Effects of different techno-economic regimes on viability of deep energy renovation of an existing Swedish multi-family building

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Keywords

deep renovations, energy savings, refurbishment, deep renovations, energy efficiency measures, existing buildings, cost effectiveness

Abstract

This paper presents and demonstrates a method for analysis of cost-effectiveness of energy efficiency measures for buildings. Based on the method, cost-optimal energy efficiency measures are calculated considering total and marginal investment costs as well as net present value of energy savings for the measures under different technical and economic scenario. The method is applied to a 1970s Swedish multi-family building to explore the profitability of different energy renovation measures when implemented individually or in packages. The measures analysed include improved thermal insulation for exterior and basement walls as well as attic floor, improved new windows, efficient electrical appliances, efficient water taps, and exhaust air ventilation heat recovery systems. Our results show that the economic viability of the retrofit measures is sensitive to the techno-economic parameters used including, real discount rates, energy price increases and technical lifetime of retrofit measures. Still, about 34–51 % reduction of final heat demands is economically viable for the analysed building. Resource-efficient taps is the most cost-effective measure while improved thermal envelope insulation for exterior walls is the least cost-effective among the measures analysed for the studied building. This study shows the significance of different technical and economic parameters in achieving deep-energy savings from renovation of a building in a cold climate.

Introduction

Energy renovation of the existing building stock is increasingly discussed as crucial for a resource-efficient low-carbon built environment [1–3]. In the EU, 35 % of the building stock is reported to be over 50 years old [4] and about 110 million buildings are suggested to be in need of some renovation or modernisation [5]. These present large potentials to reduce primary energy use, through energy efficiency renovation measures. Member states of the EU are required under the energy efficiency directive to set-out long term investment strategies to promote energy efficient renovation of buildings [6]. In Sweden an inventory compiled in the mid-2000s noted that 65 % of the residential building stock was built before the oil crisis in the 1970s [7], when energy efficiency was less emphasized in the building code. About one million homes were built in Sweden between 1965 and 1974 in a national project known as million homes program [8]. These buildings are due for renovation in the near term and there have been growing discussion about cost-effective strategies to improve their energy efficiency [9, 10].

Literature shows that significant energy savings and CO_2 emission reductions may be achieved when energy efficiency measures are implemented in existing buildings. An analysis by Zinko [11] indicated that total primary energy use and CO_2 emission could be reduced by 53 % and 29 %, respectively, with implementation of energy efficiency renovation measures for multi-family buildings in Sweden. The analysis considered space heating, domestic hot water, and electricity for household and facility management and used primary energy factors of 1.7 for purchased heat and 3.0 for purchased electricity. Based on detailed analysis of the complete energy chains from natural resources extraction to supply of final energy services, Dodoo et al. [12] estimated that total primary energy use for space and tap water heating, and ventilation could be reduced by 26-58 %, when a Swedish multi-family building constructed in mid-1990s is renovated to passive house standard. Tommerup and Svendsen [13] showed that final space heating demand of a 1960s Danish multi-storey apartment building can be reduced by 76 % with application of improved building envelope insulation, efficient new windows and mechanical ventilation with heat recovery of exhaust air. Cost-effectiveness is a vital factor in implementation of building energy renovation measures [1], as it offers economic incentive for building owners to adopt energy saving measures. Various methods for selection and optimization of cost-effective energy efficiency measures for building are noted in literature (e.g. [14–16]). The EU energy performance of buildings directive emphasize the need to take cost-effectiveness into account when measures are implemented for improved energy efficiency in buildings [17].

In this paper, we present a method for analysis of cost-optimal building energy efficiency measures and explore the final energy savings and cost-effectiveness of various renovation measures for a Swedish multi-family building under different techno-economic regimes. We analyse individual as well as packages of energy renovation measures for the building. Our analysis encompasses building envelope retrofit measures including additional insulation to basement walls, exterior walls, and roof, and also improved new windows; as well as non-building envelope retrofits including efficient electric appliances and lighting, efficient water taps, and installation of exhaust air heat recovery units in ventilation systems.

Study descriptions

ANALYSED BUILDING

The analysed building is a typical Swedish multi-family building constructed in 1972, during the million homes program. It is a municipally owned three-storey concrete-frame building (Figure 1) with a basement and is situated in Ronneby municipality, in southern Sweden. The building contains 27 apartments and has a heated living floor area of 2000 m^2. Table 1 gives the areas and current U-values of the building's envelope elements. The airtightness of the building is assumed to be 0.8 l/s m^2 at 50 Pa, based on [18]. The building has mechanical exhaust ventilation system and is district heated. The indoor air temperatures of the apartments in the building were measured during the 2014/2015 heating season and found to be 21.8 °C on the average.

Figure 1. The analysed concrete-frame building in Ronneby municipality, Sweden.

BUILDING RENOVATION NEEDS AND MEASURES ANALYSED

The building's structure and façades are in good physical condition. However, the windows require some repairs and painting, and have not been replaced since the building was constructed. The basement walls are uninsulated while the exterior walls consist of 95–120 mm mineral wool and polystyrene insulations. The insulation of the attic floor was originally 120 mm and was recently retrofitted to 350 mm. Still, the attic has space to take up additional insulation. In all, the building's insulation level is low compared to the envelope insulation thicknesses of 300–500 mm suggested to reach the energy level of the current Swedish building code [19]. The building's exhaust ventilation air channels are in good condition and slots have been created in the exterior walls around the radiators to address a problem of insufficient air supply for ventilation.

