Implications of energy efficiency renovation measures for a Swedish residential building on cost, primary energy use and carbon dioxide emission

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Abstract

Improved energy efficiency of buildings is of interest in the European Union, where the building sector accounts for 40 % of total primary energy use. Measures to improve energy efficiency in existing buildings offer significant opportunity to reduce primary energy use and carbon dioxide (CO_2) emission. In Sweden, about one million existing apartment buildings are projected to undergo renovation within the next 20 years. The final energy use in the Swedish residential and service sector is dominated by space heating and may be reduced by end-use energy efficiency measures. In this study, we analysed the potential final energy savings for space heating and cost-effectiveness of different energy efficiency measures for a Swedish multi-story residential building from a building owner perspective. The case-study building was constructed in the 1960s and is projected to undergo renovation in the coming years. The implications of the measures on primary energy use and CO_2 emission were also explored.

The analysed energy efficiency measures include improved doors and windows and additional insulation for basement walls, exterior walls and attic floor. Required investment for considered energy efficiency measures per saved energy price was used as an indication for the cost-effectiveness of energy renovation scenarios. We analysed three scenarios of energy renovation where the building is in its initial state, once with and then without a need to be renovated for repair and maintenance purpose and the scenario where the building is in its current state. The current state of the building has some modification in the attic floor, doors and windows, compared to the initial state. We performed sensitivity analysis to study the influence of different economic parameters on the cost-effectiveness of energy efficiency measures for the initial state of the building.

The results of the cost-effectiveness analysis showed that the energy savings and cost-effectiveness of the measures depend on several factors including building characteristics, energy efficiency measures and the assumptions for economic analysis (e.g. investment cost, discount rate, current energy price and the future energy price prospection). Modelling of final energy use, before and after energy renovation, and its cost analysis showed that the considered energy efficiency measures were not economically profitable with the initial economic assumption (6 % discount rate and 1.9 % annual energy price increase during 50-year lifespan). The performed sensitivity analysis indicated that the economic assumptions and different packages of efficiency measures have significant influence on the cost-effectiveness of the energy renovation scenarios. In the case of considering the renovation package of all energy efficiency measures, for instance, the energy renovation appeared to be profitable when discount rate and annual energy price increase were 3 % and 2.5 % (or larger), respectively. The primary energy use and CO_2 emission were reduced by 45 to 50 % for the same package for the building with cogeneration-based district heating.

Introduction

Buildings account for 40 % of the total energy use in the European Union (EU) (European Environment Agency, 2012). The EU Directive on Energy Performance of Buildings (European parliament, 2002) requires member states to implement energy efficiency legislation for buildings, including existing buildings that are to undergo major renovation. The Swedish government aims to reduce total energy use per heated building area by 20 % by 2020 and 50 % by 2050, using 1995 as the reference (Dodoo et al, 2010). Improved energy efficiency measures for space heating of existing buildings can provide substantial opportunity to reduce the primary energy use as well as CO_2 emission.

Energy is used within the whole life cycle of a building, including production, operation and end-of-life phases. Several studies have analysed energy use in the entire life cycle of buildings (Thormak, 2002; Adalberth, 2000; Ramesh et al., 2010; Satori and Hestnes, 2007; Karlsson and Moshfegh, 2007) and show that the operation phase contribute significantly to the life cycle energy use. Ramesh et al. (2010) conducted an overview study on life cycle energy analysis of buildings on 73 case-studies across 13 countries in northern and central Europe, Canada, tropical region of Asia and Australia. 46 cases of their study were residential and the rest were office buildings. Their results suggest that energy use during the operation phase contributes to about 80 to 90 % of life cycle energy use of residential buildings. Energy use for the space heating of buildings has substantial contribution to the total energy use during operation phase. According to the European Environment Agency (2012), energy use for space heating contributes to about 68 % of total energy use during the operation phase of buildings in European countries. In Sweden, the production of new residential buildings has declined over the last decades (Gustafsson, 2000). The existing building stock is getting older and renovation is becoming more important. About one million existing apartment buildings in Sweden are projected to undergo major renovation within the next 20 years (Itard et al., 2008). This offers a significant potential to reduce primary energy use and CO_2 emission by implementing energy efficiency measures in existing Swedish multi-story buildings.

