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Cost Optimized Building Energy Retrofit Measures and Primary Energy Savings under Different Retrofitting Materials, Economic Scenarios, and Energy Supply †

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Abstract: We analyze conventional retrofit building materials, aluminum, rock, and glass wool materials and compared such materials with wood-based materials to understand the lifecycle primary energy implications of moving from non-renewable to wood-based materials. We calculate cost optimum retrofit measures for a multi-apartment building in a lifecycle perspective, and lifecycle primary energy savings of each optimized measure. The retrofit measures consist of the thermal improvement of windows with varied frame materials, as well as extra insulation of attic floor, basement walls, and external walls with varied insulation materials. The most renewable-based heat supply is from a bioenergy-based district heating (DH) system. We use the marginal cost difference method to calculate cost-optimized retrofit measures. The net present value of energy cost savings of each measure with a varied energy performance is calculated and then compared with the calculated retrofit cost to identify the cost optimum of each measure. In a sensitivity analysis, we analyze the cost optimum retrofit measures under different economic and DH supply scenarios. The retrofit costs and primary energy savings vary somewhat between non-renewable and wood-based retrofit measures but do not influence the cost optimum levels significantly, as the economic parameters do. The lifecycle primary use of wood fiber insulation is about 76% and 80% less than for glass wool and rock wool, respectively. A small-scale DH system gives higher primary energy and cost savings compared to larger DH systems. The optimum final energy savings, in one of the economic scenarios, are close to meeting the requirements in one of the Swedish passive house standards.

Keywords: energy retrofit; retrofit cost; district heating; building material; life cycle

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1. Introduction

Buildings are responsible for 32% of total final energy use and 19% of the energy-related greenhouse gas emissions, globally [1]. About two-thirds of the greenhouse gas emissions of buildings are related to the use of energy for electricity, heating, and cooling [2]. Other emissions are generated during the production of materials, as well as the maintenance and demolition of buildings.

Energy efficiency standards for buildings are cost-effective instruments to reduce greenhouse gas (GHG) emissions, contributing to the lower total energy demand of buildings [3]. Energy efficiency standards apply to both new buildings and existing buildings undergoing major renovations. Existing buildings represent a significant energy-saving potential, especially in those countries having an established building stock. In Europe, the revised Energy Performance of Buildings Directive (2018/844/EU) [4] and Energy Efficiency Directive (2018/2002/EU) [5] stress the importance of improving the energy efficiency of existing buildings built before 1970, i.e., before the first thermal regulations appeared in building codes. Besides, buildings built before 1970 consist of about 50% of the building stock [6].

Energy retrofits can improve the thermal performance of the building envelope, as well as the energy efficiency of technical installations for heating and cooling, at different performance levels. High energy performance retrofits, namely deep energy retrofits, can reduce the heat energy demand by well over 50% in existing buildings [7] and thus help achieve the European target of 55% GHG emissions reduction by 2030 [8]. However, deep energy retrofits also entail the use of significant amounts of material, especially used to improve the thermal performance of the building envelope. To minimized the GHG emissions related to the use of materials, the European Renovation Wave Strategy has recently provided several recommendations, including the increased use of wood-based materials [9]. In Sweden, the calculation of primary energy use and GHG emissions generated from the production of materials is mandatory for new buildings built after 2021, and retrofitted buildings are also expected to comply with the same requirement soon [10]. However, limit values for primary energy use or GHG emissions of building materials have not been included in the building codes yet.

Although 11%, by floor area, of the total building stock is renovated yearly, only 0.2% undergoes deep energy retrofit measures [9]. Furthermore, deep energy retrofits usually result in high initial investment costs [11]. For this reason, it is crucial to identify the cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building. Nevertheless, several factors can influence cost-optimum retrofits. The European Commission's delegated regulation N. 244/2012 [12] recommends calculating cost-optimal levels of retrofitted building elements in terms of net present value (NPV), having performed sensitivity analyses on key economic parameters such as discount rate and energy price. In Europe, discount rates are assumed to be between 1–7%, depending on calculation methods and economic sectors, and specifically between 3–4% for energy efficiency measures in residential buildings [13]. Bonakdar et al. [14] and Dodoo et al. [15] show that the cost efficiency of retrofit measures is highly sensitive to economic parameters. They used a real discount rate of 5%, 3%, and 1%, and a real energy price increase of 1%, 2%, and 3%, respectively. Both studies concern Sweden, where trends of district heat price for the residential sector show an annual increase of 2%, between 2008–2017 [16]. The same economic parameters were assumed in the present study. Furthermore, the aforementioned European regulation defines as cost-optimal those retrofit measures having the lower use of primary energy and the lower life cycle cost, which includes the costs of both retrofit materials and energy throughout the life cycle of the retrofitted building. The present study considers the same types of cost but rather identifies cost-optimal retrofit measures based on a marginal approach. Therefore, cost-optimal retrofit measures have the lower marginal cost of retrofit materials per marginal increase of energy cost savings. The primary energy use is also calculated for both retrofit materials and energy savings.