In this analysis, the energy renovation measures analysed for the building include: improved envelope insulation for attic floor, basement walls, and exterior walls; improved windows and doors; resource-efficient taps and accessories; incorporation of ventilation channels for supply air and a ventilation heat recovery (VHR) unit; efficient household appliances and lighting. Table 2 gives details of the configurations of the analysed measures.

Methods

We propose a two-step approach to determine cost-optimal energy-efficiency measures and thereby analyse cost-effectiveness of different energy renovation measures for buildings. As a first step the energy renovation measures are analysed and cost-optimised individually. Based on this, packages of energy renovation measures are analysed in the next step. Total and marginal investment costs of the measures and packages are compared against the net present value (NPV) of resulting total and marginal energy savings over the lifetime of the measures. Total investment costs encompass material costs, installation costs, and costs for preparatory as well as ancillary works, e.g. scaffold erection. Marginal investment cost for an incremental measure is the difference in total investment cost of the measure relative to a preceding applied measure. The ratio of the NPV of the savings per investment cost must be at least 1 for a measure or a package to be cost-effective.

TECHNO-ECONOMIC SCENARIOS

Key issues connected to cost-effectiveness analyses for building energy efficiency measures include investment costs of measures, energy and cost savings of measures, lifetime of measures, discount rate and energy price changes over time. In this study, the focus is on energy renovation of existing building and a 50-year lifetime is assumed for analysed measures, based on plausible remaining service life of the studied building. The implication of using a 40- or 60-year lifetime is also explored. For the discount rate and energy price changes, three scenarios are analysed to determine their implications for cost-effectiveness of various energy renovation measures. The real discount rates and real annual energy price changes for the scenarios including business-as-usual (BAU), intermediate and sustainability scenario are shown in Table 3.

Table 1. Architectural and thermal characteristics of the analysed building.

Building element	U-value (W/m² K)	Area (m²)
Attic floor	0.11	688.0
Basement walls	1.33/1.44	57.2/286.9
Doors (clear glass windows in doors)	3.0	84.5
Exterior walls (wood panels & brick facades)	0.311/0.341/0.346	292.0/194.0/565.0
Foundation (slab on ground)	0.26	688.0
Windows (clear glass windows)	2.9	194.5

Table 2. Analysed individual energy renovation measures.

Energy renovation measure	Description
Attic insulation improvement	50 to 500 mm mineral wool insulation
Basement walls insulation	50 to 350 mm styrofoam insulation panels
Exterior walls insulation improvement	45 to 510 mm mineral wool insulation
Improved windows	1.5 to 0.7 W/m² K U-value
Resource-efficient taps	Faucet aerators for kitchen & washbasin taps and showers
Efficient appliances and lighting	Best available technologies
Ventilation heat recovery system	Central and semi-centralized air handing units (AHUs)

Table 3. Scenarios analysed for real discount rate and annual energy price increase.

Scenario	Real discount rate (%)	Real annual energy price increase (%)
Business-as-usual (BAU)	5	1
Intermediate	3	2
Sustainability	1	3

ENERGY BALANCE AND SAVINGS MODELLING

In this study, the energy balance of the studied building and final energy savings of the energy renovation measures are calculated in hourly time-step using the VIP-Energy simulation program (version 3.1.3)[20], which is validated by the IEA BESTEST [21]. The final energy use and energy savings are simulated using the 2013 hourly weather data for the city of Ronneby (latitude 56.26, longitude 15.27), and with input parameter values for the Swedish context documented by Dodoo et al. [22, 23]. The 2013 weather data is obtained from the meteonorm database [24] and shows that average outdoor temperatures, solar radiation, wind speed and relative humidity for Ronneby were 8 °C, 116 W/m², 4 m/s and 82 %, respectively. In the simulations, space heating temperature set-point of 22 °C is assumed for the building's living area based on measured indoor temperature in each apartment and 18 °C for the common areas. However, temperature set-point in the living area is assumed to be lowered to 21 °C when new improved windows are implemented, based on Bonakdar et al. [15]. The final energy savings for switching to energy efficient appliances and lighting is calculated based on typical European data from Aníbal de Almeida et al. [25], who conducted a large scale monitoring of household equipment. The final energy savings is calculated considering non-tenants owned equipment in the building (freezer, refrigerator, washing machine, clothes dryer, dishwasher, oven/cooker, facility lights) as well as tenants owned electronics, e.g. TVs, VCR/DVD players, cable boxes, personal computers. Tap water heating reduction of 40 % and cold water savings of 64 m3 / person are assumed when resource-efficient faucets including taps replace conventional alternatives, based on [26] and [27], respectively. Starting point of the energy savings modelling is application of measures that consequently reduce internal heat gains including efficient electric equipment and reduced hot water recirculation losses. Hence heat savings is improved when envelope renovation measures are applied.