There are large numbers of energy efficiency measures that may potentially reduce energy use during the operation phase of buildings. These measures may include ventilation heat recovery systems, efficient hot water taps, efficient electrical appliances and improved thermal performance of building envelope elements.

Various researchers have studied energy implication of different energy efficiency measures for buildings renovation. Gustavsson et al. (2011) analysed a multi-story wood-framed residential building constructed in 1995 in southern part of Sweden. They evaluated the effects of various final energy efficiency measures on district heated (henceforth DH) buildings. They found that applying building element measures (i.e. improved doors and windows, additional exterior walls insulation and additional roof insulation) could reduce the required final energy for space heating by 35 %. In another study, Dodoo et al. (2010) analysed the effect of retrofitting a wood-framed building to a passive house standard. They considered various types of efficiency measures including the improvement of building elements as well as ventilation heat recovery and improved tap water. They found that space heating energy demand of the building reduces by 39 % by improving the insulation on external walls and roof and by changing doors and windows. The cost-effectiveness of the building energy renovation has not been considered in those studies. There are more strategies to reduce primary energy use and CO_2 emission than just decreasing building heat demand by implementing energy efficiency measures. The significant contribution of energy supply system to primary energy use and CO_2 emission has been studied and confirmed by various researchers (Dodoo et al., 2010; Dodoo et al., 2011; Joelsson et al., 2009).

In this study we analysed the economic benefit of implementing energy efficiency measures from end-user point of view. We calculated the initial investment of the building envelope energy renovation over the saved energy demand for space heating (Hermelink, 2009) as an indication for energy renovation cost-effectiveness. Our focus is on the building envelope elements. That includes doors, windows, exterior walls, basement walls and attic. We also analysed the primary energy use and CO_2 emission reduction due to implementing the energy efficiency measures. We considered cogeneration-based DH system for primary energy and CO_2 emission calculations.

Methods

GENERAL APPROACH

We modelled energy efficiency improvement measures to analyse their primary energy, carbon dioxide and economic implications. Our general approach consists of three parts: 1) modelling final energy use for space heating when implementing energy efficiency measures; 2) performing cost analysis of energy efficiency measures and 3) calculating primary energy and CO_2 emission reduction due to energy renovation scenarios. The considered measures are doors and windows replacement with the improved ones, extra insulation on exterior walls, basement walls and attic floor. Current state of the building has some modification compare to its initial state. The details of the modifications were extracted from a recent study of the building (Jansson and Nilsson, 2011). We modelled and analysed the building for both current and initial states to explore the difference in the cost-effectiveness of energy renovation scenarios.

CASE-STUDY BUILDING

This study is based on a case-study multi-family building constructed in 1964 in the city of Växjö in southern part of Sweden. It has 3 floors and eighteen apartments in addition to 6 flats in ground floor. It is a concrete-frame building with brick cladding. Figure 1 shows a picture of the building. Total heated floor area of the building is 1,429 m^2. Total ventilated volume is 3,710 m^3. The required information of the building for the analysis was extracted from existing drawings provided by the owner of the building. This includes details of dimension and thermal characteristics of building components.

The roof consists of a concrete slab with the thickness of 200 mm and mineral wool insulation layer of 150 mm in its initial state. The current state of the roof has an additional 400 mm thick mineral wool (U-value = 0.097 W/m^2K). The current windows of balconies have the U-value of 1.9 W/m^2K while that was 2.9 W/m^2K in initial state (Jansson and Nilsson, 2011). The details of exterior walls are different in different sides of the building. The eastern and western exterior walls consist of 140 mm concrete, 100 mm mineral wool and 120 mm brick façade. The northern and southern exterior walls

Figure 1. South-west view of the case-study building.

Table 1. Energy efficiency measures for the initial and current states of building envelope elements.