Recent studies investigate the factors influencing the cost efficiency of single and aggregated retrofit measures to achieve high energy performance levels. Liu et al. [17] analyze the cost efficiency of retrofit measures in a cold climate, including envelope retrofit, solar thermal panels, and efficient heat exchange and recovery ventilation system, showing that the cost efficiency of envelope retrofits increases when supported by the upgrade of technical installations. Arumägi and Kalamees [18] find similar results, though highlighting that the assumed heat source influences the primary energy and energy cost savings significantly. Mata et al. [19] highlight that envelope retrofits are profitable in cold climates when assuming a service life of 40–50 years but less profitable in warm climates [20]. In Sweden, La Fleur et al. [21] show that attic floor insulation is the most profitable insulation measure with a service life of 40 years, but the insulation of external walls is needed to achieve high energy performance levels. In Norway, Chen et al. [22] find that insulation measures give the highest energy savings but they are profitable only when coupled with new efficient technical installations. Mauro et al. [23] analyze cost-optimal retrofit measures in a Mediterranean climate, including envelope retrofit, replacement of heating and cooling systems, and installation of photovoltaic panels, with and without incentives, showing that cost-optimal levels do not usually include envelope retrofit. Zangheri et al. [24] observe that envelope retrofits can be cost-efficient in a warm climate when avoiding the need for cooling systems. D'Agostino et al. [25] show that, in a warm climate, the insulation thickness of cost-optimal envelope retrofits is below 10 cm and this value is consistent with other similar studies, i.e., [26]. Fokaides et al. [27] show that the use of photovoltaic panels in a warm climate is effective to achieve nearly-zero energy standards, as it can reduce fossil-based energy use for cooling significantly. These studies suggest that envelope retrofits are usually less profitable than the upgrade of technical installations, but they do not investigate how to optimize the cost of envelope retrofits. Furthermore, the costs of envelope retrofits usually include the costs of retrofit materials and construction but do not include the retrofit's end of life.

Although the profitability of envelope retrofits is challenging, a few studies analyze the effects of using different materials on the energy and cost savings of envelope retrofits. These studies usually focus on insulation materials. Lucchi et al. [28] calculate cost-optimal materials for internal insulation of walls and find that polystyrene, glass wool, rock wool, and wood fiber have the lowest life cycle cost, even though the cost difference between materials is less significant when increasing the insulation thickness. Annibaldi et al. [29] calculate cost-optimal materials for external insulation of walls, finding that rock wool and glass wool have the lowest life cycle cost but wood-based insulation is competitive with low insulation thickness. Furthermore, the study shows that cost-efficiency could be reduced in real retrofits, due to underestimated thermal transmittance of existing walls and material wastage on site. Basińska et al. [30] find that hygro-thermal properties of insulation materials have negligible effects on the energy demand of a building. Marrone et al. [31] show that super insulation materials give competitive cost savings compared to traditional insulation materials (e.g., rock wool) when incentives are applied, though the assumed service life could influence the profitability of such insulation materials. All the presented studies compare the profitability of insulation materials in terms of minimum life cycle costs or maximum cost savings. Instead, the present study compares both insulation and windows materials in terms of marginal cost savings in the context of different envelope retrofit measures.

Another approach is to use multi-objective optimization models to optimize the selection of various retrofit choices. For example, Diakaki et al. [32] use the multi-objective approach to select insulation materials and highlight that the cheapest insulation material is preferable when cost efficiency is prioritized in envelope retrofits. However, the multi-objective optimization approach does not allow to identify the cost-optimal solution, but only to select the most convenient set of choices based on pre-defined criteria.

