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Passive house renovation of Swedish single-family houses from the 1960s and 1970s

Evaluation of cost-effective renovation packages

Tomas Ekström

Division of Energy and Building Design
Department of Architecture and Built Environment
Lund University
Faculty of Engineering LTH, 2017
Report EBD-T--17/22

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 116 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 7 500 employees and 47 700 students attending 287 degree programmes and 2 200 subject courses offered by 69 departments.

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Passive house renovation of Swedish single-family houses from the 1960s and 1970s

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LICENTIATE THESIS

Keywords

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Abstract

Single-family houses (SFHs) constructed between 1961 and 1980 account for approximately one-third of the total energy use, 31 TWh, for space heating and domestic hot water in Swedish SFHs. These are responsible for about 40 percent of the total energy use in all buildings. There are roughly 715,000 houses from this period and they are largely homogeneous in technical terms, with low levels of thermal insulation, and ventilation with heat recovery is rare. The average energy use for houses from this period is about 40 percent higher than SFHs constructed between 2011 and 2013.

The BETSI study showed an extensive need for renovation in the SFH building stock. About 70 percent of the evaluated SFHs had some damage – found in all parts of the houses – although most damage was not categorized as severe. The fact that many of these houses need to be renovated provides an excellent opportunity to incorporate energy efficiency measures to reduce both operational cost and greenhouse gas emissions related to energy use.

The aim of this project was to evaluate the possibility for cost-effective renovations of SFHs to Passive House level, while improving the indoor climate. Included in the assessments are thermal comfort and moisture safety, and the alternative of installing local renewable energy production and energy storage. The approach involved theoretically applying the energy efficiency measures to two case study buildings. These reference houses were based on typologies determined from the initial literature review.

The research project began with identifying pilot renovation projects aimed at drastically reducing the energy demand of existing SFHs. Based on the renovation measures used in these projects, possible energy efficiency measures were identified and evaluated to find the

energy savings potential from this type of extensive energy renovation. The results showed great potential, and such renovations could reduce the final energy use by over 65 percent.

This was followed by a sensitivity analysis to determine the impact of different input parameters and building properties of the reference houses used in the energy simulations. These results showed a significant dependence on location of the reference houses if the Passive House requirements were to be fulfilled. The results were also used to limit the number of alternative energy efficiency measures used in the subsequent LCC analysis.

A LCC analysis was carried out to determine cost-effective renovation packages to Passive House level. This built on the previous energy simulations by including the energy costs of adding and evaluating different types of heat generation and distribution systems. This was done to determine the operational costs of the houses and investment cost of implementing the energy efficiency measures. Also included was the alternative of implementing renewable energy production.

The results show that Passive House renovations can be cost-effective, but this is largely dependent on the type of heat generation used in the houses – based both on the difference in operational costs and on the requirements for Passive House. The most cost-effective individual renovation measure was installing an exhaust air heat pump and the least cost-effective was installing new windows. In houses using direct electric heating, the Passive House renovation package was the most cost-effective alternative.

Contents

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Finally, I am deeply grateful to my family for their support.

Nomenclature

Latin

Atemp	Heated floor area, over 10 °C.	m^2
ACH	Air changes per hour	1/h
SFP	Specific Fan Power	kW/(m^3/s)
U-value	Thermal transmittance/Heat loss coefficient	W/(m^2·K)

Greek

η	Efficiency	-
λ	Thermal conductivity	W/(m·K)
Ψ_k	Linear thermal transmittance of thermal bridge, k	W/(m·K)

Abbreviations

AHU	Air handling unit
BBR	Swedish building regulation
BETSI	Buildings Energy, Technical Status and Indoor Environment (national survey)
DHW	Domestic hot water
EEM	Energy efficiency measure
€	Euro
FEBY 12	Forum for Energy Efficient Buildings 12
HRV	Heat recovery ventilation
HVAC	Heating, Ventilation and Air Conditioning
IRR	Internal Rate of Return
LCC	Life cycle cost
MFH	Multi-family houses
NPV	Net present value
PH	Passive House
PV	Photovoltaics
RH	Reference house
SEK	Swedish Crowns
SFH	Single-family house
SMHI	Swedish Meteorological and Hydrological Institute

Sveby	Standardize and verify energy performance in buildings

Appended papers

This thesis is based on the following peer-reviewed journal paper and three peer-reviewed conference papers:

Paper I: *"Renovation of Swedish Single-family Houses to Passive House Standard – Analyses of Energy Savings Potential"* Ekström, T. and Blomsterberg, Å., In the proceedings of the Sustainable Built Environment 16 Conference on Build Green and Renovate Deep, 5-7 October, 2016, Tallinn, Estonia. Energy Procedia, 2016. 96: p. 134-145. *(Ekström & Blomsterberg, 2016b)*

Paper II: "*Renovation of Swedish single-family houses to passive house standard - Sensitivity analysis" Ekström, T., Davidsson, H., Bernardo, R. and Blomsterberg, Å.* In the proceedings of the 3rd Asia Conference of International Building Performance Simulation Association - ASim2016, held on November, 27-29, 2016 in Jeju(Cheju) island, Korea. *(Ekström & Blomsterberg, 2016a)*

Paper III: *"Evaluation of cost-effective renovation packages to Passive House level for Swedish single-family houses from the sixties and seventies" Ekström, T., Bernardo, R. and Blomsterberg, Å.* Submitted to the journal Energy and Buildings, 2017-08-02. (Ekström, Bernardo, & Blomsterberg, 2017)

Paper IV: “R*enovating Swedish single-family houses from the sixties and seventies to net-zero energy buildings” Ekström, T., Bernardo, R., Davidsson, H. and Blomsterberg, Å.* Submitted to Solar World Congress 2017, 29 Oct – 2 Nov, Abu Dhabi, UAE. (Ekström, Bernardo, Davidsson, & Blomsterberg, 2017)

1 Introduction

This chapter contains the background, hypothesis and objectives of the research and the structure of the thesis. The background begins with an overview of environmental issues and the connection to energy use in buildings both in Sweden and internationally, followed by the reasons for focusing the research on SFHs constructed in the 1960s and 1970s.

1.1 Background

There are many reasons why a building may need renovation, including degradation, high maintenance and energy costs, to improve the indoor climate, to improve living standard, and to help mitigate climate change. Regardless of the reason, the question that usually follows is, *"What is the best way to renovate my house?"* followed by, *"How much would it cost and is it profitable?"* There are already many answers to the first question, with technical solutions adapted for the different conditions of houses. But the second question is what this research is trying to answer by investigating cost-effective energy efficiency measures (EEMs) and renovation packages.

Single-family houses (SFHs) constructed between 1961 and 1980 account for approximately one-third of the total energy use in Swedish SFHs, which in turn use about 40 percent of the total energy use in buildings (Swedish Energy Agency, 2015b). There are roughly 715,000 houses from this period (Statistics Sweden, 2015b). They are largely homogeneous in technical terms, with low levels of thermal insulation, and ventilation with heat recovery is rare (Boverket, 2010a). The average energy use for houses from this period is about 40 percent higher compared to SFHs constructed between 2011 and 2013 (Swedish Energy Agency, 2015a).

A survey of the current condition of the Swedish building stock (BETSI) (Boverket, 2010b) was conducted by the Swedish National Board of Housing, Building and Planning. In this survey, 1800 representative buildings from the entire building stock – 821 of which were SFHs – were inspected to determine renovation needs (Boverket, 2009). The survey included the technical status, deterioration, lack of maintenance (Boverket, 2010b) and the energy use (Boverket, 2010a) of the buildings. The need for renovation in the SFH building stock was found to be extensive. About 70 percent of the evaluated SFHs had some damage – found in all parts of the houses – although most damage was not categorized as severe. The fact that many of these houses need renovation (Boverket, 2010b) provides an excellent opportunity to incorporate EEMs, to reduce both the operational cost and greenhouse gas emissions related to the energy use.

When deciding on the level of energy renovations, there are two main categories of motivators: those that are top-down and based on regulation and those that are bottom-up and concern the operational cost for the homeowner. The national and international goals for a sustainable future have an overall objective of reducing greenhouse gas emissions to mitigate global warming and climate change (European Commission, 2011; SOU, 2016). As a contribution to attainment of these goals, the Swedish Government has set a target for a 50-percent reduction in total energy use per heated floor area by 2050, compared to the level in reference year 1995 (Sahlin, 2006). This has led to increasingly stringent energy requirements in the Swedish building regulations (BBR), both for new constructions and when renovating existing buildings (Boverket, 2015, 2016b). For the homeowner, the operational cost of the house has increased over time, as energy prices have risen (Swedish Energy Agency, 2016b), see Figure 1.1. By implementing EEMs, the homeowner could reduce dependency on bought energy and probably operational costs.

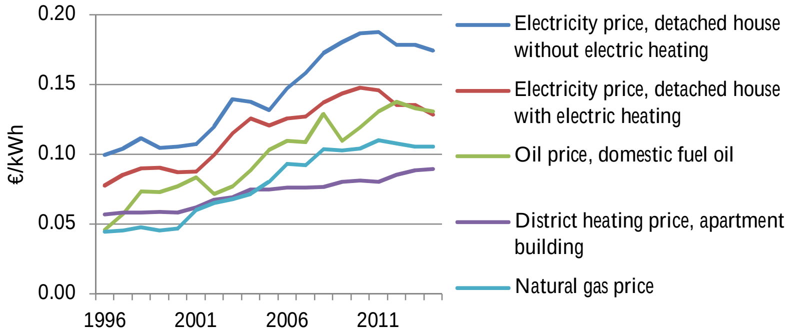


Figure 1.1. Energy prices for the residential and services sector since 1996, real prices (2015), € per kWh (Swedish Energy Agency, 2016b).

Both motivators have increased awareness and demand for ways to reduce the energy use of buildings, which is necessary to fulfil the Swedish Government's goals. Since any renovation performed on the building envelope today will have a service life extending past the deadline in 2050, the current building stock will account for much of the total energy use in buildings in 2050. Therefore, it is important that when renovating, the energy use is reduced as much as possible, but the level will probably be determined by the financial incentives for the homeowner. Consequently, there is a need for evaluating cost-effective EEMs and presenting packages for extensive energy renovations.

One challenge when performing energy efficiency renovations is financing the investment cost. This is often done by taking out a loan. However, to get the loan accepted the renovation either needs to increase the value of the property or reduce the operational cost to offset the interest cost of the loan. The increased property value is largely dependent on the location, making it a project-specific aspect not applicable to the overall building stock. The operational costs are dependent on the building, climate, inhabitants and energy prices. These aspects can be standardised for an evaluation of the building stock, but the energy savings potential must be credible.

By following a standard or certification, the end results from energy renovations are defined, increasing credibility of the expected energy savings. The Passive House (PH) label is now an established certification in many parts of the world (Erlandsson et al., 2012; Passive House Institute, 2015). In recent decades, the planning and construction of a new Passive House has developed from being a novelty (Janson, 2010) to a widely available construction method (Database, 2016) with an increased investment cost of up to 10 percent compared to conventional constructions (Feist, 2007; Konášová & Freitas, 2014; Passivhuscentrum Västra Götaland, 2015). Recently, the focus has shifted to also carrying out renovations to Passive House level (Database, 2016; IEA, 2014), but in Sweden this has mainly been directed at renovating multi-family houses (IEA, 2014).

In recent years, some pilot renovation projects for SFHs have been carried out (Isover, 2008; Molin, 2012; Orvarson; Paroc, 2014) to show the feasibility of this type of extensive energy renovation. Outside Sweden there are a number of renovations of SFHs that are classified as either low energy, passive or even plus energy houses (Database, 2016). However, these international projects are based on houses with different construction methods, shapes and sizes compared to the Swedish SFHs from the 1960s and 1970s, and often also include extending the house or even adding an extra floor when renovating. As shown in previous studies (Ekström & Blomsterberg, 2016a, 2016b), many of these parameters have a significant impact on the energy use of a house and the EEMs needed to reach the Passive House requirements, making comparisons difficult.

The main research regarding SFHs in Sweden has either examined specific solutions, e.g. specific types of heat generation and solar thermal systems (Ricardo Bernardo, 2013; Boverket, 2008; Persson, 2003) or the reduction of energy use by a certain percentage (Heier, Bergdahl, & Börjesson, 2014b; Weiss, 2014). Following this line of research, this study aims to further increase knowledge regarding cost-effective renovation packages to Passive House level for SFHs with extensive renovation needs. A holistic approach to renovation measures, energy savings potential and cost-effectiveness is used, based on the Swedish Passive House standard, *FEBY12* (Erlandsson et al., 2012). The holistic approach allows for much more significant energy savings, while also improving the thermal comfort, indoor air quality and moisture safety of the houses.

1.1.1 The Swedish building stock

In Sweden, there are about 4.7 million residential dwellings, including SFHs and multi-family houses (MFHs). Of these, SFHs account for roughly two million houses, but the heated floor area for each is much larger compared to the average apartment size of MFHs. Consequently, the total floor areas of SFHs is 293 million m², while for MFHs the total is 179 million m² (Swedish Energy Agency, 2015b). Swedish SFHs are usually owned by the inhabitants. For houses constructed between 1961 and 1980 this is the case for about 95 percent of the houses. The most common way of constructing a SFH has been as a detached house – about 80 percent of the houses – with two storeys (Boverket, 2010b).

The residential and service buildings sector accounts for about 40 percent of the total energy use in Sweden (Swedish Energy Agency, 2015b). Of this proportion, the total energy use for space heating and domestic hot water (DHW) is divided as follows: SFHs (41 percent), MFHs (32 percent), and service buildings (27 percent), see Figure 1.3 (Swedish Energy Agency, 2015b). The energy use in the residential and services sector has been constant over time while the total heated floor area of the sector has increased, as shown in Figure 1.4. This increased energy efficiency is also evident in Figure 1.5, which shows that the annual average use of energy in SFHs has fallen over time, so the energy efficiency in the existing building stock has already been improved. This is probably partly because of the rapid adoption of heat pumps in Swedish SFHs, where almost one million have been installed (Swedish Energy Agency, 2015a). Another explanation is the increased energy efficiency in newly constructed houses, as can be seen in Figure 1.6.

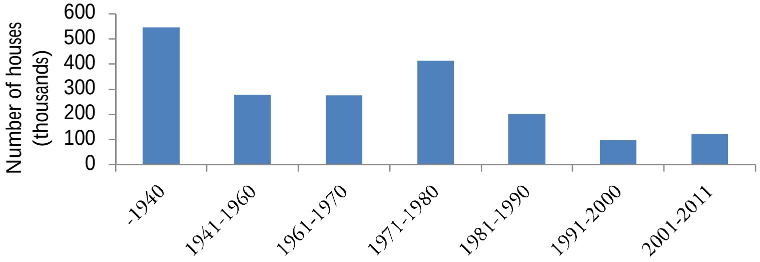


Figure 1.2. *Number of SFHs by year of completion (Swedish Energy Agency, 2015a).*

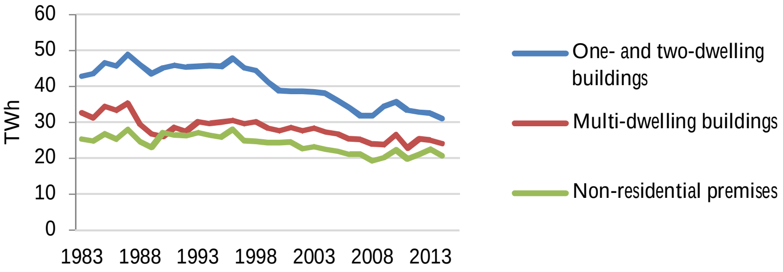


Figure 1.3. *Energy use for heating and hot water in dwellings and non-residential premises, from 1983 to 2014, TWh.*

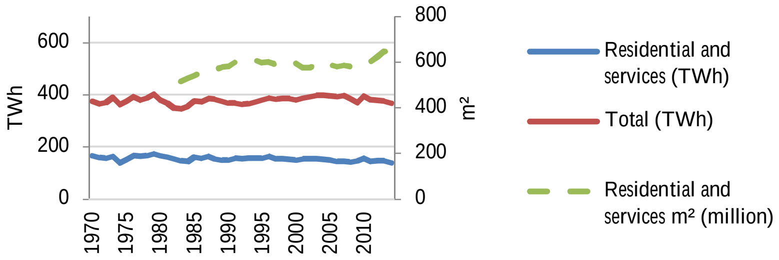


Figure 1.4. *Total energy use for residential and service buildings, total Swedish energy use from 1970 to 2014, and heated floor area from 1983 to 2014(Swedish Energy Agency, 2015b, 2016b).*

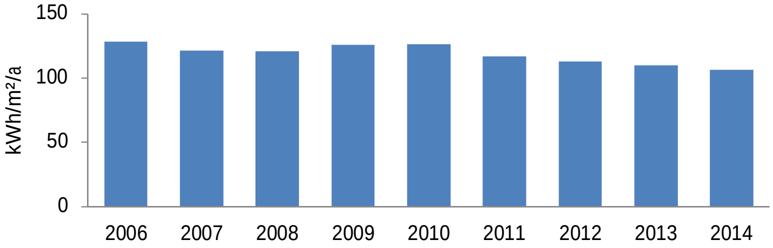


Figure 1.5. Average energy use in total Swedish SFH housing stock between 2006 and 2014 in annual kWh/m²(Swedish Energy Agency, 2015a).

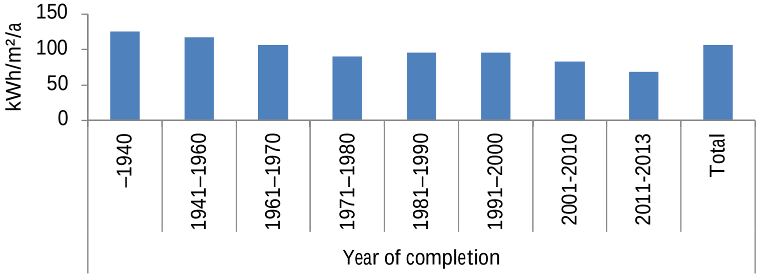


Figure 1.6. Average energy use for heating and hot water for SFHs in 2014, by year of completion, in kWh (Swedish Energy Agency, 2015a).

When evaluating the possible increased energy efficiency in a house, it is important that the energy use before the renovation is known. This is a key issue, especially in SFHs, since the available monitoring of space heating, domestic hot water and auxiliary electricity is usually limited. In some cases, such as houses using electric heating, there might only be one measurement covering space heating, domestic hot water, auxiliary electricity and household electricity. This is also important to bear in mind when analysing statistics regarding energy use in buildings. There are always some assumptions involved because of the limitations in monitoring.

For SFHs constructed from 1961 to 1980, there is a distinct difference in the method of construction used before and after the building regulation from 1975, SBN 75 (Statens Planverk, 1975). This regulation came into effect as a consequence of the 1973 oil crisis, which increased the cost of heating since many houses were heated by oil, triggering an increased focus on energy efficiency in buildings. For SFHs built after SBN75 came into effect, more thermal insulation and balanced ventilation with heat recovery became more common, instead of the earlier passive stack alternative without heat recovery. The commonly used construction methods for external walls was either a lightweight concrete or wooden frame with intermediate mineral wool insulation, the thickness of which can be seen in Table 1.1.

Table 1.1. Commonly used construction methods for the external walls presented by year of construction (Björk, Nordling, & Reppen, 2009; Boverket, 2010b; Ekström & Blomsterberg, 2016b).

Time of completion	1961 until SBN75	After SBN75
Lightweight concrete walls	230 mm to 250 mm	-
Wood frame construction with intermediate mineral wool insulation	95 mm to 100 mm	About 180 mm

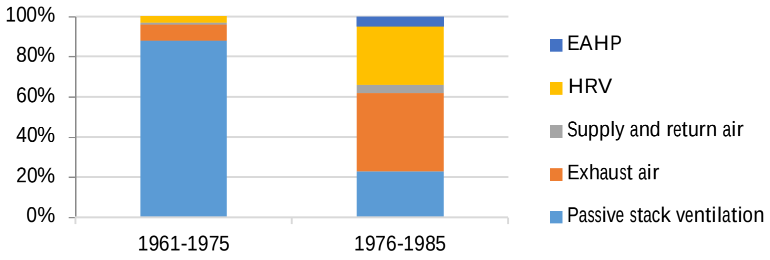


Figure 1.7. Existing ventilation systems used in SFHs by year of construction, from the BETSI report (Boverket, 2010b).

The existing HVAC systems in the SFH building stock vary widely, as can be seen in Figure 1.7 and Table 1.2. A commonly used system before SBN 75 was passive stack ventilation with trickle vents above double-glazed windows, combined with radiators, either hot-water or direct electric heating. Using this system, a good ventilation rate can be achieved during the heating season when the stack effect is high. Outside the heating season, the ventilation rate drops because of reduced stack effect and is often found lacking, as measured in BETSI (Boverket, 2009). Instead the inhabitant must rely on opening windows to increase the supply air flow rate.

After SBN 75, the use of mechanical exhaust air and balanced ventilation with heat recovery (HRV) became more common, leading to greater variation in installed ventilation systems with no single system dominating the market as was previously the case. Many houses originally used heat generation from either an oil-heated boiler and hot-water radiators or direct electric heating. After the oil crisis in 1973, many homeowners started to convert heat generation to alternatives not dependent on oil. This sometimes led to moisture problems, since the measures changed the stack effect in the buildings and consequently the air change rate.

Since then, electricity prices have increased steeply and homeowners have tried to find alternative heat generation systems or combinations, e.g. heat pumps, which have been installed in about 50 percent of the total SFHs building stock because of their ease of use and cost-effectiveness (Swedish Energy Agency, 2015a). The currently used systems for heat generation are shown in Table 1.2. As can be seen, the use of oil is almost negligible, representing less than 1 percent of the currently used heat generation systems.

Table 1.2. Currently used heating systems in SHFs by year of construction, in 2014 (Swedish Energy Agency, 2015a).

	Year of construction	1961 - 1970	1971 - 1980	1961 - 1980	Total - 2014	Combined with heat pump	Unit
Used heating system	Electric, direct	10	35	25	15	61	Percentage of total
	Electric, hydronic	15	12	13	16	71	
	Oil	1	0	0.5	1		
	Bio fuel	18	22	20	28		
	Heat pump - ground source	21	11	15	18		
	District heating	24	13	18	13		
	Other (combinations)	9	7	8	9	-	

1.1.2 Driver and barriers for the homeowner

The need for renovation in the ageing existing building stock is evident. But is extensive renovation possible? Is there a demand for it? Are there other limitations obstructing the renovation rate?

There is a great difference between a deep renovation of a SFH compared to a MFH. The difference not only stems from the difference in physical size but also in the ownership and financing. Some important findings of a study presented by the then SP (The Swedish Research Institute), now RISE, (Ruud et al., 2011, p. 17) regarding construction of new SFHs are that the difference between SFHs and MFHs in terms of ownership and value of the property impacts the possibility of realizing a renovation. Since the transaction fee involved in a renovation of a SFH is small compared to a renovation of a MFH, or constructing a new building, the interest from construction companies in carrying out a renovation is relatively low. Knowledge about renovations is generally lower among owners of SFH compared to owners of MFH. The MFH owners are also in a better condition to buy the knowledge, if they do not possess it themselves.

Location and house prices

The location of a house impacts both the technical solutions needed to perform a renovation, because of the geology and climate, and the financial conditions of the project, because of the difference in property value. The technical aspects are often manageable, even though they can drive up costs. The location determines the financial conditions and, in many cases, will be the critical aspect when deciding whether to perform a renovation or not. This is because the location largely limits the value of the property and the possibility of an increased valuation from a renovation. The difference in selling prices over time for SFHs in Sweden by location can be seen in Figure 1.8 (Statistics Sweden, 2016).

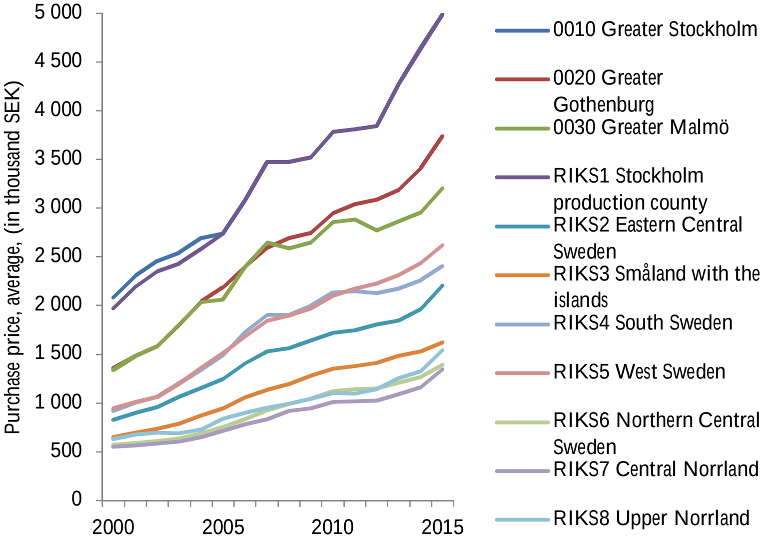


Figure 1.8. *Change in selling prices of SFHs divided by region from 2000 to 2015 (Statistics Sweden, 2016)*

The cost of performing an extensive renovation is relatively similar regardless of location, unlike the difference in property value. This means there is a great difference in the economic limitations of performing an extensive energy renovation depending on the location of the property, regardless of the financial position of the owner.

The knowledge and business model of the banks that grant loans also need to improve. When estimating property value, banks must consider the reduced operating cost of a building that has been renovated with a focus on energy efficiency as compared to a renovation that does not include any energy efficiency measures.

Cultural heritage limitations

One important aspect when renovating is preserving the cultural heritage value of a building. If a building is deemed to be of cultural value, this imposes a limiting factor on what type of renovation measures are permitted. In the BETSI survey, the surveyor assessed each building in terms of whether there could be any values to preserve. The assessment was that 65 percent of the houses could add thermal insulation on the outside of the external walls and 74 percent could add thermal insulation in the roof (Boverket, 2010b). This leaves many houses that are limited to other measures to increase energy efficiency.

Driving forces for a renovation

There are many reasons why homeowners carry out a renovation. The condition of the house and the nearing of, or even passing, the end-of-life can be the spark for starting the project. Other reasons may apply, such as new ownership of the property, new family constellations, to increase the standard of living, or just to change the appearance of the building or a part of the building. This research does not consider reasons for starting a renovation. The only assumptions made are that the houses need extensive renovation, that there are no limitations regarding cultural heritage, and that the homeowner will comply with building regulations when renovating.

1.1.3 Inhabitants – influence on energy use

Inhabitant behaviour is another key issue when evaluating the energy use of a building, both in the energy simulation phase and later in performance monitoring phase. The impact of the inhabitants on the energy use of a building has been shown to be significant (Bagge & Johansson, 2011; Bagge, Johansson, & Lindstrii, 2015).

Attempts have been made to evaluate the impact of inhabitants in a standardised way. In Sweden, the main source is the *Sveby* (Levin,

2012) project. It is important to emphasise that using the input data from *Sveby*, or any other source of standardised input data, is estimating a standardised energy use of a building, forming a platform to compare the results from one building against another building, a standard or a regulation. What it is not is a way of determining the exact energy use in each house, even if the houses are built in the same way. The impact of the inhabitants on the energy use is just that significant. When using standardised input data in MFH, there is an inherent normalization (or smoothing) because of the different behaviours and daily routines of the inhabitants in the apartments. However, in SFHs, there is usually only one family and thereby fewer inhabitants to serve as normalization.

Indoor temperature is a significant parameter impacting the space energy use, often stated to affect energy use by 5 percent per degree Celsius. The indoor temperature measurements in SFHs from the BETSI study, presented in Figure 1.9, indicate the possible variation found in SFHs. Another significant parameter that impacts energy use is household electricity. This has increased in SFHs, from about 3800 kWh per year in 1970 to about 5900 kWh per year in 2014 (Swedish Energy Agency, 2015a). In *Sveby*, there is a normalized value based on the size of the building. This variation is partly evaluated in Paper II, where some of the parameters were included and evaluated in the local sensitivity analysis.

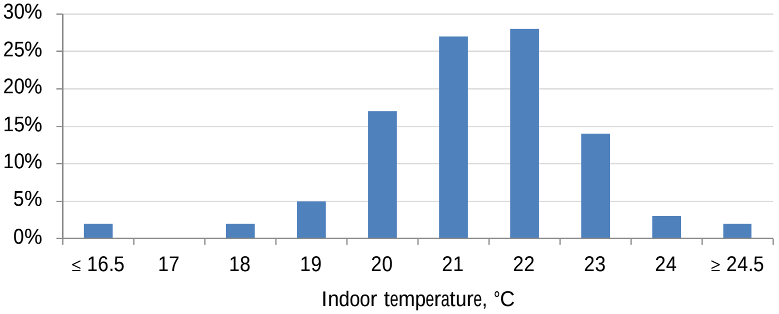


Figure 1.9. Measured indoor temperature in SFHs from the BETSI report.

Rebound effect

When implementing energy efficiency measures dependent on inhabitants changing their behaviour, energy demand may increase after a certain time has passed. This is because, over time, inhabitants often revert to their old habits, and energy savings from the energy efficiency measures are reduced. This effect is called the rebound effect. Renovation measures evaluated in this study will focus on alternatives that are either passive, i.e. involving no effort from the inhabitants, or automatic, thereby improving energy efficiency without input from the inhabitants.

1.1.4 Regulations & requirements

The current (2016) regulations and requirements regarding energy use in buildings in Sweden focus on specific energy use. This includes the energy needed for space heating, domestic hot water and auxiliary electricity in a building per heated floor area, heated to above 10 °C, and excluding any garage space (Boverket, 2016a). Energy use is stated for an average year, so any measured energy use must be corrected, for example by applying the degree day method (Swedish Meteorological and Hydrological Institute (SMHI), 2016). Implementation of renewable energy can reduce the specific energy use.

Swedish building regulation

In BBR 23, the aim was to clarify the regulations regarding renovation of buildings. Extensive renovations must comply with the provisions of the current Swedish building regulation, BBR 23 (Boverket, 2016a). The main parts relevant to this research are the requirements regarding minimum air flows, airtightness and the thermal transmittance of the building envelope. For the air flow and airtightness, the regulation explicitly states that fresh air flow should be ensured when improving the airtightness of the building (Boverket, 2016a, p. 148). Also, the condensation point must be considered when improving the thermal transmission of the building envelope.

A degree of interpretation is needed when applying the regulation to a renovation project. Energy efficiency requirements are not stipulated, but if the other requirements specified in BBR are fulfilled, the energy efficiency requirements should also be fulfilled whenever possible (Table 1.4). If the energy efficiency requirements are not fulfilled when renovating, alternative requirements apply for the building envelope. These requirements stipulate the level of the thermal transmittance (U-values) of the building envelope that must be fulfilled, shown in Table 1.3.

Table 1.3. Required U-values when renovating each part of the building envelope and not fulfilling the energy efficiency requirements according to the Swedish building regulation.

U_i	U_{Roof}	$U_{Extermal\ wall}$	U_{Floor}	U_{Window}	U_{Door}	Unit
BBR	0.13	0.18	0.15	1.2	1.2	W/(m² ·K)

Passive House requirements – FEBY12

This research follows the Swedish Passive House standard, *FEBY12* (Erlandsson et al., 2012). Inspiration has also been drawn from the guidelines in EnerPHit from the *Passive House Institute* (Passive House Institute, 2015). The *FEBY12* requirements, presented in Table 1.4, do not include any separate requirements when renovating an existing building compared to a newly constructed building in terms of specific energy use. *FEBY12* does not include specific components or requirements, except for windows, door and airtightness.

Table 1.4. Building regulations and Passive House standard requirements (Boverket, 2015; Erlandsson et al., 2012).

	Climate zone	Unit	I	II	III	IV
Specific energy use		Without electric heating				
	BBR 24	kWh/(m^{2}·a), heated floor area	≤ 130	≤ 110	≤ 90	≤ 80
	Passive House	kWh/(m^{2}·a), heated floor area	≤ 63	≤ 59	≤ 55	≤ 55
		Electric heating				
	BBR 24	kWh/(m^{2}·a), heated floor area	≤ 95	≤ 75	≤ 55	≤ 50
	Passive House	kWh/(m^{2}·a), heated floor area	≤ 31	≤ 29	≤ 27	≤ 27
		Passive House requirements, other				
Power demand		W/m^{2}, heated floor area	≤ 19	≤ 18	≤ 17	≤ 17
Airtightness, q_{50}		l/(s·m^{2}), building envelope area	≤ 0.30 at ± 50 Pa			
Windows and glazing		W/(m^{2} ·K)	Average U-value ≤ 0.80			

1.1.5 Known problems in low-energy buildings

The Swedish Energy Agency assessed common problems in low-energy buildings (Swedish Energy Agency & Boverket (Swedish National Board of Housing Building and Planning), 2015), both residential and commercial. The most common problems found that must be considered when renovating to Passive House level were:

- The low air permeability combined with a high exhaust air flow in the kitchen fan leads to a large under-pressure, making it difficult to open windows and doors, which is a safety problem.
- Smoke leaking from the fireplace into the building.
- Overheating indoors because of lack of solar shading.

1.1.6 Previous work regarding renovations

Compared to the amount of research and pilot projects on renovation of MFHs, the available research regarding renovation of SFHs in Sweden is much more limited. Widening the search from the period between 1961 and 1980 to focus on all SFHs in Sweden increases the results. Weiss (Weiss, 2014) investigated the possibility of reducing the energy use by 50 percent for SFHs built before 1981 in the Swedish county of Dalarna. Heier (Heier, 2013) examined a possible method to find packages of energy efficiency measures (Heier, Bergdahl, & Börjesson, 2014a).

As part of the literature review performed in this research, pilot projects regarding deep renovation of SFHs to Passive House level were compiled. Four pilot projects were found, all in the southern part of Sweden: Villa Kyoto (Orvarson); Villa Kanndalen (Isover, 2008); Finnängen (Molin, 2012) and; RenZERO (Paroc, 2014). Basic data about the projects is presented in Table 1.5. Internationally there is a greater diversity in performed renovations, as can be seen in the *Passive House Database* (Database, 2016).

Table 1.5. Completed renovation projects to Passive House level in Sweden(Isover, 2008; Molin, 2012; Orvarson; Paroc, 2014).

Projects		Units	Villa Kyoto	Villa Kanndalen	RenZERO	Finnängen
Construction year			1977	1970	1945	1976
Renovation year			2014	2008	2013	2010
Heated floor area		A_{temp}	155	-	200	212 / 246*
Energy use – before renovation		kWh/(m^2·a)	122	162	128	165
Energy use - after renovation		kWh/(m^2·a)	0	45	30	0
Improved	Walls, increased insulation	mm	+150	+150	+300	(Total *U*-value = 0.10 W/(m^2·K))
	Roof, increased insulation	mm	+500-600	+290	+360	(Total *U*-value = 0.08 W/(m^2·K))
	Windows, new	W/(m^2·K)	0.9	0.9	0.9	0.8
	Airtightness, after renovation	l/(s·m^2)	0.3	0.3	0.3	Measured, 0.10-0.15
	Foundation, increased insulation	mm	+160	+100	-	Yes
Heat recovery ventilation			Yes	Yes	Yes	Yes
Solar collectors			Yes	Yes	No	Yes
PV solar cells			Yes	No	No	Yes
Ground source heat pump			Yes	No (district heating)	Yes	Yes

** Building was extended, which increased the floor area of the house.*

1.2 Hypotheses and objectives

The hypotheses behind this research project are as follows:

- For Sweden to fulfil the goal of reducing total energy use by 50 percent by 2050, energy efficiency in buildings needs to be improved.
- By 2050, most of the energy use in buildings will come from buildings that already exist today, so energy efficiency must be improved in existing buildings.
- Of Sweden's 641 million square metres of residential and services buildings, roughly 45 percent are SFHs. But the numbers of performed energy renovations in SFHs are few.
- The low level of realization of deep energy renovation of SFHs is because of the lack of knowledge regarding cost-effective renovation measures.

The aim of the project is to increase knowledge about how the building sector can ensure cost-effective renovations to Passive House level with an improved indoor environment. It is important to take a holistic approach when evaluating possible improvements to energy efficiency in buildings, by considering the entire building system when deciding on renovation measures and HVAC systems.

1.2.1 Scope and limitations

The project focuses on evaluating cost-effective energy efficient renovation measures to Swedish Passive House standard, *FEBY12*, for detached single-family houses constructed between 1961 and 1980. The project includes an inventory of realized Passive House renovations and available building products for low-energy renovation, simulations of the building energy use, and the impact on the indoor thermal comfort.

Life cycle cost (LCC) analysis is used to evaluate and propose renovation packages for achieving Passive House standard renovations with current technology. As part of the project the renovation need and challenges were identified and described.

The scope of the research:

- Existing detached SFHs in Sweden.
- Constructed 1961 to 1980, chosen because of:
    - their numbers,
    - high energy use, and
    - standardized construction method.
- Evaluating cost-effective energy efficient renovation measures to Swedish Passive House standard, *FEBY12*.
- Evaluating measures currently available on the Swedish market.
    - While drawing inspiration from international projects and research.
- Improve the indoor climate.
- Moisture-safe renovation measures.
- Local renewable energy production and storage.

Limitations of the research, issues not considered:

- How to motivate homeowners to renovate.
- The alternative to demolish the house.
- Financing of the renovation packages.
- Business models.
- Architectural aspects of the renovation measures.
- Cultural heritage aspects
- Daylight, size of windows and doors kept as original.
- Noise.

1.3 Outline of the thesis

Chapter 1 introduces the issue of energy use and energy efficient renovations in residential buildings and specifically SFHs. Also presented is the aim of the research project and the research questions it aims to answer. Contents of subsequent chapters are as follows:

Chapter 2 – Method	Gives a theoretical framework based on the literature review regarding different deep renovations and energy efficiency strategies.
Chapter 3 – Reference houses	Presents the properties of the reference houses used in the case studies.
Chapter 4 – Renovation measures	Presents the risks and possibilities relating to renovating different parts of the houses, and the evaluated renovation measures.
Chapter 5 – Results & discussion	Presents the overall results from all the papers included in the thesis and evaluations not included in the published papers. Discusses the relevancy of those results.
Chapter 6 – Conclusion	Presents the conclusions from the papers and an overview of how they impact each other.
Chapter 7 – Future work	Proposes alternatives for continued work in the research field.
Appendix	Includes input data for simulations and the results from the moisture safety evaluation.
Published papers	-

2 Method

The chapter begins with a description of the overall method used in the research project, followed by more detailed descriptions of the methods used in each paper. Renovation packages, input data, simulation software, and evaluation tools are presented.