Building envelope elements	Energy efficiency measures	Initial U-value, W/m^{2}K	Improved U-value, W/m^{2}K
Windows	Removing the existing windows and installing the new triple-glazed windows	2.9	0.9
External doors	Removing the existing doors and installing the new doors	3.0	0.9
East/West exterior walls of the facade	Adding extra 195 mm mineral wool panels (λ-value = 0.036 W/mK) with air gap and new cladding	0.339	0.119
North/South exterior walls of the facade	Adding extra 195 mm mineral wool panels (λ-value = 0.036 W/mK) with air gap and new cladding consideration	0.290	0.113
Basement exterior wall	Adding extra 200 mm extra insulation of EPS panel (λ-value = 0.039 W/mK), (Pordrän, 2012)	0.63	0.149
Attic floor	Adding extra 250 mm mineral wool	0.248	0.093

Table 2. Total area (m^2) of the elements of building envelope.

Building elements on each façade	Windows	Doors	Basement walls	Exterior walls of facades	Basement and attic slab
West facade	7.3	2.1	27.9	104.5	398
East facade	6.2	0.0	31.14	104.5	
North facade	55.0	7.8	82.51	226.4	
South facade	114.7	35.4	36.27	170.51	

consist of 70 mm lightweight concrete, 100 mm mineral wool and 120 mm brick façade. The basement exterior walls consist of concrete with mineral wool insulation on the internal side of the walls. We assumed that an extra 200 mm thick polystyrene panel (EPS) with moisture barrier protected against refilled soil with a layer of nonwoven fabric (Pordrän, 2012). The basement floor slab consists of 250 mm concrete and 50 mm mineral wool. The connections between exterior walls and floor slabs as well as the corners of the building, where two walls are connected together, are recognised to be the main sections for thermal bridges. Table 1 shows the details of considered energy efficiency measures and the initial and improved U-values of the considered elements. Surface area of building elements are listed in Table 2. We used these figures to calculate total amount of insulation materials needed for energy renovation. We did not consider any efficiency measure for the basement floor slab to avoid evacuation as there are residential flats in basement level of the building.

The ventilation system of the building is an exhaust air fan. We assumed that it has the pressure of 200 Pa and efficiency of 50 % with the flow rate of 0.35 l/m^2/sec. The building envelope average airtightness was assumed to be 0.8 l/m^2 at 50 Pa (Dodoo et al., 2010). In this study the focus is on the influence of building envelope improvement on heat loss reduction and the economic implication of the considered improvements. Therefore electricity use for household and facility management, hot water circulation system and ventilation system were assumed not to be changed. We assumed a lifespan of 50 years after renovation for the building and that the renovation takes place in 2012.

FINAL ENERGY SIMULATION

We modelled final energy use for space heating with and without building's improvements to determine the benefits obtained from the renovation after 50 years. Calculation was performed using the simulation programme of VIP+ (Structural Design Software, 2012) for energy renovation scenarios. VIP+ is a dynamic energy balance programme that models buildings final energy for space heating, hot water, ventilation system, and household and facility electricity. The programme has been validated by the International Energy Agency building energy simulation test and diagnostic method (IEA BESTEST). The programme calculates the energy balance considering a building's thermal characteristics, orientation, heating and ventilation systems, indoor and outdoor temperatures and operation schedule. We assumed indoor temperature of 22 °C for living and 18 °C for common areas. Ambient temperature, relative humidity, wind velocity and the sun radiation, for the city of Växjö were taken from the defined data in VIP+ (Structural Design Software, 2010).

COST ANALYSIS

The cost for implementing the considered energy efficiency measures (investment cost) was calculated based on the renovation work tariff in Sweden (Wikells sektionsfakta-ROT, 2012). The cost of required materials, installation and construction work as well as the required man-hour for each work, the cost of excavation for basement walls insulation and required scaffolding for the works on the external side of the facades were taken into account. All costs refer to the year 2012 average exchange rate of €1=SEK 8.9 based on the European Central Bank (ECB, 2012).

The economic value of reduced final energy use due to energy efficiency measures was calculated as the net present value of saved energy cost for the assumed lifespan. The case-study building is heated by DH. The cost of energy use for space heating was calculated based on the DH tariff (from 01/01/2012) of VEAB, the municipal energy utility in Växjö (VEAB, 2012). Total energy cost for space heating includes capacity charge and energy charge. The summation of energy charge and capacity charge before and after energy renovation was calculated. We assumed a discount rate of 6 % and an energy price increase of annually 1.9 %. This energy price increase was derived from analysis of real DH energy price (including energy tax and VAT) between 1993 and 2011 (Swedish Energy Agency, 2011). Figure 2 illustrates this trend.