Finally, there is growing attention on the use of materials in retrofit interventions. This study provides an insight into the primary energy use and costs of retrofit materials for insulation and windows. Furthermore, this study fills the gap of previous literature by analyzing the effects of using different retrofit materials on the cost-optimal levels of envelope retrofit measures adopting a marginal approach. We analyze conventional retrofit building materials, such as aluminum, rock, and glass wool materials, and compare such materials with wood-based materials to understand the lifecycle primary energy implications of moving from non-renewable to wood-based materials. The cost-optimal levels are calculated considering the entire life cycle of retrofit materials. Insulation materials and window materials are the focus of this study. We use a typical building, from the Swedish million program from the seventies, to illustrate the outcome of the analysis and to connect the analysis to a real context. Renewable-based district heating (DH) systems are assumed to supply the heat to the building. The study also explores the sensitivity of calculated cost-optimal retrofit measures when assuming different economic and district heating supply scenarios.

2. Considered Building and Retrofit Measures

The considered building is a 3-story multi-apartment building built-in 1972 in Ronneby, Sweden (56.2° N, 15.3° E). It comprises 27 apartments with a total heated floor area of 4000 m^2 and a ventilated volume of 5200 m^3. Figure 1 shows the floor plan. The building is constructed in a concrete frame. The external walls have 95–120 mm of mineral wool and/or polystyrene insulation and are covered with partially bricks and partially wood panels (East and West façades). The basement walls, which are partially underground and partially above ground, are not insulated. Figure 2 shows the construction details of the existing external walls and basement walls. The attic floor consists of 160 mm of concrete slab and 130 mm of mineral wool insulation. The U-value is equal to 0.29, 0.31–0.35, and 1.34–1.45 W/m^{2}K in the attic floor, external walls, and basement walls, respectively. The existing windows have an estimated U-value of 2.9 W/m^{2}K. The building has a mechanical exhaust ventilation system and is connected to the local district heating (DH) system. The considered building shows typical construction features of buildings built within the Swedish Million Programme in the Seventies [33]. Multi-apartment buildings built within the Million Programme are equal to about 30% of the existing multi-apartment buildings in Sweden [34].

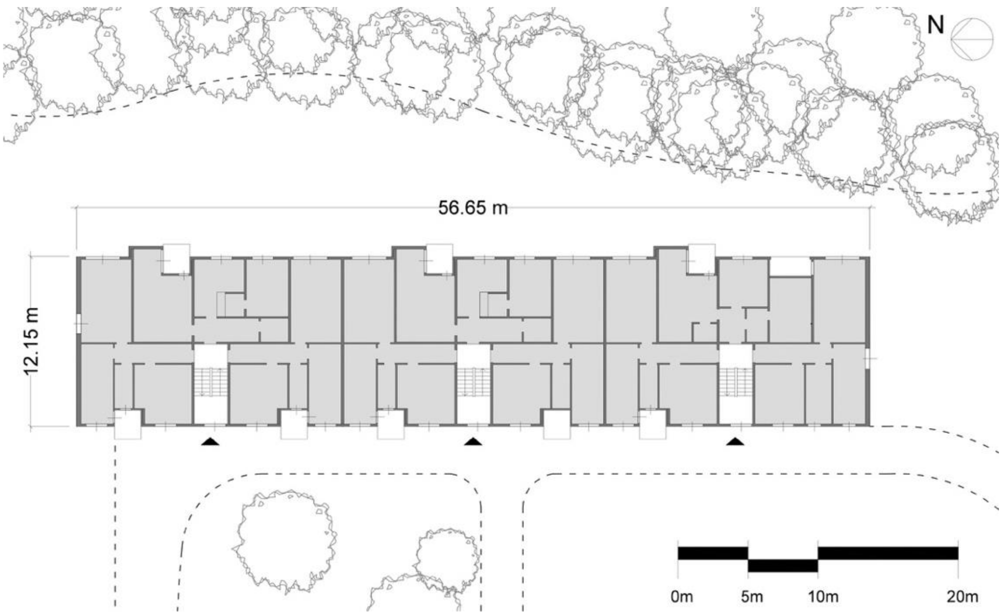

Figure 1. Floor plan of the considered building with typical context.