ECONOMIC MODELLING

Based on the calculated final energy savings, the NPV of total and marginal energy cost savings are calculated for the different scenarios using the 2015 district heating tariff for Ronneby [28] and Swedish average electricity price data from [29]. Optimisations are done considering different configuration for single measures (Table 3). For thermal envelope insulation, a range of thicknesses are analysed while for windows a variety of improved U-values are considered. For VHR, options with centralised or semi-centralized AHUs are analysed while for faucets and appliances the best technologies available are considered. The NPV of energy cost savings is calculated as:

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \quad (1)$$

where

n lifespan of measure (years)

t a specific year

C_t annual energy cost savings for a specific year

r discount rate

The energy cost savings is calculated as the net energy savings multiplied with energy price (district heat or electricity) considering assumed real annual energy price increase. The marginal saved energy for a measure is calculated as the difference in NPV of energy cost savings for the incremental measure with reference to the prior applied measure. The investment costs of the analysed building energy renovation measures are calculated using a model developed in spreadsheet and 2015/2016 Swedish building renovation works tariffs [30]. The calculated investment costs for each energy renovation measure include costs for materials and their on-site installations, as well as costs for required preparatory and ancillary works, e.g. installation of scaffold. The investment costs for new improved windows are estimated taking into account the need for repairs and maintenance of the existing windows. For the exterior walls, the investment cost calculations include costs involved in extending roof overhangs and windows and door sills due to increased insulations. The investment costs for taps and electric appliances are calculated assuming need for replacement. The other analysed building elements as attic floor and exterior walls are in good physical conditions and investment costs for their energy renovations are calculated assuming no need for repairs or maintenance. The calculated costs are expressed in euros, using the year 2015 average exchange rate of €9.23/SEK. The marginal cost of investment for a measure is calculated as the change in investment cost relative to the preceding applied measure.

Results

The final energy implications of replacing various existing household appliances and lighting with efficient alternatives are shown in Table 4, as well as associated total investment costs. In all, annual electricity savings of 30.2 MWh (15.1 kWh/m^2) is achieved while annual heat use is increased by 22.7 MWh (11.4 kWh/m^2) with all the efficient electric equipment. Annual household electricity use is reduced from 59.8 MWh (29.9 kWh/m^2) to 46.6 MWh (23.3 kWh/m^2) with only the efficient non-tenants owned equipment and to 29.6 MWh (14.8 kWh/m^2) with all efficient appliances in the building including non-tenants as well as tenants owned equipment.

The final energy and cold water savings as well as investment costs associated with replacement of existing taps and faucets with resource-efficient alternatives are shown in Table 5. The calculated investment costs given outside the brackets are for one-time replacement while those inside the brackets are for three replacements corresponding to a 50-year period. Resource-efficient faucets including taps give annual final heating energy and cold water savings of 20 MWh (10 kWh/m^2) and 3,456 m^3, respectively.

Annual final energy demands of the building including space heating, tap water heating, and electricity for ventilation and household purposes are given in Table 6. Annual heat use is increased from 100 to 114 kWh/m^2 when measures which results in reduced internal heat gains, including efficient electric equipment and reduced hot water recirculation losses, are implemented.

The impact of different thicknesses of insulations for attic floor, exterior walls and basement walls on envelope U-value and space heating demand of the building are summarized in Tables 7–9. Also presented in the tables are total and marginal investment costs for the different insulations thicknesses. Space heating demands reduced between 0.5 to 2.3 % with additional attic floor insulation thicknesses of 50 to 500 mm, and between 4.1 to 12.3 % with additional exterior wall insulation thicknesses of 45 to 510 mm. Basement wall insulation thicknesses ranging between 50 to 350 mm resulted in space heating demand reductions of 5.2 to 8 %.

Table 10 gives the final heat savings, total and marginal investment costs, u-values and total solar transmittance (g-values) for different improved new window options for the building. Space heating reductions ranging from 24.1 to 32.8 % are achievable with the options. The changes in total final energy savings are quite modest compared to the marginal investment costs for windows with U-value of 1.0 to 0.7 W/m^2 K, as more advanced technology is typically required to achieve such windows, e.g. low-emissivity coating and infill gasses.

Table 11 presents the final heat savings and total investment costs for installation of ventilation heat recovery (VHR) systems with centralised or semi-centralised AHUs. Final heat savings of 18 to 19 % is obtained when the VHR systems are modelled for the building. The option with semi-centralised

Table 4. Energy savings and investment costs for implementation of efficient household appliances including lighting. The investment costs given outside the brackets are for one-time replacement while those inside the brackets are for three replacements corresponding to a 50-year period.