The ratio of energy renovation investment per reduced energy cost was calculated for all considered energy renovation measures for the assumed lifetime of the measures (50 years). The reduced energy cost is the accumulative net present value of annual saved energy cost for 50 years after energy renovation. We assumed that the thermal conductivity of building envelope elements remain constant during 50 years after energy renovation with regard to the local climate condition.

We considered three scenarios for energy renovation of the building as follow:

1. The building is in its initial state and it is already in need for major renovation due to required repair and maintenance. In such a case, part of the energy renovation work may be provided by the repair and maintenance works. They include ground excavation which could be required for changing the drainage channels around the building or the cost of removing the existing doors and windows and installing the new ones. We also excluded the scaffolding cost for installing an extra insulation on exterior walls assuming that the existing façade is in need for some repair and scaffolding is already provided. There is high likelihood that multi-story residential buildings would need major renovation to maintain their serviceability after about 50 years. Therefore the energy renovation may be considered as a side benefit of the required maintenance.
2. The building is in its initial state and does not need renovation for the purpose of repair and maintenance. In this case all renovation measures were considered only for the purpose of heat loss reduction from the building envelope.
3. The building is in its current state where the building has some modifications within last decade (Jansson and Nilsson, 2011). In this scenario we assumed that the costs of implementing energy efficiency renovation measures are for the case that the building does not need renovation for repair and maintenance.

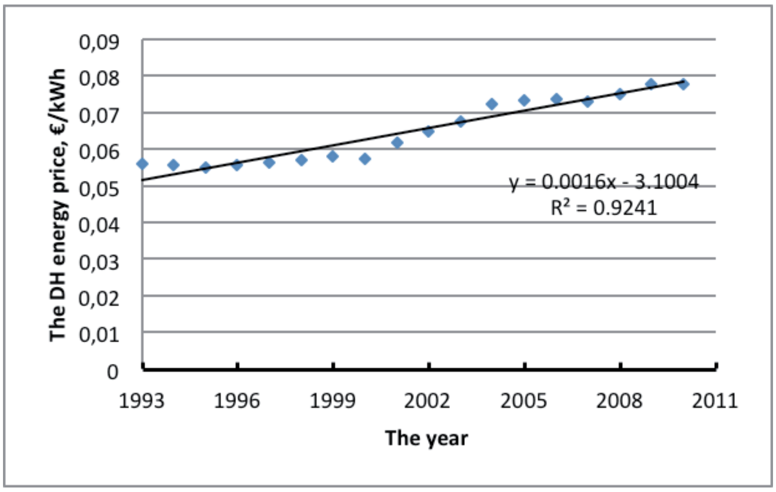

Figure 2. Real energy price for household in Sweden including energy tax and VAT within last 18 years, €/kWh.

Table 3. The investment cost of energy renovation measures for the initial state of the building when there is need for repair and maintenance work.

Energy renovation scenarios (energy efficiency measures in cumulative order)	Investment cost (cost of energy efficiency measure implementation), €
Attic floor extra insulation	7 900
+ Basement walls extra insulation	24 700
+ Exterior walls extra insulation	92 200
+ Windows replacement	182 800
+ Doors replacement	211 600

Table 4. The investment cost of energy renovation scenarios for the case when all renovations are for energy conservation purpose.

Energy renovation scenarios (energy efficiency measures in cumulative order)	Investment cost (cost of energy efficiency measure implementation), €
Attic floor extra insulation	10 900
+ Basement walls extra insulation	28 800
+ Exterior walls extra insulation	107 500
+ Windows replacement	228 400
+ Doors replacement	266 800

The considered energy efficiency measures were sorted in order of the cost-effectiveness of individual measures (i.e. the cost of energy efficiency measure per reduced final energy price). The packages of energy renovation were then defined as the cumulative combination of the sorted measures. The reason for analysing the combination of considered measures is the interaction effects of them on the heat losses from building envelope. In this study, the total investment cost of energy renovation packages are the linear summation of individual measures costs. While in reality, the total cost of a renovation package may be lesser due to the volume effect of the work. This effect was not considered in this study. Table 3 shows the investment cost of the energy renovation measures assuming that the building requires renovation for repair and maintenance purpose.