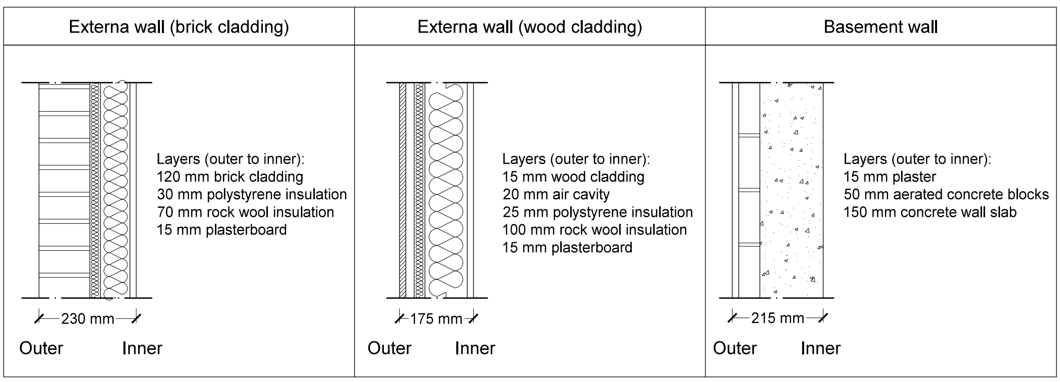

Figure 2. Construction details of the external wall with brick/wood cladding and basement wall.

The heat supply to the building is from the DH system of Ronneby. This DH system is composed of heat-only boilers (HOBs), including two wood chip boilers with flue gas condensers, three wood pellet boilers, and three oil boilers. Oil HOBs are mostly used as a peak-load unit, while wood pellets and wood chips HOBs a medium- and base-load units, respectively. The base-, medium- and peak-load production units operate depending on the variations of the district heat demand over the year and the operating cost of each unit. The annual heat production is 110 GWh and the peak heat demand is 33 MW based on 2013 data, under climate conditions fairly representative of the climate normal.

Analyzed retrofit measures are extra insulation in the attic floor, external and basement walls, as well as the substitution of old windows with new windows with lower U-value. The extra insulation in the external and basement walls is assumed to be applied on the outer side of the existing walls. We consider three different insulation materials for attic floor and external walls: glass wool, rock wool, and wood fiber, having a thermal conductivity of 0.042, 0.037, and 0.038 W/mK and density of 20, 40, and 40 kg/m^3, respectively; as well as extruded polystyrene XPS for basement walls, having a thermal conductivity of 0.030 W/mK and density of 32 kg/m^3, as they are the most common and suitable insulation materials in a Nordic context including Sweden. Extruded polystyrene is selected for basement walls as it shows higher moisture resistance compared to the other insulation materials. We also considered thermally-improved windows with U-value between 1.2 and 0.6 W/m^{2}K with aluminum and wood frame, respectively. Window frames having different frame materials but improved thermal insulation can perform equally [35]. Different U-values of windows can be achieved with different types of glazing units, low-emittance coating, and high-density gas fill. U-values equal to 1.2 and 1.0 W/m^{2}K are achievable with double-glazed windows having a single low-e coating, and argon and krypton gas fills, respectively. U-values equal to 0.8 and 0.6 W/m^{2}K are achievable with triple-glazed windows with double low-e coating, and argon or krypton gas fills, respectively. Spacers with improved thermal insulation properties are also considered in all the windows. We select improved U-value ranges for the attic floor, external walls, basement walls, and windows based on previous studies on retrofitted buildings with passive house levels [36,37]. We assume a remaining service life of the retrofitted building of 50 years.

3. Methodology

This study uses a four-fold approach: (i) modeling the retrofit measures for the thermal building envelope to calculate the final energy savings for space heating; (ii) calculating the primary energy savings due to the retrofit and the primary energy use for the production and disposal of retrofit materials; (iii) performing the cost optimization analysis for each retrofit measure using the marginal cost difference method; (iv) analyzing the sensitivity of cost-optimal measures to discount rates and energy price increase, as well as to the price of district heat under different scales of DH systems.

The primary energy and cost optimum calculations have been developed following a life cycle approach including production, use, and end-of-life stages of retrofit measures.