2.1 Overall method

The overall method used in this research project to evaluate cost-effective renovation packages to Passive House level through life cycle cost (LCC) analysis is shown in Figure 2.1.

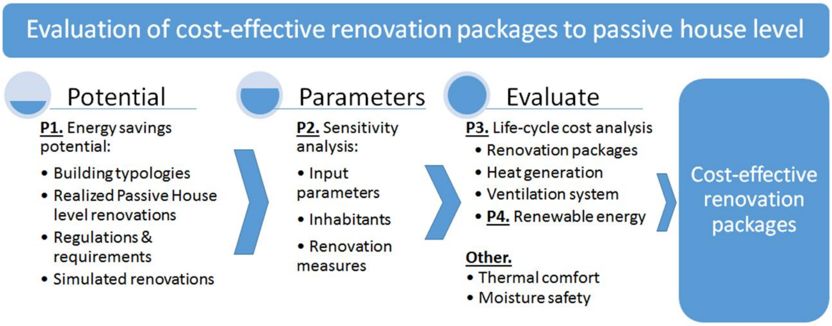


Figure 2.1. Overall method used for the evaluation of cost-effective renovation packages. P1 to P4 are abbreviations for the papers included in this thesis.

The method focused on numerical calculations based on simulations applied to representative reference houses. These were used in the case study to determine the impact of the renovation packages on the building stock from the 1960s and 1970s. The same steps were used in all evaluations: compile information and data, process the gathered information, and adapt it to the reference houses for evaluation. The assessment was divided into the four main parts (Papers I-IV) and some feasibility evaluations.

1) Paper I: Background and energy savings potential.
2) Paper II: Sensitivity analysis of parameters to evaluate their impact on the energy savings potential.
3) Paper III: Cost-effective renovation packages to Passive House level.
4) Paper IV: Evaluate the possibility of achieving a net-zero energy building when performing a Passive House renovation by implementing local renewable energy production.
5) Feasibility evaluations: The impact on the thermal comfort and moisture safety was evaluated.

2.1.1 Literature review

To obtain an overview of current knowledge, a literature review focused on previous and current regulations, Passive House requirements, and pilot projects regarding Passive House renovation. Information was also gathered on different renovation measures, housing construction, properties, labour and material costs, variations in input data for the energy simulations, moisture-safe low-energy constructions, and the impact on the indoor climate.

The following steps were applied in the literature review:

I. identify relevant search words;
II. determine relevant databases with scientific research articles on similar subjects;
III. search the databases with different combinations of the search words from step (I);
IV. read abstracts and export potential articles to a reference organizer tool, EndNote X7 (Clarivate Analytics, 2017);

V. read and evaluate exported articles, and use relevant content as reference.

2.1.2 Building energy simulations

The building energy simulations in this research follow the bottom-up engineering model. The model uses the building properties as input data for the heat balance simulation to estimate the energy use of the houses. Information was collected on such parameters as geometry, structures, climate data, indoor temperature, and household electricity. The energy simulations were performed in the validated dynamic energy simulation program *IDA ICE 4.7* (EQUA, 2016).

Building simulations included a detailed building model of the reference houses, with different zones for each room. The input data for the simulation models involved structures, thermal transmittance, airtightness, inhabitants, internal heat gains and shading, and was obtained from and prioritized as follows: firstly, specific data for reference houses; secondly, Passive House requirements and; thirdly, *Sveby* [61] was used for normalized user-related input data. When these input data were not applicable, alternative data were gathered and evaluated, as described in separate chapters below.

The reference houses were assumed to be inhabited by a family of two adults and two children. The sensitivity analysis considered in more detail the impact from the number of inhabitants. Weather data files included in the building energy simulation program, *IDA ICE 4.7*, from the Swedish Meteorological and Hydrological Institute (SMHI) with long-term measurements of climate and weather were used in the simulations for each location. In Swedish conditions, cooling is not commonly available in residential buildings, so is excluded from the evaluation. A specific building model was used for each energy efficiency measure and renovation package.

The input data used for energy simulations was gathered from the available information about the reference houses, *Sveby* and the Passive House requirements, *FEBY12*, presented in Table 2.1.

Table 2.1. Compilation of the input data for SFHs from different sources used in the energy simulations (Erlandsson et al., 2012; Levin, 2012).

SVEBY	
Indoor temperature:	21 °C
Increased air flow in kitchen (without heat recovery):	30 min per day
Airing add-on:	4 kWh/m^2 per year
Shading, factor:	0.5
Domestic hot water:	20 kWh/m^2 per year
of which, free heating:	20%
Household electricity:	30 kWh/m^2per year
of which, free heating:	70%
Inhabitants	
Numbers:	Based on size of house
Presence:	14 hours per day
Free heat:	80 W per person
FEBY12	
Airtightness:	0.3 l/(s·m^2) at ± 50 Pa pressure difference
Average U-value for windows and doors:	0.80 W/(m^2·K)
Regulation losses:	
Airing:	Included in the regulation losses

The climate data files available from SMHI in *IDA ICE 4.7* include hourly data for dry-bulb temperature (°C), relative humidity of air (%), wind speed (m/s), direction of wind (°), direct normal radiation (W/m^2), and diffuse radiation on horizontal surface (W/m^2) (EQUA, 2016; Sveby & SMHI, 2016).

In the original simulations, the orientation was set to the same as that shown on the available drawings for the reference houses. This was later evaluated in the sensitivity analysis in Paper II by rotating the reference houses by 90°, 180° and 270°. No shading elements were included in the site since the actual site is not known, so an average reduction to 50 percent of the solar gains according to *Sveby* was used (Levin, 2012).

Several other properties must be determined before performing an energy simulation. Ground properties are calculated according to the *ISO-13370* standard in *IDA ICE 4.7*. The airtightness can be used to simulate the infiltration in the dynamic energy simulation program *IDA ICE 4.7* or the infiltration can be entered directly as infiltration at normal pressure difference. Pressure coefficient for external surfaces is needed when using wind driven infiltration. In this case, the worst case of the three alternatives, exposed, semi-exposed and sheltered, available in *IDA ICE 4.7* was used, i.e. exposed. This was simulated and compared with the results of fixed infiltration, which gave a similar result.

The existing DHW system was assumed to comprise a DHW tank and piping. The tank is replaced by a new energy efficient alternative that fits into the overall heating system. An auxiliary heater is included in the water tank as top heating. Normal DHW demand from *Sveby* was used in the energy simulations.

This research does not assess the energy efficiency of different household appliances and lighting alternatives, but it is assumed that new and highly energy efficient alternatives are installed in the renovation packages. The average household electricity use of 5900 kWh per year was assumed to be the demand in the reference houses when evaluating the size of the PV system, but in the energy simulations the *Sveby* normalized input data was used.

Thermal transmittance, building envelope: The thermal transmittance of the different parts of the building envelope was determined by:

1. gathering information about the construction,
2. determining the layers of different materials in the construction,
3. determining the thermal conductivity for each material (Burström, 2007),
4. calculating the thermal transmittance in *ENORM 2004* (EQUA, 2004).

Thermal bridges: Calculations were needed to determine thermal transmittance through the thermal bridges. Information was lacking in the drawings and descriptions gathered for the reference houses, so estimations were used in the earlier evaluations before detailed drawings became available. An added thermal transmittance of the building envelope was assumed to be 25 percent, based on *Miljöbyggnad (Sweden Green Building Council, 2014).* Based on the available information regarding the building envelope, some estimations, and the renovation measures added, the thermal bridges were later simulated in *HEAT2* (BLOCON, 2016) for the minimum and Passive House levels for RH1 and RH2.

Windows and glazing: The light transmittance and Solar Heat Gain Coefficient (SHGC) were assumed for the original windows based on the information that the original windows were double glazed. For the new windows, the values were assumed to those for normal glazing without shading.

2.1.3 Simulation and calculation software

The software used to simulate the energy use of the reference houses for the different cases, the product properties of the evaluated energy efficiency measures, and associated cost of performing these are presented in Table 2.2. The table also shows how the results from the simulations were used as input in other simulations to determine the overall results.

Table 2.2. Compilation of software used to simulate energy use, costs and product properties of the EEMs, and description of how the software was used.

1. Energy and thermal simulations	
IDA ICE 4.7	Dynamic multi-zone building energy simulation software IDA Indoor Climate and Energy (EQUA, 2016), used for energy simulations. Input regarding thermal bridges from simulations in HEAT2 and specific product properties from respective simulation software, see section 3, Product properties.
HEAT2 version 10	Two-dimensional transient and steady-state heat transfer software, HEAT2 (BLOCON, 2016), used to calculate the heat transfer coefficient from the foundation EEM and the thermal bridges. The results were used as input to the total building energy simulation performed in IDA ICE 4.7.
SAM	The software System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL, 2017) used to simulate renewable energy production and local storage systems.
ENORM 2004	Energy simulation software ENORM 2004 (EQUA, 2004), used to calculate the heat transfer coefficient (U-value) of the building envelope.
2. Economic analysis	
Wikells Sektionsdata 4.20	Software (Wikells Byggberäkningar AB, 2016) that compiles the cost (both materials and labour) of constructing new and renovating existing buildings, used to estimate the investment cost for performing the evaluated EEMs. Includes costs for building envelope, HVAC, excavation, electrical installation, etc.
BeLok – Totaltool	Used to evaluate the total renovation packages regarding life cycle cost analysis (BeLok, 2015). The method was produced for use in commercial building projects, but can be used in SFHs with some adaptation as described in Heier (Heier, 2013).
Investment calculation for photovoltaics	Software (Stridh, 2016) calculating the net present value and internal rate of return for an investment in photovoltaics, including tax reduction and investment grant.
3. Product properties	
Enervent Optimizer	Energy simulation software from AHU supplier *Enervent* used to simulate energy use in fans, efficiency of the heat exchanger, and heat recovery at specific air flows for their AHUs(Enervent Oy, 2016).
REC Indovent – TemoCalc	Energy simulation software from AHU supplier *REC Indovent* used to simulate energy use in fans, efficiency of the heat exchanger, and heat recovery at specific air flows for their AHUs (REC Indovent AB, 2016).
Swegon ProCASA 6.2	Energy simulation software from AHU supplier Swegon used to simulate energy use in fans, efficiency of the heat exchanger, and heat recovery at specific air flows for their AHUs (Swegon AB, 2016).
NIBE DIM	Software from heat pump supplier Nibe, used to indicate appropriate heat pumps based on the energy demand of the reference houses when implementing heat pumps (Nibe Energy systems AB, 2015).

2.1.4 Choosing case study buildings

The study used a case study approach, consisting of four reference houses. These four houses represent different typologies depending on when and where the houses were built. The four reference houses were chosen after gathering information from: building regulations from the evaluated time period (Kungliga Byggnadsstyrelsen, 1960; Statens Planverk, 1967, 1975); the book *Så byggades husen (How houses were constructed, in Swedish)* (Björk et al., 2009); the typologies, construction and installations presented in the *Typology Approach for Building Stock Energy Assessment (TABULA)* project (Spets, 2012; TABULA Project Team, 2012); and the results presented in the BETSI project (Boverket, 2010a, 2010b) from the Swedish National Board of Housing, Building and Planning. Different parameters were identified and used to identify houses to be used as reference houses in the case study.

Based on where most houses were built during the time period, while incorporating the aim of varying the climate, the four locations chosen were Malmö, Stockholm, Gothenburg (Statistics Sweden, 2015a), and Umeå. The latter was chosen because it is one of the northern cities with most houses constructed in the period. The city planning office in each city was contacted and asked to gather information about neighbourhoods in these cities that were constructed during this period and that matched the parameters identified. From this information, drawings and descriptions were gathered for four areas and houses in each of the four locations. Information was compiled and the 16 houses were compared, and one in each location was chosen for in-depth analysis, presented in Table 2.3.

Table 2.3. Parameters compared when deciding on the reference houses for the case study.

Location		Malmö	Stockholm	Gothenburg	Umeå
Construction year		1965	1965	1961	1977
Roof	Ridged		X		X
	Pent	X		X	
Shape	Rectangular		X	X	X
	Function displaced	X			
Facade	Wood panel				X
	Combination of bricks and wood	X		X	
	Plaster		X		
Constr.	Wooden studs			X	X
	Concrete			X	
	Light weight concrete	X	X		
Floors	One floor			X	
	One and a half or two floors		X		X
	Cellar	X			
Energy source	Oil	X	X	X	
	Electricity				X
	District heating				
Vent.	Passive stack ventilation	X	X	X	
	Mechanical exhaust ventilation				
	HRV				X

Between 1961 and 1985, the most common foundation was concrete slab with or without a cellar. This type accounts for over 75 percent of all foundations in SFHs by area (Boverket, 2010a). The four reference houses all have a concrete slab foundation.

The remaining 25 percent mainly comprises the crawl space foundation. When comparing these two alternatives from an energy efficiency perspective, the crawl space makes it much simpler to improve the thermal insulation of the existing building. There are other aspects to consider, such as the problem of moisture in crawl spaces in Sweden, but from the energy perspective this construction can be improved to the level of a new Passive House, so no further analysis is required here.

Information about the houses

When performing this type of evaluation for the entire building stock, there are many challenges regarding drawing conclusions that are valid for the building stock. Difficulties stem both from deciding typological houses, constructions and locations, but also the available information for specific buildings.

Such challenges started already at house level, since available documentation for the reference houses is from a period before digital drawings, so copies of physical paper drawings were collected. The available documentation varied greatly in quality and detail. This made it difficult to determine the original constructions and the thermal bridges of the building envelope. This information was rarely found for the reference houses. This problem was also stated in the BETSI survey, which in many cases found that drawings and descriptions were missing (Boverket, 2010b).

The time scale, since construction, means there may have been alterations not recorded in the documentation. To improve the accordance between the physical house and the theoretical house, the house should be inspected before the work continues, but this was not possible in this study. However, the aim was to focus on the entire building stock, so inspecting specific houses was less important.

2.2 Methods used in each paper

The objectives and methods used in each of the four papers are described in separate sections below. For more details, check the appended papers.

2.2.1 Paper I: Energy savings potential

The purpose of Paper I was to evaluate the energy savings potential in SFHs constructed 1961 to 1980 when renovating using conventional EEMs and, if possible, to attain Passive House level. The overall method used is presented in Figure 2.2.

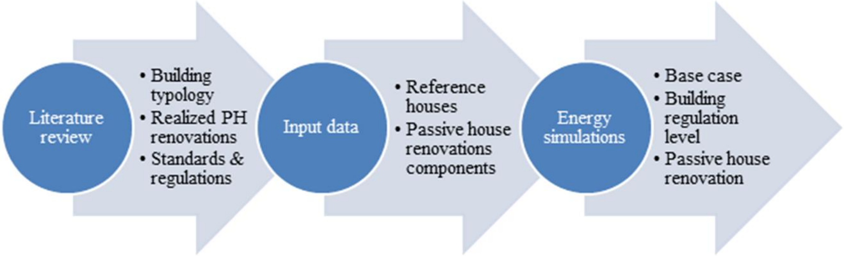


Figure 2.2. Illustration of the overall method used in Paper I to evaluate the energy savings potential in SFHs from 1961 to 1980.

The study began with determining how houses were constructed between 1961 and 1980, by gathering information about typologies, construction methods, HVAC, and locations. Four reference houses were identified for use in the case study to evaluate different renovation measures. The renovation measures were based on measures used in the four pilot projects in Sweden where SFHs were renovated to Passive House level, presented in Table 1.5. The reference houses were then simulated in a dynamic building energy software, *IDA ICE 4.7 (EQUA, 2016)*, to determine the energy use of the base case before renovation and the energy savings potential from renovation.

The focus was on the final energy use of the houses, so no consideration was taken to the current type of heat distribution and generation, or any alternatives. The energy simulation used normalized input data from *Sveby (Levin, 2012)* and *FEBY12 (Erlandsson et al., 2012)* for the inhabitant-dependent parameters.

2.2.2 Paper II: Sensitivity analysis

In Paper II, attention switched to evaluating the uncertainty of the previous results, arising from the possible alternatives for the input data and renovation measures. The overall method used in Paper II is presented in Figure 2.3. The aim was to determine the impact from each parameter on the total energy savings potential. This was evaluated using a local sensitivity analysis, involving nine parameters in 22 different cases. The focus continued to be on the final energy use of the houses.

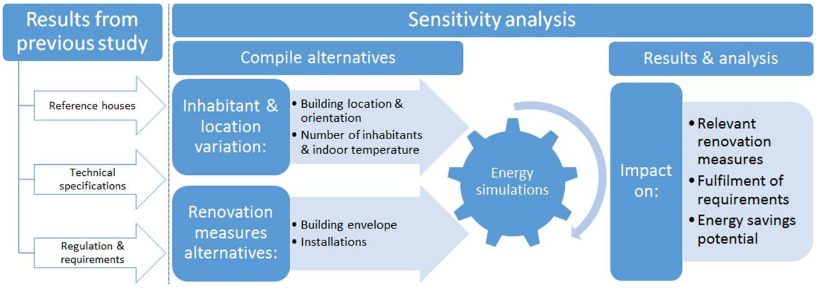


Figure 2.3. *Illustration of the overall method used in Paper II to perform the sensitivity analysis regarding input data and renovation measures.*

Evaluation of inhabitant-dependent parameters was limited because of the lack of input data regarding specific households. The schedule for how many hours and at what times the inhabitants were home was not changed or evaluated, nor was the impact of airing. Normalized input data from *Sveby* and *FEBY12* was used in both cases.

The influence of inhabitants on final energy use in the reference houses was assessed by using input data from *Sveby* (Levin, 2012) and varying the number of inhabitants and desired indoor temperature. This normalized usage simplifies the presence of the inhabitants with a uniform usage profile. Taking into account real fluctuations of the presence and usage profile could result in even greater variations in energy demand, as shown in measurement studies like THUVA II (Bagge et al., 2015).

2.2.3 Paper III: Cost-effective renovation packages

In Paper III the purpose was to evaluate cost-effective Passive House renovation packages. This analysis was based on the results from the two previous papers, continuing the evaluation of the energy savings potential while adding the cost perspective. This was done by life cycle cost (LCC) analysis. The overall method used in Paper III is presented in Figure 2.4.

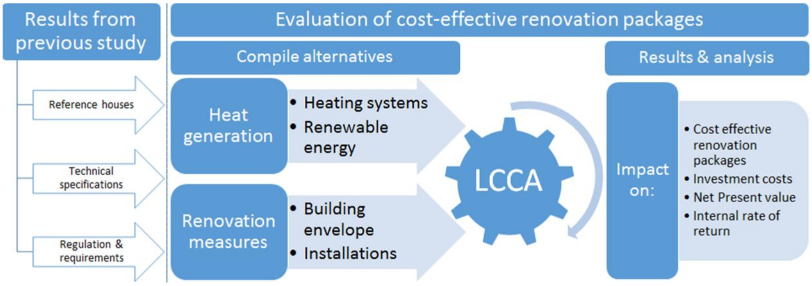


Figure 2.4. Illustration of the overall method used in Paper III to evaluate cost-effective renovation packages to Passive House level.

To include the operational costs, this evaluation includes common systems for heat generation and distribution to determine system efficiency and energy costs. Various types of heat generation were applied to the reference houses and energy use was simulated. These results were then used to evaluate the impact on the cost-effectiveness of the renovation packages. The paper also included an assessment of implementing local renewable energy production – a solar domestic hot water system and a photovoltaic (PV) system. As an addition to the PV system, this was evaluated with and without an energy storage system, a lithium-ion battery. The energy simulations were carried out using the software *System Advisor Model* (NREL, 2017) and the economic calculations using the software *Investment calculation for photovoltaics* (Stridh, 2016).

To compare the cost-effectiveness of the Passive House renovation packages, three levels of renovation were considered.

The first (minimum level) was based on the functional requirements stipulated in the building regulation and the renovations needed due to deterioration. The functional requirement is an air flow rate of 0.35 l/s per floor area through installing mechanical ventilation. The extent of renovation needed for the building envelope and installations for the minimum level renovation were based on the results from the BETSI study (Boverket, 2010b), while assuming the building had not been renovated since construction.

The second (building regulation [BR] level) was based on the levels required for each part of the building envelope when renovated and the thermal properties improved. These were excluded in the minimum level because only the facades were considered.

The third (Passive House (PH) level) was based on the results from earlier studies (Ekström & Blomsterberg, 2016a, 2016b), and determined the renovation level of each energy efficiency measure. The specific requirement of each energy efficiency measure for each renovation level is presented in Table 2.4. The expected service life was assumed to be 40 years for the building envelope and 20 years for installations based on the used service life as presented in (Boverket, 2008).

Table 2.4. Description of the evaluated overall renovation levels, with renovation measures and the required performance level.

Renovation level		1.Minimum RH1/RH2	2. Building regulation (BR)	3. Passive House (PH)	Units
Building envelope	Facades	New	New	New	
	External walls	RH1: 0.54 RH2: 0.23	0.18	0.10 ±0.02	W/(m²·K)
	Roof	RH1: 0.36 RH2: 0.15	0.13	0.10 ±0.02	W/(m²·K)
	Foundation	RH1: 0.32 RH2: 0.23	-	Improved, see Figure 4.1	W/(m²·K)
	Cellar walls	RH1: 0.54 RH2: -	+100 mm thermal insulation	+200 mm thermal insulation	W/(m²·K)
	Windows	RH1: 2.80 RH2: 2.00	1.2	0.80	W/(m²·K)
	Doors	RH1: 1.50 RH2: 1.50	1.2	0.80	W/(m²·K)
	Thermal bridges	Calculated	25% of $U_{tot} \cdot A_{tot}$	Calculated	
	Airtightness, at ± 50 Pa	-	0.3	0.3	l/(s·m²)
	Drainage	New	New	New	
Installations	Ventilation system	Mechanical exhaust air	Mechanical exhaust air	Balanced, with heat recovery / Exhaust air heat pump	
	Ducts	New return air ducts	New return air ducts	New air ducts.	
	Heat distribution	New	New	New, depends on used heat generation.	
	Heat generation	New	New	New, depends on evaluated heat generation, see Table 4.3	

Renovation level		1.Minimum RH1/RH2	2. Building regulation (BR)	3. Passive House (PH)	Units
DHW	Heater	New	New	New	
	Pipes	New	New	New	
	Fixtures	New	New	New	
	Household purpose electricity	-	-	Not included, new energy efficient appliances and lighting assumed.	

A LCC analysis was used to evaluate the cost-effectiveness of energy efficiency measures and renovation packages. This method considers the costs of investment, operation and maintenance over the life cycle of a measure. Since the energy efficiency measures have different expected service lives and some costs and savings occur in later stages of the life cycle, the method of net-present value (NPV) was used. This calculates all costs, regardless of when they occur, expressed as a present value.

The *BELOK Totaltool* (version 2) method was used to consider the total renovation packages and calculate the life cycle cost (BeLok, 2015). In this method, the investment cost is compared to the changes in maintenance and operational cost during the life cycle from the implementation of a renovation measure, based on the following equations:

$$LCC_{total} = C_{investment} + C_{maintenance} + C_{energy} - C_{residual\ value} \qquad (1)$$

Maintenance:

$$C_{maintenance} = a_{maintenance} \cdot \frac{1-(1+i)^{-n}}{i} \qquad (2)$$

Energy:

$$C_{energy} = E_{energy} \cdot e_{energy} \cdot \frac{1-\left(\frac{1+i}{1+q}\right)^{-n}}{\frac{1+i}{1+q}-1} \qquad (3)$$

Residual value:

$$C_{residual\ value} = c_{residual\ value} \cdot (1+i)^{-n} \qquad (4)$$

$C_{investment}$ = Investments cost [€]

$a_{maintenance}$ = Annual maintenance cost [€/ year]

E_{energy} = Annual energy demand [€/ year]

e_{energy} = Energy price [€/ kWh]

$c_{residual\ value}$ = Investments value at end of calculation period [€]

n = Calculation period [years]

i = Real interest rate [%]

q = Real increase of annual energy price [%]

The interest rate used when performing an estimate of profitability consists of three parts – real interest rate, expected inflation and a risk premium (Lind, 2014). For an investor or company, any investment needs to equal or outperform other alternatives to justify investment, leading to a higher interest rate. Since this study focuses on SFHs and private homeowners, the interest rate only needs to equal that of a loan taken to cover the investment cost of implementing the energy efficiency measures.

However, some assumptions were needed about the interest rate and inflation over time to determine the real interest rate (i) used in the calculations. Annual inflation was assumed to be two percent, based on the goal of the Swedish central bank, Riksbanken (Riksbanken, 2017). The interest rate of the loan was assumed to be two percent higher than inflation. This is the real interest rate used in the calculations of the NPV. The annual energy price increase above inflation (q) was assumed to be zero percent.

All costs used in the LCC analysis were calculated as the marginal costs of implementing an energy efficiency measure at the different renovation levels as compared to only performing a minimum level renovation. All costs were estimated in Swedish Crowns (SEK) and converted to Euro (€) at a conversion rate of 10 SEK for €1. Another economic calculation used is the internal rate of return (IRR). This uses the NPV calculation to calculate the highest interest rate for which the profitability requirement from a measure can be attained (two percent in this study) instead of calculating the NPV at a specific interest rate.

The investment costs, both material and labour, were mainly estimated based on the specific conditions of the reference houses and information from *Wikells Sektionsdata* (Wikells Byggberäkningar AB, 2016), which describes common material and labour costs in Sweden. When the information was not available from this source, the cost was obtained from the specific supplier of the evaluated material or product. Tax reduction is available for labour costs, called repairs, conversion and extension (ROT) (Swedish Tax Agency, 2016). This covers 30 percent of the labour costs, up to a total of €5000 per person and year, depending on the amount of taxes the person has paid during the year. To simplify the estimation of the labour cost for installations of heat pumps and other types of heat generation, a template of 30 percent is applied for the total installation cost of an air-to-water heat pump and 35 percent of the total installation cost of a brine-to-water heat pump (Swedish Tax Agency, 2014) and 24 percent for other types, e.g. pellet-fired and electric boilers (CTC, 2016). In all cost estimations in this study, value-added tax (VAT) and ROT were included in the total prices.

To determine the operational costs, the energy demand of the building was simulated and combined with the evaluated heat generation and energy prices. The energy prices for the types of heat generation considered differ depending on many parameters, e.g. the business model of the energy provider, taxes and certificates. When available, monthly prices were used to determine the annual operational cost for heating and electricity. Information on electricity prices was obtained regarding average annual grid service price per kWh and monthly electricity prices per kWh for the variable price rate for SFHs (Statistics Sweden, 2017). The electricity price depends on the demand of the house, so different grid service and electricity prices were used for houses using electric heating (direct electric, electric boiler and heat pumps) and houses using non-electric heating (pellet-fired boiler and district heating). Added to these are the costs of electricity certificate (Swedish Energy Agency, 2016a), energy tax (Swedish Tax Agency, 2017b) and VAT. Fixed fees were not included, since they do not vary with the demand and consequently are not impacted by the evaluated measures.

Based on this information, average electricity prices are about €0.13 per kWh for houses using electric heating and €0.177 per kWh for houses using non-electric heating. The energy prices for the other types of heat generation are based on stated annual average prices for SFHs, and were €0.052 per kWh including VAT for pellets (Swedish Energy Agency, 2016b) and €0.083 per kWh including VAT for district heating (Boverket, 2013). The efficiency was assumed to average 85 percent for pellet-fired boilers and 98 percent for electric heating and district heating (Boverket, 2008). The maintenance cost is estimated to be unchanged compared to the minimum level renovation in all cases, except when adding balanced mechanical ventilation to RH1, which in the minimum level only had mechanical exhaust air.

2.2.4 Paper IV: Net-zero energy building

The purpose of Paper IV was to evaluate the possibility of attaining a net-zero energy building (NZEB) by implementing on-site renewable electricity production when implementing an extensive renovation to Passive House level.

A possible PV installation on the roof of RH1 and RH2 was simulated, with the aim of covering the annual electricity demand of the houses. As in Paper III, this paper also focuses on the impact of location, evaluating the reference houses – RH1 and RH2 – located in three different locations. This was to evaluate the impact of a different climate and solar radiation on the bought energy and local electricity production and possibility of achieving NZEB. The energy simulations were carried out using the software *System Advisor Model* (NREL, 2017) and the economic calculations using the software *Investment calculation for photovoltaics* (Stridh, 2016).

2.2.5 Miscellaneous: Thermal comfort and moisture safety

Thermal comfort

The thermal comfort was only evaluated for the non-heating season. The PH renovation is assumed to only improve the thermal comfort during the heating season because of the improved performance of the building envelope and HVAC system. As mentioned in earlier sections, the main problem regarding thermal comfort is during the non-heating season regarding overheating problems.

The thermal comfort evaluation regarding overheating during the non-heating season was performed by evaluating the operative temperature (above 25 degrees Celsius) of the houses in three steps:

I. Before renovation, no shading
II. PH renovation, no shading
III. PH renovation, with shading.

The shading properties were:

- Windows with a solar gain factor of 0.52 in all three cases.
- Shading device was a standard blind between the outer panes of the windows. This had a multiplier for the solar heat gain of 0.33 when used.

The simulations were performed in *IDA ICE 4.7* for the warmest week of the year in the climate file and are presented as the operative temperature in degree Celsius. Only the rooms of the reference houses (e.g. living room and bedroom) used for a prolonged time were included.

Moisture safety

Moisture safety was evaluated in a separate study, included in the appendix of this thesis. The results are only referenced and discussed by this author.

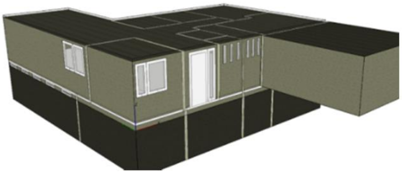
3 Reference houses

In this chapter, the four reference houses used in the case study are presented, together with the basic data and information obtained from the original drawings and descriptions.

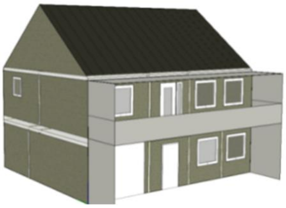
3.1 Overview

Four reference houses were used to evaluate the feasibility and costs of the renovation measures. The measures were applied to each of the houses based on their specific condition. These four reference houses are RH1: Malmö, RH: Göteborg, RH: Stockholm and RH2: Umeå, presented in Table 3.1. All four reference houses were included in the evaluations in Papers I and II, but for the later evaluations in Papers III and IV only RH1 and RH2 were included, hence the lack of numbers in the name designated for two houses. This was done to reduce the workload while only using the most common topologies. Detailed information is only presented for RH1 and RH2.

Table 3.1. Basic data and visualisation from the IDA ICE 4.7 building model for the four reference houses.



Reference house 1:	*Malmö*	*Reference house:*	*Göteborg*
Location:	*Malmö*	*Location:*	*Gothenburg*
Year built:	1965	Year built:	1961
Heated floor area:	230 m^2	Heated floor area:	140 m^2



Reference house:	*Stockholm*	*Reference house 2:*	*Umeå*
Location:	*Stockholm*	*Location:*	*Umeå*
Year built:	1965	Year built:	1977
Heated floor area:	163 m^2	Heated floor area:	142 m^2

For each location, the climate data from the closest monitoring station available in *IDA ICE 4.7* was used. The coordinates for the four climate files, closest to the evaluated reference houses, is shown in Table 3.2.

Table 3.2. Coordinates for the climate data files used for each reference house (Sveby & SMHI, 2016).

	Coordinates - Climate files			
Reference house	*Malmö*	*Göteborg*	*Stockholm*	*Umeå*
Latitude	55.592	57.672	59.283	63.826
Longitude	13.025	11.958	18.040	20.261

3.2 Reference house 1

Reference house 1 (RH1) is a one-storey house with a cellar constructed in 1965 with a total heated floor area of 230 m² located in the south of Sweden in the city of Malmö. The floor plans are presented in Figure 3.1. The original construction comprised:

- roof with truss construction and 100 mm intermediate mineral wool insulation;
- cellar with a concrete floor 100 mm thick, probably with 50-mm thermal insulation, and
- cellar walls of 250 mm light-weight concrete;
- external walls above ground were either (RH1a) 250 mm thick light-weight concrete or (RH1b) 100 mm wooden frame construction with intermediate mineral wool insulation.

See the section drawing in Figure 3.2 for more details. For ventilation, a passive stack ventilation system was originally used and the heating system was a hot-water radiator system with an oil heated boiler.

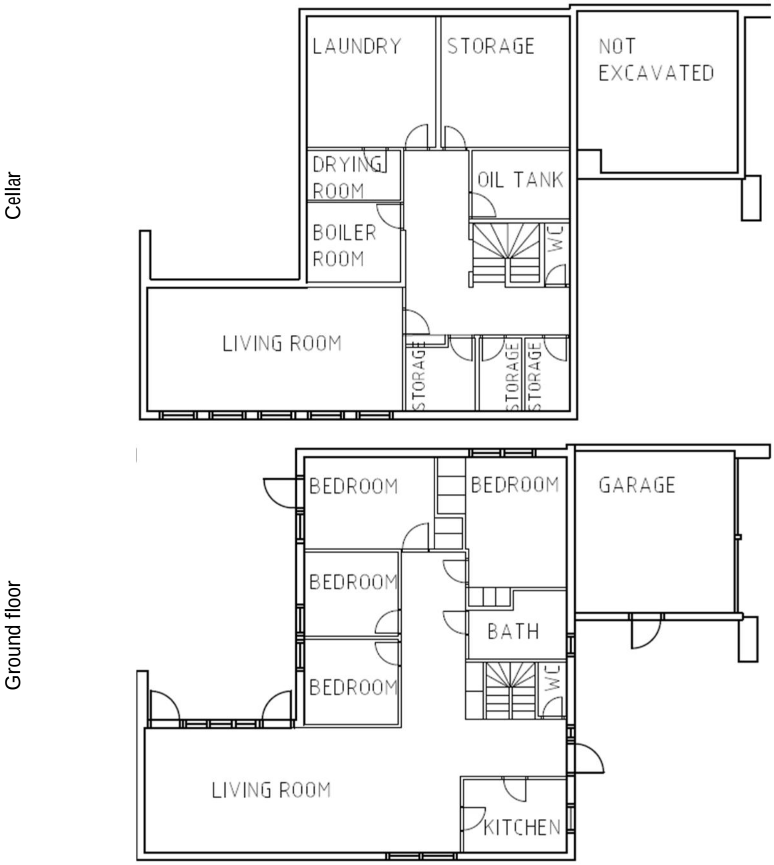


Figure 3.1. *Floor plans of the basement and ground floor for reference house 1.*

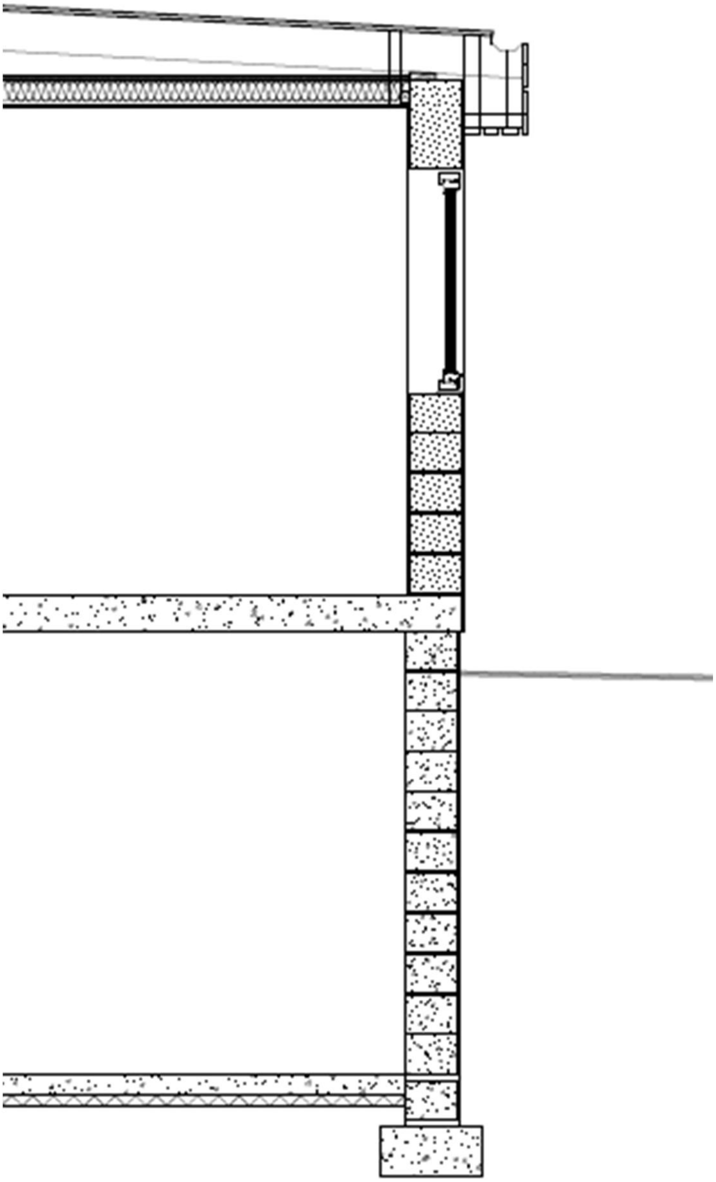


Figure 3.2. Section drawing of reference house 1a before renovation.

3.3 Reference house 2

Reference house 2 (RH2) is a 1½-storey house constructed in 1977 with a total heated floor area of 142 m² in the north of Sweden in the city of Umeå. The floor plans are presented in Figure 3.3. The original construction comprised:

- roof with truss construction and 220 mm intermediate mineral wool insulation;
- concrete floor 100 mm thick, probably with 100 mm thermal insulation; and
- 180 mm wooden frame construction with intermediate mineral wool insulation.