Table 4 presents the investment cost of energy renovation measures for the case that the initial state of the building is not in need of repair and maintenance work and the renovation is considered only for the purpose of heat loss reduction from the building envelope.

The cost of adding extra insulation on the attic floor of the building current state is estimated to be €8,490. This is the only difference in investment cost for current state of the building compare to its initial state assuming no need for repair and maintenance work. In addition to the uncertainty in the renovation costs, there are other uncertainties that may influence the cost-effectiveness of energy renovation. We assumed cases where discount rate changes between 6, 5, 4 and 3 %. We also assumed that energy price increase over the lifespan of the building changes between 1.9 and 4 %.

PRIMARY ENERGY AND CO_2 ANALYSIS

Primary energy use and CO_2 emission for the different energy renovation scenarios were analysed using the ENSYST software (Karlsson 2003). The software calculates primary energy use and CO_2 emission considering the entire energy chain from natural resource extraction to final energy supply, taking into account the fuel inputs at each stage in the energy system chain and the energy efficiency of each process. The case-study building is connected to the Växjö's DH system, which consists of different production units. In 2011 the DH production of the system was 619.2 GWh, of which biomass-based CHP plant, oil-fired CHP plant, biomass-based heat only boiler (HOB) and light-oil HOB accounted 82.2 %, 2.0 %, 13.3 % and 2.4 %, respectively. This data was used in the ENSYST software, with assumed DH distribution loss of 7 %. The assumed DH distribution losses for the connected multi-story buildings is based on similar studies (e.g. Gustavsson, Joelsson and Sather (2010) Dodoo, Gustavsson and Sather (2010), Gustavsson, Dodoo, Truong et al. (2011)). A CHP plant cogenerates heat and electricity and therefore an allocation issue may arise. Here we allocated the cogenerated electricity using the subtraction method, assuming that the cogenerated power replaces electricity from a similar technology using a stand-alone plant (Gustavsson and Karlsson, 2006).

Results

Tables 5 to 7 show the results of the final energy modelling of the building and the cost-effectiveness analysis of the considered energy renovation measures. Tables 5, 6 and 7 present the cases of initial state of the building with a need for repair and maintenance renovation, initial state of the building without need for repair and maintenance renovation and the current state of the building with no need for repair and maintenance renovation, respectively.

The calculated ratios of investment per saved energy price for initial state of the building (Tables 5 and 6) suggest that improving attic floor insulation is the most cost-effective energy renovation following with the combination of attic floor

Table 5. Final energy use of the building in its initial state before and after energy renovation and the cost-effectiveness of considered energy renovation measures. The energy renovation is assumed as part of a major renovation of building.

Energy renovation measures	Final energy use for space heating, kWh/m^2/year	Saved energy price, €/year (in 2012)	Investment cost (cost of efficiency measure implementation), €	NPV of saved energy price (50 years life time), €	Investment / NPV of saved final energy price (after 50 years)
Initial state of building (reference)	107.6	0	0	0	n/a
Attic floor extra insulation	102.8	370	7 900	7 800	1.01
+ Basement walls extra insulation	97.8	770	24 700	16 500	1.49
+ Exterior walls extra insulation	78.1	2320	92 200	49 600	1.86
+ Windows replacement	54.2	4350	182 800	93 100	1.96
+ Doors replacement	46.9	4930	211 600	105 500	2.01

Table 6. Final energy use of the building in its initial state before and after energy renovation and cost-effectiveness of considered energy renovation measures when no need is assumed for building repair and maintenance.

Energy renovation measures	Final energy use for space heating, kWh/m^2/year	Saved energy price, €/year (in 2012)	Investment cost (cost of efficiency measure implementation), €	NPV of saved energy price (50 years life time), €	Investment / NPV of saved final energy price (after 50 years)
Initial state of building (reference)	107.6	0	0	0	n/a
Attic floor extra insulation	102.8	370	10 900	7 800	1.39
+ Basement walls extra insulation	97.8	770	28 800	16 500	1.74
+ Exterior walls extra insulation	78.1	2320	107 500	49 600	2.17
+ Windows replacement	54.2	4350	228 400	93 100	2.45
+ Doors replacement	46.9	4930	266 800	105 500	2.53

Table 7. Final energy use of the building in its current state before and after energy renovation and cost-effectiveness of considered energy renovation measures when no need is assumed for building repair and maintenance.