3.1. Final Energy Calculation

We calculate the final energy use for space heating of the analyzed building with and without retrofit measures. We use the VIP-Energy simulation software [38] to perform dynamic hourly energy balance calculations of the building. VIP-Energy is validated by the International Energy Agency's BESTEST, ANSI/ ASHRAE Standard 140 and CEN 15,265 to have reliable algorithms and calculation models and widely used by consultants and researchers in a Nordic context. The detailed hour-by-hour dynamic calculation of the energy balance of a building is based on the interaction of thermal envelope characteristics, technical installations, and outdoor climate variables. The software has multi-zone features and uses a series of one-, two- and three-dimensional models to calculate the energy balance of buildings. Energy flows calculations are based on transmission and heat storage capacity, air infiltration, ventilation, hot water, cooling, solar heat gains, recovered heat, persons, and process heat gains. The heat storage capacity of the building structure is calculated as a series of thermal resistance and capacitance with a finite difference in response to thermal variations. For a summary of used models and equations see [39]. Detailed mathematical descriptions of the model for heat storage capacity are given in Johannesson [40] while Nylund [41] gives the equations used for modeling ventilation systems and air infiltration. The HDKR (Hay-Davies-Klucher-Reindl) model is used to calculate the solar radiation available in a building and the mathematical description of this model is given in [42]. The energy balance calculation adopts hourly climate data for Ronneby in 2013 retrieved from the Meteonorm database [43], which includes profiles of outdoor air temperature, relative humidity, solar radiation, and wind speed. The climate of Ronneby is a temperate continental climate without dry seasons and with warm summer (i.e., class Cfb of Köppen climate classification). The following key parameter values are adopted for the building: indoor air temperatures of 22 °C for living areas and 18 °C for common areas, respectively; internal heat gains from building occupants and electrical appliances of 2.16 and 3 W/m^2, respectively, with a constant profile over the year. The ventilation system installed in the studied building includes ventilation fans with assumed efficiency of 33% and a pressure of 400 Pa without ventilation heat recovery (VHR) units. We assume these ventilation fans as representative of standard fans in existing buildings such as the considered building. The air exchange rate is assumed to be 0.1 and 0.35 l/s m^2 when the building is unoccupied and occupied, respectively, based on the Swedish building code [44].

3.2. Life Cycle Primary Energy Calculation

3.2.1. Primary Energy Savings

The primary energy savings due to different retrofit measures depend on the DH system supplying heat to the building. Nevertheless, as the retrofit measures are expected to last for the remaining lifetime of the building, they influence the energy supply during that time. In this study, we assume that a change in heat demand immediately influences the operation of a DH production unit. That production unit is the marginal production unit of the DH system at that specific instance. We identified the marginal production unit of the DH system of Ronneby based on the 2013 hour-by-hour production data. In the DH system of Ronneby, the conversion efficiency of HOBs based on fuel oil, wood chips, and wood pellets is 90, 108, and 89%, respectively, considering the lower heating value of fuels [45]. The conversion efficiency of HOBs using wood chips is above 100% due to the recovery of condensation heat through the flue gas condenser. The fuel cycle energy input of the energy carriers is assumed to be 11% for fuel oil and wood pellets, and 3% for wood chips [46] and includes the energy used to extract, refine and transport fuels to the conversion plant and excludes the conversion of fuel to heat at the conversion plant. The distribution loss when heat is delivered is assumed to be 11.7% based on 2008–2017 Swedish average data [16].

3.2.2. Primary Energy Use for Retrofit

The primary energy use associated with the production and final disposal of retrofit materials, including transport, is calculated based on ecoinvent data [47]. We assume that the insulation materials and windows used in the retrofit measures do not need replacement during the remaining service life of the building. Besides, a previous study shows that primary energy use for maintenance is negligible [36]. The transport of construction and demolition waste is calculated based on haul distances in Sweden: 10 km for landfill and processing; 90 km for incineration; 100 km for aluminum recycling; 200 km for mineral wool; and 1000 km for glass recycling. We assume burnable materials (i.e., XPS, wood fiber, and windows' rubber and wood) to be incinerated, and other materials to be recycled at the end of the life cycle. The remainder is delivered to landfill. The primary energy savings due to recycling are included assuming the substitution of primary raw materials with recycled retrofit materials with an efficiency of 92% for aluminum [48], 120% for glass [49], and 9% for glass/rock wool [50]. The heating value of wood materials is calculated assuming that 95% of end-of-life wood could be recovered with a moisture content of 15%.

3.3. Life Cycle Cost and Cost Optimum Calculation

To identify cost-optimal retrofit measures, we calculate the cost-optimal balance between the marginal energy cost savings and the respective marginal costs of the retrofit measures as in Equation (1):

$$f(x) = S(x) - I(x) \quad (1)$$

where S(x) is the saved cost of final energy and I(x) is the investment for implementing the measure.

All costs are expressed in terms of net present value (NPV) as in Equation (2):

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \quad (2)$$

where n = service life of the buildings (years); t = a specific year; C_t = annual net cost for a specific year; and r = real discount rate. The costs refer to the year 2021, with an average exchange rate of 1 € = 10.59 SEK, based on the European Central Bank. We assume a reference economic scenario with a real discount rate of 3% and an annual energy price increase of 2%. In a sensitivity analysis, we use two alternative economic scenarios, namely Business-as-usual (BAU) and Sustainability, with a discount rate of 5 and 1% and an energy price increase of 1 and 3%, respectively. Table 1 summarizes the economic scenarios and adopted values for real discount rate and energy price increase.