See the section drawing in Figure 3.4 for more details. For ventilation, a balanced mechanical ventilation system with heat recovery was originally used and the heating system was a hot-water radiator system with an electric heated burner. For both houses, the insulation level of the concrete slab and the thermal transmittance of the windows and doors did not appear in the available documentation, nor did the performance of the HRV in RH2. Instead, these were estimated based on the building regulation in force at the time of construction and information about commonly used construction methods.

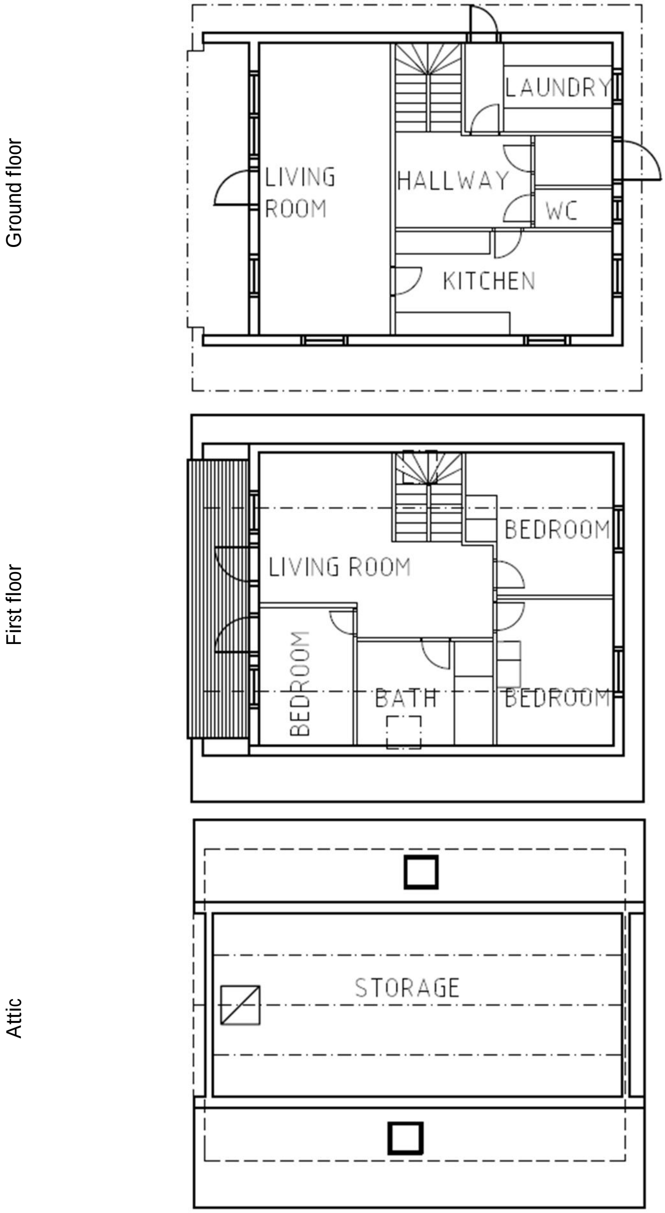


Figure 3.3. Floor plans for reference house 2.

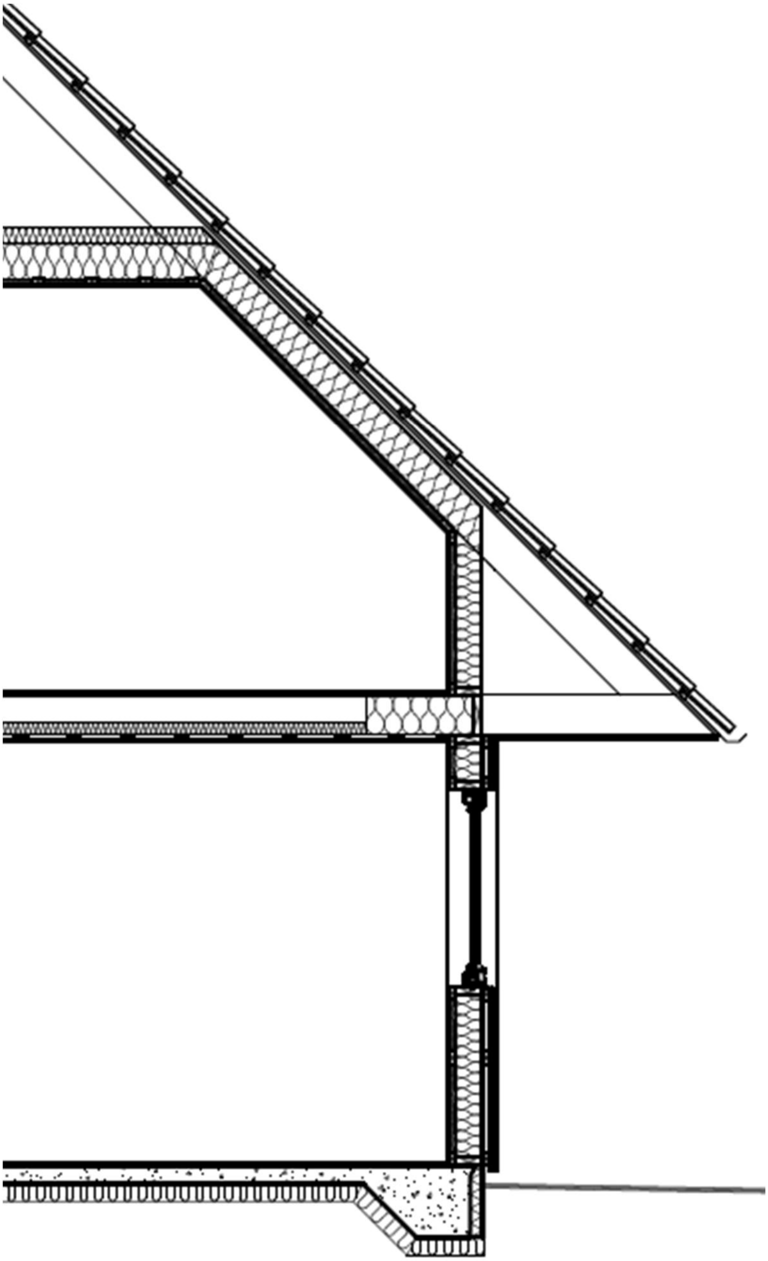


Figure 3.4. Section drawing of reference house 2 before renovation.

4 Renovation measures

In this chapter, the renovation measures and how their implementation impacts various aspects of the building and the inhabitants are described.

4.1 Overall requirements

When deciding on relevant renovation measures to examine, methods are described in ByggaF (Fuktcentrum & Lund university, 2013) regarding moisture safety, ByggaE (Gustavsson, Ruud, Lane, & Andersson, 2013) regarding energy efficiency, and ByggaL (Sikander, 2011) regarding airtightness. The overall intention of this research project was to follow these methods as far as possible when deciding on renovation measures to examine.

4.2 Building envelope

All parts of the building envelope need cost-effective improvement in terms of energy efficiency to fulfil the Passive House requirements. To limit inconvenience to the inhabitants during construction, the aim was to use renovation measures that minimized the amount of work done on the inside of the houses. Another aim was to retain the area of liveable space. Adding the thermal insulation to the outside of the existing building envelope improves the thermal bridges. These are usually the cause of much of the thermal transmittance through the building envelope and need to be considered in detail before any renovation. Consequently, all thermal insulation in the renovation was added on the outside of the existing building envelope.

The commonly used thermal insulation materials in Sweden are mineral wool, expanded polystyrene (EPS) and extruded polystyrene (XPS). The type used depends on the part of the building envelope that is insulated. Other alternatives are polyisocyanurate (PIR), polyurethane (PUR), expanded polystyrene with graphite (EPS with graphite), rigid thermoset phenolic insulation, aerogels, and vacuum insulation panel (VIP). The thermal conductivity of each material is presented in Table 4.1. Only the most commonly used alternatives – mineral wool and EPS insulation – were used in the cost analysis. The aim is to evaluate more alternatives in later studies.

Table 4.1. Insulation materials and their thermal conductivity

Thermal insulation material	Mineral wool	EPS	EPS with graphite	PIR/PUR	Rigid thermoset phenolic	Aerogel	VIP
Thermal conductivity	0.031-0.036	0.036	0.031	0.024-0.027	0.018-0.020	0.014	0.005

All four reference houses have a concrete slab foundation, with between 50 mm and 100 mm of thermal insulation placed either below or above the concrete slab. The available drawings and descriptions are not conclusive in all cases as to where the insulation was placed when the houses were constructed.

Adding thermal insulation below the existing concrete floor was not considered because of the problems involved with removing the existing construction. An alternative when adding thermal insulation to the concrete floor slab is to add it above the existing floor. This would reduce the available floor-to-ceiling height, since the joists and roof are fixed in height. The BBR stipulates the minimum available floor-to-ceiling height in residential buildings. The minimum height is 2.4 metres in residential buildings, but 2.3 metres is permitted in an attic storey or a basement of SHFs, and 2.1 metres in some limited spaces (Boverket, 2016a, p. 26).

The floor-to-ceiling height varies both between the reference houses and inside each house between different floors and, in some cases, even on the same floor. The limitation in floor-to-ceiling height imposes various problems in all reference houses, as shown in Table 4.2. Not even RH: Göteborg, with a floor ceiling height between 2.4 and 3 metres, could any insulation be added, since the smallest height would then be less than 2.4 metres. Consequently, these renovation measures are not evaluated. The available floor-to-ceiling height also limits the possibility of using a floor-heating system in these houses.

Table 4.2. Floor-to-ceiling height of reference houses.

Reference house	Malmö	Göteborg	Stockholm	Umeå	Unit
First floor	-	-	2.5	0.9 - 2.3	*Floor ceiling height, m*
Ground floor	2.4	2.4 - 3.0	2.5	2.4	
Basement	2.2	-	-	-	

The only improvement to the thermal transmission of the foundations of the reference houses was by adding thermal insulation in the ground outside the existing construction, as shown in an example in Figure 4.1.

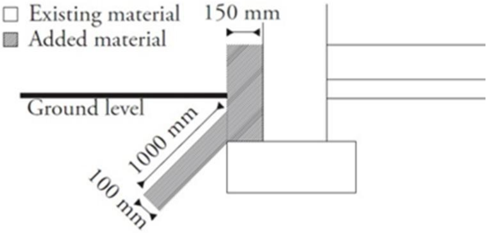


Figure 4.1. Example of thermal insulation added to the foundations.

In addition to a concrete slab foundation, there are several other parts of the building envelope of the reference houses where improvement to the thermal transmission is not feasible.

RH1 has an attached garage extending out of the building. For the adjacent wall, cellar wall below and connected thermal bridges, the thermal insulation could not be improved to the same level as the rest of the house. A common feature of construction during this period was the extending eaves (see floor plans in Figure 3.1), which increases the cost of improving the wall-to-wall thermal bridges.

There were fewer obstacles to adding thermal insulation to the existing constructions in RH2 compared to RH1. The main problem was that the existing balcony reduced the possibility of improving some thermal bridges where it connects to the external wall. The main obstacle in RH2 was how to achieve the airtightness required both for achieving the Passive House level and to improve moisture safety. Because of the use of a wood frame construction, a vapour barrier and wind breaker is needed. In the existing construction, there is already a vapour barrier, but a layer must be added to improve airtightness. This was added on the outside of the existing construction as a new layer, as can be seen in the section in Figure 4.2.

The renovation measures for the building envelope are presented below. For each of the three existing external walls in RH1a, RH1b and RH2, an alternative was evaluated (see drawings in Figure 4.2). For an overview including the roof and details, see the section drawings in Figure 4.3, Figure 4.4 and Figure 4.5.

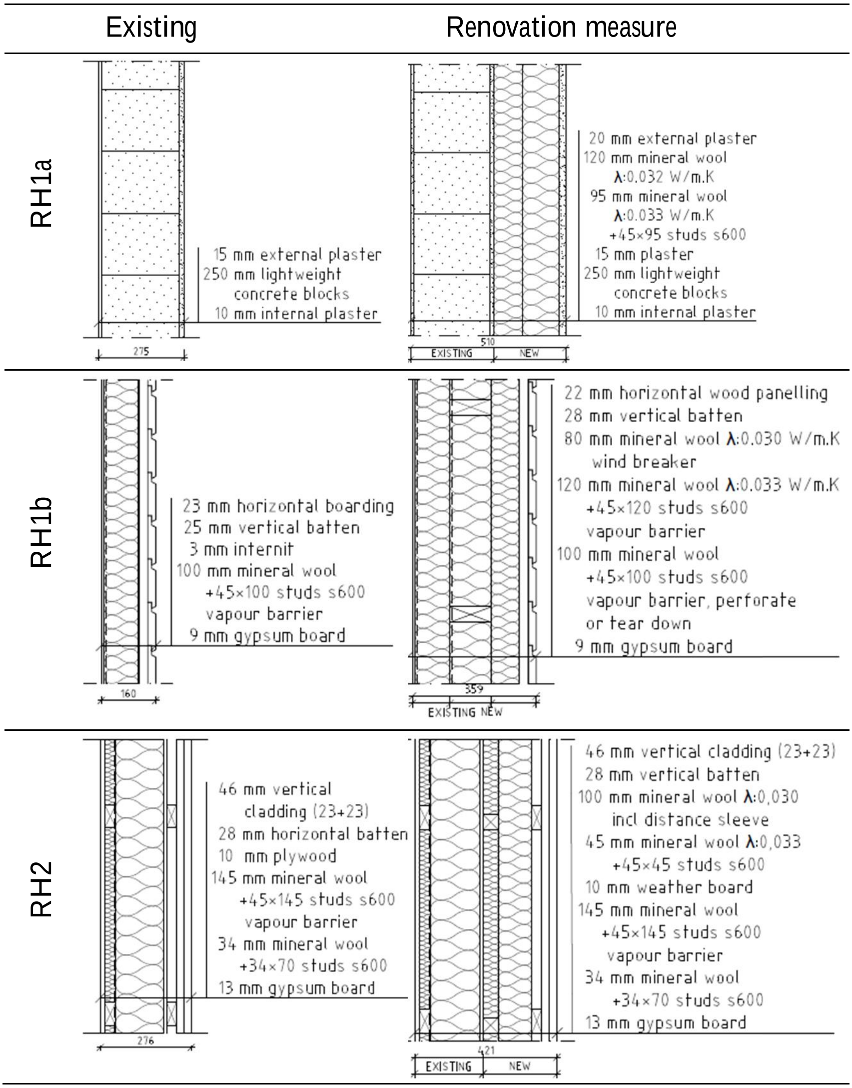


Figure 4.2. Vertical drawing of external wall for RH1a, RH1b and RH2, existing and renovation measure.

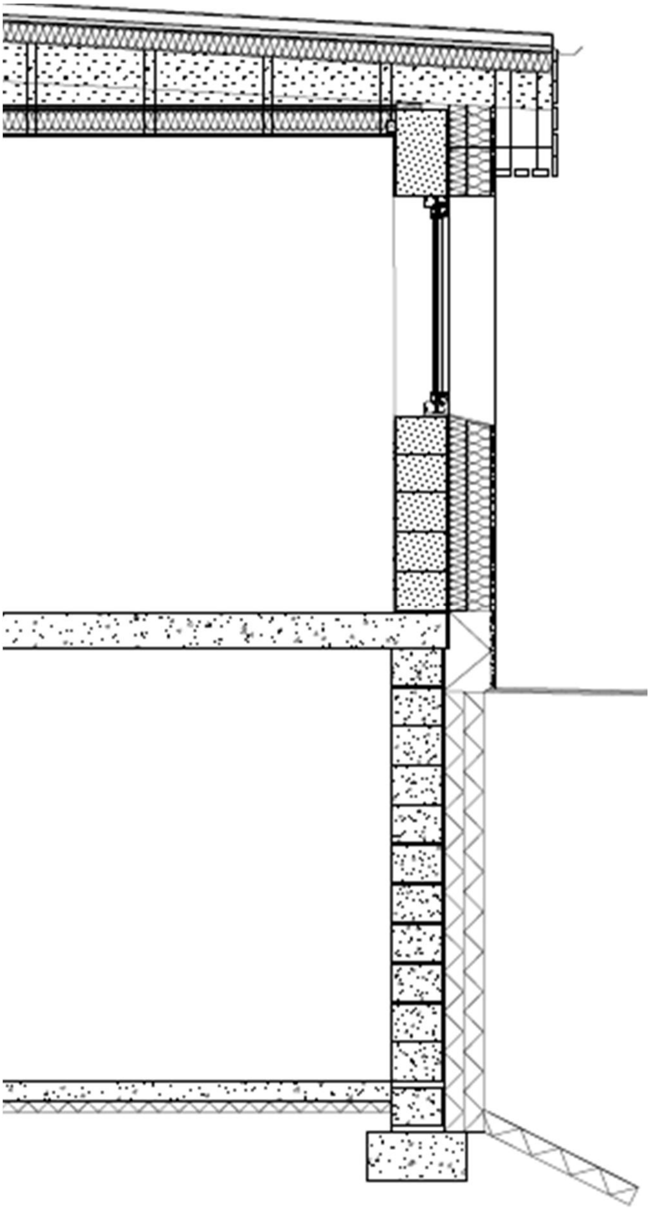


Figure 4.3. Section drawing of RH1a after renovation with Passive House renovation package.

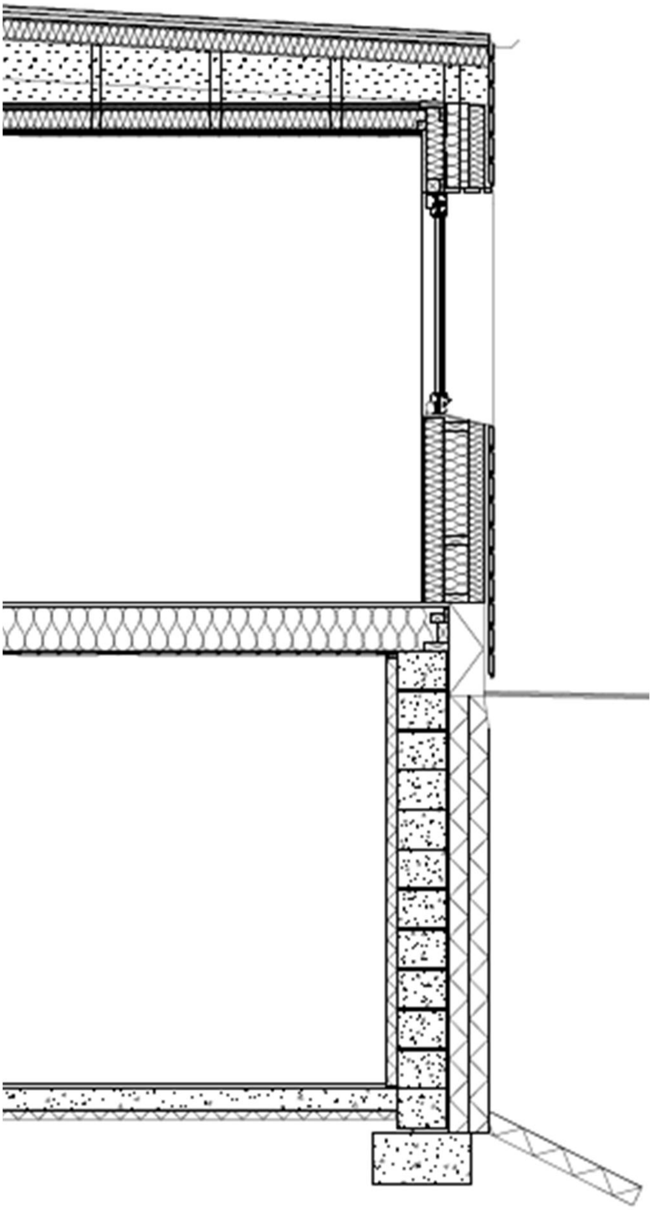


Figure 4.4. *Section drawing of RH1b after renovation with Passive House renovation package.*

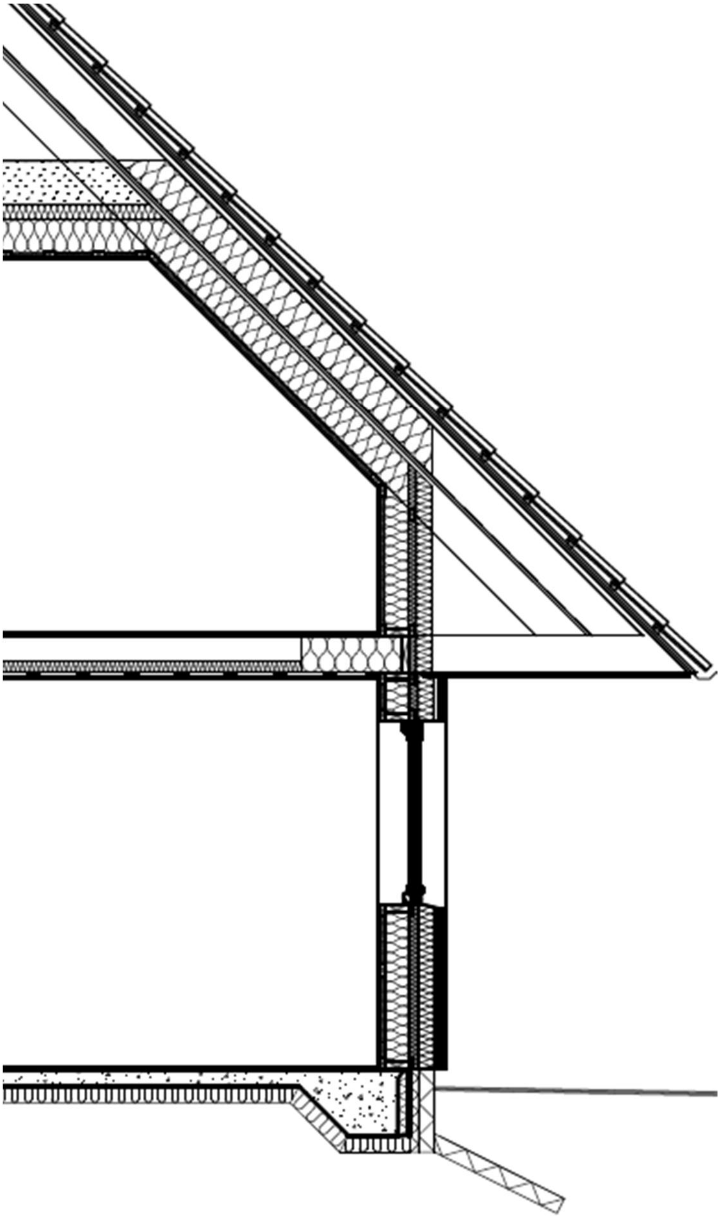


Figure 4.5. *Section drawing of RH2 after renovation with Passive House renovation package.*

4.3 HVAC

The HVAC system has a large impact on the energy use of a building. Existing HVAC systems in the reference houses are old and inefficient, so it is important to improve the performance of the HVAC system as part of an extensive energy renovation. How to do this depends on the type of system currently used in the buildings. The various types are described below, along with the criteria alternatives evaluated.

4.3.1 Ventilation system

The ventilation system currently in use in all reference houses except RH2: Umeå is a passive stack ventilation system. The existing ductwork consists of only exhaust air vents and ducts. RH2: Umeå has a complete supply and exhaust duct system and an air handling unit with heat recovery. However, it was assumed that all ducts would need to be replaced because the air permeability is probably poor for a new high-performance ventilation system. These measures were included in the minimum renovation.

In Paper II, the energy savings potential from using a variable air volume (VAV) system was evaluated. In Paper I and Paper III, only a constant air volume (CAV) system was included in the energy efficiency measures. The evaluation of the air handling units was based on these minimum requirements:

Standard fresh air flow:	≥ 0.35 l/(s·m^2) (Boverket, 2016a; Folkhälsomyndigheten, 2014)
Reduced fresh air flow:	≥ 0.10 l/(s·m^2) (Boverket, 2016a)
Temperature heat recovery:	≥ 80%
SFP:	≤ 1.5 kW/(m^3/s), at normal air flow
Heat recovery:	*counterflow* or *rotary* heat exchanger

Evaluated VAV systems should include the following, where possible:

- Automation control, based on the level of VOC and relative humidity.

- Variable supply air temperature.
- By-pass function, i.e. when there is no need of heat recovery.
- Cooling recovery.
- Connection to kitchen fan and fireplace, when available, to reduce any under-pressure.
- Monitoring of air flow and energy use.

The cooker hood will be ventilated by a separate duct system and exhaust fan, without heat recovery. The usage of this is assumed to half an hour per day, as stated in *Sveby* (Levin, 2012), and with an air flow of about 50 l/s.

Mechanical ventilation: To ensure the required ventilation level of fresh air, mechanical ventilation is used and, for energy efficiency, some type of heat recovery is needed. To attain Passive House level performance either a:

I. Heat recovery ventilation (HRV) system, with a high efficiency rotating or counter-flow heat exchanger, or an
II. Exhaust-air heat pump (EAHP) should be installed.

For these alternatives to be comparable in terms of thermal comfort, noise and air quality, both alternatives need to:

1) pre-heat the supply air,
2) include sound attenuation, and
3) filter the incoming fresh air.

Based on the above mentioned minimum requirements and a report from the Swedish Energy Agency (Swedish Energy Agency, 2016c, 2016d) about the energy efficiency of air handling units from different suppliers, the following suppliers were chosen: Swegon, Rec Indovent and Pingvin. Each supplier’s high-efficiency air handling unit for SFHs was evaluated and the units compared. For the EAHP the supplier NIBE were used.

4.3.2 Heat distribution and generation

It is essential to assess the type of heat generation and distribution system used in a house to determine the bought energy. An important step in improving energy efficiency of existing buildings is to examine the current heat generation and distribution system and identify possible alternative systems.

There are many alternatives for heat distribution, the most commonly used in Sweden being radiators, convectors, floor-heating and pre-heated supply air. All alternatives have different advantages and disadvantages. The following reasoning was used to decide which alternatives to evaluate. The available floor-to-ceiling height limits the use of floor heating, since the low level of thermal insulation would lead to increased heat losses. Not all houses have supply air ducts, making pre-heated air impossible without changing the ventilation system. All houses already have radiators, either electric or hot-water based, making this the most suitable alternative. Radiators were therefore chosen as heat distribution for all types of heat generation.

The next step was to examine the types of heat generation that could be installed in the houses and the investment cost of these alternatives. Local conditions determine what alternatives that can be installed, e.g. district heating requires an available system to connect to and using a pellet boiler in densely populated areas could lead to high levels of local air pollution, so it is regulated differently in different municipalities. Houses currently using district heating or biofuel are not assumed to change their heat generation. This is because they have already invested in a system largely based on renewable energy and with competitive energy prices. Changing the type of heat generation would probably increase dependency on electricity. Houses currently using direct electric heating are also evaluated using a hydronic distribution system, including the cost of converting the distribution system to hot-water radiators.

Another common alternative involves combinations of energy carriers, where one is used as base heating and another as top heating. There are many different combinations, but these are excluded from this study. A possible benefit from using a combination of energy carriers is that one may be more cost-effective in a particular season, e.g. electricity during the summer and biofuel during the winter.

A summary of the currently used heat generation systems and those examined in this study is presented in Table 4.3. Included in the minimum level is to keep the existing system, just replacing it with a new version of the same type. This gives a total of 10 alternative heat generation systems.

Table 4.3. Types of heat generation in existing houses and the alternatives evaluated.

Currently used heat generation	Evaluated alternatives after renovation			
	Keep original	Heat pump	Pellet	District heating
Direct electric heating	X	X*	X*	X*
Electric heating	X	X	X	X
Pellet	X	-	-	-
District heating	X	-	-	-

*Includes cost of converting to hydronic heating system.

The domestic hot water system also needs improvement due to ageing in all levels of renovation, so the cost of improving the DHW distribution system is included in the minimum level renovation. Improving the heat generation of DHW is included in the evaluated alternatives for heat generation.

4.4 Local renewable energy production and storage

The possibility of installing local renewable energy production was assessed, both as an alternative and as a compliment to the renovation measures. Various renewable energy sources are available, but the assessment was limited to a solar domestic hot water (SDHW) system and a photovoltaic (PV) system with and without an energy storage system, a lithium-ion battery to store the produced electricity when production exceeds demand.

A government grant is available in Sweden when installing a PV system that covers 20 percent of the investment costs (Svensk författningssamling 2016:900, 2009). Alternatively the homeowner could apply for a ROT (repairs, conversion, extension) tax reduction (30 percent) for the labour costs of installing the system, available both to PV and solar domestic hot water systems (Swedish Tax Agency, 2016). The two alternatives cannot be combined. The investment cost subsidy was included in the economic calculations.

4.4.1 Solar domestic hot water systems

The most conventional solar domestic hot water systems in Sweden are made of flat-plate solar collectors with forced circulation and a storage tank with an internal heat exchanger, as illustrated in Figure 4.6.

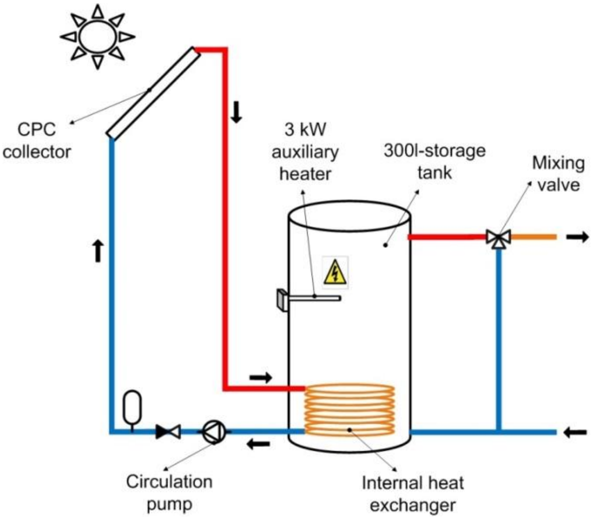


Figure 4.6. Conventional solar thermal system for domestic hot water production in Sweden (Ricardo Bernardo, 2013).

The evaluation of the solar thermal system aimed for a system that could produce energy equal to approximately 50 percent of the annual domestic hot water demand of each reference house. Based on other studies (SP (now RISE), 2015), this usually involves a collector area of 5 m² with a storage tank of 300 litres. The International Energy Agency reports that the investment cost for a solar thermal domestic hot water system in Sweden with a 5 m² collector area and storage of 300 litres would be approximately 5000 € excluding VAT (IEA, 2016).

From a systems perspective, it may not be possible to implement this extra system into the overall system used for heat generation. This is because the solar thermal system needs a storage tank to store the produced heat until there is a demand, which is not needed for all types of heat generation system. For example, a new pellet boiler is used for producing heat for both space heating and DHW and district heating produces DHW directly when there is a demand.

The annual demand for domestic hot water was assumed to be 20 kWh per heated floor area (based on *Sveby*) for each of the reference houses. The assumed variation in DHW demand for the evaluation is presented in Figure 4.7 and Figure 4.8.

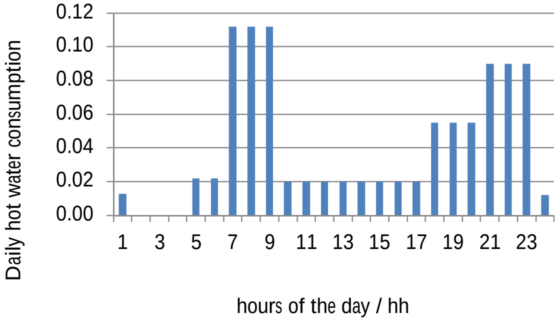


Figure 4.7. Daily variation in domestic hot water consumption based on a simplification (R. Bernardo, Davidsson, & Karlsson, 2012).

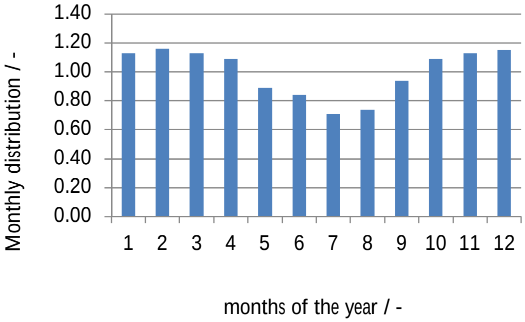


Figure 4.8. Annual variation in domestic hot water consumption based on FEBY12 (Erlandsson et al., 2012).

4.4.2 Photovoltaics

Compared to a solar thermal system, it is easier to integrate a PV system with the other systems of the houses, since it works regardless of which system the house uses for heat distribution or generation. The aim is to determine the size of the system so that production covers the annual electricity demand of the reference houses, often referred to as net-zero energy buildings (NZEB). This is also the maximum level for which it is possible to get a tax reduction of €0.06 per sold kWh to the grid, up to a maximum annual overproduction of 30,000 kWh (Swedish Tax Agency, 2017a). The only impact the used heat generation has on the PV system is the size of the installed system.

Since the demand depends on several parameters, such as the type of used heat generation, the location of the house, and the behaviour of the inhabitants, some assumptions regarding these factors are needed to determine the size of the PV system.

Household electricity use, which reflects the behaviour of the inhabitant and the energy efficiency of the installed household appliances, is assumed to be the same as the average energy use for household electricity in Swedish SFHs, which is 5900 kWh per year (Swedish Energy Agency, 2015a). Variation in household electricity demand was assumed as shown in Figure 4.11 and Figure 4.12.

The heat demand was simulated based on the different heat generation systems: direct electric heating, heat pumps and non-electric heating. The nominal efficiency of the PV panels was assumed to be 20.6 percent, with an assumed degradation of 0.3 percent in the economic calculations, and an inverter with a conversion efficiency of 96 percent.

At times when production of electricity is greater than the demand in the building, the electricity can be sold to the electricity grid. In Sweden, electricity can only be sold to the grid at the spot price. To increase the incentive to sell electricity to the grid, the house owner can apply for an electricity certificate and tax subsidy.

The total price per kWh for bought electricity in Sweden is based on several parameters. In addition to the electricity price there is also the grid service price, electricity certificate (Swedish Energy Agency, 2016a), and electricity tax (Swedish Tax Agency, 2017b), and VAT is added to these price. The fixed fees were not included, since they do not change with the energy demand, so are not impacted by the reduced energy use from the implemented measures.

To determine the electricity price to use in the evaluation, information was obtained regarding the average annual grid service price per kWh and monthly electricity prices per kWh for the variable price rate for SFHs (Statistics Sweden, 2017). The average electricity price depends on the electricity demand of the house – if the heat generation is based on electricity, the electricity demand is high so the prices are lower, and if non-electric heat generation is used, the electricity demand is lower and the price per kWh is higher. This study only considered houses using electric heating, so only the electricity prices for houses using electric heating were used. Average electricity prices are about €0.13 per bought kWh for houses using electric heating, as shown in Figure 4.9.

The estimated price for each kWh sold to the grid was €0.05 based on an estimate in '*Investment calculation for photovoltaics*'. Other prices included are the electricity certificate of €0.013, compensation for the grid owner of €0.005, certificate of origin of €0.0005, and a tax subsidy of €0.06, which is available for the first 15 years of production. All costs were estimated in Swedish Crowns (SEK) and converted to Euro (€), at a conversion rate of 10 SEK for €1.

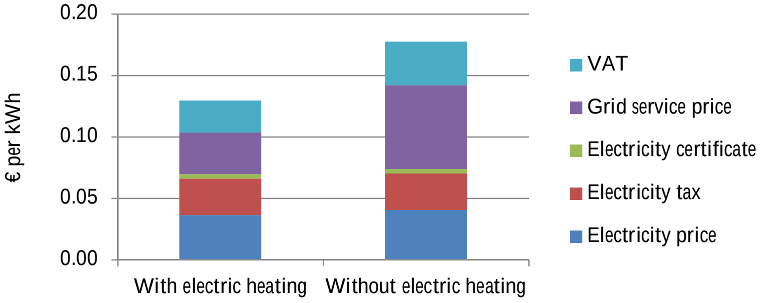


Figure 4.9. Average annual price for electricity bought from the grid for houses using electric and non-electric heat generation.

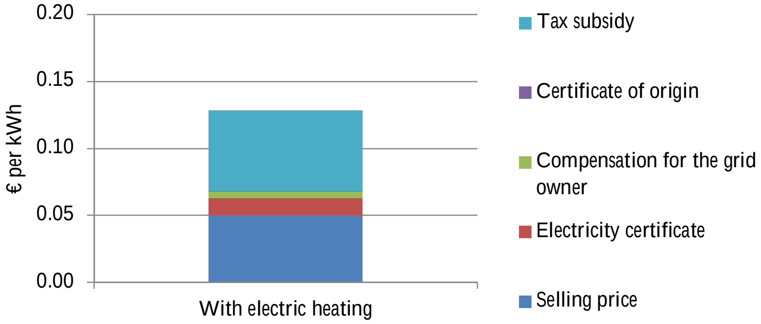


Figure 4.10. Average annual price for electricity sold to the grid for houses using electric heat generation.

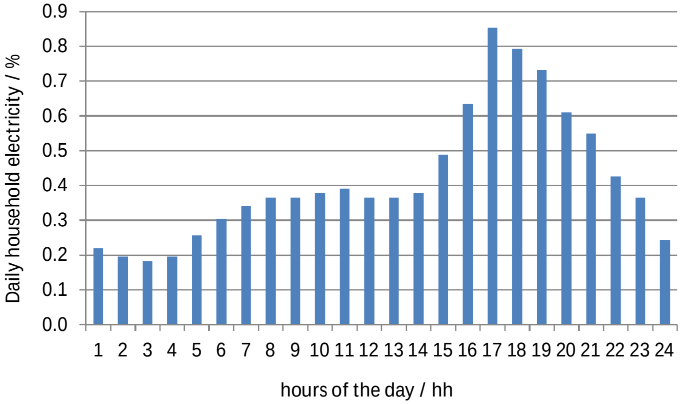


Figure 4.11. *Assumed daily profile for household electricity use based on measurements of Swedish Passive Houses. This does not account for specific energy use (Nilsson & Westberg, 2012).*

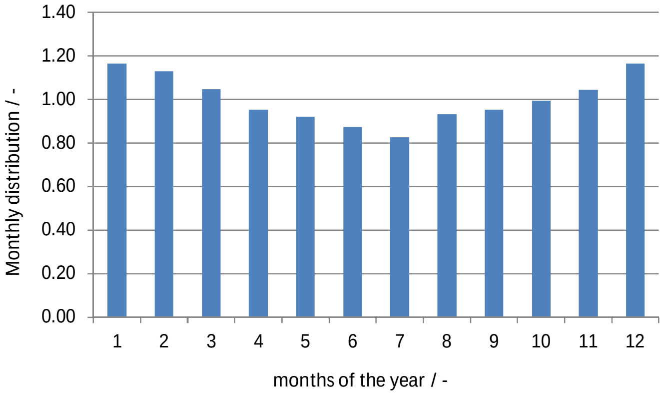


Figure 4.12. *Assumed annual distribution of household electricity use, based on measurements of Swedish Passive Houses (Nilsson & Westberg, 2012).*

Detailed input data for the simulations are presented in the appendix.