Energy renovation measures	Final energy use for space heating, kWh/m^2/year	Saved energy price, €/year (in 2012)	Investment cost (cost of efficiency measure implementation), €	NPV of saved energy price (50 years life time), €	Investment / NPV of saved final energy price (after 50 years)
Current state of building (reference)	98.57	0	0	0	n/a
Attic floor extra insulation	97.57	80	8 500	1 700	5.15
+ Basement walls extra insulation	92.57	470	26 400	10 000	2.64
+ Exterior walls extra insulation	72.99	2 010	105 200	42 900	2.45
+ Windows replacement	53.34	3 700	230 400	79 300	2.91
+ Doors replacement	46.04	4 280	268 800	91 600	2.93

and basement walls insulation improvement. However, none of the considered measures are profitable from end-use economic point of view with our economic assumption (i.e. 6 % discount rate and 1.9 % annual energy price increase) over the assumed 50-year lifespan of the measures.

The ratios of investment per saved final energy price suggest that energy renovation measures for initial state of the building are more cost-effective than the same measures considered for the energy renovation of the building in its current state. For example improving attic floor insulation is the least cost-effective measure in the current state of the building. This is because an extra insulation was added on attic floor 10 years ago (Jansson et al., 2011). We assumed a scenario that the case-study building is in need for a major renovation for the purpose of repair and maintenance (Table 5). In such a case part of the investment is allocated to renovation and the cost-effectiveness is improved.

Figure 3 illustrates the sensitivity analysis results of the cost-effectiveness for different discount rates and annual energy price increase for initial state of the building. The results in-

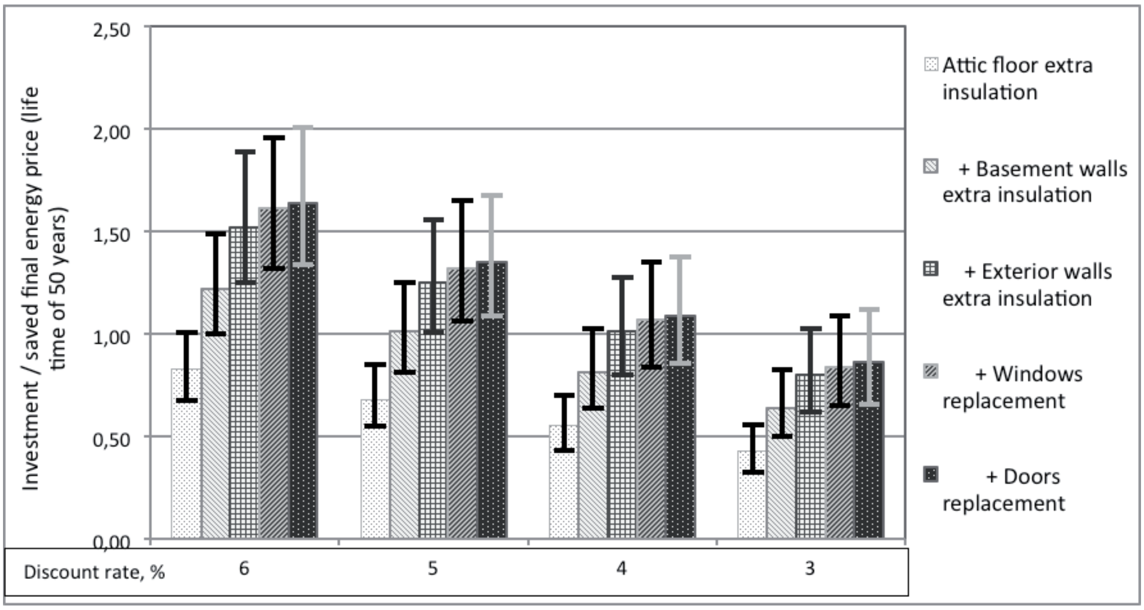

Figure 3. The influence of varied discount rates and annual energy price increase on cost-effectiveness. Error bars represent annual energy price increase between 1.9 % to 4 %. The main bars are drawn for 3 % of energy price increase.

dicate significant influence of annual increase in energy price and, specially, discount rate on the cost-effectiveness. Error bars represent the increased energy price changes from 1.9 % (highest point) to 4 % (lowest point). This Figure is for the scenario where the building is in its initial state and is in need for repair and maintenance work (the scenario in Table 5).