Table 1. Real discount rate and energy price increase in BAU, Reference, Sustainability scenarios.

	BAU	Reference	Sustainability
Real discount rate	5%	3%	1%
Energy price increase	1%	2%	3%

3.3.1. Energy Cost Savings

We calculate the heat energy cost savings due to different retrofit measures on annual basis, using the 2021 DH tariff of Ronneby. The district heat tariff is based on a charge of 10.86 €/MWh per year for buildings having an annual district heat demand below 200 MWh, and a variable charge of 0.055 €/kWh [51], excluding value-added tax. Energy cost savings are expressed as positive values.

3.3.2. Retrofit Costs

The material and labor costs are based on the 2021 database of average contractor prices in Sweden [52]. The cost of extra insulation on external walls includes scaffolding. The cost of final demolition and waste transport is based on [52]. We consider that 95% by weight of demolition waste is recovered for energy purposes (i.e., burnable materials) or recycling (i.e., recyclable materials), while the remainder is landfilled. The landfill cost is based on the 2021 landfill tax, equal to 52.4 €/ton [53], and increased by an annual rate of 4%, equivalent to the average annual increase of the landfill tax in Sweden between 2000 and 2020. The incineration cost of waste from construction and demolition activities is based on the 2021 incineration tax, equal to 9.4 €/ton [54], and increased by an annual rate of 25%, according to the calculation method set by the Incineration Tax Act 2019:1274 [55]. However, it cannot be higher than the landfill cost, as suggested by European policy [56]. The incineration tax does not apply to wood materials in Sweden [57]. Recyclable materials (i.e., glass and rock wool in insulation, glass, and aluminum in windows) are assumed to have no disposal cost.

4. Results

4.1. Cost-Optimal Retrofit Measures

Tables 2–4 show the improved U-values of the attic floor, external walls, and basement walls, respectively, due to implementing different thicknesses of extra insulation made up of different materials. Table 5 shows different U-values of new windows. The respective final and primary energy savings, as well as the energy cost savings and retrofit costs of different material options, are also shown in the aforementioned tables. Both the energy cost savings and retrofit costs are calculated in terms of NPV based on the economic assumptions in the Reference scenario. The final and primary energy savings are calculated considering marginal changes in the DH supply systems due to different retrofit measures. The initial building (without retrofit options) shows a final energy use of 108 kWh/m^2/year and primary energy use of 157 kWh/m^2/year for space heating.

Table 2. Thicknesses, final and primary energy savings, energy cost savings, and retrofit costs of extra insulation of different materials on the attic floor with equally improved U-value.

U-Value	Thickness			Final Energy Saving	Primary Energy Saving	Primary Energy Use			Energy Cost Savings	Retrofit Costs		
W/m^{2}K	m	m	m	kWh/m^2/Year	kWh/m^2/Year	kWh/m^2/Year			k€	k€		
	Glass Wool	Rock Wool	Wood Fiber			Glass Wool	Rock Wool	Wood Fiber		Glass Wool	Rock Wool	Wood Fibre
0.180	0.12	0.09	0.09	44.3	49.7	0.19	0.13	0.03	231.8	9.2	8.3	11.7
0.160	0.13	0.12	0.12	44.8	50.2	0.20	0.18	0.04	234.4	9.6	9.2	13.2
0.140	0.17	0.16	0.16	45.3	50.8	0.27	0.24	0.05	237.0	11.4	11.0	16.3
0.120	0.23	0.20	0.20	45.6	51.2	0.36	0.29	0.07	239.0	13.6	12.7	19.3
0.100	0.32	0.28	0.28	46.2	51.8	0.50	0.41	0.10	241.8	18.6	16.3	25.6
0.080	0.44	0.40	0.40	46.7	52.4	0.69	0.59	0.14	244.4	24.0	22.1	35.4

Table 3. Thicknesses, final and primary energy savings, energy cost savings, and retrofit costs of extra insulation of different materials on external walls with equally improved U-value.