4.4.3 Energy storage systems

To increase the proportion of locally produced electricity that can be used in the house, or self-consumption as defined in (Luthander, Widén, Nilsson, & Palm, 2015), a local energy storage system could be used to store the excess electricity from the local renewable energy production. This would allow the locally produced electricity to be also used at night, further reducing the need to buy electricity from the grid.

Because of the tax subsidy, cost savings from storing the electricity locally are limited. Instead, the aim was to evaluate the possibility of further reducing the specific energy use of the houses and to compare the investment cost to that of alternative renovation measures. This would help to identify cost-effective alternatives to achieving the PH standard.

There are several battery typologies, using lead acid, lithium ion, sodium-sulphur or vanadium redox flow batteries, none of which had emerged as a technology leader in 2012 when Battke et al. (Battke, Schmidt, Grosspietsch, & Hoffmann, 2013) compared them from a life cycle cost perspective. Since then, at least from a consumer perspective, the lithium-ion battery has taken the lead for home ESS. The suppliers of local electricity storage commonly use lithium-ion batteries as a storage medium and in sizes of 12 kWh to 14 kWh as a standard battery size, and this can be extended with additional batteries if needed (Tesla, 2017).

To further increase the adoption rate of local production of renewable energy and reduce the stress on the electrical grid, the Swedish government introduced another investment subsidy for the installation of local electricity storage in batteries (Svensk författningssamling 2016:899, 2016). This grant applies if there is local production of renewable energy and the storage increases utilization of the produced electricity. This subsidy covers 60 percent of the total investment cost up to SEK 50,000 per household.

5 Results & discussion

In this chapter, the results presented in each of the papers are summarised and discussed, as well as the overall results of the project. The chapter also outlines some of the evaluations performed during the research project that were not included in any of the papers.

5.1 Papers I-IV

5.1.1 Paper I: Energy savings potential

The results showed a reduction in the final energy use of between 65% and 75% for all reference houses. However, the step-by-step simulations showed that only the reference houses RH1: Malmö and RH2: Umeå could reach Passive House level after renovation. The main reason was that there is currently no economic and technically feasible way to improve the concrete foundation to the same insulation level as that of a newly constructed Passive House.

These results indicate an important limitation, i.e. that not all parts can be improved to the desired level. Instead it is likely that the next step would be to install renewable energy production, since the space heating demand was lowered by between 75% and 80% while the use of domestic hot water was assumed not to change.

Compared to the average specific energy use for existing houses according to statistics on bought energy, the simulated final energy use for the base cases was higher. One possible reason for this discrepancy is that the statistics concern an average for all houses from the respective time period and their current state in 2013, including any renovations and improvements since their construction. The four reference houses fulfilled the building regulation in force during the time of construction, and many houses today are known to be not extensively renovated in terms of energy, so this is probably not the main reason for the difference.

Another possible reason is that, while the statistics are based on bought energy, the simulations are based on final energy. A common measure in Swedish SFHs is the installation of some type of heat pump, performed in about 50 percent of the building stock, which reduces bought energy compared to the final energy. This is probably the main reason for the difference, since the simulated final energy use does not consider heat generation, e.g. if a heat pump is installed.

The step-by-step renovations highlight one of the problems of performing deep renovations on houses that originally had passive stack ventilation. When the air quality is ensured by mechanical ventilation according to the regulatory air flow, it sometimes increases energy use, depending on the original air flow and ventilation system, because of increased heat losses and auxiliary electricity demand, which decreases the cost-effectiveness of the renovation measure.

5.1.2 Paper II: Sensitivity analysis

This paper builds on the results from Paper I by evaluating the results and uncertainties arising from the previous study. The results show that the final energy use can be reduced even further, to between 75% and 80%, of which the space heating is reduced by between 80% to 90%, by introducing additional or more energy efficient renovation measures.

The climate zone was shown to have the greatest impact on the final energy use, with demand for space heating being twice as high in the coldest evaluated climate compared to the mildest. The second largest increase in space heating demand was caused by the indoor temperature setting, where a change of ±1 °C from the original 21 °C corresponds to a change in the annual space heating demand of 4 to 7 kWh/m^2.

The impact of the number of inhabitants on the final energy use of the reference houses was less than expected. While the input data regarding inhabitants, household electricity and domestic hot water varies greatly, the impact on the specific energy use is relatively small. This is because the input data items counterbalance each other; more inhabitants increase internal gains and household electricity, which reduces the need for space heating, but at the same time more inhabitants also increase the demand for domestic hot water. The results show a variation of up to 10%, depending on chosen input. Using the *Sveby* normalised input data resulted in the highest specific energy use, indicating that considering the actual number of inhabitants in a household will only reduce the simulated specific energy use. Inhabitant behaviour was not analysed. The inhabitant-dependent parameters all have a greater individual impact on energy use than individual fine-tuning of the renovation measures.

Attaining Passive House standard will depend greatly on the location. The additional annual specific energy use allowed in the *FEBY* requirements (Erlandsson et al., 2012) for northern Sweden compared to the south is 8 kWh per heated floor area, m². This is significantly less than the increased energy demand of 20-34 kWh per heated floor area, m², in the reference houses renovated to Passive House standard.

Incorporating all the most energy efficient renovation measures from the sensitivity analysis leads to all reference houses fulfilling the Passive House requirements in their respective original location and the mildest climate, but only the reference houses in Malmö and in Umeå fulfilled the Passive House requirements when located in the coldest climate. Although further investigations are required, these results indicate that the *FEBY12* requirements probably underestimate the climatic differences within Sweden. This makes it more difficult and costly to reach PH level in the north.

5.1.3 Paper III: Life cycle cost analysis

This paper continued to build on the results from the previous papers by evaluating the cost-effectiveness of the renovation measures through LCC analyses. These analyses were carried out by including the investment costs of the renovation measures and the heat generation, from which the operational cost can be estimated.

Three renovation levels were compared: 1) Minimum – based on the functional requirements from the building regulation and the required renovations because of deterioration, which has a limited influence on the energy use; 2) Building regulation (BR) – includes the energy efficiency requirements and; 3) Passive House (PH). All costs used in the LCC analysis were calculated as the marginal costs of implementing an energy efficiency measure as compared to only implementing the minimum level renovation.

The main results are presented here; for all results and details, see Paper III in the appendix. Both reference houses were evaluated with each type of heat generation. The impact from this on the specific energy use is presented in detail in the paper, but here only the overall impact on the operational cost is presented.

Annual energy costs are presented in Table 5.1 for the reference houses with each of the evaluated types of heat generation. The alternatives presented in bold and underlined fulfil the Passive House requirements while the alternatives underlined need to also implement local renewable energy production to fulfil the requirements.

Table 5.1. Annual energy costs per reference house and evaluated type of heat generation. Alternatives in bold and underlined fulfil the PH requirements, and those underlined fulfil the requirements when combined with the installation of local renewable energy production.

		Reference house 1 (€ per year)			Reference house 2 (€ per year)		
Renovation level		1. Min.	2. BR	3. PH	1. Min.	2. BR	3. PH
Heat generation systems	Direct electric heating	5 580	3 030	1 630	3 800	2 500	1 310
	GSHP	1 510	880	570	1 200	750	480
	EAHP	2 690	1 050	700	2 210	1 240	730
	Pellet-fired boiler	2 740	1 460	830	1 920	1 310	670
	District heating	3 650	1 960	1 080	2 520	1 690	880

When comparing the annual operational costs of the different types of heat generation, the decision of which alternative to use becomes more complicated. Even though more energy is bought for a house using a pellet-fired boiled than a house using direct electric heating or district heating, because of the systems efficiency, the annual energy cost is lower because of the energy cost. The energy cost is roughly halved compared to direct electric heating. For RH2, the alternative of using a pellet-fired boiler has a lower annual energy cost than the EAHP. The GSHP provides the lowest annual energy costs for both reference houses, but it also has the highest total investment cost. Lowest annual energy costs are achieved using the alternatives GSHP, EAHP and pellet-fired boiler.

The results from the LCC analysis, performed in the software Totaltool (BeLok, 2015) for both reference houses are presented for the different renovation levels as investment cost, internal rate of return (IRR) and net present value (NPV) in Table 5.2. This method calculates the relative LCC of implementing energy efficiency measures, so the goal is a negative cost.

The results show that the most cost-effective individual measure is to only install a heat pump, especially when also considering the IRR. The most cost-effective combination of type of heat generation and renovation package was shown to be where an exhaust air heat pump was installed; these cases also have the highest IRR.

When comparing the renovation packages some interesting results emerge. For RH2, when using direct electric heating, the PH renovation is the most cost-effective renovation level with both a lower LCC and higher IRR compared to the BR level. For RH1, only the NPV is lower, while the IRR is also lower. This is because of the higher investment cost of the PH level compared to the BR level.

For houses using district heating, the results are mixed; the LCC is higher for the PH level renovation but the IRR is also higher. Similar results are shown for houses using pellet-fired boilers; the IRR is almost equal in the PH and BR level renovations but the PH has a lower LCC. This is because of the low energy prices for these types of heat generation.

Another difference is that, for the PH level renovation package, the IRR decreases when installing a GSHP compared to the direct electric heated alternative, as opposed to increasing in the BR level renovation package. The results for all renovation levels improve when a GSHP is included in the evaluation but the IRR is reduced for the PH level renovation, because of the reduced energy savings potential from installing a GSHP in an energy efficient house. This is also because of the high base investment cost with a relatively small increase in cost when installing an alternative with higher maximum power. The marginal cost of changing from a low-powered heat pump of 7 kW to a high-powered alternative of 16 kW is about €3500 to €4500, while the base cost is about €12,000.

Table 5.2. Investment cost and results from the LCC analysis, presented as NPV and IRR, for different types of heat generation at different renovation levels for the reference houses. The relative LCC of implementing energy efficiency measures is presented. Alternatives in presented in red are not profitable.

		Reference house 1 – 230 m^2			Reference house 2 – 142 m^2		
		1. Min.	2. BR	3. PH	1. Min.	2. BR	3. PH
Direct electric heating	Investment cost (€)	-	31 300	48 300	-	24 000	39 700
	NPV (€)	-	- 44 100	- 61 300	-	- 11 600	- 27 500
	IRR (%)	-	8.5	7.6	-	4.5	5.0
GSHP	Investment cost (€)	15 800	44 800	59 800	15 400	37 500	51 300
	NPV (€)	- 87 300	- 85 800	- 74 000	- 47 000	- 37 300	- 31 100
	IRR (%)	24.0	10.0	7.3	14.2	5.8	4.3
EAHP	Investment cost (€)	9 900	41 200	53 100	9 900	33 900	43 800
	NPV (€)	- 65 300	- 88 100	- 82 900	- 46 500	- 48 500	- 45 000
	IRR (%)	28.0	10.9	8.6	20.8	7.6	6.1
Pellet-fired boiler	Investment cost (€)	-	31 300	48 300	-	34 300	39 700
	NPV (€)	-	- 4 100	- 2 800	-	18 900	6 100
	IRR (%)	-	2.7	2.0	-	- 1.6	0.3
District heating	Investment cost (€)	-	31 300	48 300	-	24 000	39 700
	NPV (€)	-	- 16 800	- 21 400	-	1 300	- 4 600
	IRR (%)	-	4.7	4.0	-	1.7	2.0

A profitability calculation helped to determine the combination of heat generation where it would be cost-effective to also implement local renewable energy production, either a SDHW system or a PV system, for the reference houses. This method calculates the total LCC, so the goal is a positive cost, unlike the previous method where the relative LCC of implementing energy efficiency measures was compared. For information about the size of the evaluated systems, see details in Paper III.

The results, presented in Table 5.3, show that implementing a SDHW system is not profitable when using a non-electric heat generation system, indicated by the negative NPV and low IRR. Nevertheless, installing a SDHW system would still be needed to fulfil the Passive House requirements in RH2. Results for the PV system show it is profitable to invest, both with and without a battery, for both reference houses using all types of heat generation system. The results when implementing two batteries, 14 kWh each, are not presented, since the impact on the specific energy use was low, marginal cost was high and it was not profitable for any of the evaluated combinations with different types of heat generation.

Table 5.3. Profitability calculations for the implementation of local renewable energy production systems in the reference houses, presented with investment costs, NPV and IRR. Alternatives presented in red are not profitable.

	Heat generation		Investment cost (€)	NPV (€)	IRR (%)
		Reference house 1			
SDHW	Direct electric heating		5 500	1 670	3.3
	Pellet-fired boiler		5 500	- 3 050	- 2.6
	District heating		5 500	- 1 540	- 0.4
PV	Non-electric	No battery	11 400	3 390	5.2
		14 kWh battery	14 500	1 810	3.2
	GSHP	No battery	19 900	3 230	3.8
		14 kWh battery	23 000	110	2.0
	Electric heating	No battery	19 900	3 710	4.0
		14 kWh battery	23 000	700	2.3
		Reference house 2			
SDHW	Direct electric heating		5 500	- 820	0.5
	Pellet-fired boiler		5 500	- 4 200	- 4.8
	District heating		5 500	- 3 130	- 2.8
PV	Non-electric	No battery	11 900	4 000	5.6
		14 kWh battery	15 000	2 570	3.7
	GSHP	No battery	17 000	3 350	4.2
		14 kWh battery	20 100	270	2.1
	Electric heating	No battery	27 400	5 930	4.4
		14 kWh battery	30 400	2 910	3.0

This showed that in most cases, and using the commonly used types of heat generation in Swedish SFHs, the Passive House renovation is a cost-effective alternative. To fulfil the Passive House requirements, some houses might need to also implement local renewable energy production. This was analysed, and the results showed that it was not cost-effective to implement a solar thermal system in most cases, but implementing a PV system was cost-effective. The downside of the PV system is the high investment cost involved, similar in size to the marginal cost of performing a Passive House renovation compared to a

BR renovation. This shows the importance of comparing alternatives, both regarding the energy savings potential and the costs involved.

5.1.4 Paper IV: Renovation to net-zero energy building

Based on the results from the previous papers, the question emerged of whether a NZEB could be achieved when renovating to Passive House standard by implementing a PV system.

Overall the assessment showed that it is not cost-effective to aim for NZEB when implementing a PV system, based on the evaluated alternatives. However, it was in many cases possible to attain the NZEB level with the available roofs, but this depends on the location and type of heat generation of the houses.

The assessment was performed with the aim of maximizing the annual PV production, so for RH1 the PV panels were installed flat to the roof, the tilt could be optimized to increase production from the PV system and the cost-effectiveness. However, by doing this, the annual PV production is reduced because of the limited space and thus the NZEB level would not be attained.

5.2 Feasibility evaluations

The impact on thermal comfort and moisture safety from the renovation packages was assessed.

5.2.1 Indoor thermal comfort

The thermal comfort was assessed by comparing the operative temperature during the non-heating season in rooms that are used for prolonged periods. The results from the thermal comfort simulations are presented for two rooms in each reference house, the living room and the bedroom with the largest glazing area.

The results, presented in Table 5.4 for RH1 and in Table 5.5 for RH2, confirm the problem with overheating in low-energy building, showing increased temperatures after renovation. The results also show that installing a shading device, in this case blinds between the outer panes of the windows, mitigate the problem, to even less of a problem than before renovation.

Table 5.4. Operative temperature for living room and bedroom in RH1 for three evaluated alternatives, before renovation, after PH renovation and after PH renovation with shading. Simulated for the period from 2015-07-13 to 2015-07-19.

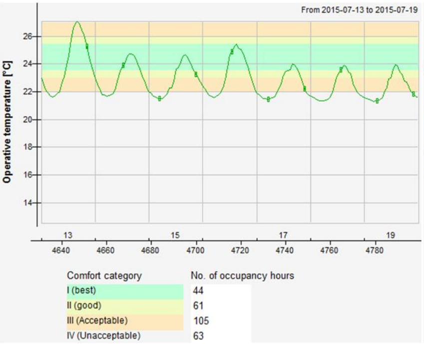
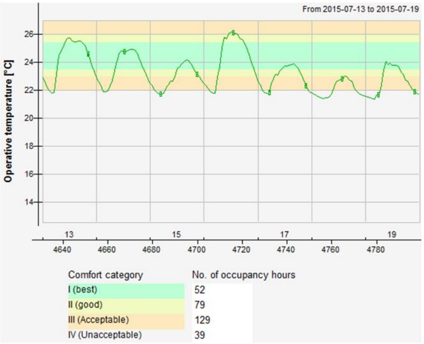
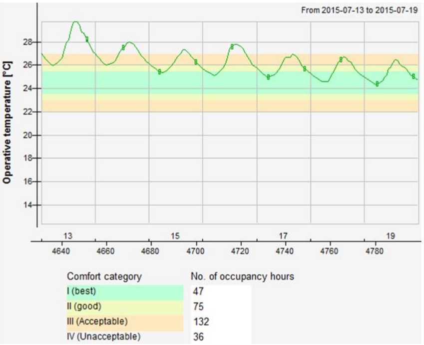
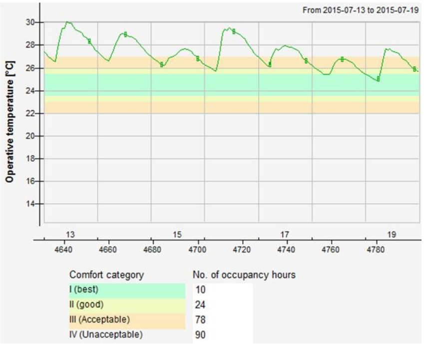
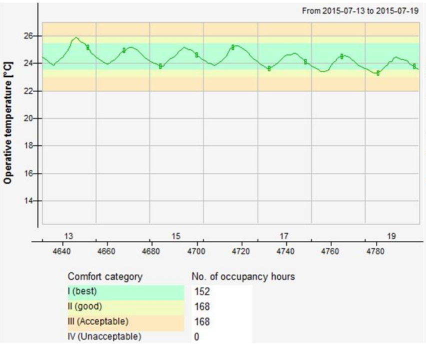
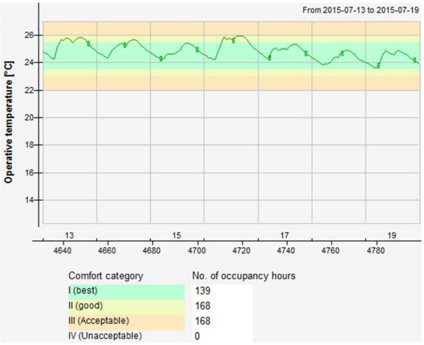
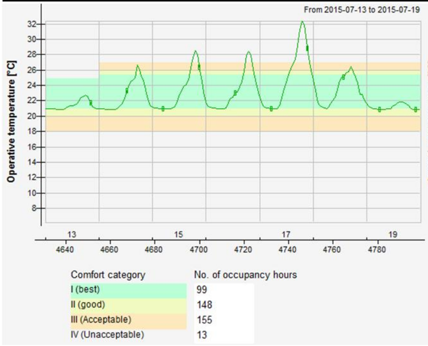
Living room	Bedroom
I. Before renovation, no shading	
	
Comfort category — No. of occupancy hours I (best) 44 II (good) 61 III (Acceptable) 105 IV (Unacceptable) 63	Comfort category — No. of occupancy hours I (best) 52 II (good) 79 III (Acceptable) 129 IV (Unacceptable) 39
II. PH renovation, no shading	
	
Comfort category — No. of occupancy hours I (best) 47 II (good) 75 III (Acceptable) 132 IV (Unacceptable) 36	Comfort category — No. of occupancy hours I (best) 10 II (good) 24 III (Acceptable) 78 IV (Unacceptable) 90
III. PH renovation, incl. shading	
	
Comfort category — No. of occupancy hours I (best) 152 II (good) 168 III (Acceptable) 168 IV (Unacceptable) 0	Comfort category — No. of occupancy hours I (best) 139 II (good) 168 III (Acceptable) 168 IV (Unacceptable) 0

Table 5.5. *Operative temperature for living room and bedroom in RH2 for three evaluated alternatives, before renovation, after PH renovation and after PH renovation with shading. Simulated for the period from 2015-07-13 to 2015-07-19.*

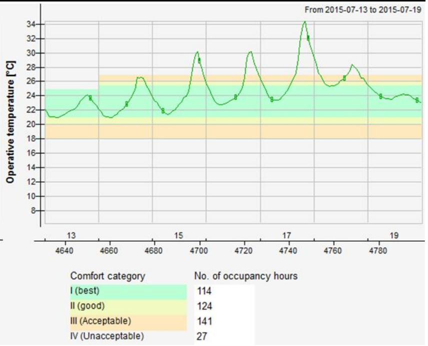
Living room

Bedroom

I. Before renovation, no shading

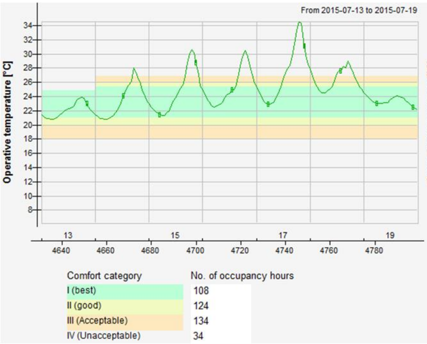


Comfort category	No. of occupancy hours
I (best)	99
II (good)	148
III (Acceptable)	155
IV (Unacceptable)	13

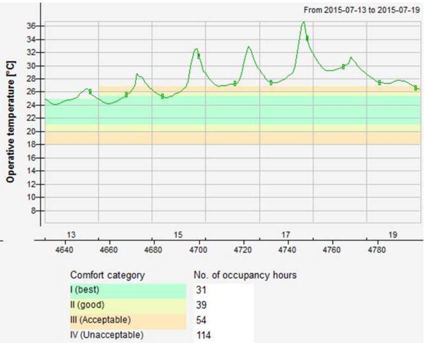


Comfort category	No. of occupancy hours
I (best)	114
II (good)	124
III (Acceptable)	141
IV (Unacceptable)	27

II. PH renovation, no shading

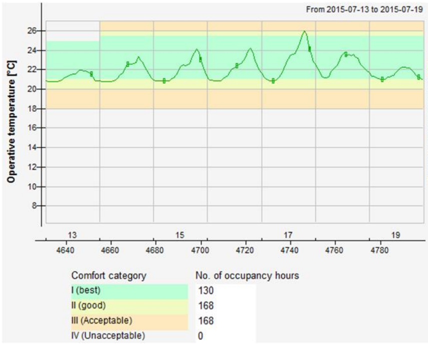


Comfort category	No. of occupancy hours
I (best)	108
II (good)	124
III (Acceptable)	134
IV (Unacceptable)	34

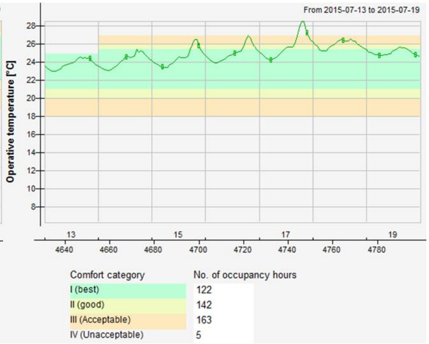


Comfort category	No. of occupancy hours
I (best)	31
II (good)	39
III (Acceptable)	54
IV (Unacceptable)	114

III. PH renovation, incl. shading



Comfort category	No. of occupancy hours
I (best)	130
II (good)	168
III (Acceptable)	168
IV (Unacceptable)	0



Comfort category	No. of occupancy hours
I (best)	122
II (good)	142
III (Acceptable)	163
IV (Unacceptable)	5

5.2.2 Moisture safety

The moisture safety of the renovation measures for the building envelope was assessed in a separate part of this research project and is included in the appendix, with the method, results and discussions.

Based on the results, the moisture safety of the structures is improved by implementing the renovation measures in all cases. A clarification is needed for the renovated lightweight concrete wall in RH1a, presented in Figure 4.2. The studs must be of non-organic material for the structure to be moisture safe.

6 Conclusions

The results from Papers I-IV show that implementing Passive House level renovation packages makes it possible to reduce the final energy use by at least 65 percent in the reference houses. Depending on the existing and chosen type of heat generation, the bought energy can be reduced by up to 90 percent, as compared to the energy bought before renovation. By implementing local renewable energy production and storage, annual bought energy could be reduced to zero kWh.

The results show that this can be done in a cost-effective way, reducing both the operational cost and LCC while generating other benefits such as improved thermal comfort and indoor air quality. This is possible because of the holistic approach, improving the total building envelope and HVAC systems. This conclusion is based on calculating the marginal costs compared with a minimum renovation, which restores the functionality of the building and repairs what has deteriorated over time.

The results clearly show the merits of detailed calculations of energy saving packages and LCC. The evaluated renovation packages implemented in the reference houses could most likely be implemented in many similar houses and be cost effective, if the houses need a renovation to restore functionality and repairs, i.e. only the marginal cost for lowering the energy use is taken into account. This should ideally be done for each individual building, as the conditions differ which impact the results. There is however some barriers for the homeowner such as location and prices.

Location has a large impact on the required renovation measures needed to fulfil the Passive House requirements. For RH2 (the reference house in Umeå), adding local renewable energy production to reduce specific energy use is needed to fulfil the Passive House requirements.

While implementing a SDHW system was shown not to be a cost-effective alternative, the PV system was. The downside is the high investment cost of €11,000 to €30,000 for a PV system.

The main challenge with proposing the implementation of the Passive House renovation package is the increased investment cost, shown to be an additional €10,000 to €15,000 compared to the BR renovation package. The investment cost is a significant limiting factor for the realization of comprehensive energy renovations. These results, showing the cost-effectiveness of a Passive House renovation package, are important information that could be used as a basis for decisions when the homeowner is considering the renovation level.

It may be more cost-effective to invest in a Passive House level of renovation rather than implementing renewable energy. The investment cost is similar, so it is important to evaluate which alternative is most cost-effective, although both alternatives have other benefits and limitations. A PV system can often be installed without much inconvenience to the inhabitant. While the PH renovation package probably causes more inconvenience during implementation, it also leads to benefits such as improved thermal comfort and noise reduction.

One condition for the profitability of these renovation packages is that the house is already in great need of renovation. If this is not the case, the marginal costs increase, as more of the renovation must be paid for by the reduction in energy costs, thereby reducing the profitability.

The results show that cost-effectiveness is largely dependent on the type of heat generation used in the houses, based both on the difference in operational costs and Passive House requirements. The most cost-effective renovation measure was installing an EAHP and the least cost-effective was installing new windows. For houses using direct electric heating, the Passive House renovation package was the most cost-effective alternative. For houses using other types of heat generation, the Passive House renovation package was cost-effective, but no more cost-effective than the BR level.

Energy prices have a large impact on the results from the LCC analysis. The higher the energy price, the more cost-effective is the Passive House renovation package compared to the other alternatives. As shown in Figure 1.1, energy prices have increased over time and, by implementing the Passive House renovation package, the homeowner's dependency on energy supply decreases and their resilience against increasing energy prices improves.

Installing Passive House windows was shown to be more cost-effective than installing BR windows. A recommendation is to include PH windows in all projects where the windows are changed; the sizes and shapes of the windows make it possible to achieve the low U-value.

Installing a heat pump is the most cost-effective measure regardless of renovation level. Of the two evaluated alternatives, GSHP and EAHP, installing an EAHP is more cost-effective because of its high performance and comparatively low investment cost, partly because it eliminates the need for a separate air handling unit for ventilation.

Implementing the Passive House renovation packages also helps to fulfil the Swedish Government's goal of halving energy use in buildings by the year 2050.

7 Future work

In this chapter, proposals for possible continuations of the research project are described, based on identified needs for further research.

7.1 Pilot project

A desirable continuation of this project would be to test the recommended renovation measures by implementing them in pilot projects. Implementing these renovation measures in houses would test the feasibility and reliability of the construction measures, while also allowing a detailed assessment of the energy savings potential.

Such an implementation project should include a pre-implementation evaluation phase, where the energy use in the house is monitored in detail, preferably for a whole year, before the renovation starts. During the evaluation phase, alternative renovation measures could be assessed and the LCC could then be based on tenders from companies willing to perform the renovation. Monitoring should continue for at least another year after completion. It is important to distinguish the different energy posts, space heating, domestic hot water, facility electricity, and household electricity. This is rarely done in existing buildings, which makes the pre-implementation phase so important.

7.2 Multi-benefit evaluation

Another possible area of study would be to evaluate alternative renovation measures based on a multi-benefit method. The aim would be to consider all benefits gained from this type of extensive renovation. This should include such parameters as environmental impact of the renovation measures – emissions of greenhouse gas equivalents – evaluated in a life cycle assessment, and assessments of thermal comfort and life cycle cost.

Sammanfattning

Småhus byggda mellan 1961 och 1980 utgör cirka en tredjedel av det totala energibehovet på 31 TWh för uppvärmning och tappvarmvatten i svenska småhus. Dessa använder i sin tur cirka 40 procent av den totala energianvändningen i alla byggnader. Det finns omkring 715 000 småhus från denna period och de är byggda på ett homogent sätt i tekniska termer – med låg isolerings mängd – och de har sällan ventilation med värmeåtervinning. Normalanvändningen av energi i småhus från denna period överstiger dagens småhus - byggda mellan 2011 och 2013 - med cirka 40 procent.

Resultaten från BETSI-utredningen visar på ett omfattande behov av renovering. Omkring 70 procent av de undersökta småhusen hade någon form av skada – vilka hittades i alla delar av byggnaden – även om de flesta inte kategoriserades som allvarliga skador. Faktumet att manga småhus behöver renoveras innebär ett utmärkt tillfälle att samtidigt som de renoveras även inkludera energieffektiva renoveringslösningar för att både reducera driftkostnader men även utsläpp av växthusgaser relaterade till energianvändningen.

Målet med detta forskningsprojekt var att utvärdera möjligheten att genomföra kostnadseffektiva renoveringar av småhus till Passivhus-nivå samtidigt som det leder till andra förbättringar, som ett bättre inomhusklimat. Undersökningen inkluderar även lokal förnyelsebar energiproduktion och energilagring. Även inkluderat i undersökningen är mervärden från att genomföra denna typ av renovering, så som termisk komfort och fuktsäkerhet. Utvärderingarna genomfördes genom att simulera att renoveringslösningar tillämpades på två typhus inkluderade i fallstudien. Typhusen valdes baserat på identifierade typologier från litteraturstudien som genomförts i projektet.

Forskningsprojektet påbörjades genom att söka efter genomförda pilotprojekt som drastiskt minskat energianvändningen i småhus. Baserat på de renoveringslösningar som använts i dessa projekt bestämdes möjliga renoveringslösningar att undersöka för att bestämma den möjliga energibesparingspotentialen från att genomföra Passivhusrenoveringar i småhus. Resultaten visade på en stor besparingspotential på över 65 procent i de utvärderade typhusen.

Som en fortsättning på denna undersökning genomfördes en känslighetsanalys för att avgöra hur stor påverkan vissa parametrar hade på energibesparingspotentialen i den första undersökningen. Resultaten från denna fortsättande studie visade på ett stort beroende mellan energibesparingspotentialen och klimatet samt möjligheten att uppfylla Passivhuskraven. Resultaten användes även för att minska på antalet renoveringslösningar som kom att användas i nästa steg av projektet, utvärderingen av kostnadseffektiva renoveringspaket till Passivhusnivå.

Undersökningen fortsatte genom att bestämma kostnadseffektiva renoveringspaket till Passivhusnivå vilket genomfördes genom en livscykelkostnads-analys som bygger vidare på energisimuleringarna genom att även inkludera energipriser - genom att utvärdera olika typer av värmekällor - och investeringskostnader i analysen. Inkluderat i denna undersökning är även alternativen lokal energiproduktion genom solfångare och solceller samt energilagring i batterier.

Resultatet från livscykel-kostnads analysen visar på att passivhusrenoveringen är kostnadseffektiv, vid användning av vissa typer av värmekällor. Beroende både på skillnaden i driftkostnad och i passivhuskraven. Den mest kostnadseffektiva renoveringsåtgärden var att installera frånluftsvärmepump och den minst kostnadseffektiva åtgärden var att installera passivhus fönster. I hus som använder direktel till värme så är passivhusrenoveringen det mest kostnadseffektiva renoveringspaketet.

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Appendix

Renewable energy

Input data for the solar simulation performed in SAM.

Input type	Value
Weather file	Malmö (1020 kwh/m^2 global horizontal solar radiation) Umeå (905 kwh/m^2 global horizontal solar radiation)
PV	
Module	Nominal efficiency 20.6% Temperature coefficient 0.31%/°C Nominal operating cell temperature method with 4-6 cm air-gap between roof and module installed at the height of one-story building
Inverter	Conversion efficiency 96% (SMA)
PV system design	
Shading	No shading for Umeå, tilted roof. Mutual shading
Degradation rate	0%/year
Battery 14 kWh	
Chemistry	Lithium-ion
Capacity	13.3 kWh
Voltage	454 V
Maximum power	5 kW
Round trip efficiency DC side	92% (DC connected)
Controller	Minimize electricity used from the grid. Priority

	of electricity use to meet the load: 1) PV 2) battery 3) grid. The battery can only be charged by the PV, not by the grid.
Minimum/maximum state of charge	0% / 100%
Battery lifetime	Changed once during the lifetime after 12.5 years without degradation.
Simulation period	25 years.

Moisture analysis of external walls, before and after renovation

- Calculations and analysis carried out by Kajsa Flodberg Munck, NCC Building (Dipl. Fuktsakkunnig)
- Calculation models verified by Dr. Stephen Burke

Moisture calculations were carried out on the different external wall types in order to see how added thermal insulation and other materials would affect the moisture performance after renovation.

Method

Calculations were carried out in WUFI (Fraunhofer Institute of Building Physics), a dynamic, one-dimensional hygrothermal calculation tool for heat and moisture analysis of building envelope constructions. The one-dimensional calculations were carried out in an elevation through the insulation layers, without the effect of wooden studs and beams. Relative humidity and temperature in the materials were simulated in WUFI and the risk of mould growth on the wooden studs was evaluated separately in a mould resistance design (MRD) model (Thelandersson, 2013)). Whether microbial growth will occur or not, depends on humidity, temperature, duration of exposure, and type of material. The MRD-model predicts the onset of growth in a material based on climate history of combined relative humidity and temperature. The MRD-model is based on laboratory tests on various wooden materials under specified climate conditions. The MRD-model is controlled by a basic parameter in the form of a critical dose D_{crit}, which depends on the substrate or material surface on which growth may take place.

Three different wall types (RH 1a, RH 1b and RH 2) were calculated before and after renovation when new insulation was added. Material and climate data were retrieved from different databases in WUFI. However, the vapour barrier in WUFI was modified to correspond to a typical Swedish vapour barrier (0,2 mm plastic foil) with a vapour resistance (Z_v) of minimum 1 500 000 s/m. The vapour resistance (Z_v = 1 500 000 s/m) was converted into a diffusion resistance factor (µ-value) of 375 000 [-] and was used in the calculations.

Calculation input:

Wall orientation	South (higher influence of driving rain)	
Initial moisture content	RH 60%	
Initial material temperature	20°C	
Climate file	Lund; LTH Data	
Indoor moisture production	4 g/m^3	
Indoor temperature	20 °C	
Simulation period	Five years (October 2017 – October 2022)	
Ventilation rate	in air gap	30 ACH (constant)
Driving rain penetration	1%	
D_{crit}	17 days (Norweigan spruce, sawn)	

The air flow in the air gap behind the ventilated facade was modelled in WUFI according to Mundt-Petersen (Mundt-Petersen, 2015), with three layers of air in the gap with two different moisture capacities, with the total width of 28 mm (2+24+2 mm).

Leakages from driving rain penetrating the facade were assumed to be 1% and added as a load in the thin air gap layer closest to the material behind the air gap. In the non-ventilated façade in RH1a, the leakage was added as a load in the external render layer.

The initial moisture content in existing and new materials was assumed to 60% relative humidity. A five year simulation time was assumed to even out the effect of higher or lower initial moisture content.

A south-orientated façade was studied as the worst case because of the high influence of driving rain. According to Mundt-Petersen (2015), the influence of driving rain has a significantly higher impact on the relative humidity in the construction compared to the positive influence caused by solar radiation.

Results

Only results from the “worst-case” WUFI monitor position in each wall are presented in this report, i.e. the position with the highest relative humidity containing organic materials and therefore having a risk of mould growth. Relative humidity and temperature (results from WUFI) and risk of mould (result from the MRD-model) are presented for the worst monitor position in each wall.

RH1a - Lightweight concrete wall, before renovation

The existing light-weight concrete wall contains no wooden studs or other organic material. The relative humidity and temperature results are therefore presented for the light-weight concrete layer, see the worst monitor position in Figure A.1.

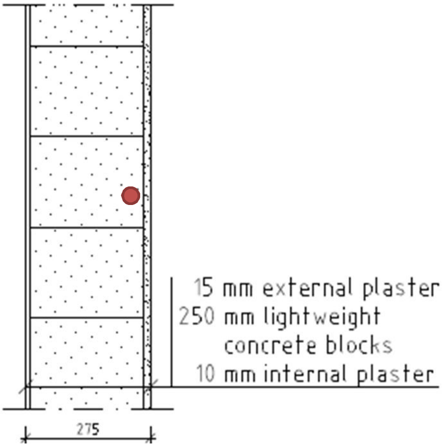

Figure A.1. RH1a - Lightweight concrete, before renovation. Monitor position in red.