Efficient appliances and lighting	Household electricity use (MWh/year)	Electricity savings (MWh/year)	Increase space heat use (MWh/year)	Total investment cost (k€)
Initial	59.8	–	–	–
Freezer	54.8	5.0	2.50	3.9 (11.8)
Refrigerator	57.9	1.9	0.93	3.9 (11.8)
Washing machine	58.5	1.3	0.16	3.8 (11.4)
Clothes dryer	58.3	1.5	0.76	3.3 (10.0)
Dishwasher	58.6	1.2	0.16	4.4 (13.1)
Oven/cooker	58.2	1.6	0.58	9.4 (28.2)
Lights (Facility)	59.1	0.7	0.04	0.2 (0.6)
All above (non-tenants owned equipment)	*46.6*	*13.2*	*5.2*	*28.9 (86.9)*
All equipment (non-tenants & tenants owned)	29.6	30.2	22.7	

Table 5. Final heat and cold water savings, and investment costs for implementation of resource-efficient taps and faucets. The investment costs given outside the brackets are for one-time replacement while those inside the brackets are for three replacements corresponding to a 50-year period.

Taps and faucets accessories	Tap water use (MWh/year)	Final heat savings (MWh/year)	Total water savings (m^3/year)	Total investment cost (k€)
Initial	49.8	–	–	–
Resource-efficient	29.8	20	3,456	1.3 (3.9)

Table 6. Annual final energy demand of the building without (outside brackets) and with (inside brackets) measures to reduce hot water circulation losses and household electricity use.

Building	Final energy demand (kWh/m² [living area])				
	Space heating	Tap water heating	Ventilation electricity	Household electricity	Total
Existing	100.0	24.9	3.0	29.9	157.8
+ Reduced hot water recirculation losses	102.7	24.9	3.0	29.9	160.5
+ Efficient appliances	114.1	24.9	3.0	14.8	156.8

Table 7. Improved U-values, final heat savings, and investment costs for implementation of different thicknesses of additional attic floor insulation.

Extra mineral wool insulation to roof attic	Improved U-value (W/m^2K)	Space heating use (MWh/year)	Final heat savings (MWh/year)	Total investment cost (k€)	Marginal investment cost (k€)
Initial	0.11	228.2	–	–	–
50 mm	0.098	227.1	1.1	7.7	–
100 mm	0.088	226.3	1.9	8.6	0.9
150 mm	0.079	225.6	2.6	10.4	1.8
200 mm	0.073	225.0	3.2	11.6	1.2
250 mm	0.067	224.6	3.6	13.4	1.8
300 mm	0.062	224.1	4.1	14.8	1.4
350 mm	0.058	223.8	4.4	17.2	2.4
400 mm	0.054	223.5	4.7	18.3	1.1
450 mm	0.051	223.2	5.0	20.8	2.5
500 mm	0.048	223.0	5.2	22.3	1.5

Table 8. Improved U-values, final heat savings, and investment costs for implementation of different thicknesses of additional exterior wall insulation.

Extra mineral wool insulation to exterior walls	Improved U-value (W/m^2K)	Space heating use (MWh /year)	Final heat savings (MWh/year)	Total investment cost (k€)	Marginal investment cost (k€)
Initial	0.311 / 0.346	228.2	–	–	–
45 mm	0.225 / 0.244	218.8	9.4	160.1	–
70 mm	0.197 / 0.212	215.4	12.7	165.1	5.0
95 mm	0.175 / 0.187	213.0	15.2	169.0	3.8
120 mm	0.158 / 0.168	211.0	17.2	172.4	3.4
195 mm	0.122 / 0.127	206.8	21.4	184.7	12.3
240 mm	0.107 / 0.112	205.2	23.0	198.8	14.0
290 mm	0.095 / 0.098	203.8	24.4	210.8	12.0
340 mm	0.085 / 0.087	202.6	25.6	214.5	3.7
390 mm	0.076 / 0.079	201.8	26.4	224.7	10.2
510 mm	0.062 / 0.064	200.2	28.0	249.0	24.3

Table 9. Improved U-values, final heat savings, and investment costs for implementation of different thicknesses of basement wall insulation.

Styrofoam insulation to basement walls	Improved U-value (W/m²K)	Space heating use (MWh/year)	Final heat savings (MWh/year)	Total investment cost (k€)	Marginal investment cost (k€)
Initial	1.33/1.44	228.2	–	–	–
50 mm	0.45/0.46	216.2	12.0	16.3	–
100 mm	0.27/0.28	213.3	14.9	22.2	5.8
150 mm	0.19/0.20	212.0	16.2	25.7	3.6
200 mm	0.151/0.152	211.2	17.0	31.7	5.9
250 mm	0.123/0.124	210.6	17.6	35.5	3.9
300 mm	0.10/0.11	210.2	18.0	41.2	5.6
350 mm	0.091	209.9	18.3	45.0	3.9

Table 10. Improved U- and g-values, final heat savings, and investment costs for implementation of different improved new windows.

Improved new windows	Total solar transmittance (g-value)	Space heating use (MWh/year)	Final heat savings (MWh/year)	Total investment cost (k€)	Marginal investment cost (k€)
Initial	0.76	228.2	–	–	–
1.5 W/m² K	0.64	173.1	55.1	92.8	–
1.2 W/m² K	0.62	164.8	63.4	106.6	13.8
1.1 W/m² K	0.58	162.8	65.4	115.9	9.3
1.0 W/m² K	0.54	160.9	67.3	140.8	24.9
0.9 W/m² K	0.52	158.4	69.8	158.4	17.6
0.8 W/m² K	0.51	155.8	72.4	180.1	21.8
0.7 W/m² K	0.50	153.2	75.0	209.2	29.0

Table 11. Final energy savings and investment costs for implementation of different VHR systems. The investment costs are given for a 25-year (outside brackets) or for a 50-year period (inside brackets).