U-Value	Thickness			Final Energy Saving	Primary Energy Saving	Primary Energy Use			Energy Cost Savings	Retrofit Costs		
W/m^{2}K	m	m	m	kWh/m^2/Year	kWh/m^2/Year	kWh/m^2/Year			k€	k€		
	Glass Wool	Rock Wool	Wood Fiber			Glass Wool	Rock Wool	Wood Fiber		Glass Wool	Rock Wool	Wood Fibre
0.180	0.11	0.10	0.10	51.8	58.2	0.28	0.24	0.06	271.2	16.0	15.5	21.1
0.160	0.14	0.13	0.13	53.0	59.6	0.35	0.31	0.07	277.8	19.4	18.0	24.9
0.140	0.19	0.18	0.18	54.3	61.1	0.48	0.43	0.10	284.6	22.6	21.5	31.1
0.120	0.25	0.22	0.22	55.1	61.9	0.63	0.52	0.12	288.5	26.5	24.4	36.1
0.100	0.33	0.30	0.30	56.1	63.1	0.84	0.71	0.17	294.0	32.4	30.3	46.3
0.080	0.46	0.42	0.42	57.1	64.2	1.16	1.00	0.23	299.0	43.1	40.1	63.1

Table 4. Thicknesses, final and primary energy savings, energy cost savings, and retrofit costs of extra insulation of polystyrene (XPS) on basement walls with improved U-value.

U-Value	Increased U-Value	Thickness	Final Energy Saving	Primary Energy Saving	Primary Energy Use	Energy Cost Savings	Retrofit Costs
W/m^{2}K	W/m^{2}K	m	kWh/m^2/Year	kWh/m^2/Year	kWh/m^2/Year	k€	k€
0.420	0.98	0.50	6.9	7.8	0.16	36.2	11.3
0.370	0.05	0.60	7.3	8.2	0.19	38.3	13.3
0.300	0.07	0.80	7.9	8.9	0.25	41.3	16.0
0.260	0.04	0.10	8.3	9.4	0.32	43.6	19.3
0.220	0.04	0.12	8.6	9.7	0.38	45.2	22.6
0.180	0.04	0.15	9.0	10.1	0.47	46.9	27.7

Table 5. Final and primary energy savings, energy cost savings, and retrofit costs of new windows using aluminum and wood frames with equally improved U-value.

U-Value	Increased U-Value	Final Energy Saving	Primary Energy Saving	Primary Energy Use		Energy Cost Savings	Retrofit Costs	
W/m^2K	W/m^2K	$kWh/m^2/Year$	$kWh/m^2/Year$	$kWh/m^2/Year$		k€	k€	
				Alum.	Wood		Alum.	Wood
1.2	0.2	54.8	61.6	0.51	0.22	287.0	135.5	117.9
1.0	0.2	55.9	62.9	0.55	0.26	292.9	140.6	122.1
0.8	0.2	57.0	64.2	0.61	0.32	298.8	161.9	139.8
0.6	0.2	57.9	65.1	0.71	0.41	303.1	200.6	171.9

Decreasing the U-value by insulating the building envelope (i.e., attic floor, external walls, basement walls) reduces the final energy use and, proportionally, the primary energy use and costs for space heating. However, decreasing the U-value by a constant amount requires increasingly thicker insulation, resulting in increasingly higher primary energy use and costs due to retrofit materials. The primary energy use varies widely depending on the retrofit material. For example, wood fiber insulation uses about 76% and 80% less primary energy than glass wool and rock wool, respectively. Wood frames in windows use about 60% less primary energy than aluminum frames. Compared to the primary energy savings due to retrofit, the primary energy use of insulation materials is low, less than 1%, for U-values higher than 0.1 W/m^2K but is more significant for lower U-values. Besides, the percentage may vary depending on the energy supply system (see sensitivity analyses in Section 4.2).

The retrofit costs vary widely depending on the retrofit measures and materials. In the analyzed retrofit measures, the energy cost savings per unit of retrofit cost are larger for the extra insulation of attic floor, followed by the extra insulation of external and basement walls, and the substitution of old windows with new thermally-efficient windows. The cost of extra insulation on the attic floor is about 8% and 33% lower when using rock wool instead of glass wool and wood fiber, respectively. The respective values for extra insulation on external walls are about 6 and 31%. The cost of wood-framed windows is 14% lower than aluminum-framed windows. Cost variations are mainly due to the cost of retrofit materials as the respective work cost is assumed to be unchanged.