Results from the simulation, presented in Figure A.1, shows that the relative humidity at the monitor position is constant high over the year, between 95% and 98%. This is likely to depend on the non-ventilated and non-drained façade construction and the assumed driving rain penetration. The simulated relative humidity is higher than the critical value for concrete materials and the construction does not seem to recover over time. However, the risk of mould inside the construction is low, as long as there is no dirt or other organic material in the construction. The mould risk has not been investigated in the MRD-model since the model only contains data for wooden materials.

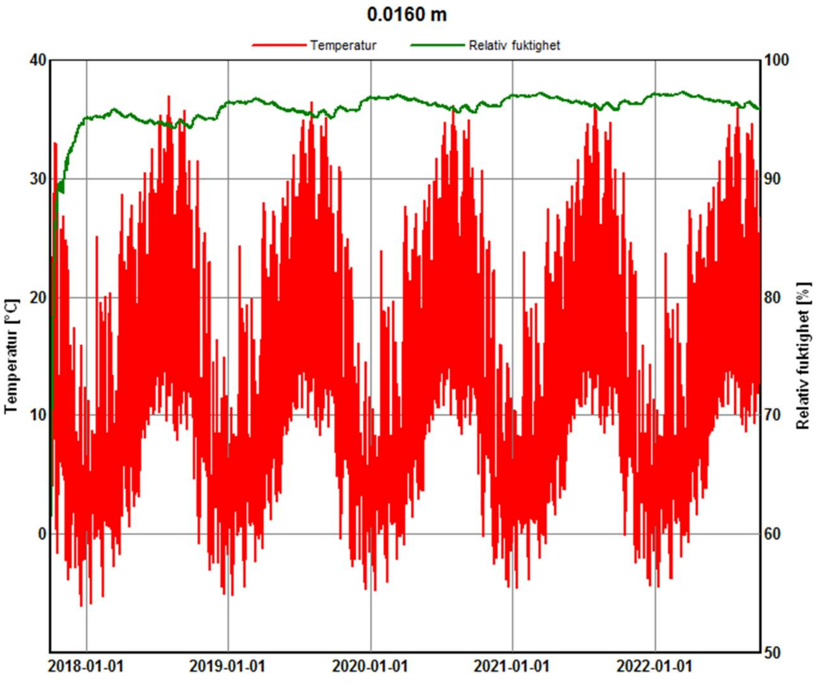

Figure A.2. RH (green line) and T (red line) in the concrete layer, before renovation.

RH1a - Lightweight concrete wall - After renovation

The renovated wall has two new layers of insulation on the outside of the concrete construction. The first insulation layer contains wooden studs and is therefore assumed the worst layer (see Figure A.3).

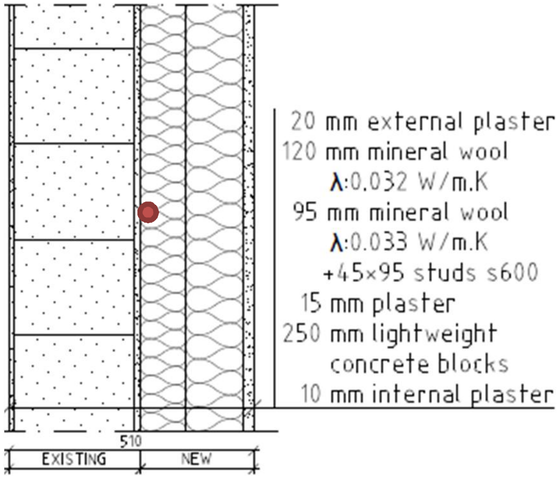

Figure A.3. RH1a - Lightweight concrete, after renovation. Monitor position in red.

Figure A.4 shows that relative humidity in the insulation layer exceeds 95% during the summertime. Figure A.5 shows that the mould risk at the wooden studs is high above the growth limit and heavy growth could occur the first summer. The risk of mould growth on the wooden studs is extremely high due to the lack of ventilation and drainage in the façade. Thus, the wooden studs should be replaced with steel studs or other non-organic material.

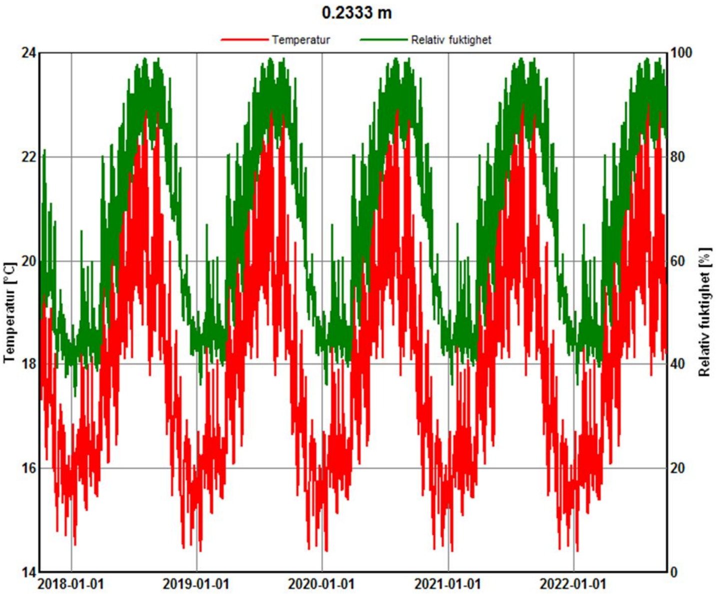

Figure A.4. RH and T in the 95mm insulation layer with wooden studs, after renovation

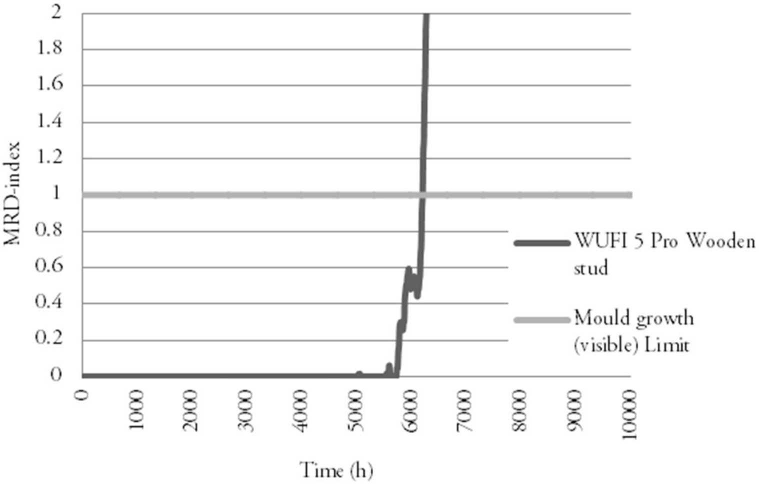

Figure A.5. Mould risk in the 95mm wooden studs, after renovation.

RH1b - Wooden frame construction from the 1960s, before renovation

The existing wall from the sixties has one insulation layer with wooden studs. Figure A.6 shows the monitor position used with this wall.

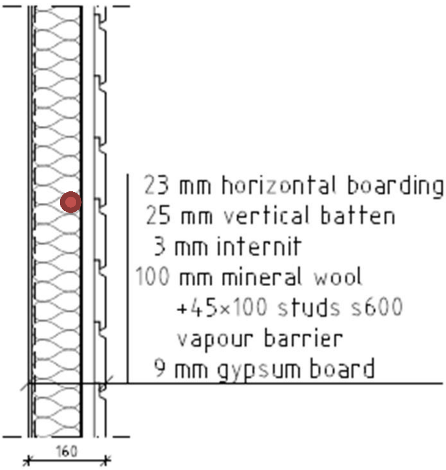

Figure A.6. RH1b - Wooden frame construction from the sixties, before renovation. Monitor position in red.

Figure A.7 shows that relative humidity in the insulation layer reaches 90% during the wintertime and 80% during the summertime. Figure A.8 shows that the mould risk reaches 2 on the MRD Index after about one year which indicates a risk of heavy mould growth.

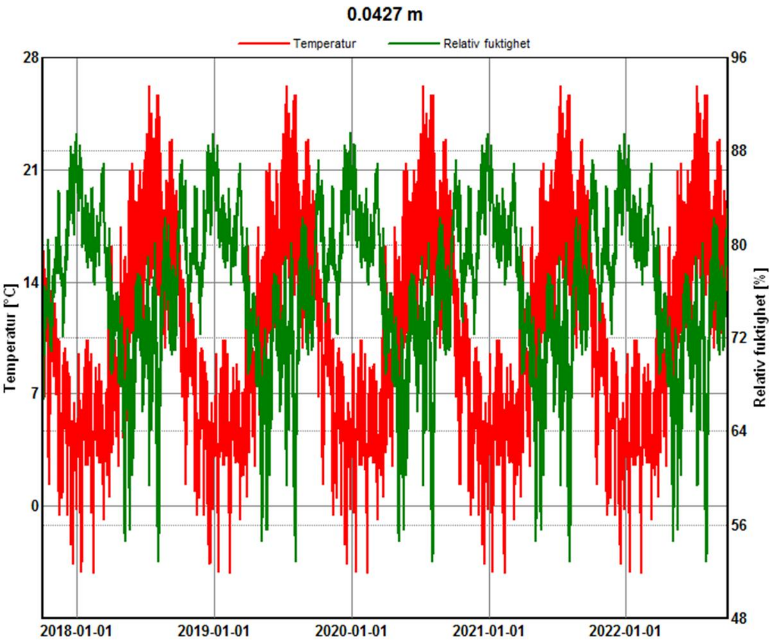

Figure A.7. RH and T in the 100mm insulation layer, before renovation

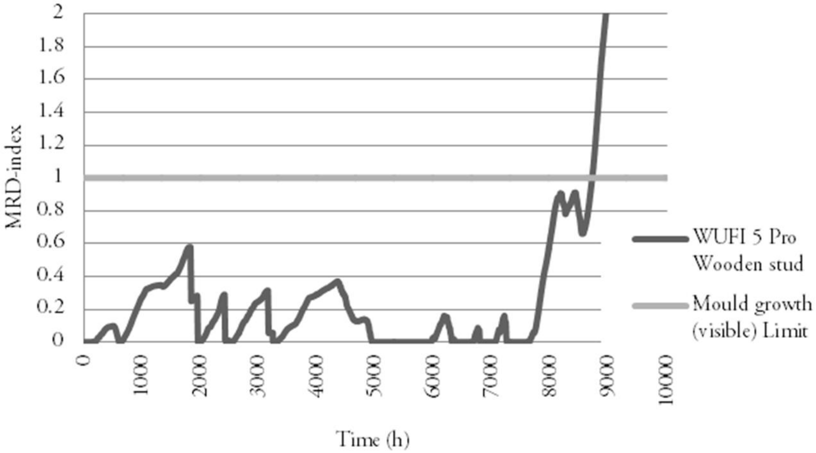

Figure A.8. Mould risk in the 100mm wooden studs, before renovation

RH1b - Wooden frame construction from the 1960s, after renovation

The renovated wall has a new vapour barrier and two new insulation layers on the outside of the original construction. The first insulation layer contains wooden studs and is therefore assumed the worst layer (see monitor position in Figure A.9).

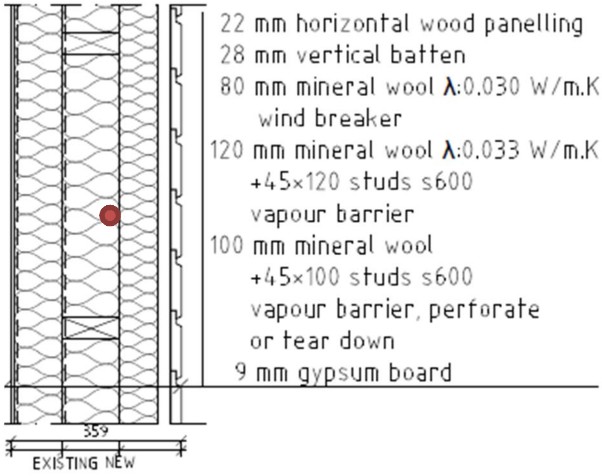

Figure A.9. RH1b - Wooden frame construction from the sixties, after renovation. Monitor position in red.

Figure A.10 shows that the relative humidity in the insulation layer reaches 80% in the early autumn. Figure A.11 shows that the risk of visible mould growth is low and is below the critical limit. The wall is therefore considered better after renovation and the risk of mould is considerably lower in the new construction.

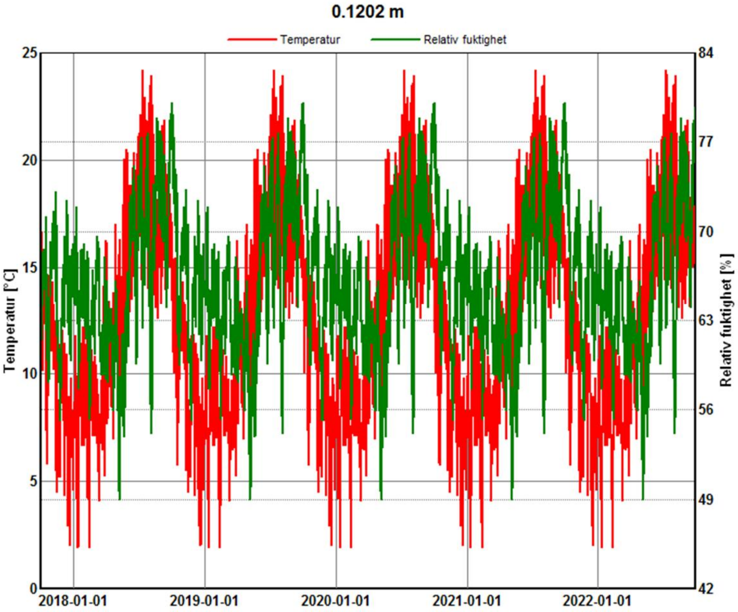

Figure A.10. RH and T in the 120mm insulation layer, after renovation.

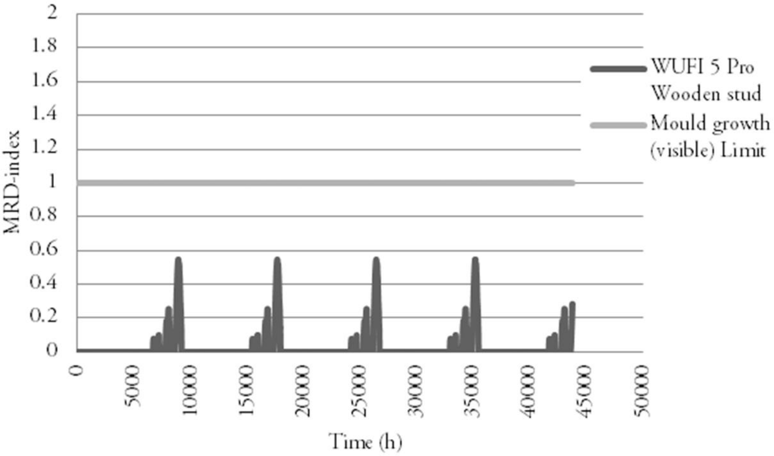

Figure A.11. Mould risk in the 120mm wooden studs, after renovation.

RH2 - Wooden frame construction from the 1970s, before renovation

The existing wall from the seventies has two insulation layers with wooden studs and the results are presented for the outer (worst) layer, see monitor position in Figure A.12.

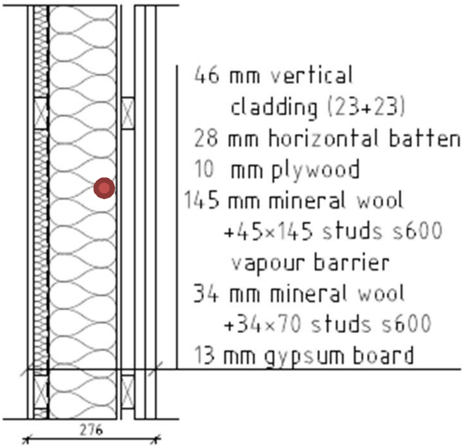

Figure A.12. RH2 - Wooden frame construction from the seventies, before renovation. Monitor position in red.

Figure A.13 shows that the relative humidity in the 145 mm insulation layer reaches 84% during the wintertime. Figure A.14 shows that the risk of visible mould growth is low and is far below the critical limit.

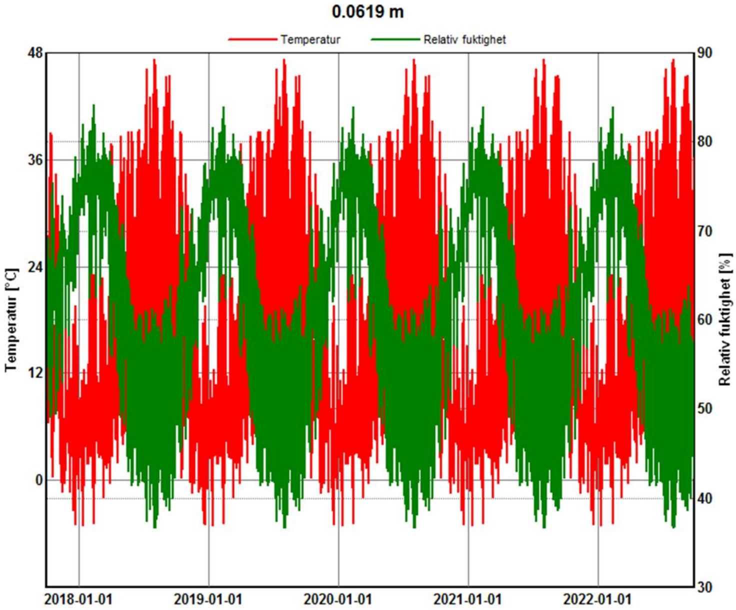

Figure A.13. RH and T in the 145mm insulation layer, before renovation

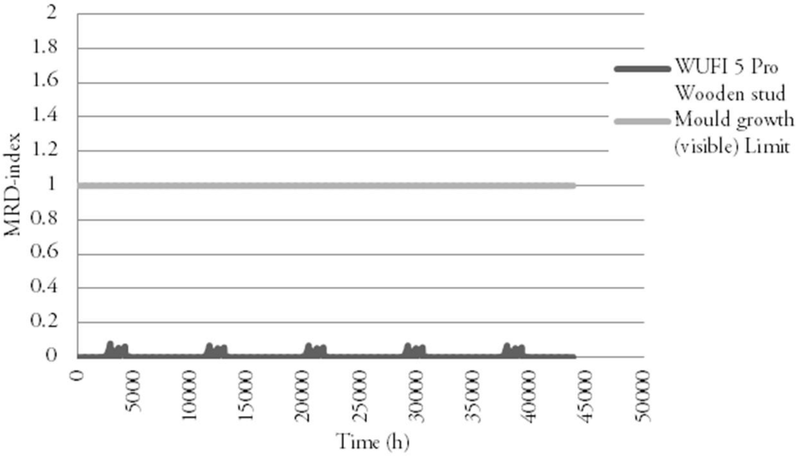

Figure A.14. Mould risk in the 145mm wooden studs, before renovation.

RH2 - Wooden frame construction from the 1970s, after renovation

The renovated wall has two new insulation layers on the outside of the original construction. The first insulation layer contains wooden studs and is therefore assumed the worst layer (se monitor position in Figure A.15).

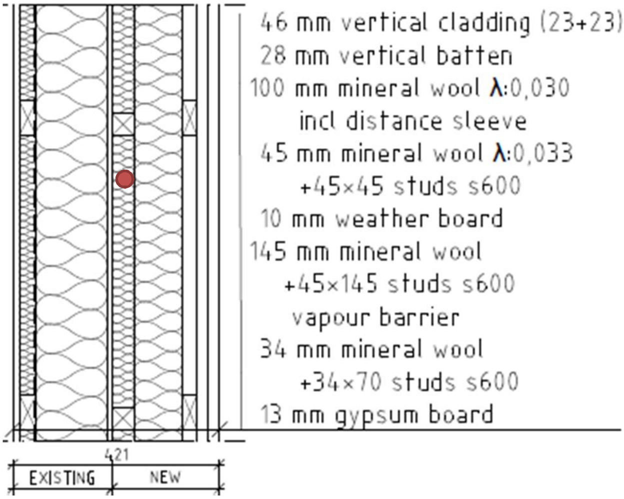

Figure A.15. RH2 - Wooden frame construction from the seventies, after renovation

Figure A.16 shows that relative humidity in the insulation layer reaches 90% during the wintertime and 85% during the summertime. However, Figure A.17 shows that the risk for mould growth is almost non-existent. The wall is therefore considered at least as good after renovation, from a mould-growth risk perspective.

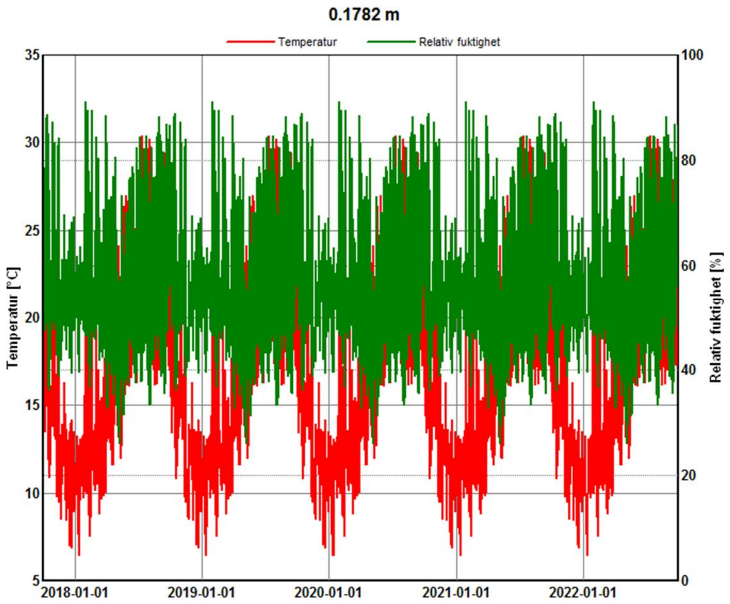

Figure A.16. RH and T in the 45mm insulation layer, after renovation

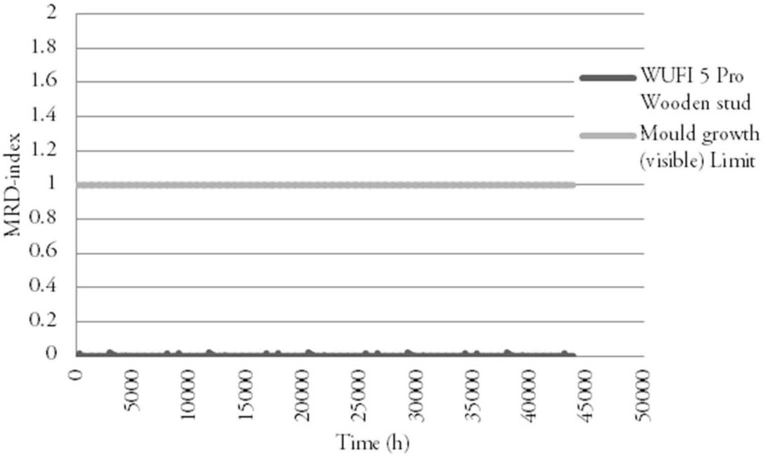

Figure A.17. Mould risk in the 45mm wooden studs, after renovation.

Discussion

The lightweight concrete wall (RH1a) has a non-ventilated and non-drained render façade. Therefore, the construction is very sensitive to driving rain penetration. Incoming water takes a long time to dry out. When adding new insulation layers, the studs should be non-organic materials. Simulations of the first insulation layer show that the moisture exposure is high during the warmest season, which is favourable for mould growth on organic materials. Another possible solution is to add a ventilated façade when renovating.

The two wooden frame walls (RH1b and RH2) perform better after renovation, from a mould-growth risk perspective. None of them indicates a risk of mould growth after renovation.

The results from this analysis prove the importance of taking in consideration temperature and duration when analysing mould risk in wooden constructions. Even though the relative humidity reaches high levels during periods of the year, the risk of mould growth can be low because of cold temperatures and a short duration of exposure.

Published papers

The chapter contains a list of all included papers and the contribution of each of the listed authors.

List of papers and contribution of the authors

As part of the licentiate work, four papers were published, one peer-reviewed journal paper and three peer-reviewed conference papers:

Paper I: *"Renovation of Swedish Single-family Houses to Passive House Standard – Analyses of Energy Savings Potential"* Ekström, T. and Blomsterberg, Å., In the proceedings of the Sustainable Built Environment 16 Conference on Build Green and Renovate Deep, 5-7 October, 2016, Tallinn, Estonia. Energy Procedia, 2016. 96: p. 134-145. *(Ekström & Blomsterberg, 2016b)*

The co-author helped define the research, reviewed the article and discussed the content.

Paper II: "*Renovation of Swedish single-family houses to Passive House standard - Sensitivity analysis" Ekström, T., Davidsson, H., Bernardo, R. and Blomsterberg, Å.* In the proceedings of the 3rd Asia Conference of International Building Performance Simulation Association - ASim2016, held on 27-29 November 2016 in Jeju

(Cheju) island, Korea. *(Ekström & Blomsterberg, 2016a)*

The co-authors helped with reviewing the article and discussing the content.

Paper III: *"Evaluation of cost-effective renovation packages to Passive House level for Swedish single-family houses from the sixties and seventies" Ekström, T., Bernardo, R. and Blomsterberg, Å.* Submitted to the journal Energy and Buildings, 2017-08-02. (Ekström, Bernardo, & Blomsterberg, 2017)

The co-authors helped by conducting some simulations, reviewing the article and discussing the content.

Paper IV: "R*enovating Swedish single-family houses from the sixties and seventies to net-zero energy buildings" Ekström, T., Bernardo, R., Davidsson, H. and Blomsterberg, Å.* Submitted to conference . (Ekström, Bernardo, Davidsson, et al., 2017)

The co-authors helped by conducting some simulations, reviewing the article and discussing the content.

Paper I

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2016) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep, 5-7 October 2016, Tallinn and Helsinki

Renovation of Swedish single-family houses to passive house standard – Analyses of energy savings potential

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Abstract

A third of Sweden's two million single-family houses were built in the period 1961-1980, and many of them are in need of renovation. These houses have a high energy use and are in technical terms fairly homogenous. This investigation evaluates the theoretical energy savings potential of renovating houses from this period. Four reference houses were selected and simulated using common renovation measures. The results indicate that most of the existing single-family housing stock will likely not be able to attain the passive house standard after renovation and using today's technology. This is explained by the fact that some house characteristics impose a limiting factor on the energy renovation. Such examples are the shape, foundation and composition of the building envelope. Nevertheless, it is still possible to drastically reduce the final energy use by approximately 65-75 %.

Keywords: deep renovation, energy retrofit, detailed energy simulations, single-family houses

1. Introduction

Single-family houses built in the period 1961-1980 account for one-third of the energy use in Swedish single-family houses, which in turn use about 40 % of all energy in buildings [1]. These houses were built fairly

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homogeneous in technical terms, with low levels of thermal insulation and heat recovery ventilation (HRV) is rare [2]. Thus there are great potential to improve energy efficiency and indoor environment. A literature review showed few completed deep renovations of single-family houses to passive house level and overall there is little written regarding the subject. Although the initial inventory showed that it is technically possible to renovate to the level of passive house the profitability is questionable. Many of the houses built during this period need to be renovated due to ageing [3]. This provides an opportunity to also incorporate energy efficiency measures.

The overall aim of the research project is to increase the knowledge regarding cost effective deep renovations to passive house level. This will be done through detailed energy simulations, life-cycle cost analysis (LCCA) and life-cycle assessment (LCA) with solutions that preserve the architectural expression of the houses. This investigation is the starting point, focused on estimating the energy savings potential of four reference single-family houses. The simulations were based on the Swedish passive house standard, FEBY 12, (Forum for energy-efficient buildings) [4], as well as a comparison with the current Swedish building regulation, BBR 22 [5].

1.1. Background - Single-family houses built during the 60s and 70s

During the 1960s there was a substantial demand for new housing in Sweden. To overcome this, the "million-program" was initiated with the goal to construct one million dwellings during 1965-1975, including both multi- and single-family houses. To construct this many dwellings in the short timeframe the buildings were built in a standardized way, which makes them suitable candidates for standardized renovations. This project focus on the single-family houses built in the period 1961-1980. From this period there are almost 714.000 single-family houses and they account for much of the energy use in single-family houses, see Table 1. The 1973 international oil crisis increased the costs for space heating, since many houses were heated by oil. The increased energy cost lead to a new focus on reducing the energy use of buildings. As a result the requirements on energy efficiency increased with the building code in 1975, SBN 75 [6], and the result can be seen in the average annual energy demand in Table 1.

Table 1. Number of houses and annual energy demand per heated floor area for space heating and domestic hot water [7, 8].

Years	**Units**	**1961-1970**	**1971-1980**	**1961-1980**	**Total - 2012**
Number of houses	thousands (2012)	288	426	714	2014
Average annual energy demand	kWh/m^2/a	106	90	96	106

1.1.1. Constructions used in the 60s and 70s

To compile the commonly used constructions from each of the decades a literature review was performed. It also included finding common shapes and compositions of the building envelope of houses, i.e. form and amount of windows of the building envelope. There was some variation and influences originated both from abroad and from Swedish building regulation. While some constructions were quite standardized, e.g. during 1961-1985 the most common foundation was concrete slab with or without a cellar, which account for over 75 % of all m^2 of foundation in houses from this period [2]. For the concrete slabs the insulation thickness and placement varied between 70-100 mm both above and/or below the slab. For houses with crawl spaces, the joists were filled with insulation [9].

1961-1970 – To accommodate the increased production rate, many houses were built in groups with prefabricated construction. This meant less time at the building site and with the expectation of less building problems. In the beginning of the decade most houses were built as one story houses, alternatively adding a cellar with a recreation room, which in the later parts changed to one-and-a-half or two story houses. Large window sections became common, which increased the window-to-wall ratio, and two types of roof constructions were used, either ridged roof or pent roof. The house shape was either rectangular or L-shaped with function displaced rooms; the rooms were placed based on their use and likely connection, i.e. garage, storage, laundry room and kitchen on one side of the house and living room and bedrooms on the other. The used façade material was either wood panel or bricks or a combination of both [9, 10]. Inside the façade material an asphalt board was placed outside the 100 mm thick stud framework with intermediate mineral wool insulation. On the inside of the wall a diffusion-proof plastic foil was placed to increase the air tightness and lastly a gypsum wallboard. As an alternative construction, light-weight concrete was used with a thickness of about 200-250 mm. The roof was made out of roof trusses with intermediate mineral wool insulation of about 125 mm. For ventilation a passive stack system was used [10].

1971-1980 - The production of houses continued to rise during this decade in part because of subsidies from the state. The typical composition of a house from the 70s is a one-and-a-half story house with a 45° ridged roof, sharply projecting eaves, with a balcony under the eaves on the gable side of the house. For the façade a common combination was bricks on the ground floor and wood panel on the upper floor. In the areas built in groups, wooden panels were the dominant façade material towards the end of the decade. The commonly used construction system was still stud framework with intermediate thermal insulation, but the thickness of the insulation layer increased to 170-190 mm. A plastic vapor barrier was placed on the inside of the wall to further increase the air tightness. The roof was still made of roof trusses with intermediate insulation but the insulation thickness increased to about 245 mm of mineral wool [9]. During this period, the ventilation system was changed from passive stack in the beginning to mechanical ventilation with or without heat recovery ventilation as the focus on energy efficiency increased [10].

1.2. Regulation for renovation - Swedish building regulation, BBR, and passive house standard

The current Swedish building regulation, BBR 22, states that if a planned renovation is extensive the building should fulfill the level of a newly constructed building after renovation, which includes a requirement on the specific energy use. Included in the specific energy use is the energy needed for space heating, domestic hot water (DHW), and property electricity, i.e. electricity used in pumps and fans needed for the functioning of the house. This energy use is then divided by the heated floor area, A_{temp}. This includes the area inside the external wall that is heated to 10 °C or more, garage is always excluded. The requirements are divided into four levels, depending on climate zone, and two categories, with and without electric heating, see Table 2. The Swedish passive house standard includes two main requirements, specific energy use and power demand. These are divided into three climate zones, where climate zone 3 is the same as 3 and 4 in the Swedish building regulation. Also included are the passive house requirements for air tightness and *U*-values for windows and glazing according to FEBY 12.

Table 2. Building regulations and passive house standard requirements *[4, 5]*.

	Climate zone	**Unit**	**I**	**II**	**III**	**IV**
			Without electric heating			
Specific energy use	BBR 22	kWh/(m²·a), heated floor area	≤ 130	≤ 110	≤ 90	≤ 80
	Passive house	kWh/(m²·a), heated floor area	≤ 63	≤ 59	≤ 55	≤ 55
			Electric heating			
	BBR 22	kWh/(m²·a), heated floor area	≤ 95	≤ 75	≤ 55	≤ 50
	Passive house	kWh/(m²·a), heated floor area	≤ 31	≤ 29	≤ 27	≤ 27
			Passive house requirements, other			
	Power demand	W/m², heated floor area	≤ 19	≤ 18	≤ 17	≤ 17
	Air tightness, q_{50}	l/(s·m²), building envelope area	≤ 0.30 at ± 50 Pa			
	Windows and glazing	W/(m² ·K)	Average *U*-value ≤ 0.80			

In the case in which a renovated building is not able to fulfill the requirements on specific energy use (depending on the circumstances) or only a part of the building envelope is renovated. Then there are separate recommendations for the thermal transmittance, *U*-value, for each part of the building envelope. In Table 3 the U-value for passive house components and building regulation requirements on the different parts of the building envelope are shown.

Table 3. Minimum level of *U*-values when renovating according to BBR 22 [5] and passive house components.

	U_i	U_{Roof}	$U_{Extermal\ wall}$	U_{Floor}	U_{Window}	U_{Door}
BBR	W/(m²·K)	0.13	0.18	0.15	1.2	1.2
Passive house components*	W/(m²·K)	0.08	0.10	0.10	0.80	0.80

**Based on compiled completed passive house renovation projects.*

The Swedish building regulations also regulate the ventilation air flows allowed in residential buildings. The minimum average outdoor air flow rate per floor area when someone is present in a room is 0.35 l/(s·m²) and 0.10

l/(s·m²) when empty. There should also be a forced air flow- function to be able to evacuate excessive moisture and other indoor air pollutants when needed.

1.3. Realized renovations to passive houses standard

In Sweden four completed pilot renovations of single-family houses to passive houses level were found during the literature review. These four houses are Villa Kyoto, Villa Kanndalen, RenZERO-concept and Finnängen, see Table 4 for detailed information. For all of these a need to renovate was identified and the owner wanted to do more than just a normal renovation. All had the goal to lower the energy use by a large margin while improving the indoor climate by following the Swedish passive house standard, FEBY 12. Three of the houses included some kind of renewable energy solution when renovating. The costs for completing these projects were high and with payback periods of between 30-44 years, the cost effectiveness might be questionable. However, for the houses where the increased value is known, this was enough to compensate for the investment cost, being in an attractive location[11].

Table 4. Completed renovation projects to passive house level in Sweden[11-14].

Projects		**Units**	**Villa Kyoto**	**Villa Kanndalen**	**RenZERO**	**Finnängen**
Constructed		year	1977	1970	1945	1976
Renovated		year	2014	2008	2013	2010
Heated floor area		A_{temp}	155	-	200	212 / 246*
Energy use - before/after renovation		kWh/(m²·a)	122 / 0	162 / 45	128 / 30	165 / 0
Improved	Walls, increased insulation	mm	+150	+150	+300	(Total *U*-value = 0.10 W/(m²·K))
	Roof, increased insulation	mm	+500-600	+290	+360	(Total *U*-value = 0.08 W/(m²·K))
	Windows, new	W/(m²·K)	Yes, 0.9	Yes, 0.9	Yes, 0.9	Yes, 0.8
	Air tightness, after renovation	l/(s·m²)	Yes, 0.3	Yes, 0.3	Yes, 0.3	Yes, measured, 0.10-0.15
	Foundation, increased insulation	mm	+160	+100	-	Yes
Heat recovery ventilation			Yes	Yes	Yes	Yes
Solar collectors			Yes	Yes	No	Yes
PV solar cells			Yes	No	No	Yes
Ground source heat pump			Yes	No (district heating)	Yes	Yes

* *Performed a building extension which increased the floor area of the house.*

2. Methodology

An overview of the method is shown in Figure 1, starting with literature reviews, from which the gathered information was compiled as input data for the simulation models and to determine the relevant simulations. A literature review of different regulations and certification systems used in Sweden was performed to find criteria for specific energy use, air tightness and other parameter that impact the energy use. The literature reviews also included how typical houses were built 1961-1980, their constructions, shapes and composition of the building envelope. This information was then used to compile criteria, which the comparison and selection reference houses were based on. Another literature review compiled energy renovations to passive house standard in northern Europe. This was done to find out how common this type of renovation is, their used renovation measures, costs and achievable energy savings. This information was then used as input to the energy simulations.

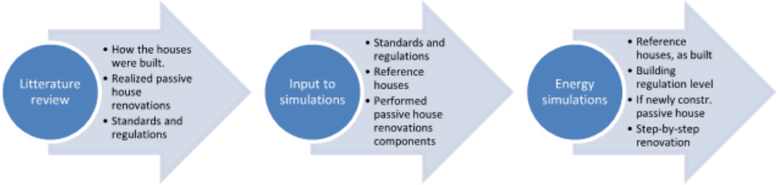

Figure 1. Overview of method used.