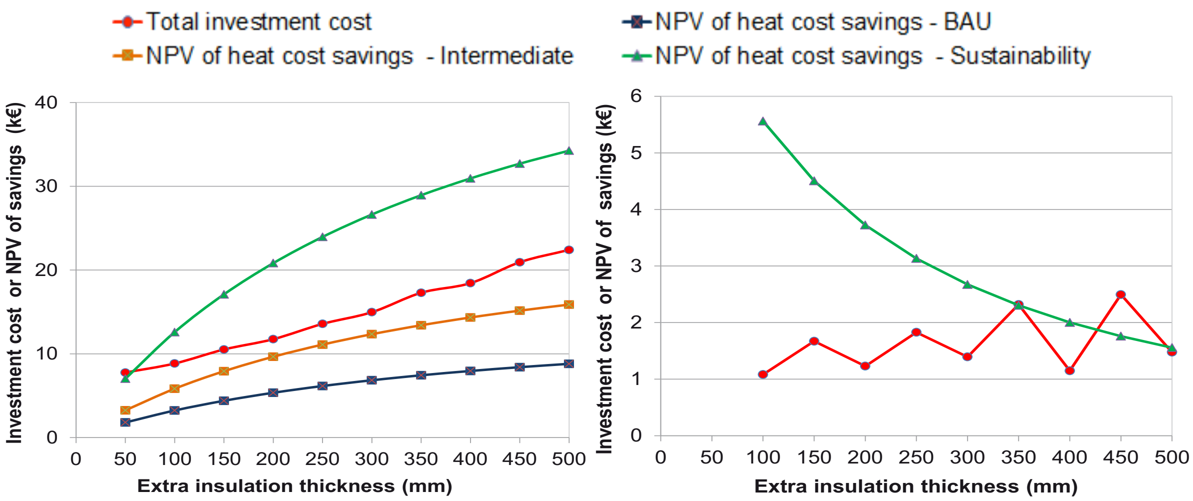
Ventilation system with heat recovery	Space heating use (MWh/year)	Final heat savings (MWh/year)	Increase electricity use (MWh/year)	Total investment cost (k€)
Initial	228.2	–	–	–
Centralised unit	186.4	41.8	2.2	70.8 (141.6)
Semi-centralised (3) units	185.0	43.2	1.4	84.1 (168.2)

Table 12. NPV of total net energy cost savings for 50 years and the ratios of the NPV to total investment costs for efficient electric appliances including lighting for different scenarios.

Description	NPV of total net energy cost savings (k€)			NPV of total net energy cost savings (€)/ total investment cost (€)		
	BAU	Intermediate	Sustainability	BAU	Intermediate	Sustainability
Freezer	18.8	33.9	73.2	1.6	2.9	6.2
Refrigerator	3.4	6.1	13.2	0.3	0.5	1.1
Washing machine	4.9	8.9	19.1	0.4	0.8	1.7
Clothes dryer	4.9	8.8	19.0	0.5	0.9	1.9
Dishwasher	4.8	8.7	18.7	0.4	0.7	1.4
Oven/cooker	5.8	10.4	22.4	0.2	0.4	0.8
Lights (Facility)	2.6	4.7	10.2	4.1	7.4	16.0
All above (non-tenant owned)	47.9	86.3	186.2	0.6	1.0	2.2

Table 13. NPV of total energy and water cost savings and the ratios of the NPV to total investment costs for implementation of resource-efficient taps under different scenarios with a time horizon of 50 years.

Description	NPV of total energy and water savings (k€)			NPV of total energy and water savings (€) / total investment cost (€)		
	BAU	Intermediate	Sustainability	BAU	Intermediate	Sustainability
Resource-efficient	247.4	445.9	962.0	63.4	114.3	246.7



(a) Total optimisations (b) Marginal optimisations

Figure 2. Total investment costs and total NPV of heat cost savings (left) and marginal investment costs and marginal NPV of heat cost savings (right) for various thicknesses of attic insulation. The NPV of heat cost savings is calculated for various scenarios of 50 years.

AHUs gives relatively lower ventilation electricity use and slightly more final heat savings but results in about 15 % higher investment cost, in contrast to that with centralised AHU.

Table 12 shows that all non-tenant owned efficient equipment together are cost-effective for intermediate and sustainability scenarios, but not for BAU scenario. For the BAU scenario, only efficient lighting and freezer are cost-effective when considering the equipment individually. Lighting equipment is the most while oven/cooker is the least cost-effective when considering the equipment individually. Increased cost for heating is considered.

Table 13 shows the NPV of total energy and water cost savings as well as the ratios of the NPVs to total investment costs for resource-efficient faucets and taps, for different scenarios with a time horizon of 50 years. The ratios range from 52.9 to 204.7, showing that the faucets are substantially cost-effective under all scenarios.