Figure 4 and 5 illustrates the space heating primary energy use and resulting CO_2 emission when implementing the different energy renovation consecutively, respectively.

Discussion and conclusions

The implications of energy efficiency measures for building envelope elements on cost, primary energy use and CO_2 emission were analysed in this study. We calculated the energy renovation cost per saved energy price for different renovation packages (combinations of energy efficiency measures), different discount rates and energy price increase during 50-year lifespan. Building characteristics, energy efficiency measures and economic assumptions (i.e. the cost of implementing energy efficiency measures, discount rate, energy price and its increase over time) may change the cost-effectiveness of building energy renovation. Therefore providing a certain general answer for profitability of energy renovation could not be suggested.

The analysed energy renovation scenarios were not economically profitable assuming 6 % discount rate and 1.9 % annual energy price increase during a 50-year lifespan. A sensitivity analysis was performed to study the contribution of economic parameters to the cost-effectiveness of energy renovation of building elements. Sensitivity analysis results demonstrate the significant influence of discount rate and energy price increase on the cost-effectiveness of energy renovation. All considered energy renovation packages appeared to be cost-effective assuming 3 % discount rate with annual energy price increase of 3 %. The reduction of discount rate from 6 % to 3 %, improved the cost-effectiveness of energy renovation between 44 % and 51 % depending on the annual increase of energy price (changes between 1.9 % and 4 % annually).

Thermal performance condition of the building envelope elements before renovation appeared to play an important role in the cost-effectiveness of the energy renovation. This was observed by comparing the initial and current states of the attic floor. Improved attic insulation was the least cost-effective measure (investment per saved energy price of 5.2) among the considered energy renovation measures for the current state of the building. While this measure appeared to be the most cost-effective energy renovation measure (investment per saved energy price of 1.0) for the initial state of the building assuming 6 % discount rate and 1.9 % energy price increase. That is due to the current state of attic which has an additional layer of insulation compared to the initial state. The extra insulation layer reduced the contribution of the attic floor to the heat loss from the building envelope. This suggests that the contribution of different building elements to the building envelope total heat loss could be one of the driving factors for the building energy renovation strategy.

The investment cost of energy renovation is a significant parameter that may largely vary as the insulation materials, doors and windows and their installation costs may change significantly from one case to another. We assumed a case that the energy renovation is considered as a side benefit of a required renovation for repair and maintenance purpose. In this scenario the energy renovation cost is reduced and the cost-effectiveness of efficiency measures is improved. This improvement varied between 14 % and 27 % depending on the energy renovation measure and on the parts of investment costs that are allocated to the renovation (e.g. the costs of scaffolding, ground excavation for basement walls insulation and the installation cost of doors and windows).

The energy renovation packages of considered energy efficiency measures were chosen in the order of the cost-effectiveness. The results showed that improving attic floor insulation and the combination of all considered measures are the most