The energy use and savings potential was simulated using a validated dynamic energy simulation tool, IDA Indoor Climate and Energy 4.7 [15]. The reference houses were simulated as the houses were built to find a base case, grounded on their original constructions. Incremental changes of the base cases were done until the result equaled a passive house renovation e.g. improved *U*-values, air tightness, installations etc. based on available renovation measures. This was done to show the variation in results from the measures depending on the house's shape and composition of building envelope as well as how the steps affect each other. The best-case scenario for the energy savings potential were simulated using the models of the reference houses with constructions and installations as in a newly constructed passive house. The building regulation level of renovation was also simulated as a comparison to show the increased potential from a passive house renovation and what the minimum level of renovation would be. To simulate the energy demand of the reference houses, the thermal transmittance, or *U*-value, for each part of the building envelope were calculated. For foundations the calculations were done according to the standard; ISO 13370:2007 [16] and for other parts of the building envelope the standard; ISO 6946:2007 [17] was used. In Sweden the area for which these *U*-values are used for are the inner surfaces of a building envelope. This means all external connections, such as wall to wall, wall to foundation etc., are not included in the area. These connections are instead included in the thermal bridges. The thermal bridges were assumed as an increase of the total heat losses by 25 % in these simulations, based on the Swedish certification system Miljöbyggnad [18]. To determine the reduction of the thermal transmittance through the foundation from the implemented renovation measure, the foundations were simulated using the two-dimensional transient and steady-state heat transfer program HEAT2 [19]. The results were then used in the total building energy simulation performed in IDA ICE.

3. Reference houses

3.1. Choice of reference houses

The objective was to find houses that cover as many of the constructions and architectural designs that were used in the 1960s and 1970s. First, it was decided that four houses were enough to balance the amount of simulations needed and at the same time get variation between the houses. Next, the locations were chosen with the aim to spread them across Sweden to try to represent the whole country. This was based on city size, location and the amount of single-family houses that were built there in this time period. The chosen locations are Malmö, Göteborg, Stockholm and Umeå, since in these cities over 200.000 (roughly 30 %) single-family houses were built during this time period. With the increased focus on energy efficiency in the building regulation from 1975 the goal was to find houses built both before and after this regulation took effect. Based on the literature review a compilation of criteria was done, see Table 5. For each location four houses of different types were picked to be compared. Their drawings and descriptions were collected from the city-planning office. Out of these 16 houses, four was chosen, see Table 5.

Table 5. Criteria and reference houses.

Location		**Malmö**	**Stockholm**	**Göteborg**	**Umeå**
Construction year		1965	1965	1961	1977
Roof	Ridged		X		X
	Pent	X		X	
Shape	Rectangular		X	X	X
	Function displaced	X			
Facade	Wood panel				X
	Combination of bricks and wood	X		X	
	Plaster		X		
Constr.	Wooden studs			X	X
	Concrete			X	
	Light weight concrete	X	X		
Floors	One floor			X	
	One and a half or two floors		X		X
	Cellar	X			
Energy source	Oil	X	X	X	
	Electricity				X

	District heating				
Vent.	Passive stack ventilation	X	X	X	
	Mechanical exhaust ventilation				
	HRV				X

3.2. Description of reference houses

The four chosen reference houses are presented in Table 6 with basic information and an illustration of the building model from IDA ICE 4.7. The building models are based on available drawings and descriptions and the models were made with one zone for each room in the houses.

Table 6. Basic data for reference house, Malmö, Göteborg, Stockholm and Umeå.

Location:	**Malmö**	
Year built:	1965	
No. of floors:	1 + Cellar	
A$_{temp}$:	230 m^2	
Ventilation:	Passive stack ventilation	
Description: Function displaced one story house with cellar and a pent roof, light weight concrete walls and a concrete slab foundation. Garage attached.		
Location:	**Göteborg**	
Year built:	1961	
No. of floors:	1	
A$_{temp}$:	140 m^2	
Ventilation:	Passive stack ventilation	
Description: Rectangular one story house with a pent roof, sandwich concrete walls and a concrete slab foundation.		
Location:	**Stockholm**	
Year built:	1965	
No. of floors:	2	
A$_{temp}$:	163 m^2	
Ventilation:	Passive stack ventilation	
Description: Rectangular two story house with a ridged roof, light weight concrete walls and a concrete slab foundation. Garage inside building envelope.		
Location:	**Umeå**	
Year built:	1977	
No. of floors:	1½	
A$_{temp}$:	142 m^2	
Ventilation:	Balanced ventilation with heat recovery	
Description: Rectangular one-and-a-half story house with a ridged roof, wood frame structure walls insulated with mineral wool and a concrete slab foundation.		

3.3. Building envelope of reference houses – before renovation

Based on the available drawings and descriptions of the reference houses, the material types and thicknesses of the building envelope were determined, see Table 7. All four of the reference houses have a concrete slab foundation but the house in Malmö also has a cellar. The insulation type and thickness of the foundation is known for the houses in Malmö and Göteborg, but not for the houses in Stockholm and Umeå. When not known, the insulation thickness was estimated based on the building regulation current at the time of construction [20] [21] [6].

Table 7. Reference houses building envelope, material type and thickness.

Location	Malmö	Göteborg	Stockholm	Umeå
Exterior walls (inside – outside)	Render + 250 mm light concrete + render	Sandwich element: 60 mm concrete + 100 mm min. wool + 60 mm concrete. Light frame constr.: 100 mm min. wool / stud frame + 9mm gypsum board	Render + 250 mm light concrete + render	10 mm plywood + 180 mm min. wool/stud frame (145 + 70)×34 mm + 13mm gypsum board
Roof (top – bottom)	Roof truss 45×195 c/c 1200 mm + (80 + 30) mm min. wool	Concrete roof: 130 mm min. wool + 220 mm concrete. Truss roof: Roof truss + 150 mm min. wool	Roof truss 45×195 c/c 1200 mm + 200 mm saw dust + 25 mm min. wool	Roof truss 45×195 c/c 1200 mm + 300 mm min. wool
Exterior floors (top – bottom)	Total thickness 250 mm, 70 mm insulation, type unknown + ~180 mm concrete	Total thickness 250 mm, unknown insulation, assumed to 100 mm + ~150 mm concrete	Total thickness 250 mm, 100 mm min. wool/stud frame + ~150 mm concrete*	Total thickness 250 mm, unknown insulation, assumed to 100 mm + ~150 mm concrete*

* *Estimation of insulation thickness based on regulation in force at time of construction.*

Based on the gathered information the *U*-values were calculated for the reference houses. Regarding windows and external doors, the gathered information was not enough to determine the *U*-values. Instead they were estimated based on information of used *U*-values from the time period. In 1967, the then new building regulation, SBN 1967 [21], required the *U*-values for windows to be 2.7 W/($m^2 \cdot K$) or lower to fulfill the regulations. With the release of a new regulation in 1975, SBN 1975 [6], the required *U*-value for windows improved to 2.0 W/($m^2 \cdot K$) or lower. For the three reference houses built 1961-1965 there was no regulation in force regarding *U*-values for windows. So the estimation was based on the closest alternative, SBN 1967, to 2.8 W/($m^2 \cdot K$). For external doors there were no regulation regarding *U*-values, so they were estimated to 1.5 W/($m^2 \cdot K$). See Table 8, for a summary of the calculated and estimated *U*-values for the reference houses.

Table 8. Building envelope *U*-values for reference houses before renovation.

	Building envelope	**Reference houses - Base case**			
	Location	**Malmö**	**Göteborg**	**Stockholm**	**Umeå**
U-value W/($m^2 \cdot K$)	Roof	0.36	0.26	0.31	0.15
	Foundation, floor against ground	0.32	0.23	0.23	0.23
	Foundation, floor against air	-	-	0.33	-
	Cellar wall	0.54	-	-	-
	Wall	0.54	0.33	0.54	0.23
	Windows	2.8	2.8	2.8	2.0
	Doors	1.5	1.5	1.5	1.5
	Addition for thermal bridges:	25%			

3.4. The ratio between the building envelope area and the heated floor area

In Table 9 the ratio between the area of different parts of the building envelope and the heated floor area of the reference houses are presented. The presented ratios are between the total building envelope area and the heated floor area and window area to floor and to façade area. Higher ratios indicate a higher need for space heating, since the building envelope is larger or have a higher thermal transmittance. By analyzing the ratio of a house some initial assumptions can be made, e.g. by comparing the ratio for the reference houses. By comparing the ratios, it is likely that the houses in Göteborg and Stockholm will need more effective renovation measures to reach the same level of final energy use as the houses in Malmö and Umeå.

Table 9. The ratio between the building envelope area and the heated floor area.

	Reference house	**Malmö**	**Göteborg**	**Stockholm**	**Umeå**
Ratio	$A_{\text{building envelope}}/A_{\text{temp}}$	207%	308%	232%	213%
	$A_{\text{window}}/A_{\text{temp}}$	22%	28%	20%	13%
	$A_{\text{window}}/A_{\text{facade}}$	20%	26%	17%	13%

3.5. Input data for simulation

To simulate the final energy use all input data must be determined. For energy simulations, work has been performed to standardize the input data in Sweden. This is compiled in SVEBY, Standardize and verify energy performance for buildings [22], and it gives default values for internal heating loads and other input such as indoor temperature, forced ventilation air flows in kitchen, solar shading, domestic hot water use, household electricity use, number of inhabitants in the houses and their presence [22]. Based on SVEBY the simulated annual DHW energy use per heated floor area was 20 kWh/(m^2·a) and the simulated house hold electricity was 30 kWh/(m^2·a). From FEBY 12 input regarding the airing and regulating losses for the heating system was gathered.

For the reference houses with passive stack ventilation the actual ventilation air flow is unknown and some assumptions regarding the air flows were needed. As part of the BETSI evaluation of the Swedish building stock the air flow in naturally ventilated single-family houses was measured, using the standard ISO 16000-8 [23], to a mean flow per heated floor area equal to about 0.23 l/(s·m^2) with a normal ceiling height of 2.4 m. This includes the air flow both from infiltration and from the ventilation air gaps used for the passive stack ventilation [10]. This means that the houses with passive stack ventilation most likely do not fulfill the current building regulation requirements regarding minimum ventilation air flow. Thus, the energy demand will also be lower than if the regulation was fulfilled. The reference house in Umeå was built with a mechanical heat recovery ventilation system with a plate heat exchanger. The exact specifications are not known, so the dry heat recovery efficiency according to SS-EN 308:1997 [24] was assumed to be 50 % and the specific fan power, SFP, was assumed to be 2.0 kW/(m^3/s).

3.6. Step-by-step simulations

To determine the impact on the energy demand of different renovation measures, a step-by-step simulation was performed. This was used to find the energy savings potential for this type of deep renovation project and indicate if it is possible to achieve the Swedish passive house level. This evaluation does not include the effects of the energy sources or heating systems, which will be evaluated in future work. The renovation measures are based on commonly used renovation measures in completed passive house renovations from the literature review. The order of the steps has been chosen based on how common the measures were, relative cost based on the completed renovations, how they affect each other and depending on which energy item they effect. The different measures are divided into nine steps, where step 5 and 6 also are divided into parts. The measures for each step are described below, mainly in specific values, e.g. *U*-values or ventilation air flows. All steps include the measures from the step before, i.e. Step 2: Windows/doors, also includes the measures from Step 1: Roof. The measures that improve the building envelope also impact the air tightness, but by how much are hard to determine. So the improvements to air tightness were saved for Step 5 – Air tightness. This means the energy savings from Step 1-4 is underestimated. In this evaluation it does not matter, since all steps need to be performed to reach the level of quality and energy demand that is the goal of the project. The used values are chosen based on real constructions and solutions that are achievable today when renovating and found in completed passive house renovations. The exact solution to reach those specific values are not included in this paper, but will be evaluated in future work.

Step 1: Roof - Increasing the total insulation thickness equal to a *U*-value of 0.08 W/(m^2·K).

Step 2: Windows & door – New windows and doors, with a *U*-value of 0.80 W/(m^2·K).

Step 3: Foundation – Due to the original foundations for the reference houses all being concrete slabs, the added insulation was placed outside the slab, as illustrated in Figure 2.

Step 4: External walls - Increasing the total insulation thickness equal to a *U*-value of 0.10 W/(m^2·K).

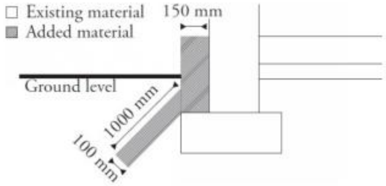

Figure 2 - Illustration of the renovation measure for the foundation, exact solution depend on the original construction of the reference house.

Step 5, part I and II: Air tightness – Passive stack ventilation and building regulation air flows – The air tightness of the building envelope was improved to 0.3 $l/(s{\cdot}m^2)$. Simulating the improved air tightness was divided into two parts for the houses with passive stack ventilation; part I keeping the existing ventilation and part II with mechanical exhaust ventilation without heat recovery. Part I will reduce the total ventilation air flow of the passive stack ventilated houses, to a level a lot lower than before and even further from the regulation level, which is a common problem in old houses with this ventilation system. This will also lower the simulated energy demand much lower than what would be a realistic level, since the houses will not fulfill the building regulation, indicated by the simulation of part II. The part II was not needed for the house in Umeå, which already has HRV.

Part I: The houses are simulated with an air tightness of 0.3 $l/(s{\cdot}m^2)$ and their existing ventilation system, either passive stack or mechanical.

Part II: A mechanical exhaust air ventilation without heat recovery was added to fulfill the building regulation ventilation air flow per floor area of 0.35 $l/(s{\cdot}m^2)$. The SFP was assumed to be 0.6 $kW/(m^3/s)$, which is the highest allowed for this type of ventilation in BBR 22 [5].

Step 6, part I and II: Heat recovery ventilation – A balanced ventilation system with heat recovery was installed for all reference houses. The dry temperature efficiency was assumed to be 80 % and the SFP was assumed to be 1.5 $kW/(m^3/s)$. Supply air temperature after the heat recovery was heated to a temperature of 19 °C so the air temperature is below room temperature to ensure good air circulation. The HRV measure was divided into part I with constant air volume (CAV) and part II with demand controlled ventilation (DCV).

Part I: The CAV ventilation air flow per floor area was 0.35 $l/(s{\cdot}m^2)$ based on the building regulation.

Part II: For the DCV the air flow when someone is present in the house was 0.35 $l/(s{\cdot}m^2)$, but when empty the DCV reduces the air flow to 0.10 $l/(s{\cdot}m^2)$.

Step 7: Electronic controlled thermostats - For the base case it was assumed that standard indoor temperature mechanical controlled thermostats were used. After renovation the indoor temperature electronic controlled thermostats was used, with the aim of decreasing the regulation losses from 11 % to 7 % according to FEBY 12 [4].

Step 8: Circulation pump - The circulation pumps in the base case were assumed to be the original pump from when the houses were built. The pumps was exchanged to new circulation pumps that are more efficient and that also has a pump stop, which will turn the pump off if there is no space heat demand [25]. The period that the pump is turned off will also increase because of the fact that the other renovation measures lower the space heat demand of the houses. The hours are estimated based on the heating season from the energy simulations.

Step 9: Indoor temperature variation - Indoor temperature variation was used, reducing the indoor temperature from the standard 21 °C to 18 °C when no one is home and when the inhabitants are asleep. This was assumed to be between 08:00 and 16:00 on weekdays and, at night, 23:00-06:00 on weekdays and 00:00-08:00 at weekends. This was done with a central controlled thermostat.

3.7. Comparison calculations

For comparison, two alternatives were simulated for the reference houses; the first was the minimum level of renovation with measures based on fulfilling the building regulations for new construction. Secondly the best-case scenario where the houses were simulated as if newly constructed passive houses, see Table 3 for U-values.

The ***"building regulation level renovation"*** comparison was simulated with the U-values fulfilling the regulation and with the building envelope air tightness improved to 0.3 $l/(s{\cdot}m^2)$. The circulation pump was exchanged and a mechanical exhaust ventilation system without heat exchange was installed with a ventilation air flow of 0.35 $l/(s{\cdot}m^2)$ per floor area. The SFP was assumed to be 0.6 $kW/(m^3/s)$. The foundation was not improved due to the problem with fulfilling the specific U-value requirement; all other input remained as in the base case.

The ***"if newly constructed passive house"*** comparison had the same input as step 9 in the step-by-step renovations, but instead of the measures for improving the foundation in step 3 a foundation equal to a new passive house foundation was used, with an U-value of 0.90 $W/(m^2{\cdot}K)$.

4. Results

The simulated results are presented in Table 11 as final energy use, which includes space heating, DHW and property electricity. These results are presented to show the potential for different renovation measures and their respective energy savings potential. The results are presented per reference house, starting with the base case and then adding the steps 1-9 and ending with the total reduction from all measures. Lastly, the simulated comparisons *"building regulation level renovation"* and *"if newly constructed passive house"* as well as the passive house requirements from FEBY 12 are presented. The results are divided into annual final energy use per heated floor area and the reduction in percentage per step compared to the base case.

Table 10. Resulting annual final energy use per heated floor area and reduction vs. base case from step-by-step and comparison simulations.

Info.	**Reference house**	**Malmö**		**Göteborg**		**Stockholm**		**Umeå**	
	Heated floor area, A_{temp},m^2	230		140		163		142	
	Units	kWh/($m^2{\cdot}a$)	%	kWh/($m^2{\cdot}a$)	%	kWh/($m^2{\cdot}a$)	%	kWh/($m^2{\cdot}a$)	%
Step-by-step renovation	Baseline case	160	0	229	0	209	0	187	0
	Step 1: Roof	137	-14	205	-10	203	-3	181	-3
	Step 2: Windows & doors	106	-34	124	-46	144	-31	137	-27
	Step 3: Foundation	104	-35	112	-51	139	-34	133	-29
	Step 4: External wall	62	-61	89	-61	84	-60	115	-38
	Step 5, part I: Air leakage	47	-70	63	-72	66	-68	104	-44
	Step 5, part II: Air leakage	97	-39	119	-48	129	-38	-	-
	Step 6, part I: CAV	60	-63	77	-67	80	-62	81	-57
	Step 6, part II: DCV	56	-65	72	-68	76	-64	76	-59
	Step 7: Electrical thermostat	55	-66	71	-69	74	-65	74	-60
	Step 8: Circulation pump	50	-68	64	-72	68	-68	67	-64
	Step 9: Indoor temperature variation	49	-69	61	-73	66	-69	63	-66
	Total reduction	**-111**	**-69**	**-168**	**-73**	**-143**	**-69**	**-124**	**-66**
Comparison	Building regulation level renovation	116	-25	158	-31	166	-21	133	-28
	If newly constructed passive house	42	-74	55	-76	57	-73	55	-70
	Passive house requirement	≤ 55	-	≤ 55	-	≤ 55	-	≤ 63	-

5. Conclusions & discussion

This study show that there is great energy savings potential for all reference houses while using, by today's standard, common renovation measures and ignoring costs at this stage. The results from the simulations show a reduction of the final energy use by 65-75% for all four reference houses, presented in Table 11. Still, the step-by-step simulations show that only the reference houses in Malmö and Umeå were able to reach the passive house level when renovating, since today there is no economically feasible way to improve the concrete foundation to the same level as for a newly constructed passive house. Furthermore, the comparison simulations show that even while assuming the houses as *"if newly constructed passive house"*, the shape and composition of the building envelope have such a large impact that one reference house, Stockholm, with a small margin does not fulfill the passive house requirements and another reference house, Göteborg, is just at the level. While it might be possible to improve all steps even further to try and reach the passive house level this will likely not be a cost effective solution since none of the realized passive house renovations have tried to do so. These results points out an important limitation when renovating single-family houses to passive house level, not all parts can be improved to passive house level. Instead it is likely that the next step should be some kind of renewable energy solution, since the space heating demand was lowered by 75-80% in these simulations while the domestic hot water use was assumed not to change. This means that out of the total annual final energy use of 49-66 kWh/m^2 after a complete renovation, 20 kWh/m^2 are from domestic hot water. Thus a renewable energy solution that decreases the need for bought energy for heating the domestic hot water could have a large impact on the end results.

Compared to the statistical specific energy use for existing houses presented in Table 1 the simulated final energy use for the base cases presented in the results in Table 11 were higher. One reason for this discrepancy is that the statistical energy use is an average for all houses from the respective time period and in their current state in 2013, including any renovations and improvements performed since their construction. Determining how houses were built during this period showed many possible variations which also could indicate a great variation in the energy use. The four reference houses fulfilled the building code requirements during the period of construction and it is known that many houses today are not extensively energy renovated, so this is likely not the reason for the difference. But a common measure in Swedish single-family houses is the installation of some type of heat pump, which reduces the bought energy compared to the final energy. This is likely the main reason for the difference, since the simulated final energy use does not take into account the energy source, i.e. if a heat pump is installed. Thus the exact level of specific energy use the houses could reach by implementing these renovation measures depends on the houses' specific conditions. Regardless of how accurately the four reference houses represent the total housing stock, based on these results, it is likely most houses could be renovated to reduce the final energy use by at least 60 % if the evaluated measures in this study were implemented, unless other limitations are valid such as cultural heritage protection.

Compared with the simulated *"building regulation level renovation"* for new construction the step-by-step renovation reduces the final energy use by more than twice as much, a 20-30 % reduction compared to 65-75 %. The step-by-step renovation for all reference houses fulfills the building regulation requirement regarding specific energy use for newly constructed houses, which is a requirement when performing extensive renovations. Renovating according to the building regulation using only the fixed U-values does not fulfil the building regulation requirements for specific energy use.

Regarding the step-by-step renovations, there are some steps that show some interesting results. In Step 5, part II the impact of the ventilation air flow on the final energy use of a house is shown, increasing the energy use by almost 100 % relative to part I. This highlights one of the problems with performing deep renovations on houses that originally had passive stack ventilation. When the air quality is ensured by mechanical ventilation according to the regulatory air flow, it could also increase the energy use and decrease the cost effectiveness of the renovation measures, depending on the original air flow. This also indicates the problem that naturally ventilated houses usually have too low ventilation air flow compared to today's building regulation, especially in the period from March to October, but this can also be true in winter. Up until step 9 all steps have been an improvement of the indoor climate by reducing draught and temperature differences, which can improve the operative temperature, in a room while also lowering the energy use. The measures in step 9 won't worsen the indoor climate if done right, but there is always some risk that the lowered indoor temperature is sensed as too cold by the inhabitant.

6. Future work

As a continuation of this work a sensitivity analysis will be performed to determine uncertainties arising from the renovation measures used in this study and which parameter that impact the results the most. This will be done by varying the input data used for different parameter in the simulations, e.g. how varying the internal gains or air tightness impacts the energy demand of the houses. The next step will be to compile variations of the simulated renovation measures and estimate the associated costs of implementing them. These alternatives will be evaluated in future work by LCCA and LCA, and will also include renewable energy solutions and thermal comfort simulations, to try and find cost-effective combinations of renovation measures to reach the Swedish passive house standard.

Acknowledgements

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Paper II

Renovation of Swedish single-family houses to passive house standard – sensitivity analysis.

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ABSTRACT

A third of Sweden's two million single-family houses were built in the period 1961-1980, and many of them are in need of renovation. Energy use in these houses is high, and they are fairly homogeneous in technical terms. A previous study of four reference houses showed that final energy use could be reduced in theory by approximately 65-75 % after renovation, by implementing conventional passive house components renovation measures. This paper evaluates the results and uncertainties arising from the previous study by performing a local sensitivity analysis of the most important input parameters, such as number of inhabitants, climate zone, orientation of the houses and alternative renovation measures in a Swedish context. The results presented in this paper show that the previously estimated final energy use reduction can be increased even further, to 75-80 %, by introducing additional renovation measures. The climate zone was shown to have the largest impact, with twice as much space heating required in the coldest evaluated climate compared to the mildest. The impact from inhabitants was less than expected, due to a counterbalancing impact on the final energy use from internal gains and domestic hot water.

KEYWORDS

Deep renovation, Energy retrofit, Detailed energy simulations, Single-family houses.

INTRODUCTION

Single-family houses built between 1961 and 1980 account for one-third of the energy use in Swedish single-family houses, which in turn use about 40 % of all energy in buildings (Swedish Energy Agency 2015). There are roughly 715,000 houses from this period (Statistics Sweden 2015) and they are fairly homogeneous in technical terms, with low levels of thermal insulation, and ventilation with heat recovery is rare (Boverket 2010). Many of these houses need renovation (Boverket 2010), which provides an excellent opportunity to incorporate energy efficiency measures.

In a previous paper (Ekström 2016) theoretical renovation measures were simulated, based on conventional measures from four completed passive house renovations of single-family houses in Sweden, and the energy savings potential was analysed. The

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evaluation used four reference houses as case studies (Table 1). The simulations were performed with standardised input data and a specific location for each reference house. The evaluation showed that not all reference houses would reach passive house level with the evaluated renovation measures, however a possible reduction of the final energy use (excluding household electricity) of 65-75 % could be attained if all evaluated measures were implemented.

The purpose of this paper is to: 1) evaluate the uncertainties arising from the used input data in the simulated theoretical renovations of the four reference houses described in the previous paper (Ekström 2016); 2) determine which of the parameters that have the most impact on the result of the energy simulations; 3) evaluate additional renovation measures. This knowledge is important in deciding which parameters are relevant for inclusion in the planned future cost evaluations.

Table 1. Basic data and visualisation for the four reference houses.

	
Location: Malmö, built: 1965, heated floor area: 230 m^2	Location: Göteborg, built: 1961, heated floor area: 140 m^2
	
Location: Stockholm, built: 1965, heated floor area: 163 m^2	Location: Umeå, built: 1977, heated floor area: 142 m^2

METHODOLOGY

A sensitivity analysis was carried out based on different plausible variations of the input data for the inhabitants and locations, as well as different renovation measures. An overview of the method used is shown in Figure 1.

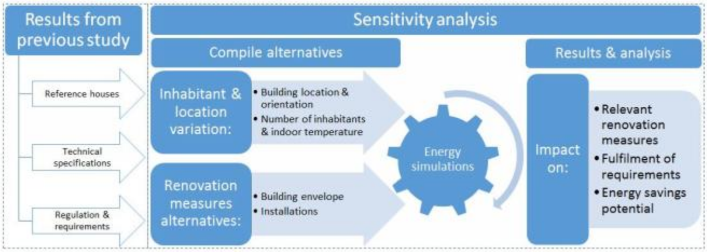

Figure 1. Overview of methodology.

The results from the previous energy simulations were evaluated in a local sensitivity analysis, where one parameter at a time is changed while the others remain constant. The base case used for the reference houses in this study is the total renovation described in the previous study. The first step was to compile additional available renovation measures and installations from suppliers and identify different inhabitant dependent input data for the simulations. The output from the energy simulations (space heating, domestic hot water and property electricity) was then analysed to show what input data is most relevant to use in future work to identify cost-effective renovation measures. The energy use was simulated using a validated dynamic energy simulation tool, IDA Indoor Climate and Energy 4.7 (EQUA 2016). The building models were based on available drawings and descriptions, with one zone for each room.

INPUT DATA FOR SENSITIVITY ANALYSIS

Nine parameters were considered for the sensitivity analysis, where each parameter had different cases as input data. Such a combination formed 22 cases in total, which are described below together with the base case (see Table 2).

Base case – theoretical renovation measures in previous paper

For energy simulations there are standardised input data in Sweden that consider the influence of inhabitants, compiled in Sveby, the sector standard for energy in buildings (Levin 2012). Input regarding the airing and regulating losses for the heating system were taken from the Swedish passive house standard, FEBY 12 (Erlandsson 2012). The thermal bridges were regarded as an increase of the total thermal transmittance by 25 % in the simulations, based on a recommendation from the Swedish certification system, Miljöbyggnad (2014). These standardised input data were used in the previous paper and also in the evaluations in this paper.

The input data for walls, roofs, windows, doors and air tightness used in the previous study were based on renovation measures from completed passive house renovations in Sweden; see base case in Table 2. Due to the original foundations all being concrete slabs, the insulation was placed outside the slab, as illustrated in Figure 2. A demand-controlled and balanced heat recovery ventilation system was installed to reduce the ventilation losses; see base case in Table 2. Indoor electronic room thermostats were installed, reducing regulation losses to 7 % according to FEBY 12.

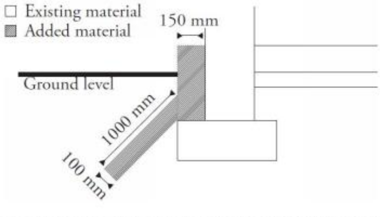

Figure 2. Example of renovation measure used for the foundation.

More efficient circulation pumps were installed (Swedish Energy Agency 2014). Indoor temperature variation was used, reducing the indoor temperature from the standard 21 °C to 18 °C when no one is home and when the inhabitants are asleep. This was assumed to be between 08:00 and 16:00 on weekdays and, at night, 23:00-06:00 on weekdays and 00:00-08:00 at weekends.

Climate and inhabitant variation

The first parameter was climate, which was evaluated by placing all four reference house building models both in the mildest climate (Malmö) and coldest (Umeå) of the four locations. The next parameter was orientation, which affects the solar radiation striking window glazing, evaluated by rotating the houses 0°, 90°, 180° and 270°. The indoor temperature was also evaluated. While the average indoor temperature in Sweden for single-family houses is 21 °C (Levin 2012), the following indoor temperatures were also evaluated: 20 °C, 22 °C and 23 °C.

The number of inhabitants was varied and their corresponding impact on the internal gains, household electricity and domestic hot water was evaluated. The number of inhabitants was assumed to be from two to five, which accounts for over 90 % of the 200 evaluated households in terms of household electricity in a report by the Swedish Energy Agency (Zimmermann 2009). The Sveby standard includes two different ways of estimating household electricity and domestic hot water. The first, used in the base case, is a normalised annual energy usage for a single-family household of 30 kWh/m² for household electricity, and 20 kWh/m² for domestic hot water. The other alternative is based on the number of inhabitants, cases 9 and 10. The annual household electricity need is calculated to be 2500 kWh plus 800 kWh per inhabitant living in the household, and for domestic hot water, annual energy usage per inhabitant is 781 kWh. Of the household electricity, 70 % was assumed to be utilised as internal gains, based on the Sveby recommendation (Levin 2012).

Alternative renovation measures

The parameters external walls and roofs were evaluated with different insulation thicknesses, based on gathered construction alternatives from suppliers and on the original construction of the houses, to determine the impact from achievable *U*-values. The parameter windows and doors were varied on the basis of existing window alternatives from suppliers and their *U*-value. The parameter air tightness was compared to the best achieved in the completed passive house renovations, Finnängen (Molin 2012), as well as the impact from an estimated level of a failed air sealing. For the demand-controlled heat recovery ventilation system, three alternative air handling units (AHU) were chosen from different suppliers included in an evaluation performed by the Swedish Energy Agency (2016), each with specific performance in terms of temperature efficiency, air flows and specific fan power (SFP).

Evaluated cases

Table 2 shows an example of one of the reference houses, Malmö, with all the evaluated input data in cases 1-22. All cases were evaluated for each of the reference houses. Cases 9 and 10 use input data that are a combination of number of inhabitants, household electricity and domestic hot water, where case 9 is based on the fewest number of inhabitants (2) and case 10 on the highest (5). Cases 11 onwards involve the input regarding alternative renovation measures that were evaluated.

Table 2. Compilation of all cases, with examples from reference house Malmö.

Parameter		*Base case*	*Cases*			*Units*
Location		Original	***1:*** Malmö	***2:*** Umeå	-	Climate
Orientation		0	***3:*** 90	***4:*** 180	***5:*** 270	°
Indoor temperature		21	***6:*** 20	***7:*** 22	***8:*** 23	°C
Inhabitants		3	***9:*** 2	***10:*** 5	-	Number
Household electricity		30	17.8	28.3		kWh/m^2/a
Domestic hot water		20	6.8	17		kWh/m^2/a
U-value	External wall	0.10	***11:*** 0.09	***12:*** 0.08	***13:*** 0.07	W/(m^2·K)
	Roof	0.08	***14:*** 0.07	***15:*** 0.06	-	W/(m^2·K)
	Window & door	0.80	***16:*** 0.90	***17:*** 0.70	-	W/(m^2·K)
Air tightness (based on envelope area)		0.30	***18:*** 0.50	***19:*** 0.10	-	l/(s·m^2)
HRV	Air flow – max.	0.35	***20:*** 0.35	***21:*** 0.35	***22:*** 0.35	l/(s·m^2)
	Air flow – min.	0.10	0.15	0.10	0.10	l/(s·m^2)
	SFP	1.50	1.26	1.30	1.25	kW/(m^3/s)
	Temperature eff.	80.0	85.0	87.0	89.9	%

RESULTS

The results from the 22 simulated cases (Table 2) in the local sensitivity analysis for the four reference houses are shown in Table 3 and presented per heated floor area. The space heating for the reference houses before renovation is presented for comparison. The specific energy use for the base case is divided into its components. For each case, the impact on energy use relative to the base case is shown.

The results in Table 3 show that climate had the largest impact on the space heating demand; this was doubled when all reference houses were located in the coldest climate (Umeå) instead of the mildest (Malmö). Still, the renovation measures reduced the space heating by 75-80 % for all houses and in all climates compared to before renovation. The second largest increase in space heating demand was caused by the indoor temperature setting, where a change of ±1 °C from the original 21 °C corresponds to a change in the annual space heating demand of 4 to 7 kWh/m^2. Rotating the houses had a great impact on the houses with the largest and most uneven distribution of windows between the facades, increasing the annual space heating demand of up to +7 kWh/m^2 for reference house Göteborg. The annual space heating of reference houses with a more even distribution of windows was in the range of +1-3 kWh/m^2.

Table 3. Results from energy simulations for base case (total energy use) and the 22 cases (deviation from base case, kWh/m²/a) for all four reference houses.

Reference houses			*Malmö*	*Göteborg*	*Stockholm*	*Umeå*
Unit		*Type*	kWh/m²/a			
Before renovation		Space heating	135	201	184	154
Base case (after renovation)		Space heating	26.0	37.6	42.3	39.8
		Domestic hot water	20.0	20.0	20.0	20.0
		Property electricity	3.2	3.5	3.4	3.5
		Specific energy use	49.2	61.1	65.7	63.3
Parameter	***Case***		Relative energy use compared to base case			
Location	***1:***	Space heating	0.0	-3.4	-10.2	-20.6
	2:	Space heating	27.7	30.7	21.4	0.0
Rotation	***3:***	Space heating	2.1	3.5	0.5	0.5
	4:	Space heating	3.1	6.6	-1.1	1.2
	5:	Space heating	1.6	4.3	1.2	0.4
Indoor temp.	***6:***	Space heating	-4.3	-5.5	-5.7	-4.1
	7:	Space heating	5.3	6.2	6.2	4.6
	8:	Space heating	11.4	13.5	13.2	9.9
Inhabitant + household electricity + domestic hot water	***9:***	Space heating	7.9	2.9	5.8	3.3
		Domestic hot water	-13.2	-9.0	-10.4	-9.0
		Specific energy use	-5.3	-6.1	-4.6	-5.7
	10:	Space heating	-1.4	-11.8	-9.6	-13.0
		Domestic hot water	-3.0	7.9	4.0	7.5
		Specific energy use	-4.4	-3.9	-5.6	-5.5
External wall	***11:***	Space heating	-0.9	-0.9	-1.2	-1.1
	12:	Space heating	-1.9	-1.8	-2.4	-2.3
	13:	Space heating	-2.9	-2.5	-3.7	-3.4
Roof	***14:***	Space heating	-0.4	-0.9	-0.5	-0.6
	15:	Space heating	-1.0	-2.0	-1.1	-1.3
Windows & doors	***16:***	Space heating	1.3	3.6	2.7	3.3
	17:	Space heating	-1.3	-3.5	-2.7	-3.2
Air tightness	***18:***	Space heating	2.1	3.3	2.2	2.6
	19:	Space heating	-2.1	-3.3	-2.2	-2.6
HRV	***20:***	Specific energy use	-0.9	-0.9	-1.1	-1.4
	21:	Specific energy use	-0.4	1.1	0.9	1.1
	22:	Specific energy use	-1.8	-2.9	-3.4	-3.7

DISCUSSION

Input data regarding inhabitants, household electricity and domestic hot water varies greatly, but the impact on the specific energy use is relatively small. This is because the input data items counterbalance each other; more inhabitants increase internal gains and household electricity, which decreases the need for space heating, but at the same time more inhabitants also increase domestic hot water use. The results show a variation of up to 10 %, depending on chosen input. Using the Sveby normalised input data resulted in the highest specific energy use, indicating that taking into consideration the actual number of inhabitants in a household will only decrease the simulated specific energy use. An evaluation of inhabitant behavior was not performed. The influence of inhabitants was assessed by using a normalized usage of a house commonly used in energy simulations in Sweden, Sveby (Levin 2012) and by varying the number of inhabitants and desired indoor temperature. This normalized usage simplifies the presence of the inhabitants with a uniform usage profile. Taking into account real fluctuations of the presence and usage profile could result in even larger variations of the energy demand, as shown in measurement studies like THUVA II (Bagge 2015).

The exact level of air tightness that can be attained in each of the reference houses are not known, this depends both on the original construction and the focus that is put into making the houses air tight. The needed products to improve the air tightness to the three evaluated levels are likely the same. Instead the difference in performance likely depend on the workmanship when performing the renovation measure to reach the higher level of air tightness and improved energy efficiency.

The results from the different types of AHU show that, since the specifications for the alternatives are very different, determining the specific energy use without simulation would be difficult. This is because all alternatives have their strengths in different areas, such as temperature efficiency, SFP or possible variations of air flows, but the overall performance is very similar. Case 22 is the most energy efficient, with an improvement of roughly 5 kWh/m²/a depending on the AHU chosen. This shows the importance of simulating and comparing many alternatives before a decision is made.

CONCLUSIONS AND IMPLICATIONS

As shown in the sensitivity analysis, more can be done to reduce the space heating to reach the passive house level for specific energy use of 63 kWh/m² for Umeå's climate zone and 55 kWh/m² for the other reference houses. The inhabitant-dependent parameters all have a greater individual impact on energy use than individual fine-tuning of the renovation measures. However, by combining the evaluated renovation measures, the energy demand in the reference houses base case can be further reduced from 65-75 % to 75-80 %, leading to a total reduction of the space heating between 80-90 %. The combination of the best cases of the renovation measures, cases 11-22, save roughly 9-15 kWh/m²/a, which is the same magnitude as increasing the indoor temperature by 2 °C. This shows the importance of reducing the indoor temperature when possible.