Figures 2–4 show the NPV of total and marginal heat cost savings for improved insulation for attic floor, exterior and basement walls, for different scenarios with a time period of 50 years. Also shown are the total and marginal investment costs for the measures. In Figure 5, similar results for improved new windows are shown. For the marginal optimisations, optimal thickness for insulation and U-values for window occurs around where the curve for NPV of heat cost savings intersects that for investment costs. In Figure 2, the total optimisations show that additional attic insulation for the building is only cost-effective under sustainability scenario and the marginal optimisations show that optimal attic floor insulation is 500 mm for this scenario. Figure 3 shows that additional exterior walls insulation is not cost-effective for all scenarios as the total investment costs are higher than the NPV of total heat cost savings, and hence no marginal optimisation is done in this case. Basement wall insulation is cost-effective under all scenarios (Figure 4). However for BAU scenario, total investment costs are higher than NPV of total heat cost savings after more than150 mm insulation for basement walls. The marginal optimisations noticeably show optimal basement wall insulation of 150 mm for both intermediate and sustainability scenarios. For BAU scenario, the optimal basement wall insulation is 50 mm as this insulation thickness is cost-effective in the total optimisations and other insulation thicknesses above this are not cost-effective in the marginal optimisations. However, 200 mm of basement wall insulation is about cost-effective for the sustainability scenario. The total optimisations in Figure 5 show that all the improved new windows are cost-effective under intermediate and sustainability scenarios while under BAU scenario only windows of 1.2 to 1.5 W/m^{2}K U-values are cost-effective. The marginal calculations show that the optimal windows U-values are 1.2, 1.2 and 1.1 W/ m^2 K for BAU, intermediate and sustainability scenarios, respectively. However, a window with U-value of 0.9 W/m^{2}K is about cost-effective under sustainability scenario.

Table 14 show the NPVs of net energy cost savings and the ratios of NPVs to investment costs for the VHR systems with centralised or semi-centralised AHUs. Both types of system are

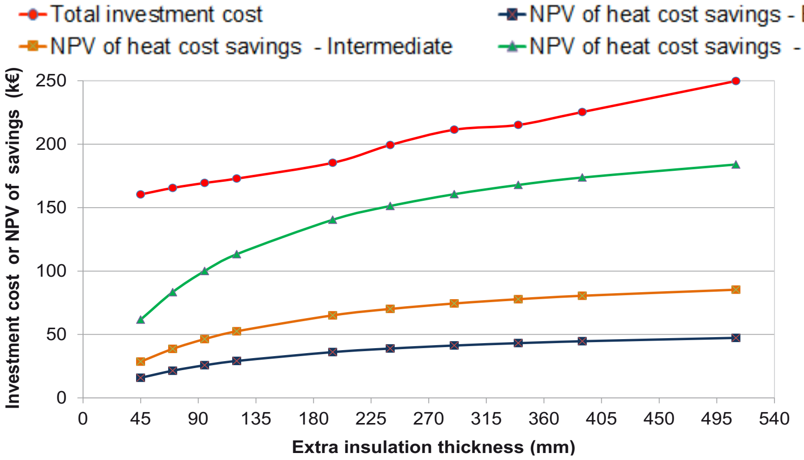
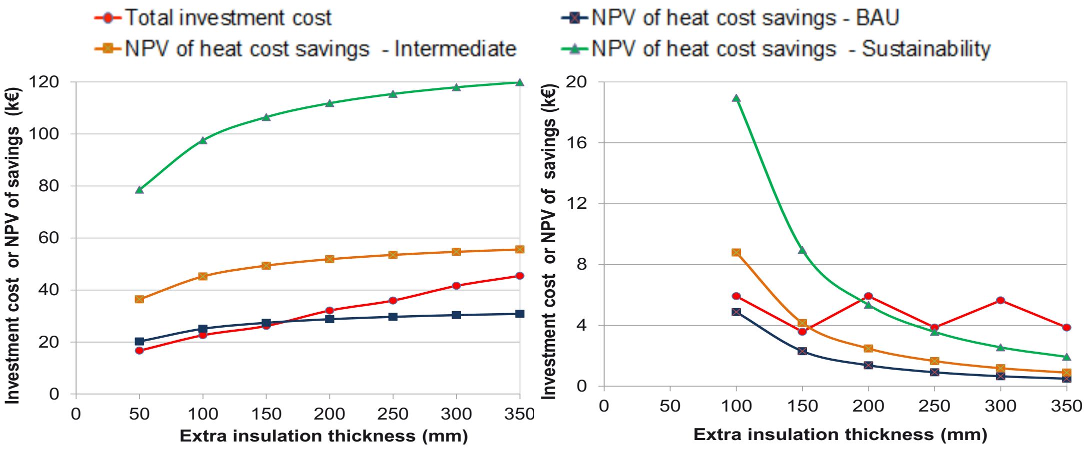
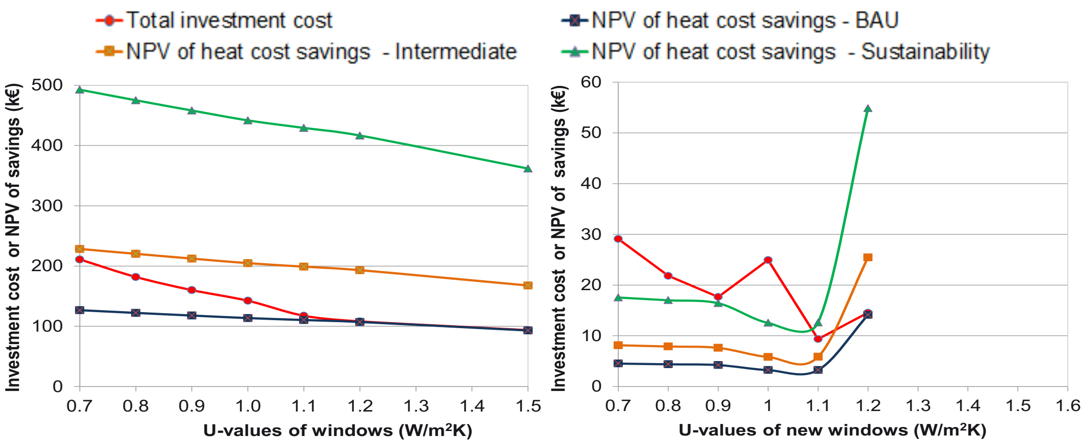


