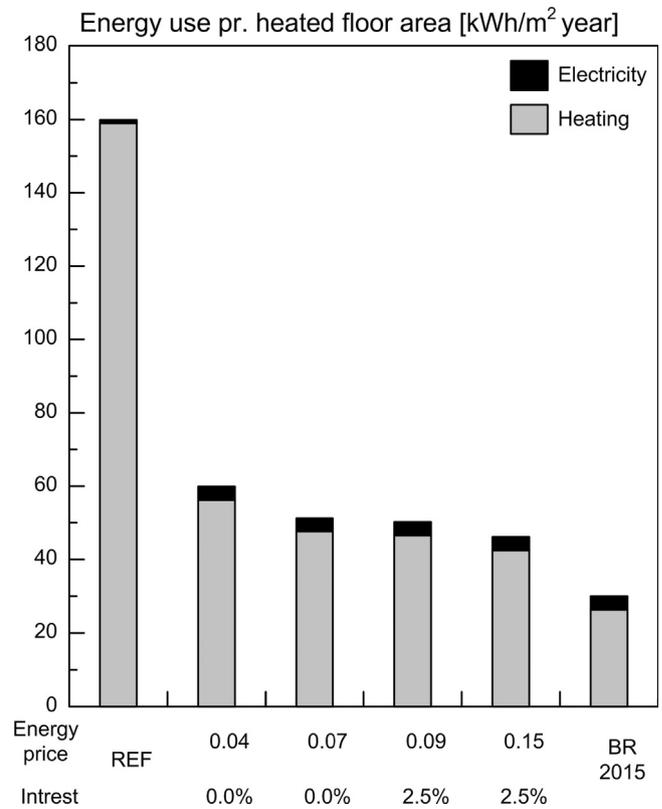

Fig. 4. Yearly energy consumption per heated floor area for the building.

Table 7
Amount of energy saving measures in relation to energy price and real interest rate.

Perspective	Macroeconomic (0%)				Private financial (2.5%)			
Energy price	0.04 €/kWh		0.07 €/kWh		0.09 €/kWh		0.15 €/kWh	
Measure #	CCE [€/kWh]	Type [–]	CCE [€/kWh]	Type [–]	CCE [€/kWh]	Type [–]	CCE [€/kWh]	Type [–]
Mechanical ventilation	0.18	Central DCV	0.18	Central DCV	0.22	Central DCV	0.22	Central DCV
Windows—yard	0.04	New 3 panes	0.04	New 3 panes	0.06	New 3 panes	0.06	New 3 panes
Window—street	0.06	New 3 panes	0.06	New 3 panes	0.09	New 3 panes	0.09	New 3 panes
Floor to basement	0.02	20 mm	0.05	60 mm	0.06	50 mm	0.14	105 mm
Floor to attic	0.02	170 mm	0.05	300 mm	0.06	260 mm	0.14	435 mm
Wall	0.02	50 mm	0.05	95 mm	0.06	80 mm	0.14	140 mm
End wall	0.02	30 mm	0.05	60 mm	0.06	50 mm	0.14	90 mm
Renovation cost [€ (€/m^2)]	636,800	(235)	738,300	(272)	705,500	(260)	841,600	(310)

Table 8
Economic evaluation of renovated and new building.

Perspective	Macroeconomic (0%)				Private financial (2.5%)			
Energy price	0.04 €/kWh		0.07 €/kWh		0.09 €/kWh		0.15 €/kWh	
	Refit (€/m²)	New (€/m²)	Refit (€/m²)	New (€/m²)	Refit (€/m²)	New (€/m²)	Refit (€/m²)	New (€/m²)
Market value	3100	4000	3100	4000	3100	4000	3100	4000
Expenses								
Investment[a]	670	2200	707	2200	695	2200	745	2200
Demolish		90		90		90		90
Heat	10	5	14	8	11	6	18	11
Electricity	4	4	4	4	3	3	3	3
Profit ±	**2416**	**1701**	**2374**	**1698**	**2391**	**1701**	**2334**	**1696**

[a] Investment in renovation consist of cost for energy saving measure, new bathroom and kitchen.

known. This results in a better basis on which to formulate decisions on whether to demolish or renovate. The energy price is used as a constraint in optimising the combination of energy saving measures, which makes the method easily adjustable to changes in energy pricing. This is a result of the correlation between the energy use of the individual energy saving measures and the marginal CCE_R. This, on the one hand, is an advantage of the method because the energy price is a variable difficult to forecast. On the other hand, this also implies that care must be taken using the method, because the energy price strongly influences the optimised combination of energy saving measures. A high energy price leads to greater values of insulation thickness which might not be implementable in practice as was shown by Petersen and Svendsen (2012) for new buildings. However, the difference in insulation thickness related to the energy price may only have a small influence on the total energy consumption of a building. This is due to a relatively large value of insulation thickness even at lower energy prices.

In the proposed method the energy saving measures and the corresponding evaluation of the project profit form the basis for the decision. However, several other factors such as comfort of living, improved indoor air quality, better noise protection, also influence the basis for a decision on whether to renovate. These factors are indirectly taken into account by introducing the market value of the building in the profit evaluation for the renovated building and the new building. The results from the example show that the most dominant factors influencing the final decision-making is the market value and the cost for renovating the building or demolishing it and thereafter erecting a new building. The macroeconomic and private financial scenarios indicate that renovating the building will be an economically sensible solution as compared to demolishing the existing building and erecting a new one. When considered in a broader context of the existing building stock of, e.g., Denmark, these results suggest that the existing building stock built in the period 1850–1930 should be renovated even though the energy consumption is not reduced to the extent given in this example (ca. 70%). This is due to the small influence of energy consumption on the overall economic viability of the retrofit project. However, the method must also be applied to renovation projects that include building services.

7. Conclusion

A method is developed that integrates methods of component-based optimisation and evaluation of the project economy for building renovation measures. A trade-off between investing in energy saving measures and buying energy is established entirely on the predicted future renewable energy costs. The method uses the marginal cost of conserved energy (CCE) to identify an optimised combination of energy saving measures having the energy weighted average marginal CCE_R equal to the energy price. A direct consequence of using the energy weighted average marginal CCE_R is that the method allows for several different combinations of energy saving measures optimised in regards to the future energy price. The profit of the project is determined as the market value deducting the costs for renovation/new building (incl. demolishing), maintenance and operation. The building project with the highest profit must be chosen.

The assessment method developed and demonstrated in this case study is highly relevant to and useful for the many future renovation projects. Furthermore, the proposed assessment method is a contribution towards obtaining a fossil-free energy supply network.

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This PhD thesis investigates cost-optimal energy savings and renewable energy supply in buildings with the aim of converting to fossil fuel-free societies. The possibility of supplying low-temperature district heating to existing multi-storey buildings was investigated, and specific energy saving measures that respect the heritage value of the buildings were analysed. Internal façade insulation was investigated for energy saving potential and possible moisture risks on the brick wall surface and in the wooden floor beam construction.