In the previous paper only reference house Malmö and Umeå fulfilled the passive house requirements in their original location. A comparison of the same reference house located in the mildest climate (Malmö) to the coldest (Umeå) showed that the coldest climate required twice as much energy for space heating. Therefore, attaining the passive house level will depend greatly on location, since the additional specific energy use allowed in the FEBY requirements (Martin Erlandsson 2012) of 8 kWh/m²/a, is significantly smaller than the increased energy demand of 20-34 kWh/m²/a. Comparing the reference houses in the mildest climate (Malmö) and the coldest (Umeå) also showed that the reference house in Stockholm fulfils the passive house requirements when located in the mildest climate with the base case renovation measures. While when located in the coldest climate only the reference house in Umeå fulfilled the passive house requirements. Incorporating all the most energy efficient renovation measures from the sensitivity analysis leads to all reference houses fulfilling the requirements in their respective original location and the mildest climate, but still only the reference house in Malmö and in Umeå fulfilled the passive house requirements when located in the coldest climate.

Nevertheless, energy savings from the renovation measures are great and roughly in the same relative proportions, regardless of climate. The varying results for the parameters in the sensitivity analysis shows that extensive energy renovations require detailed energy simulations of different alternatives to ensure a satisfactory result.

ACKNOWLEDGEMENTS

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Paper III

Cost-effective passive house renovation packages for Swedish single-family houses from the 1960s and 1970s.

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Abstract: This paper evaluates the cost-effectiveness of renovating single-family houses to passive house level, as compared to maintaining the existing buildings or renovating to building regulation level. The assessment involved life cycle cost analyses, and concerns the Swedish single-family housing stock constructed between 1961 and 1980, which accounts for about a third of Sweden's two million single-family houses. These houses, now in need of major renovation, are represented in this study by two reference buildings. The results show that passive house renovations can be cost-effective, but this largely depends on the type of heat generation used in the houses. The most cost-effective individual renovation measure was installing an exhaust air heat pump, and the least cost-effective was installing new windows. In houses using direct electric heating, the passive house renovation package was the most cost-effective alternative.

Abbreviations

BR = Building regulation
DHW = Domestic hot water
EEM = Energy efficiency measures
HRV = Heat recovery ventilation
LCC = Life cycle cost
PH = Passive house
PV = Photovoltaics
RH = Reference house
SDHW = Solar domestic hot water
SFH = Single-family house

Key words: cost-effective, energy efficiency measures, passive house, renovation packages, single-family houses, renewable energy production

1. Introduction

1.1 Background

Single-family houses (SFHs) constructed between 1961 and 1980 account for approximately one-third of the total energy use, 31 TWh, for space heating and domestic hot water (DHW) in Swedish SFHs. These houses account for about 40 percent of the total energy use in buildings [1]. There are roughly 715,000 houses from this period [2] and they are largely homogeneous in technical terms, with low levels of thermal insulation, and seldom have ventilation with heat recovery [3]. The average energy use for houses from this period is about 40 percent higher than SFHs constructed between 2011 and 2013 [4].

A survey of the current condition of the Swedish building stock (BETSI) [5] was conducted by the Swedish National Board of Housing, Building and Planning. In this survey, 1800 representative buildings from the entire building stock were inspected to determine the need for renovation [6]. Of these, 821 were SFHs. The survey involved assessments of the technical status, deterioration, lack of maintenance [5], and energy use [3] of the buildings. The need for renovation was found to be extensive. About 70 percent of the evaluated SFHs had some damage – found in all parts of the houses – although most were not categorized as serious. The fact that many of these houses need to be renovated [5] provides an excellent opportunity to incorporate energy efficiency measures (EEMs), to reduce both the operational cost and greenhouse gas emissions related to energy use.

When deciding on the level of energy renovation, there are two main categories of motivators, those that are top-down and based on regulation, and those that are bottom-up and concern the operational cost for the homeowner. The national and international goals for a sustainable future are part of the overall objective to reduce greenhouse gas emissions to mitigate global warming and climate change [6, 7]. The Swedish Government has set a target of a 50 percent reduction in total energy use per heated floor area by 2050, compared to the level in the reference year 1995 [8]. This has led to more stringent requirements on energy efficiency in Swedish building regulations, both for new constructions and when renovating existing buildings [9, 10].

For the homeowner the operational cost of the house has increased over time as energy prices have risen [11], see Figure 1. By implementing energy efficiency measures, the homeowner could reduce dependency on bought energy and probably reduce operational costs. Both motivators have increased awareness and demand for ways to reduce the energy use of buildings, which is necessary to attain the Swedish Government goals. Since any renovation of the building envelope today will have a service lifetime extending past the deadline in 2050, the current building stock will account for much of the total energy use in buildings in 2050. It is important that energy use is reduced as much as possible when renovating, but the level of renovation will probably be determined by the financial incentives for the homeowner. Consequently, there is a need to evaluate cost-effective EEMs and develop packages for extensive energy renovations.

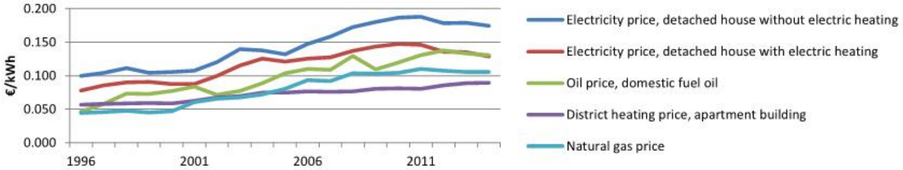


Figure 1. Energy prices for the residential and service sector, from 1996, real prices (2015), € per kWh [11].

One challenge facing the homeowner when considering an energy renovation is finance. This often involves taking out a loan to cover the costs of the renovation, but a loan will only be granted if the renovation increases the value of the property or reduces operational costs, to offset the interest cost of the loan. Increased property value is largely dependent on the location of the property, making it a project-specific aspect not applicable to the overall building stock. Operational costs are dependent on parameters such as the building performance, energy prices, inhabitants' behaviour, and climate. These parameters can be normalized, enabling an evaluation of the building stock.

Following a standard or certification when renovating provides increases the credibility of the expected energy savings. The passive house (PH) label is an established certification in many parts of the world [12, 13]. In recent decades, planning and constructing a new PH has moved from being a novelty [14] to a widely available construction method [15]. Investment cost is up to ten percent greater than conventional constructions [16-18]. Recently, focus has switched to renovating houses to PH level [15, 19], but in Sweden this has mainly involved multi-family houses [19]. Some pilot renovation projects for SFHs [20-23] show the feasibility of this type of extensive energy renovation. Outside Sweden there have been a number of renovations of SFHs that are classified as either low energy, passive or even plus energy houses [15]. However, these international projects are based on houses with different construction methods, shapes and sizes, and often include an extension on the house or even an extra floor when renovating. As shown in previous studies [24, 25], many of these parameters have a significant impact on the energy use of a house and the energy efficiency measures needed to reach the PH requirements, making comparisons difficult. The main research on SFHs in Sweden has either evaluated specific solutions, e.g. specific types of heat generation and solar thermal systems [26-28], or the reduction of energy use by a certain percentage [29, 30].

1.2 Purpose

This paper aims to increase knowledge regarding cost-effective renovation packages to PH level for SFHs, using a holistic approach in terms of renovation measures, energy savings potential and cost-effectiveness, and based on the Swedish passive house standard, FEBY12 [12]. The holistic approach enables much more significant energy savings, while improving the thermal comfort, indoor air quality, and moisture safety of the houses. The study focuses on detached single-family houses with an extensive renovation need.

2. Description of the building stock

For SFHs constructed between 1961 and 1980, there is a distinct difference in the method of construction before and after the building regulation from 1975, SBN75 [31]. This regulation was a response to the 1973 oil crisis, which increased the cost of heating because many houses were heated by oil, and consequently increased the focus on energy efficiency in buildings. SFHs built after SBN75 were constructed with more thermal insulation and balanced ventilation with heat recovery, instead of the earlier passive stack alternative without heat recovery. The commonly used construction methods for external walls was either lightweight concrete or wood frame with intermediate mineral wool insulation, the thickness of which can be seen in Table 1.

The existing HVAC systems in the SFH building stock vary widely, as can be seen in Figure 2 and Table 2. A common system was passive stack ventilation with trickle vents above double-glazed windows combined with radiators, either hot-water or direct electric heating. Using this system, a good ventilation rate can be achieved during the heating season when the stack effect is high. Outside the heating season, the ventilation rate drops because of reduced stack effect and the BETSI survey often found poor ventilation [32]. Instead the inhabitant must rely on opening windows to increase the supply air flow rate. After SBN75, the use of mechanical exhaust air and balanced ventilation with heat recovery (HRV) became more common, leading to more variation in installed ventilation systems. No single system dominated the market, as was previously the case.

Table 1.
Commonly used construction methods for external walls presented by construction year [5, 24, 33].

Time of completion	*1961 until SBN75*	*After SBN75*
Lightweight concrete walls	230 to 250 mm	-
Wood frame construction with intermediate mineral wool insulation	95 to 100 mm	About 180 mm

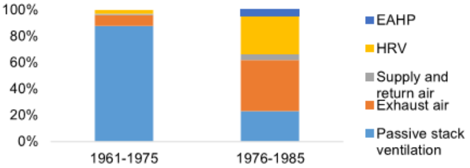


Figure 2. Existing ventilation systems used in SFHs by construction year [5].

Originally, many houses used heat generation and distribution either from an oil-fired boiler and hot-water radiators or direct electric heating. After the oil crisis in 1973 many homeowners started to convert the heat generation to alternatives not dependent on oil. This sometimes led to moisture problems because the measures altered the stack effect in the buildings and consequently the air change rate. Since then, electricity prices have increased steeply and homeowners have tried to find alternative heat generation systems or combinations, e.g. heat pumps, which have been installed in about 50 percent of the total SFHs building stock because of their ease of use and cost-effectiveness [4]. The currently used systems for heat generation are shown in Table 2. The use of oil is almost negligible, representing less than 1 percent of the currently used heat generation systems.

Table 2.
Currently used heating systems in SHFs by year of construction, in 2014 [4].

Year of construction		*1961-1970 (%)*	*1971-1980 (%)*	*1961-1980 (%)*	*Total-2014 (%)*	*Combined with heat pump (%)*
Used heating system	Electric, direct	10	35	25	15	61
	Electric, hydronic	15	12	13	16	71
	Oil burner	1	0	0.5	1	
	Biofuel	18	22	20	28	
	Heat pump - ground source	21	11	15	18	
	District heating	24	13	18	13	
	Other (combinations)	9	7	8	9	-

3. Method

A life cycle cost (LCC) analysis was used to evaluate the cost-effectiveness of the energy efficiency measures and renovation packages. The overall method is illustrated in Figure 3. This analysis is based on the cost of investment, operation and maintenance of the energy efficiency measures over their life cycle. Three levels of renovation were evaluated: 1) Minimum – i.e. no energy efficiency requirements, based on the functional requirements stipulated in the building regulation and the renovations needed because of deterioration; 2) Building regulation (BR) – includes the energy efficiency requirements; and 3) Passive House (PH). These were applied to two case study buildings – representative reference houses (RHs) – to evaluate the impact of the renovation levels on the building stock. For the LCC analysis in this study, marginal costs were used, including the extra costs and energy savings on operational costs from implementing the energy efficiency measures compared to the minimum level of renovation.

Figure 3. Overview of the method used to determine cost-effective renovation packages to passive house standard.

3.1 Description of case study reference houses

Based on the change in typology for SFHs before and after SBN75, one reference house from each period was used in the case study, see Table 3.

Reference house 1 (RH1) is a single-storey house with a cellar, constructed in 1965 with a total heated floor area of 230 m². The original constructions used were: roof with truss construction and 100 mm intermediate mineral wool insulation; cellar with a concrete floor 100 mm thick, probably with 50 mm thermal insulation, and cellar walls of 250 mm lightweight concrete;

external walls above ground of either (RH1a) 250 mm lightweight concrete or (RH1b) 100 mm wooden frame construction and intermediate mineral wool insulation. For ventilation, a passive stack ventilation system was originally used and the heating system was a hot-water radiator system with an oil heated boiler.

Reference house 2 (RH2) is a 1½-storey house constructed in 1977 with a total heated floor area of 142 m². The original constructions used were: roof with truss construction and 220 mm intermediate mineral wool insulation; 100 mm concrete floor, probably with 100 mm thermal insulation; and a 180 mm wooden frame construction with intermediate mineral wool insulation. For ventilation, a balanced mechanical ventilation system with heat recovery was originally used, and the heating system was a hot-water radiator system with an electric-heated burner.

For both houses, the insulation level of the concrete slab and the thermal transmittance of the windows and doors did not appear in the available records, nor did the performance of the HRV in RH2. These had to be estimated based on the building regulation in force at the time of construction and information obtained about commonly used construction methods.

Table 3.
Visualisation of the two reference houses with basic data about location, year of construction and heated floor area.

	
RH1: Location: Malmö, built: 1965, heated floor area: 230 m^2	**RH2:** Location: Umeå, built: 1977, heated floor area: 142 m^2

The passive house requirements in FEBY12 are divided by climate zone and type of heat generation, allowing a higher specific energy use. This includes energy for space heating, domestic hot water and facility electricity in houses located in a colder climate, or using heat generation not dependent on electricity, see Table 4 [12]. The requirements for annual specific energy use for RH1, located in climate zone III, when not using electricity for heating, is 55 kWh per heated floor area, and for RH2, located in climate zone I, 63 kWh per heated floor area. When electricity is used for heating, the required annual specific energy use is reduced to 27 kWh per heated floor area for RH1 and 31 kWh per heated floor area for RH2. For buildings using a combined heat generation system, there is a weighting between the requirements. This reduction from using electricity for heating makes it difficult to fulfil the passive house requirements when using direct electric or electric heating for heat generation.

Table 4.
Passive house requirements for specific energy use using different types of heat generation and in different climate zones from FEBY12 [12], compared with building regulation requirements [9].

Climate zone		*I*		*II*		*III*		*Unit*
	Requirements	PH	BR	PH	BR	PH	BR	
Specific energy use	Non-electric heating	≤ 63	≤ 130	≤ 59	≤ 110	≤ 55	≤ 90	kWh/(m²·a), heated floor area
	Electric heating	≤ 31	≤ 95	≤ 29	≤ 75	≤ 27	≤ 50	

3.2 Life cycle cost analysis

A LCC analysis was performed to evaluate the cost-effectiveness of energy efficiency measures and renovation packages. This method considers the costs of investment, operation and maintenance over the life cycle of a measure. Since the energy efficiency measures have different expected service lives, and some costs and savings occur in later stages of the life cycle, the method of net-present value (NPV) was used. This calculates all costs, regardless of when they occur, to a present value.

The BELOK Totaltool, version 2, was used, to consider the total renovation packages and calculate the life cycle cost [34]. In this method, the investment cost is compared to changes in maintenance and operational cost during the life cycle from the implementation of a renovation measure, based on the following equations:

$$LCC_{total} = C_{investment} + C_{maintenance} + C_{energy} - C_{residual\ value} \tag{1}$$

Maintenance:

$$C_{maintenance} = a_{maintenance} \cdot \frac{1-(1+i)^{-n}}{i} \tag{2}$$

Energy:

$$C_{energy} = E_{energy} \cdot e_{energy} \cdot \frac{1-\left(\frac{1+i}{1+q}\right)^{-n}}{\frac{1+i}{1+q}-1} \tag{3}$$

Residual value:

$$C_{residual\ value} = c_{residual\ value} \cdot (1+i)^{-n} \tag{4}$$

$C_{investment} =$ Initial investment cost [€]
$a_{maintenance} =$ Annual maintenance cost [€/year]
$E_{energy} =$ Annual energy demand [€/year]
$e_{energy} =$ Energy price [€/kWh]
$c_{residual\ value} =$ Investment value at end of calculation period [€]
$n =$ Calculation period [years]
$i =$ Real interest rate [%]
$q =$ Real increase of annual energy price [%]

In profitability calculations, the interest rate consists of three parts – real interest rate, expected inflation and a risk premium [35]. For an investor or company, any investment needs to equal or outperform other alternatives to be viable, leading to a higher interest rate. Since this study focuses on SFHs and private homeowners, the interest rate only needs to equal that of the interest paid on a loan taken to cover the investment cost of the energy efficiency measures.

Some assumptions were needed about the interest rate and inflation over time to determine the real interest rate *(i)* used in the calculations. Annual inflation was assumed to be two percent, based on the goal of the Swedish central bank, Riksbanken [36]. The interest on the loan was assumed to be two percent above inflation. This is the real interest rate used in the calculations of the NPV. Annual energy price increase above inflation *(q)* was assumed to be zero percent. All costs used in the LCC analysis are calculated as the marginal cost of an energy efficiency measure at the different renovation levels as compared to only performing a minimum level renovation. All costs were estimated in Swedish Crowns (SEK) and converted to Euro (€), at a conversion rate of SEK 10 for €1. Another economic calculation used is the internal rate of return (IRR). This uses the NPV calculation to calculate the highest interest rate at which it is still possible to achieve profitability after implementing a measure – two percent in this study – instead of calculating the NPV at a specific interest rate.

The investment costs of material and labour were mainly estimated based on the specific conditions of the reference houses and information from *Wikells Sektionsdata* [37], which presents common material and labour costs in Sweden. When information was not available from this source, the cost was obtained from the specific supplier of the material or product. A tax reduction is available for the labour cost, called repairs, conversion and extension (ROT) [38]. This covers 30 percent of the labour costs, up to a total of €5000 per person, depending on the amount of taxes the person has paid during the year. To simplify the estimation of the labour cost for installations of heat pumps and other types of heat generation, various templates were used: 30 percent for the total installation cost of an air-to-water heat pump, 35 percent of the total installation cost of a brine-to-water heat pump [39], and 24 percent for other types, e.g. pellet-fired and electric boilers [40]. In all cost estimations, value-added tax (VAT) and ROT were included in the total prices.

To determine operational costs, the energy demand of the building was simulated and combined with the prices for heat generation and energy. The energy prices for the types of heat generation differ depending on many parameters, including the business model of the energy provider, taxes and certificates. When available, monthly prices were used to determine the annual operational cost for heating and electricity. Information on electricity prices involved the average annual grid service price per kWh and monthly electricity prices per kWh for the variable price rate for SFHs [41]. The electricity price depends on the demand of the house, so different grid service and electricity prices were used for houses using electric heating (direct electric, electric boiler and heat pumps) and houses using non-electric heating (pellet-fired boiler and district heating). Added to these are the costs of electricity certificate [42], energy tax [43] and VAT. Fixed fees were not included, since they do not vary with demand, so are not impacted by the renovation measures.

Average electricity prices are about €0.13 per kWh for houses using electric heating and €0.177 per kWh for houses using non-electric heating. The energy prices for the other types of heat generation, based on stated annual average prices for SFHs, were €0.052 per kWh including VAT for pellets [11] and €0.083 per kWh including VAT for district heating [44]. The efficiency was assumed to average 85 percent for pellet-fired boilers and 98 percent for electric heating and district heating [27]. The maintenance cost is the same as that for the minimum level renovation (see Table 5 for renovation levels) in all cases except when adding balanced mechanical ventilation to RH1, which at the minimum level only had mechanical exhaust air.

3.3 Renovation packages

To determine the cost-effectiveness of the passive house renovation packages, three levels of renovation were evaluated. The first – the minimum level – was based on the functional requirements from the building regulation and the renovations needed because of deterioration. The functional requirement from the building regulation is the air flow rate of 0.35 l/s per floor area through installing mechanical ventilation. The extent of the renovation needed for the building envelope and installations for the minimum level renovation were based on the results from the BETSI study [5], while also assuming the building had not been renovated since it were constructed. The second – the building regulation (BR) level – was based on the levels required for each part of the building envelope when renovated and the thermal properties are improved: those are excluded in the minimum level because of the sole focus on the facades. The third – passive house (PH) level – was based on the results from earlier studies [24, 25] to determine the renovation level of each energy efficiency measure. The specific requirement of the energy efficiency measure for each renovation level is presented in Table 5. The expected service life was assumed to be 40 years for the building envelope and 20 years for installations based on the used service life in [27].

Table 5.
Description of the evaluated overall renovation levels, with renovation measures and the required performance level. For the minimum level, the thermal transmission of the existing building envelope for the two reference houses is presented.

	Renovation level	***1. Minimum RH1 / RH2***	***2. Building regulation (BR)***	***3. Passive house (PH)***	***Units***
Building envelope	Facades/external surfaces	New	New	New	
	External walls	RH1: 0.54 RH2: 0.23	0.18	0.10 ±0.02	W/(m²·K)
	Roof	RH1: 0.36 RH2: 0.15	0.13	0.10 ±0.02	W/(m²·K)
	Foundation	RH1: 0.32 RH2: 0.23	-	Improved, see Table 7	W/(m²·K)
	Cellar walls	RH1: 0.54 RH2: -	+100 mm thermal insulation	+200 mm thermal insulation	W/(m²·K)
	Windows	RH1: 2.80 RH2: 2.00	1.2	0.80	W/(m²·K)
	Doors	RH1: 1.50 RH2: 1.50	1.2	0.80	W/(m²·K)
	Thermal bridges	Calculated	25% of $U_{tot} \cdot A_{tot}$	Calculated	
	Airtightness, at ± 50 Pa	-	0.3	0.3	l/(s·m²)
	Drainage	New	New	New	
Installations	Ventilation system	Mechanical exhaust air	Mechanical exhaust air	Balanced with heat recovery / Exhaust air heat pump	
	Ducts	New return air ducts	New return air ducts	New air ducts.	
	Heat distribution	New	New	New, depend on used heat generation.	
	Heat generation	New	New	New, depend on evaluated heat generation, see Table 6	
DHW	Heater	New	New	New	
	Pipes	New	New	New	
	Fixtures	New	New	New	
-	Household purpose electricity	-	-	Not included, assumed as new energy efficient appliances and lighting.	

Based on available data regarding the building stock – presented in Table 2 – the alternatives for heat generation and distribution was determined, presented in Table 6. For each type of heat generation, the specific investment cost, energy prices and total efficiency were obtained and used to evaluate the impact on the LCC analysis for the renovation packages. Where direct electricity is currently used and replaced by other types of heat generation, the cost of installing a heat distribution system based on hot-water radiators is also included in the total cost.

Table 6.
Types of heat generation in SFHs, both the currently used types and the alternatives after renovation.

Currently used heat generation	***Alternatives after renovation***			
	Keep original	***Heat pump***	***Pellet***	***District heating***
Direct electric heating	X	X*	X*	X*
Electric heating	X	X	X	X
Pellet	X	-	-	-
District heating	X	-	-	-

*Includes cost of converting to hydronic heating system.

3.4 Energy efficiency measures

The solutions and products included in the assessment are commonly used and available on the Swedish construction market. For a solution or product to be included, the conditions described in Table 5 needed to be fulfilled while also being moisture and fire safe. No detailed analyses were carried out – proven solutions were applied to the existing constructions.

To ensure the required thermal transmission of building envelope for the BR and PH level renovations, the thermal insulation needed to be greater than the existing constructions. The alternative of adding insulation on the inside of the existing structure was excluded from the evaluation, because it would reduce the available floor area and volume of the house while increasing the risk of moisture problems. The only alternative was to add insulation to the outside of the existing structures.

Several alternative façade materials could be used when renovating the external wall, the most common being wood, bricks or render. These require different means of attachment to the existing wall, which must support the extra weight. The alternative of adding a new brick facade to a renovated external wall was excluded because of the increased problems and costs. External walls are assessed with renovation measures that add thermal insulation externally and with ventilated facades, either with render or panels of different types. The structures in RH1 and RH2, both existing and passive house level, are shown in the section drawings, see Table 7 and the passive house external walls in Table 8. All parts of the building envelope are improved in terms of thermal transmittance and airtightness to fulfil the specified requirements in Table 5.

Table 7.
Section drawings of the reference houses before and after renovation showing the passive house level renovation and energy efficiency measures.

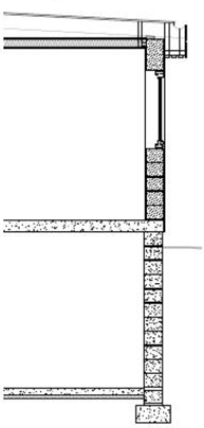
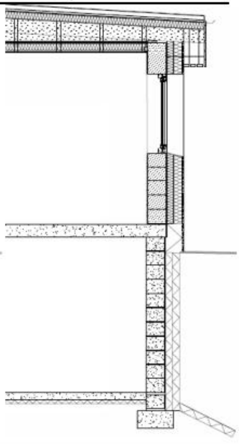
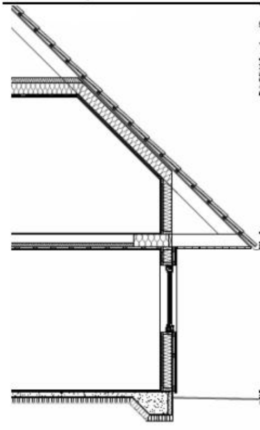
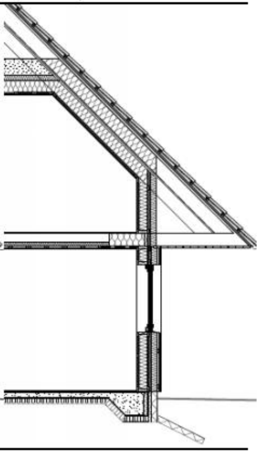
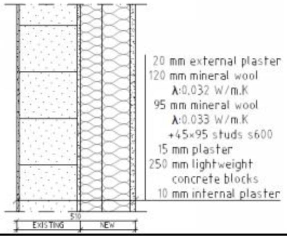
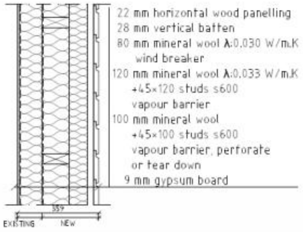
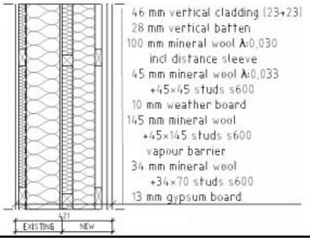
Reference house 1a		***Reference house 2***	
Before renovation	***After renovation***	***Before renovation***	***After renovation***
			

Table 8.
Renovation measure for the three evaluated external walls - RH1a, RH1b and RH2.

Reference house 1a	***Reference house 1b***	***Reference house 2***
		

Determining the airtightness of the reference houses before renovation was not possible, since pressurized measurements of the houses was not an alternative. Instead, airtightness was assumed, based on the measured average infiltration rate – 0.23 l/(s·m^2) heated floor area – of SFHs using passive stack ventilation in the BETSI survey [32]. Based on an equation in FEBY 12 [12], the figure was converted to airtightness at 50 Pa, so roughly 1.5-1.6 l/(s·m^2) of external surface area for both reference houses. This is similar to the figure in the pilot renovation project of 1.4 l/(s·m^2) [45]. However, the BETSI survey also reports great variation in the airtightness in existing houses, showing the importance of actual measurements when determining the performance of a building. After renovation, it is assumed that the airtightness fulfils the requirement for passive house of 0.3 l/(s·m^2) of external surface at 50 Pa pressure difference. When evaluating energy efficiency measures for the building envelope, airtightness was considered by calculating an average reduction of the leakage air flow through each part. When estimating the air tightness at 50 Pa for each separate part of the building envelope, it was assumed that there was no leakage air flow through the foundation, since all reference houses have a concrete slab foundation.

Mechanical ventilation was used to ensure the required ventilation level of fresh air. Some type of heat recovery is needed for energy efficiency, either by installing: (I) heat recovery ventilation (HRV) system, with a high efficiency rotating or counter-flow heat exchanger, or (II) exhaust-air heat pump (EAHP). To enable comparison of these alternatives in terms of thermal comfort, noise and air quality, both need to 1) pre-heat the supply air, 2) include sound attenuation, and 3) filter the incoming fresh air. In the case of the EAHP, the heat recovery is used for producing both space heating and domestic hot water, so the EAHP needs a hydronic heating system, either hot-water radiators or floor heating, to work. Floor heating is excluded from this evaluation because of the limited indoor height, which makes it impossible to increase the thermal insulation in the foundation to the level required to use floor heating in a passive house. Also, in the case of the EAHP, the supply air duct and terminal are placed behind the radiators to pre-heat the supply air.

The type of heat generation has a large impact on the cost-effectiveness of a renovation package because of its impact on investment cost, energy cost and overall efficiency of the heat generation system. System efficiency, energy prices, and investment costs were determined for each of the heat generation types. In the case of heat pumps, new simulation models were needed to determine the impact on the energy demand of the reference houses. For direct electric heating, pellet-fired boiler, and district heating, the same building energy simulation model was used. When evaluating the use of a heat pump for heat generation, a ground source heat pump (GSHP) with a maximum power output based on the demand of each reference house at the different renovation levels was used to determine the energy savings potential and costs. The boreholes for the GSHP were assumed to be located where the rock has a thermal conductivity of 3.0 W/(m·K), and the length of the loop was calculated based on the demand of the RHs. The EAHP is a special case where the same installation is used for both ventilation and heat generation.

The properties and efficiency of these systems were determined by simulations in the NIBE DIM [46] software. The heat pumps use inverter-controlled compressors to adjust the power output based on the demand of the houses to increase the seasonal coefficient of performance (SCOP). For the evaluation of the HRV, EAHP, GSHP, pellet-fired boiler and circulation pump, a product with an energy-efficient performance was chosen from surveys by the Swedish Energy Agency regarding the performance of each type of product [47-51]. Where a newer version of the product was available from the supplier, this was used in the assessment. Three suppliers of balanced mechanical ventilation with heat recovery had been previously assessed in terms of energy savings potential [25], all obtained from Swedish Energy Agency survey. The results were relatively comparable in terms of energy savings potential and investment cost, so only one alternative is included in this study.

3.5 Renewable energy

The possibility of implementing local renewable energy production was assessed as a supplement to energy efficiency measures and renovation packages. This involved either a solar domestic hot water (SDHW) system or a photovoltaics (PV) system. The energy simulations were carried out using the software *System Advisor Model* [52] and the economic calculations using the software *"Investment calculation for photovoltaics"* [53]. The tilt of the panels for RH1, which had an almost flat roof, was simulated at 30 degrees to reduce mutual shading, while maintaining annual production close to its maximum. For RH2, the roof inclination of 45 degrees was used.

The SDHW system was designed to meet approximately 50 percent of the annual domestic hot water demand of each house [54-56]. Solar thermal energy for space heating was not considered, since this is not usually cost-effective in Swedish conditions [54]. Based on other studies [57], the system usually equates to a collector area of 5 m^2 with a storage tank of 300 litres. The International Energy Agency reports the investment cost for a SDHW system in Sweden, with a 5 m^2 collector area and storage of 300 litres, to be approximately €5000 excluding VAT [58]. From a systems perspective, it might not be possible to implement this extra system into the overall system for heat distribution or generation. This is because the solar thermal system needs a storage tank for the produced heat until there is a demand, which is not needed for all types of heat generation systems. For example, a new pellet boiler, used for producing heat for both space heating and DHW, and district heating produce DHW directly when there is a demand.

The PV system is easier to integrate in the other systems of the house than a solar thermal system, since it works regardless of the system used for heat distribution or generation. The only impact from the heat generation on the PV is the size of the installed system. The aim is that the size of the PV system ensures that annual production covers the annual electricity demand of the reference houses, often referred to as net-zero energy buildings. This is also the maximum level for which it is possible to get a tax reduction of €0.06 per sold kWh to the grid, up to a maximum annual overproduction of 30,000 kWh [59].

Since electricity demand is dependent on the heat generation used, heating demand, and behaviour of the inhabitants, some assumptions regarding these factors were needed to determine the size of the system. Household electricity use, which is dependent on the behaviour of the occupants and the energy efficiency of the installed household appliances, is assumed to be the same as the average energy use for household electricity in Swedish SFHs, i.e. 5900 kWh per year [4]. The heating demand was simulated based on the different heat generation systems: direct electric heating, heat pumps and non-electric heating.

The nominal efficiency of the PV panels was assumed to be 20.6 percent, with a temperature coefficient of -0.3 percent per degree increased and an inverter with a maximum conversion efficiency of 96 percent.

For the passive house requirements, only the energy produced from the PV system that can be used instantly or stored locally for use later can be included as a reduction of the specific energy use. An energy storage system was assessed that would store the overproduction from the PV system during the day when demand is lower. This battery-based solution was evaluated to determine whether it could be used to reduce the specific energy use in a cost-effective way compared to the alternative of selling the electricity to the grid. The 14 kWh lithium-ion battery, with a real capacity of 13.3 kWh, and round trip efficiency on the DC side of 92 percent [60, 61], was assessed in terms of cost-effectiveness when installing either one or two batteries.

The service life of both the solar thermal and the PV system was assumed to be at least 25 years [62, 63]. The service life for batteries was assumed to be 12.5 years to simplify the calculations, based on the warranty on these products often being 10 years [60]. Degradation of the batteries was set to zero percent. A Government grant is available for installation of a PV system on a SFH, covering 20 percent of the investment costs [64]. This grant and the tax reduction for labour costs cannot be combined. The Swedish Government introduced another investment subsidy for the installation of local electricity storage in batteries [65]. The aim was to increase the adoption rate of local production of renewable energy and reduce the stress on the electrical grid. This grant is awarded on condition that there is local production of renewable energy and that the storage increases utilization of the produced electricity. The grant covers 60 percent of the total costs, up to €5000 per household.

3.6 Software for simulations and calculations

The software used to simulate energy use of the reference houses for the different cases, the product properties of the evaluated energy efficiency measures, and associated costs are presented in Table 9. The table also shows how the simulation results were used as input in other simulations to determine the overall results.

The building simulations include a detailed model of the reference houses, with different zones for each room of the houses. The input data on structures, thermal transmittance, airtightness, inhabitants, internal heat gains and shading was obtained and prioritized as follows: firstly, specific data for reference house; secondly, passive house requirements [12]; and thirdly, Sveby [66] was used for normalized user-related input data. When these input data were not applicable, alternatives were obtained and evaluated, described in detail in separate sections below. The reference houses were assumed to be inhabited by two adults and two children. Weather data files included in the building energy simulation program (IDA ICE) from SMHI (Swedish Meteorological and Hydrological Institute), with long-term measurements of climate and weather, were used for each location in the simulations. In Swedish conditions, cooling is not commonly used in residential buildings, so is excluded. Opening windows is assumed to solve the problem of overheating, and is addressed in other studies. For each energy efficiency measures and renovation package, a specific building model was used.

Table 9.
Compilation of software used to simulate energy use, costs, and product properties of the energy efficiency measures, and descriptions of how the software was used.

1. Energy and thermal simulations	
IDA ICE 4.7	Dynamic multi-zone building energy simulation software IDA Indoor Climate and Energy [67], used for building energy simulations. Input regarding thermal bridges from simulations in HEAT2 and specific product properties from respective simulation software; see section 3, 'Product properties' below.
HEAT2 version 10	Two-dimensional transient and steady-state heat transfer software, HEAT2 [68], used to calculate the heat transfer coefficient from the foundation EEM and the thermal bridges. The results were used as input to the total building energy simulation performed in IDA ICE 4.7.
SAM	The software System Advisor Model (SAM) developed by the National Renewable Energy Laboratory [52], used to simulate renewable energy production and local storage systems.
ENORM 2004	Energy simulation software ENORM 2004 [69], used to calculate the heat transfer coefficient (U-value) of the building envelope.
2. Economic analysis	
Wikells Sektionsdata 4.20	Software [37] that compiles the cost, both material and labour, for constructing new and renovating existing buildings, used to estimate the investment cost for implementing the EEMs. Includes costs for building envelope, HVAC, excavation, electrical installation, etc.
BeLok – Totaltool	Used for the evaluation of the total renovation packages regarding life cycle cost analysis [34]. The method was produced for use in commercial building projects, but can be used in SFHs with some adaptation, as shown by Heier [70].
Investment calculation for photovoltaics	Software [53] calculating the net present value and internal rate of return for an investment in photovoltaics, including tax reduction and investment grant.
3. Product properties	
Enervent Optimizer	Energy simulation software from AHU supplier *Enervent*, used to simulate the energy use for fans, the efficiency of the heat exchanger, and the heat recovery at specific air flows for their AHUs[71].
REC Indovent – TemoCalc	Energy simulation software from AHU supplier *REC Indovent*, used to simulate the energy use for fans, the efficiency of the heat exchanger, and the heat recovery at specific air flows for their AHUs [72].
Swegon ProCASA 6.2	Energy simulation software from AHU supplier Swegon, used to simulate the energy use for fans, the efficiency of the heat exchanger, and the heat recovery at specific air flows for their AHUs [73].
NIBE DIM	Software from heat pump supplier Nibe, used to indicate appropriate heat pumps based on the energy demand when implementing heat pumps [46].

4. Results & discussion

The results from the building energy simulations of the renovation packages for the two reference houses, RH1 and RH2, are presented in Table 10. The results are presented by renovation level – minimum, building regulation (BR) and passive house (PH) – and for each level the results are divided into two categories: final energy use and the energy savings potential of the energy efficiency measures (EEMs) in the renovation packages. For RH1 at minimum and BR level, the ventilation EEM increases the energy demand of the house because of the increased air flows needed to fulfil the building regulation.

Table 10.
Annual specific energy use for the evaluated reference houses, before and after different renovation packages, minimum, building regulation (BR) and passive house (PH), and the energy savings potential of each energy efficiency measure.