Figure 3. Total investment costs and total NPV of heat cost savings for various thicknesses of exterior wall insulation. The NPV of heat cost savings is computed for various scenarios of 50 years.



(a) Total optimisations (b) Marginal optimisations

Figure 4. Total investment costs and total NPV of heat cost savings (left) and marginal investment costs and marginal NPV of heat cost savings (right) for various thicknesses of basement insulation. The NPV of heat cost savings is computed for various scenarios of 50 years.



(a) Total optimisations (b) Marginal optimisations

Figure 5. Total investment costs and total NPV of heat cost savings (left) and marginal investment costs and marginal NPV of heat cost savings (right) for various improved new windows. The NPV of heat cost savings is computed for various scenarios of 50 years.

Table 14. NPV of total net energy cost savings for 50 years and the ratios of the NPV to total investment costs for VHR systems when implemented under different economic scenarios.

Ventilation system with heat recovery	NPV of total net energy cost savings (k€)			NPV of total net energy cost savings (€) / total investment cost (€)		
	BAU	Intermediate	Sustainability	BAU	Intermediate	Sustainability
Centralised AHU	61.6	111.0	239.5	0.4	0.8	1.7
Semi-centralised AHU	67.4	121.5	262.1	0.4	0.7	1.6

Table 15. Final energy savings and NPV of savings for 50 years for packages of cost-effective renovation measures (with replacement need for taps) for different economic scenarios.

Scenario	Package of measures	Annual heat savings (MWh/year)	Annual electricity savings (MWh/year)	Total investment cost (k€)	NPV of savings [energy & water] (k€)	NPV/ Investment cost
BAU	Efficient taps	20.0		3.9	247.4	63.4
	Efficient freezer & lighting		5.7 (22.7)	12.4	23.3 (92.7)	1.9
	50 mm basement insulation	12.0		16.3	20.3	1.2
	1.2 W/ m² K window	63.4		106.6	107.1	1.0
	Total	*95.4*	*5.7 (22.7)*	*139.2*	*398.1 (467.5)*	*2.9*
Intermediate	Efficient taps	20.0		3.9	445.9	114.3
	Efficient appliances		13.2 (30.2)	86.9	97.2 (222.3)	1.1
	150 mm basement insulation	16.2		25.7	49.3	1.9
	1.2 W/ m² K window	63.2		106.6	192.4	1.8
	Total	*99.4*	*13.2 (30.2)*	*223.1*	*784.8 (909.9)*	*3.5*
Sustainability	Efficient taps	20.0	–	3.9	962.1	246.7
	Efficient appliances		13.2 (30.2)	86.9	209.6 (479.6)	2.4
	150 mm basement insulation	16.2		25.7	106.4	4.1
	1.1 W/ m² K window	65.2		115.9	428.2	3.7
	500 mm attic insulation	4.9		22.3	32.2	1.4
	VHR system (centralised AHU)	34.2	-2.2	141.6	189.7	1.3
	Total	*140.5*	*11.0 (28.0)*	*396.3*	*1928.2 (2198.2)*	*4.9*

only cost-effective under sustainability scenario and the option with centralised AHU is slightly more cost-effective than that with semi-centralised AHUs.

In Table 15, the final energy savings, total investment costs and NPV of energy and water cost savings for packages of cost-effective renovation measures for the building are shown for different economic scenarios with a time horizon of 50 years. For BAU scenario with the replacement need for taps, the cost-effective package includes efficient taps, efficient appliances (lighting and freezer), 50 mm basement wall insulation and improved new windows with a U-value of 1.2 W/m² K. This gives annual final heat savings of 95.4 MWh and total electricity savings of 22.7 MWh when all the package measures are simulated together. These correspond to savings of 34 % and 35 % for final heat and electricity use, respectively. For the intermediate scenario with replacement need for taps, the cost-effective package includes efficient taps, efficient appliances together, 150 mm basement wall insulation and improved new windows with a U-value of 1.2 W/m² K. These give annual final heat and total electricity savings of 99.4 (36 %) and 30.2 (46 %) MWh, respectively. For the sustainability scenario, the cost-effective package include centralised VHR system and 500 mm of attic insulation besides efficient taps, efficient appliances together, 150 mm basement wall insulation and improved new windows with a U-value of 1.1 W/m² K, resulting in annual final heat and electricity savings of 140.5 MWh (51 %) and 28 (43%) MWh, respectively. Compared to the BAU scenario, the sustainability scenario gives 32 % and 19 % more total final heat and total electricity savings, respectively. Thus, the real discount rate and annual energy price used significantly influence the package of cost-effective energy renovation measures and thus the saved final heat and electricity.