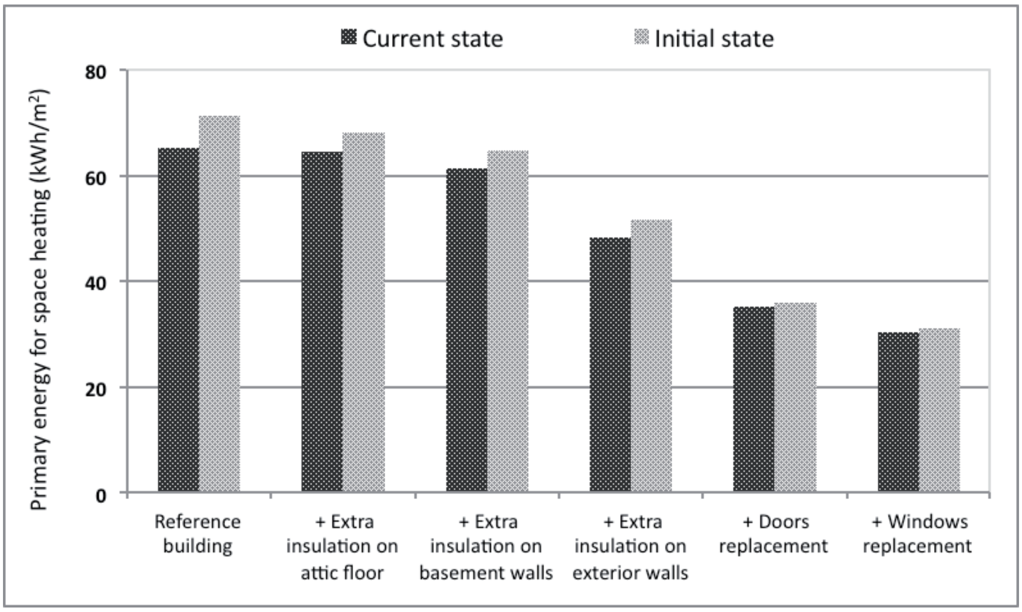

Figure 4. Annual primary energy use for space heating when implementing building envelope measures.

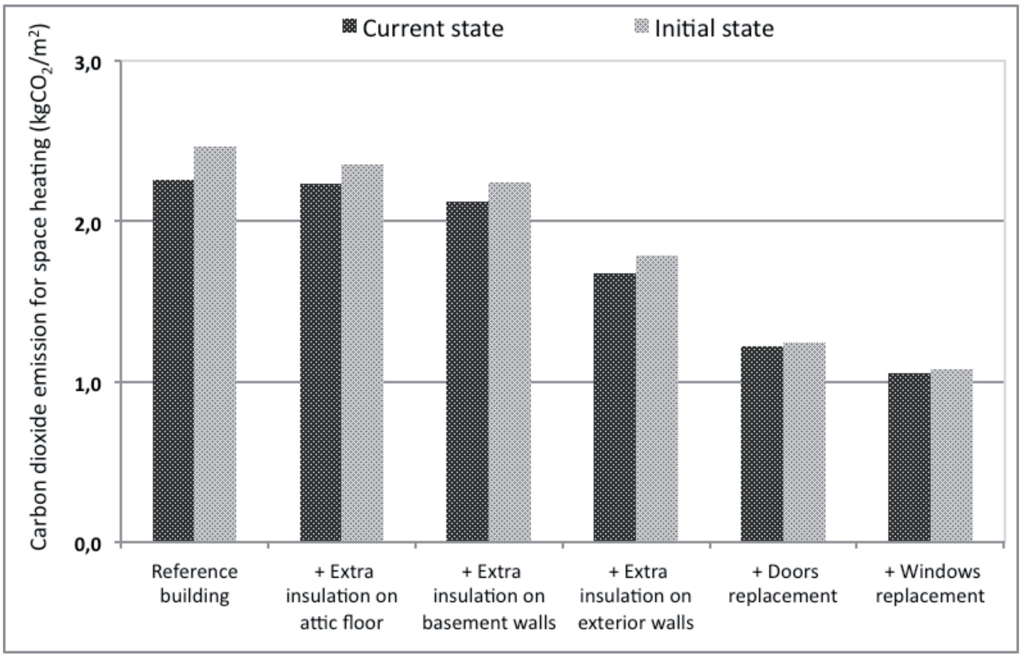

Figure 5. Annual CO_2 emission for space heating when implementing different building envelope measures consecutively.

and the least cost-effective renovation packages for the initial state of the building, respectively. Therefore, as far as the building owner economic perspective is concerned, improving attic floor insulation could be a certain decision for energy renovation to make following with the package of attic floor and basement walls extra insulation for the initial state of the building. However, focusing on the contribution of considered energy renovation packages to primary energy and CO_2 emission reduction may change the whole decision making strategy for building energy renovation. The CO_2 emission reduction due to implementing all considered energy efficiency measures is around 13 times greater than the CO_2 emission reduction due to improving attic floor insulation. While the renovation package of all considered measures is 2 times less cost-effective than improving attic floor insulation, assuming the initial state of the building. This suggests that different perspectives with different priorities may provide distinct strategies for a building energy renovation.

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