Reference house		***Reference house 1-230 m²***				***Reference house 2-142 m²***				
Renovation level		***Original***	***Minimum***	***BR***	***PH***	***Original***	***Minimum***	***BR***	***PH***	***Units***
Final energy use	Specific energy use (1. + 2. + 3.)	151	187	107	54	206	206	135	71	kWh/m²
		34 800	42 900	24 500	12 500	29 200	29 200	19 200	10 100	kWh
	1. Space heating	126	159	79	30	172	172	101	46	kWh/m²
		29 000	36 600	18 200	7 000	24 400	24 400	14 400	6 500	kWh
	2. Domestic hot water	20	20	20	20	20	20	20	20	kWh/m²
		4 600	4 600	4 600	4 600	2 900	2 900	2 900	2 900	kWh
	3. Auxiliary electricity	5	7	7	4	13	13	13	5	kWh/m²
		1 200	1 700	1 700	900	1 900	1 900	1 900	700	kWh
EEMs – energy savings potential	External walls (incl. cellar walls)	-	-	-40	-47	-	-	-13	-21	kWh/m²
				-9 100	-10 700			-1 800	-3 000	kWh
	Roof	-	-	-19	-22	-	-	-9	-13	kWh/m²
				-4 300	-5 100			-1 300	-1 800	kWh
	Windows & doors	-	-	-25	-33	-	-	-30	-46	kWh/m²
				-5 800	-7 500			-4 200	-6 500	kWh
	Foundation	-	-	-2	-2	-	-	-19	-19	kWh/m²
				-400	-400			-2 700	-2 700	kWh
	Ventilation	-	35	35	-25	-	-	-	-29	kWh/m²
			8 100	8 100	-5 700				-4 100	kWh
	Other	-	-	-	-4	-	-	-	-7	kWh/m²
					-1 000				-1 000	kWh
	Total	-	**35**	**-51**	**-132**	-	-	**-70**	**-135**	**kWh/m²**
			8 100	**-11 500**	**-30 400**			**-10 000**	**-19 100**	**kWh**

Results from the simulated final energy use show that the PH requirements for specific energy use can be attained with the renovation package for RH1. The opposite is true for RH2, where results show that the PH requirement for annual specific energy use is not fulfilled when implementing the PH level renovation package. In the case of RH2, the specific energy use must be reduced by another 8 kWh per heated floor area. This can be accomplished by either investing in more expensive EEMs with better energy performance or by implementing local renewable energy production, considered in more detail below.

Different types of heat generation were evaluated for the reference houses, to assess the cost-effectiveness of the renovation packages and the possibility of achieving the PH requirements. All three renovation levels were included. The results are presented as bought energy instead of final energy use. The implementation of heat pumps for heat generation was evaluated by performing energy simulations with a ground-source heat pump (GSHP) included in the renovation packages. The results, presented in Table 11, are divided into base heating and top heating, where the heat pump provides the base heat and an electric heater is used for top heating when the heat pump cannot provide enough heating power. The heat pumps have enough power to cover the demand throughout the year for all renovation levels. The renovations for both RH1 and RH2 fulfil the PH requirements when a GSHP with a maximum power output of 6 kW is used to generate heat.

Table 11.
Annual bought energy for the reference houses at different renovation levels when a GSHP is used for heat generation.

Reference house		**Reference house 1-230 m²**			**Reference house 2-142 m²**			
Renovation level		**Minimum**	**BR**	**PH**	**Minimum**	**BR**	**PH**	**Units**
GSHP - max power, kW		***16***	***12***	***6***	***12***	***6***	***6***	
Bought energy	Specific energy use (1 + 2 + 3)	51	30	19	65	41	26	kWh/m²
		11 650	6 800	4 400	9 200	5 800	3 700	kWh
	1. Base heating	46	27	15	51	33	20	kWh/m²
		10 650	6 100	3 500	7 300	4 700	2 900	kWh

2. Top heating	0	0	0	0	0	0	kWh/m²
	-	-	-	-	-	-	kWh
3. Auxiliary electricity	4	3	4	13	8	6	kWh/m²
	1 000	700	900	1 900	1 100	800	kWh

As an alternative to using both a GSHP and an AHU, an exhaust air heat pump (EAHP) was evaluated. Since the EAHP only uses the return air to recover energy, and is limited to reducing the exhaust air temperature to -15 °C, the maximum possible supplied heating power is limited by the available air flow. The use of an EAHP is therefore limited in less energy efficient houses and in colder climates. The results are presented in Table 12, again divided into base heating and top heating. These show that energy use for top heating increases as the energy efficiency of the houses decreases, indicating that the maximum heating power output of the EAHP was used more frequently. For the minimum level renovation packages, the top heating meets much of the total heat demand. Only RH1, located in a milder climate than RH2, fulfils the PH requirements when an EAHP is included in the PH level renovation packages.

Table 12.
Annual bought energy for the reference houses at different renovation levels when an EAHP is used for ventilation and production of space heating and domestic hot water.

Reference house		***Reference house 1-230 m²***			***Reference house 2-142 m²***			***Units***
Renovation level		***Minimum***	***BR***	***PH***	***Minimum***	***BR***	***PH***	
Bought energy	Specific energy use (1 + 2 + 3)	90	35	23	120	67	39	kWh/m²
		20 700	8 100	5 400	17 000	9 500	5 600	kWh
	1. Base heating	42	26	20	67	49	35	kWh/m²
		9 700	5 900	4 500	9 500	7 000	4 900	kWh
	2. Top heating	43	6	1	49	14	1	kWh/m²
		10 000	1 400	200	6 900	2 000	200	kWh
	3. Auxiliary electricity	4	3	3	4	4	4	kWh/m²
		1 000	800	700	600	500	500	kWh

Simulations assessed whether implementing local renewable energy production would be enough to achieve the PH requirements. The results are presented in Table 13. If a SDHW system was installed in RH2 when non-electric heating was used, the PH requirements could be attained if the system was of an appropriate size. For the PV system, both with and without a battery, the result depended on the type of heat generation used in the house. The results in Table 10 and Table 13, combined with greater PH requirements when using electricity for heat generation, suggest that electric heating cannot be used for heat generation if PH requirements are to be fulfilled. All houses that use electricity for heat generation, either direct electric heating or electric heating, will need to install a heat pump to fulfil PH requirements.

Using non-electric heat generation, such as a pellet-fired boiler or district heating, allows the PH requirements to be attained. However, for RH2, local renewable energy production is also needed. This would probably not be a cost-effective combination of heating systems. Since new pellet-fired boilers produce DHW as it is used, no storage tank is needed, but a storage tank is needed for a solar thermal system to work, thereby increasing the investment cost. For houses using district heating, this is unlikely to be an alternative, since the energy prices for district heating are reduced during the summer when the solar thermal system produces most heating, so the cost-effectiveness of the SDHW system is reduced. The size of the PV system evaluated for RH1 when using electric heating is limited by the available roof area.

Table 13.
Annual energy production from local renewable energy sources, SDHW and PV systems, with and without a battery for storing electricity, for RH1 and RH2, including installed peak power.

			Reference house 1			**Reference house 2**		
			Peak power	**Specific energy use - reduction**		**Peak power**	**Specific energy use - reduction**	
	Heat generation		**kWp**	**kWh**	**kWh per m²**	**kWp**	**kWh**	**kWh per m²**
SDHW	Direct electric heating		-	2 500	11	-	1 800	13
	Pellet-fired boiler		-	2 500	11	-	1 800	13
	District heating		-	2 500	11	-	1 800	13
	Heat pumps		Not evaluated			Not evaluated		
PV	Non-electric	Without batteries	6.7	400	2	7.0	300	2
		14 kWh battery		860	4		700	3
	GSHP	Without batteries	11.7	1 430	6	10.0	1 100	8
		14 kWh battery		2 810	12		2 400	17
	Electric heating	Without batteries	11.7	3 080	13	16.1	2 930	21
		14 kWh battery		5 040	22		4 950	35

The results presented in Table 10, Table 11, Table 12 and Table 13 are combined with the energy prices for each type of used heat generation to calculate annual operational costs. Annual energy costs are presented for the reference houses with each of the evaluated types of heat generation in Table 14. The alternatives presented in **bold and underlined** fulfil the passive house requirements while the alternatives underlined need to be supplemented by local renewable energy production to fulfil the requirements.

Table 14.
Annual energy costs per reference house and type of heat generation; alternatives in bold and underlined fulfil the PH requirements; alternatives underlined fulfil the requirements when supplemented by local renewable energy production.

		Reference house 1			*Reference house 2*			*Unit*
Renovation level		***Minimum***	***BR***	***PH***	***Minimum***	***BR***	***PH***	
Heat generation systems	1.1 Direct electric heating	5 580	3 030	1 630	3 800	2 500	1 310	€ per year
	2.1 GSHP	1 510	880	**570**	1 200	750	**480**	
	2.1 EAHP	2 690	1 050	**700**	2 210	1 240	730	
	3.1 Pellet-fired boiler	2 740	1 460	**830**	1 920	1 310	670	
	4.1 District heating	3 650	1 960	**1 080**	2 520	1 690	880	

When comparing the annual operational costs of the different types of heat generation, the decision of which alternative to use becomes more complicated. Even though more energy is bought for a house using a pellet-fired boiled than a house using direct electric heating or district heating, because of the systems efficiency, the annual energy cost is lower because of the energy cost. The energy cost is roughly halved compared to direct electric heating. For RH2, the alternative of using a pellet-fired boiler has a lower annual energy cost than the EAHP. The GSHP provides the lowest annual energy costs for both reference houses, but it also has the highest total investment cost. Lowest annual energy costs are achieved using the alternatives GSHP, EAHP and pellet-fired boiler.

Investment costs for EEMs are presented in Table 15, and costs for converting to another type of heat generation are presented in Table 16 and Table 17. For houses that currently use direct electric heating, an additional cost for converting to a hydronic heating system is needed. This cost was estimated to be €8000 for RH1 and €6000 for RH2, but was not included in any of the analyses. The investment and operational costs are used as input to the LCC analysis.

Table 15.
Marginal investment cost in €, including VAT and ROT, of the EEMs at different renovation levels for the two reference houses.

		Reference house 1		*Reference house 2*	
Renovation level		***BR***	***PH***	***BR***	***PH***
EEMs – Marginal cost (€)	External walls (incl. cellar walls)	10 100	13 900	4 400	8 700
	Roof	4 100	6 400	2 800	3 900
	Windows & doors	15 100	20 900	14 700	19 200
	Foundation	2 000	2 000	2 100	2 100
	Ventilation	0	5 100	0	5 600

Table 16.
Total investment cost in €, including VAT and ROT, for different types of heat generation, including material and labour cost and ROT.

Alternatives	***EAHP***	***FTX***	***Pellet-fired boilers & burners***	***Ground source heat pump***	***District heating***
Total investment cost	**9 900**	**5 300**	**10 300**	-	-
Material	7 600	4 700	8 400	See Table 17, specific for each reference house and renovation level	Only evaluated for houses already using district heating, costs for conversion need to be added for other alternatives.
Labour	3 300	900	2 700		
Tax reduction	1 000	300	800		

Table 17.
Total investment cost in €, including VAT, for heat generation from GSHP for different levels of renovation, including material and labour costs and ROT.

	Reference house 1			*Reference house 2*		
Renovation level	***Minimum***	***BR***	***PH***	***Minimum***	***BR***	***PH***
GSHP - max power	16	12	6	12	6	6
Total investment cost	**15 800**	**13 500**	**11 500**	**15 400**	**13 500**	**12 100**

The results from the LCC analysis, performed in the software Totaltool [34], for both reference houses are presented for the different renovation levels as investment cost, internal rate of return (IRR) and net present value (NPV) in Table 18. This method calculates the relative LCC of implementing energy efficiency measures, so the goal is a negative cost.

The most cost-effective individual measure is to only install a heat pump, especially when the IRR is also considered. The most cost-effective combination of type of heat generation and renovation package was shown to be with an exhaust air heat pump, which gave the highest IRR. Some interesting results emerge when the renovation packages are compared. For RH2, when using direct electric heating, the PH renovation is the most cost-effective renovation level, with both lower LCC and higher IRR compared to the BR level. For RH1, only NPV is lower, while IRR is also lower. This is because of the higher investment cost of the PH level compared to the BR level. For houses using district heating, the results are mixed; LCC is higher for the PH level renovation but IRR is also higher. Similar results are shown for houses using pellet-fired boilers; IRR is almost equal in the PH and BR level renovations but the PH has a lower LCC. Another difference is that, for the PH level renovations package, IRR decreases when installing a GSHP compared to the direct electric heated alternative, but increases in the BR level renovation package. The results for all renovation levels improve when a GSHP is included; the IRR is reduced for the PH level renovation because of the reduced energy savings potential from installing a GSHP in an energy efficient house. This is also because of the high base investment cost, with a relatively small increase in cost when installing an alternative with higher maximum power. Changing from a low-powered heat pump of 7 kW, with and investment cost of about €12,000, to a high-powered alternative of 16 kW only increases the investment cost by about €3500 to €4500.

Table 18.
Investment cost and results from the LCC analysis, presented as NPV and IRR, for different types of heat generation at different renovation levels for the reference houses. The relative LCC of implementing energy efficiency measures is also presented.

			Reference house 1-230 m²			***Reference house 2-142 m²***			***Units***
Renovation level			***Minimum***	***BR***	***PH***	***Minimum***	***BR***	***PH***	
Heat generation systems	Direct electric heating	Investment cost	-	31 300	48 300	-	24 000	39 700	€
		Net Present Value	-	- 44 100	- 61 300	-	- 11 600	- 27 500	€
		Internal rate of return	-	8.5	7.6	-	4.5	5.0	%
	GSHP	Investment cost	15 800	44 800	59 800	15 400	37 500	51 300	€
		Net Present Value	- 87 300	- 85 800	- 74 000	- 47 000	- 37 300	- 31 100	€
		Internal rate of return	24.0	10.0	7.3	14.2	5.8	4.3	%
	EAHP	Investment cost	9 900	41 200	53 100	9 900	33 900	43 800	€
		Net Present Value	- 65 300	- 88 100	- 82 900	- 46 500	- 48 500	- 45 000	€
		Internal rate of return	28.0	10.9	8.6	20.8	7.6	6.1	%
	Pellet-fired boiler	Investment cost	-	31 300	48 300	-	34 300	39 700	€
		Net Present Value	-	- 4 100	- 2 800	-	18 900	6 100	€
		Internal rate of return	-	2.7	2.0	-	- 1.6	0.3	%
	District heating	Investment cost	-	31 300	48 300	-	24 000	39 700	€
		Net Present Value	-	- 16 800	- 21 400	-	1 300	- 4 600	€
		Internal rate of return	-	4.7	4.0	-	1.7	2.0	%

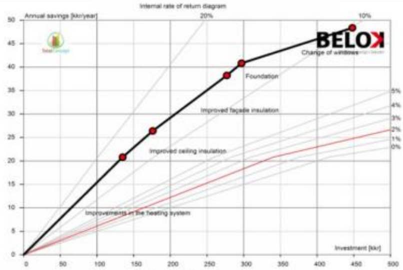
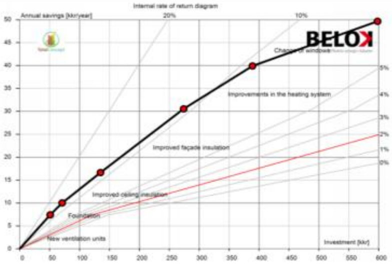
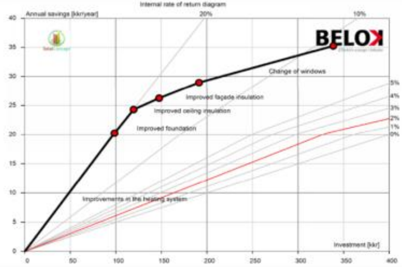
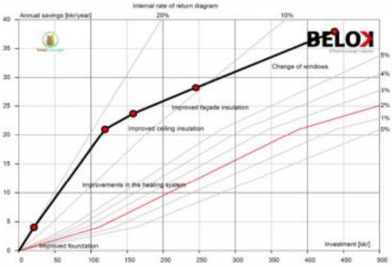
A profitability calculation determined the combination of heat generation where it would be cost-effective to supplement with local renewable energy production, either a SDHW system or a PV system, for the reference houses. This method calculates the total LCC, so the goal is a positive cost, unlike the previous calculation that compared the relative LCC of implementing energy efficiency measures. The results, presented in Table 19, show that installing a SDHW system would not be profitable when using non-electric heat generation, because of the negative NPV and low IRR. However, installing a SDHW system would still be needed to fulfil the passive house requirements in RH2. For the PV system, the results show it is profitable to invest, both with and without a battery, for both reference houses using all types of heat generation system. The results when implementing two batteries, 14 kWh each, are not presented, since the impact on the specific energy use was low, marginal cost was high, and none of the evaluated combinations were profitable with different types of heat generation.

Table 19.
Profitability calculations for the installation of local renewable energy production systems in the reference houses, presented with investment costs, NPV and IRR.

			Reference house 1			***Reference house 2***		
Local renewable energy	**Heat generation**		***Investment cost (€)***	***NPV (€)***	***IRR (%)***	***Investment cost (€)***	***NPV (€)***	***IRR (%)***
SDHW	Direct electric heating		5 500	1 670	3.3	5 500	- 820	0.5
	Pellet-fired boiler		5 500	- 3 050	- 2.6	5 500	- 4 200	- 4.8
	District heating		5 500	- 1 540	- 0.4	5 500	- 3 130	- 2.8
PV	Non-electric	Without batteries	11 400	3 390	5.2	11 900	4 000	5.6
		14 kWh battery	14 500	1 810	3.2	15 000	2 570	3.7
	GSHP	Without batteries	19 900	3 230	3.8	17 000	3 350	4.2
		14 kWh battery	23 000	110	2.0	20 100	270	2.1
	Electric heating	Without batteries	19 900	3 710	4.0	27 400	5 930	4.4
		14 kWh battery	23 000	700	2.3	30 400	2 910	3.0

The output from some of the calculations in Totaltool is presented in the figures in Table 20. These show some surprising results. In almost all cases, the renovation measure of installing new windows is the least cost-effective energy efficiency measure. At the same time, the results show that the passive house windows are more cost-effective than the building regulation windows, with both a lower LCC and higher IRR.

Table 20.
Examples of the results output from the calculations in Totaltool for different renovation levels and heat generation systems, costs in SEK.

	Building regulation level	***Passive house level***
Reference house 1 – GSHP		
Reference house 2 – EAHP		

Some general comments on the method and results:

- An alternative in SFHs is that homeowners do as much of the renovations as possible themselves, to reduce labour costs. The impact this would have on the investment costs and results have not been evaluated in this study.
- The assessment only included the marginal cost of the renovation packages when estimating the need for ROT tax reduction. It is important to verify the total costs of a project before assuming the ROT tax reduction can apply in all parts of the renovation. One uncertainty in these calculations is that the tax reduction scheme may change over time.
- Another uncertainty is the assumptions regarding energy prices and real energy price increase. In recent years, energy prices have increased faster than inflation, as shown in Figure 1, leading to a real price increase.
- Additional benefits from implementing energy efficiency measures, such as improved thermal comfort, were not considered in this evaluation.
- The possible increase in property value after the renovations was not included in the profitability estimations.

5. Conclusions

The PH level renovation packages reduce final energy use by at least 65 percent and, depending on the existing and chosen type of heat generation, bought energy by up to 90 percent, compared to the energy use before renovation. This can be done in a cost-effective way, reducing both operational cost and LCC while probably generating additional benefits such as improved thermal comfort and indoor air quality. The PH renovation package will also help attain the Government's goal of halving energy use in buildings by 2050. One condition for the profitability of renovation packages is that the houses are already in need of renovation. If not, marginal costs increase, as more of the investment costs must be paid for by the reduction in energy costs, thereby reducing the profitability.

The cost-effectiveness of the renovation packages is largely dependent on the type of heat generation used in the houses – based both on the difference in operational costs and in the requirements for PH. For houses using direct electric heating, the PH renovation package was the most cost-effective alternative. This also applies to houses using other types of heat generation, but is no more cost-effective than the BR level. The most cost-effective individual renovation measure was installing a GSHP, but when renovation packages were combined with types of heat generation, the EAHP was the most cost-effective alternative. The least cost-effective individual renovation measure was installing new windows, but installing PH windows was more cost-effective than installing BR windows.

Whether the PH requirements are met depends on the location of the house, because of the impact of climate on energy use. For RH2, located in the colder part of Sweden, when using non-electric heating and EAHP for heat generation, a local renewable energy production system was also needed to supplement the PH renovation package before the PH requirements were met. Using a PV system was shown to reduce specific energy use, and was also a cost-effective alternative. The downside is the high investment cost of between €11,000 and €30,000.

The main problem with proposing the PH renovation package is the increased investment cost, about €10,000 to €15,000 extra compared to the BR renovation package. The investment cost is often a significant limiting factor for the realization of energy renovations, both because of the availability of funds and the perceived added value from performing the renovation measures. These results, showing the cost-effectiveness of the PH renovation package, provide important information that the homeowner could use when deciding on the renovation level. It may be more cost-effective to invest in a PH-level renovation package rather than installing a renewable energy system in a BR level renovation package. The investment cost of a PV system is similar to the marginal cost of a PH-level renovation package, so it is important to evaluate which alternative is most cost-effective in each case.

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Paper IV

Renovation of Swedish single-family houses from the 1960s and 1970s to net-zero energy buildings – Case study

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Abstract

This paper evaluates whether a net-zero energy building (NZEB) can be attained by implementing on-site renewable electricity production when renovating to Passive House level. The assessment is based on the Swedish single-family housing stock constructed between 1961 and 1980, using two case study houses and three locations. Specific conditions of the houses, such as the type of heat generation and available roof area for installation of a photovoltaic system, determine whether a NZEB renovation is possible. Overall, the assessment showed that it is not cost-effective to aim for NZEB when implementing a PV system, based on the alternatives in this study.

Keywords: energy renovation, NZEB, single-family houses, renewable energy

1. Introduction

Single-family houses (SFHs) constructed between 1961 and 1980 account for approximately one-third of the total energy use, 31 TWh, for space heating and domestic hot water (DHW) in Swedish SFHs. These houses account for about 40 percent of the total energy use in buildings (Swedish Energy Agency, 2015b). There are roughly 715,000 houses from this period (Statistics Sweden, 2015) and they are largely homogeneous in technical terms, with low levels of thermal insulation, and ventilation with heat recovery is rare (Boverket, 2010a). The average energy use for houses from this period is about 40 percent higher than SFHs constructed between 2011 and 2013 (Swedish Energy Agency, 2015a). Many of these houses need to be renovated (Boverket, 2010b), providing an excellent opportunity to incorporate energy efficiency measures, to reduce both operational cost and greenhouse gas emissions related to energy use. A continuation of this is to also implement local renewable energy production to further reduce energy use.

National and international goals for a sustainable future are part of the overall objective to reduce greenhouse gas emissions and mitigate global warming and climate change (European Commission, 2011, SOU, 2016). The Swedish Government has set a target of a 50 percent reduction in total energy use per heated floor area by 2050, compared to the level in the reference year 1995 (Sahlin, 2006). Because of limitations in existing buildings, such as limited space, economic considerations, or preserving cultural heritage values, a 50 percent reduction of energy use is not possible in all buildings. To compensate for this, energy use must be reduced by more than 50 percent in some buildings to achieve an average of 50 percent energy use reduction. One way to achieve this is to renovate existing buildings to net-zero energy buildings (NZEB) whenever possible.

The purpose of this study was to determine whether a net-zero energy building (NZEB) could be attained for SFHs from 1960s and 1970s by implementing on-site renewable electricity production when implementing an extensive renovation package to Passive House level, based on the Swedish Passive House standard, FEBY 12 (Erlandsson et al., 2012).

2. Method

A photovoltaics (PV) system for local renewable electricity production was installed on two reference houses to ascertain the viability of a NZEB renovation. The assessment involved comparing the electricity production from the PV system to the energy demand of the buildings after implementing extensive renovation packages to Passive House level. The reference houses were evaluated in three different locations in Sweden – from Malmö in the south (55.52 N, 13.37 E) to Kiruna in the north (67.82 N, 20.33 E).

When the Passive House standard is applied, thermal transmission and ventilation losses are reduced by about 70 percent (Ekström and Blomsterberg, 2016). The renovation measures used to achieve the Passive House level renovation are presented in Table 1. Based on the type of heat generation commonly used in Swedish SFHs from this period, the reference houses were evaluated with two alternatives: electric heating and a ground source heat pump. Non-electric heating such as pellets and district heating were excluded because of their reliance on other energy sources. Three locations were chosen to determine whether the difference in solar radiation and ambient conditions, such as temperature, impacted the possibility of achieving NZEB. These locations were Malmö in the south, Östersund located in central Sweden, and Kiruna in the north.

Table 1. Description of the Passive House renovation level with renovation measures and the required performance level.

Renovation level		Passive House
Building envelope	Facades	New
	External walls	0.10 ±0.02 $W/(m^2 \cdot K)$
	Roof	0.10 ±0.02 $W/(m^2 \cdot K)$
	Foundation	Improved, see Table 3
	Cellar walls	+200 mm thermal insulation
	Windows	0.80 $W/(m^2 \cdot K)$
	Doors	0.80 $W/(m^2 \cdot K)$
	Thermal bridges	Calculated
	Airtightness, at ± 50 Pa	0.3 $l/(s \cdot m^2)$
	Drainage	New
Installations	Ventilation system	Balanced, with heat recovery
	Ducts	New air ducts
	Heating system	New, depends on heat generation used
	Heat generation	New, depends on evaluated heat generation
DHW	Heater	New
	Pipes	New
	Fixtures	New
	Household purpose electricity	Not included, new energy efficient appliances and lighting assumed

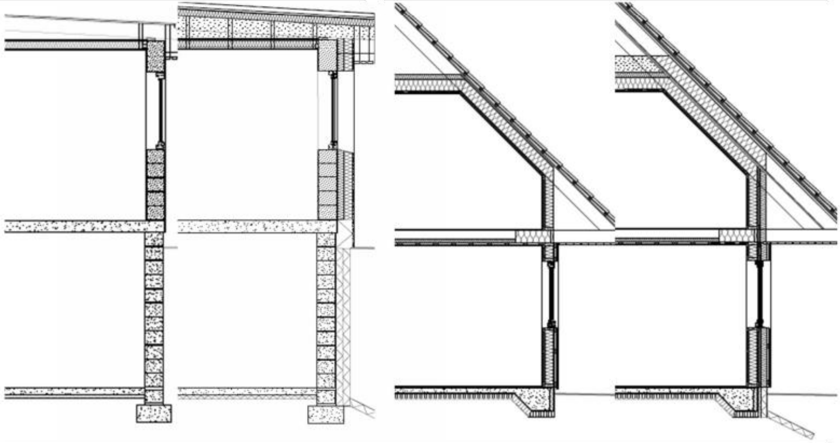
Two case study buildings represented the SFH building stock from the period (Table 2). These houses were used in earlier studies of energy savings potential (Ekström and Blomsterberg, 2016) and cost-effectiveness (Ekström et al., 2017) of renovations aimed at reaching Passive House level. More detailed information about the renovation measures can be found in those papers. The impact of renovation measures on the building envelope of the reference houses is shown in Table 3.

Table 2. Description and visualization for the two case study buildings before renovation.

Reference house 1		
Year built:	1965	
Roof area:	169 m², inclination < 5 °.	
A_{temp}:	230 m^2	
Ventilation:	Passive stack ventilation.	
Description: One-storey house with a cellar and a pent roof, lightweight concrete walls and a concrete slab foundation.		
Reference house 2		
Year built:	1977	
Roof area:	80 m² + 80 m², inclination 45 °.	
A_{temp}:	142 m^2	
Ventilation:	Balanced ventilation, with heat recovery.	
Description: One-and-a-half storey house with a ridged roof, 45°, wood frame structure walls insulated with mineral wool and a concrete slab foundation.		

Table 3. Section drawings of the reference houses before and after implementing the passive house renovation packages.

Reference house 1		Reference house 2	
Before renovation	**After renovation**	**Before renovation**	**After renovation**



The building simulations include detailed models of the reference houses, with zones for each room. The input data regarding structures, thermal transmittance, airtightness, inhabitants, internal heat gains and shading was gathered from and prioritised as follows: 1) specific data for reference house; 2) Passive House requirements (Erlandsson et al., 2012); and 3) Sveby (Levin, 2012) was used for normalised user-related input data. The reference houses were assumed to be inhabited by two adults and two children. Weather data files included in the building energy simulation program (*IDA ICE 4.7*) from *SMHI (Swedish Meteorological and Hydrological Institute)*, with long-term measurements of climate and weather, were used for each location in the simulations. In Swedish conditions cooling is not commonly used in residential buildings, so is excluded from the analysis. A specific building model was used for each alternative in the assessment.

On-site production of renewable energy was evaluated by simulating the performance of the PV system, to ascertain whether it could cover the annual energy demand of the houses. A validated dynamic building energy simulation tool, *IDA ICE 4.7* (EQUA, 2016) was used to simulate energy demand, and the simulation program *SAM 2017.1.17* (NREL, 2017) was used to simulate the production from the PV system. The nominal efficiency of the PV panels was assumed to be 20.6 percent and an expected service life of 25 years (Lindahl, 2014), with a temperature coefficient of -0.3 percent per degree increase and an inverter with a maximum conversion efficiency of 96 percent. The PV panels were placed with the same tilt as the existing roof. The simulations used hourly values to compare self-consumption of the electricity from the PV system. The definition and equation for calculating the self-consumption, or solar fraction, used in this study is presented in equation (1):

$$\text{Solar fraction } (\%) = \frac{\text{energy from PV to load}}{\text{energy load}} \quad (1)$$

The total energy demand that production from the PV system needs to cover is the demand for household electricity, space heating, domestic hot water and facility electricity. The demand for household electricity is based on the annual average use in Swedish SFHs, 5900 kWh, and the domestic hot water demand is based on the normalised annual use in Swedish SFHs of 20 kWh per heated floor area, Sveby (Levin, 2012). The energy demand for space heating and facility electricity was simulated in *IDA ICE 4.7* for the specific case study buildings at the different locations and with the different types of heat generation. The assumed variation in the domestic hot water demand for the evaluation is presented in Figure 1 and Figure 2. Variation in household electricity demand was assumed as shown in Figure 3 and Figure 4.

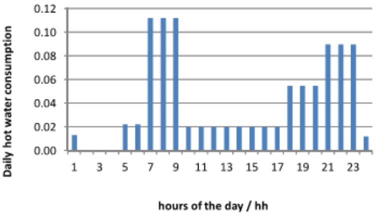


Figure 1. Daily variation of DHW consumption based on a simplification (Bernardo et al., 2012).

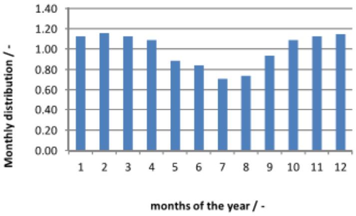


Figure 2. Annual variation of DHW consumption based on FEBY12 (Erlandsson et al., 2012).

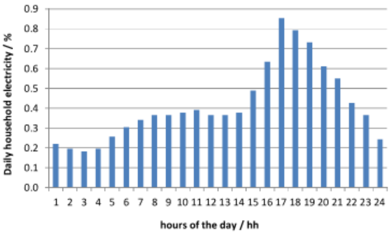


Figure 3. Assumed daily profile for household electricity use based on measurements of Swedish passive houses. This is not included in specific energy use (Nilsson and Westberg, 2012).

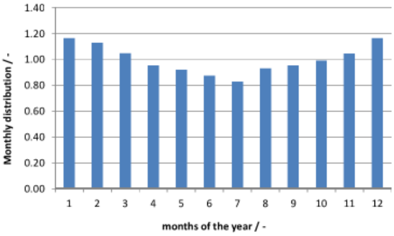


Figure 4. Assumed yearly distribution of household electricity use based on measurements of Swedish passive houses (Nilsson and Westberg, 2012).

The economic analysis, using the software *"Investment calculation for photovoltaics"* (Stridh, 2016), calculated the life cycle cost as net present value and internal rate of return. The investment cost of the system is based on the average prices, €1850 per installed kWp including VAT, presented in the software. A Government grant is available for installation of a PV system on a SFH, covering 20 percent of the investment costs (Svensk författningssamling 2016:900, 2009), which was included in the economic calculation. It was assumed that a loan was taken to cover the investment cost. The interest rate of the loan was assumed to be two percent higher than inflation, so the real interest rate used in the calculations of net present value was two percent.

The total price per kWh for bought electricity in Sweden is based on several parameters. In addition to the electricity price, there is also the grid service price, electricity certificate (Swedish Energy Agency, 2016), electricity tax (Swedish Tax Agency, 2017) plus VAT. The fixed fees were not included since they do not change with the energy demand, so they are not impacted by the reduced energy use from the renovation measures.

To determine the electricity price, information was gathered regarding average annual grid service price per kWh and monthly electricity prices per kWh for the variable price rate for SFHs (Statistics Sweden, 2017). The average electricity price depends on the electricity demand of the house – if the heat generation is based on electricity, electricity demand is higher and price per kWh lower, and if non-electric heat generation is used, electricity demand is lower and price per kWh higher. Only houses using electric heating were included in this study, so only electricity prices for such houses were included. Average electricity prices are about €0.13 per bought kWh for houses using electric heating (Figure 5). The price increase above inflation was assumed to zero.

The selling price for electricity sold to the grid, presented in Figure 6, was estimated based on the average price of €0.05 per kWh in *"Investment calculation for photovoltaics"*. Also included is the electricity certificate of €0.013, compensation for the grid owner of €0.005, certificate of origin of €0.0005, and a tax subsidy of €0.06 available for the first 15 years of production. All costs were estimated in Swedish Crowns (SEK) and converted to Euro (€) with a conversion rate of SEK 10 for €1.

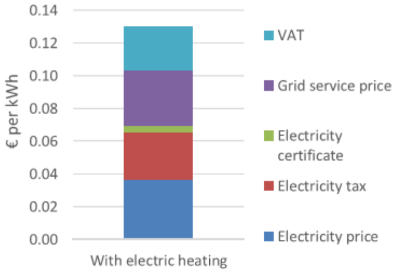


Figure 5. Average annual price for electricity bought from the grid for houses using electricity for heat generation.

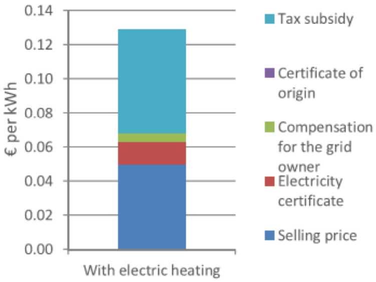


Figure 6. Average annual price for electricity sold to the grid for houses using electricity for heat generation.

3. Results and discussion

Results are presented, in Table 4 for RH1 and in Table 5 for RH2, as annual electricity demand (including space heating, domestic hot water, facility electricity and household electricity), annual electricity production from the PV system and self-consumption, based on the hourly demand and production. The aim was for the annual electricity production to equal that of the energy demand, to attain the NZEB level. The results are shown per location and type of heat generation. Also presented are the system size and the peak power of the evaluated systems. Alternatives presented in red do not attain the NZEB level.

Table 4. Results from simulation of the PV system production for Reference house 1 with roof tilt of < 5 degrees. Alternatives presented in red do not attain the NZEB level.

Heat generation	Location	PV system size m^2	Peak power kWp	Annual demand kWh	Annual production kWh	Self-consumption %
Electric heating	Malmö	114	23.5	18 400	19 000	31.1
	Östersund	114	23.5	25 400	16 900	25.0
	Kiruna	114	23.5	30 600	14 200	21.3
Ground source heat pump	Malmö	65	13.4	10 200	10 900	34.6
	Östersund	90	18.4	12 600	13 200	30.1
	Kiruna	114	23.5	14 900	14 200	25.4

Table 5. Results from simulation of the PV system production for Reference house 2 with roof tilt of 45 degrees and east-west orientation. Alternatives presented in red do not attain the NZEB level.

Heat generation	Location	PV system size m^2	Peak power kWp	Annual demand kWh	Annual production kWh	Self-consumption %
Electric heating	Malmö	90	18.4	12 800	13 200	33.1
	Östersund	131	26.8	16 100	17 000	29.0
	Kiruna	163	33.5	18 700	18 000	26.3
Ground source heat pump	Malmö	57	11.7	8 600	8 700	35.9
	Östersund	82	16.8	9 800	10 700	32.8
	Kiruna	98	20.1	10 800	10 800	29.6

The results show that fulfilling the aim of a NZEB building depends both on location and type of heat generation. In the case of Reference house 1, the PV system was limited by the size of the roof in three cases: for electric heating in Östersund and Kiruna, and for the ground source heat pump in Kiruna. For Reference house 2, this was only the case for electric heating in Kiruna. The results reflect both the increased demand for space heating in the colder climate and the reduced production from the PV system in the northern parts of Sweden.

The results from the life cycle cost calculations are presented, in Table 6 for Reference house 1 and in Table 7 for Reference house 2, with the investment cost for each system and as net present value and internal rate of return. The results are shown per type of heat generation and location. Alternatives presented in red are not profitable.

Table 6. Profitability calculations for the implementation of PV systems on Reference house 1, presented with investment costs, net present value and internal rate of return. Alternatives presented in red are not profitable.

Heat generation	Location	Investment cost (€)	Net present value (€)	Internal rate of return (%)
Electric heating	Malmö	35 250	680	2.2
	Östersund	35 250	- 4 300	0.7
	Kiruna	35 250	- 10 200	- 2.4
Ground source heat pump	Malmö	20 100	710	2.4
	Östersund	27 600	- 3 100	0.8
	Kiruna	35 250	- 9 900	- 1.2

Table 7. Profitability calculations for the implementation of PV systems on Reference house 2, east-west orientation, presented with investment costs, net present value and internal rate of return. Alternatives presented in red are not profitable.

Heat generation	Location	Investment cost (€)	Net present value (€)	Internal rate of return (%)
Electric heating	Malmö	27 600	- 2 900	0.9
	Östersund	40 200	- 9 300	- 0.5
	Kiruna	50 300	- 17 200	- 1.9
Ground source heat pump	Malmö	17 600	- 1 100	1.4
	Östersund	25 200	- 5 500	- 0.4
	Kiruna	23 000	- 11 000	- 2.2

The cost-effectiveness is also shown to be dependent on both the location and type of heat generation. It is only cost-effective to install a PV system with a size to attain NZEB for RH1 in Malmö in the south of Sweden. This is the case with both types of heat generation, although the investment cost for the electric heated house is higher.

4. Conclusion

Overall, the assessment showed that it is not cost-effective to aim for NZEB when implementing a PV system, based on the alternatives in this study, assuming a lifetime of 25 years and no increase in the electricity price. In many cases, the NZEB level could be attained with the roofs available, but this depended on the location and type of heat generation of the houses.

In this study, the aim was to maximise annual PV production, so for Reference house 1 the PV panels were installed flat on the roof and the tilt could be optimized to increase production and cost-effectiveness. However, by doing this, the annual PV production is reduced because of the limited space, so the NZEB level would not be attained.

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