Table 16 summarizes the cost-effective energy renovation packages for the building under different techno-economic scenarios including real discount rates, annual energy price increases and technical lifetime of renovation measures. The cost-effective packages of energy renovation measures are also shown for time horizons of 40 and 60 years besides the 50 years in the main analysis, to illustrate the sensitivity of different technical lifespan of the renovation measures when

Table 16. Packages of cost-effective renovation measures for the building under different techno-economic scenarios. 50 years lifespan is the period for the main analysis while 40 and 60 years lifespans show the effect of variations time horizon for the analysis.

Lifespan	BAU	Intermediate	Sustainability
40 years lifespan	Efficient taps Efficient appliances 50 mm basement insulation	Efficient taps Efficient appliances 100 mm basement insulation 1.2 W/m² K windows	Efficient taps Efficient appliances 150 mm basement insulation 1.2 W/m² K windows 400 mm attic insulation VHR system
50 years lifespan	Efficient taps Efficient appliances 50 mm basement insulation 1.2 W/m² K windows	Efficient taps Efficient appliances 150 mm basement insulation 1.2 W/m² K windows	Efficient taps Efficient appliances 150 mm basement insulation 1.1 W/m² K windows 500 mm attic insulation VHR system
60 years lifespan	Efficient taps Efficient appliances 50 mm basement insulation 1.2 W/m² K windows	Efficient taps Efficient appliances 150 mm basement insulation 1.2 W/m² K windows VHR system (centralised)	Efficient taps Efficient appliances 250 mm basement insulation 0.8 W/m² K windows 500 mm attic insulation VHR system

applied. VHR system is cost-effective under sustainability scenario for all lifespans and under intermediate scenario for a 60-year lifespan for centralised VHR system. Exterior wall insulation is the only analysed measure for the building that is not cost-effective under all considered economic scenarios and technical lifespans as the building's existing facades are in good physical condition.

Discussions and conclusions

In this study, we have proposed and demonstrated a method for analysis of cost-optimal building energy efficiency measures, and analysed the cost-effectiveness of energy efficiency renovation measures for a multi-family building. The method integrates energy balance simulation and economic calculations to determine cost-optimal measures, and compares the total and marginal investment costs of measures with the net present value of resulting total and marginal energy savings over the lifetime of the measures.

The analysis shows that calculated heat and electric savings from the measures vary considerably. Space heating reduction of 24 to 33 % is achievable with the configuration of improved new windows with U-values of 0.7–1.5 W/m^2 K while VHR systems with centralised or semi-centralised AHU result in space heat reductions of 18 to 19 %. The thermal insulation improvements considered for attic floor, basement walls and exterior walls resulted in space heating reduction in the range of 0.5–12.3 %. Household electricity use is about halved with efficient electric appliances and light. While reducing household electricity demand, the use of energy-efficient appliances and lighting also increases space heating demand and the overall implications of this need to be considered in a system perspective, as analysed in [31].

The results show that resource-efficient faucets including taps is the most cost-effective measure while exterior wall insulation is the least cost-effective measure for the building, for all economic scenarios and lifespans. In this study exterior wall insulation is the only measure that is not cost-effective under all the analysed techno-economic regimes, due to the good physical conditions of the walls of the analysed building. Attic floor insulation is cost-effective only under sustainability scenario, for all the analysed lifespans. A cost-effective package including VHR unit is achievable under sustainability scenario for all lifespans, and under intermediate scenario with a 60-years lifespan. The existing ventilation system of the analysed building has to be complemented with channels for supply air when installing VHR units. Hence if channels had been installed, instead of the current slots in the exterior walls, to address the problem of insufficient air supply in the studied building, cost could have been further reduced for the VHR units. The façades are relatively better for the analysed building compared to buildings from the same construction era [32], and investment costs for these elements may be reduced with need for repairs. The insulation of the attic floor here is an extreme as the attic floor had already recently been insulated but still application of more insulation could be cost-effective and practically possible.

This analysis shows that cost-effectiveness of building renovation measures is sensitive to the techno-economic parameters applied including, discount rates, annual energy price increases, lifespan of measures and building renovation needs. For the analysed building, the final heat savings for cost optimal energy renovation package varies between 34 % and 51 %, mostly depending on the choice of discount rate and energy price increase. This study shows the significance of different economic- and technical related parameters in achieving large energy savings from building renovation cost-efficiently.

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Acknowledgements

We gratefully acknowledge financial support from the Swedish District Heating Association, CEFUR-Ronneby kommun and the Swedish Energy Agency, and data support from Ronnebyhus AB.