Figures 3–6 show the marginal energy cost savings (i.e., black dotted line) and the marginal retrofit costs (i.e., colored dotted line) of the considered measures, including costs to build and dispose of materials. The cost-optimal retrofit measure for different materials is achieved when the energy cost saving line intersects the retrofit cost line. In the attic floor, the cost-optimal level of rock wool, glass wool, and wood fiber insulation are achieved with U-values of about 0.110, 0.130, and 0.150 W/m^2K, respectively. In the external walls, the respective U-values are about 0.110, 0.120, and 0.140 W/m^2K. In the basement walls, the cost-optimal level of XPS is about 0.370 W/m^2K. The cost-optimal level of windows is achieved when adopting a U-value of about 1.0 W/m^2K without significant variations between different frame materials. Variations of cost-optimal U-values are primarily due to the cost to build retrofit materials, followed by disposal costs. In the attic floor and external walls, it is also possible to observe that the marginal retrofit costs of materials do not always linearly depend on the U-values, especially when considering non-profitable U-values. This mainly depends on the retrofit costs, specifically the costs of production and installation of insulation materials in different thicknesses.

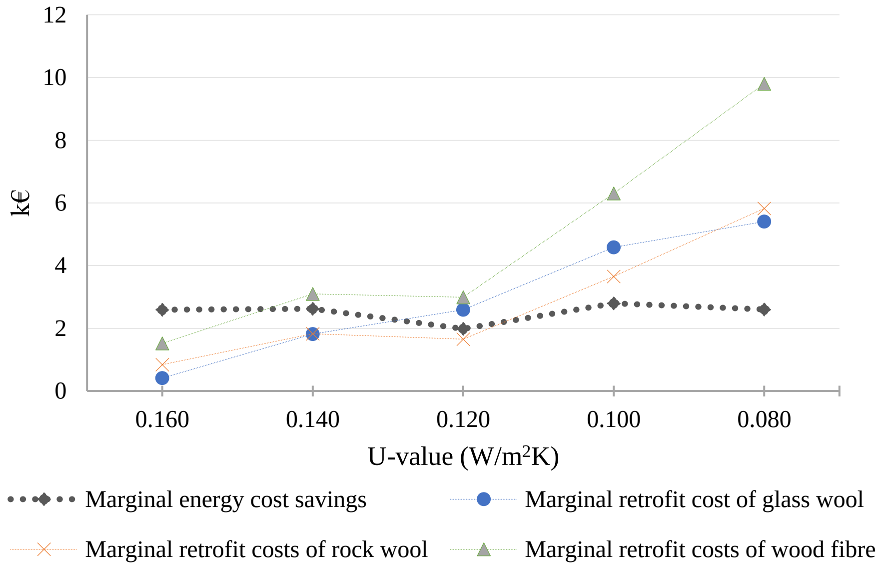

Figure 3. Marginal energy cost savings and marginal retrofit costs of extra insulation on attic floor using glass wool, rock wool, and wood fiber.

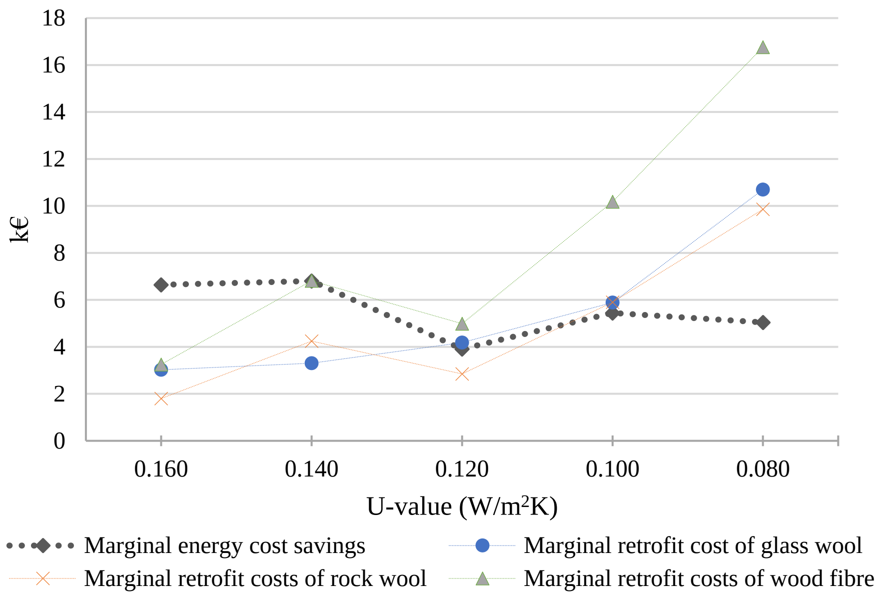

Figure 4. Marginal energy cost savings and marginal retrofit costs of extra insulation on external walls using glass wool, rock wool, and wood fiber.

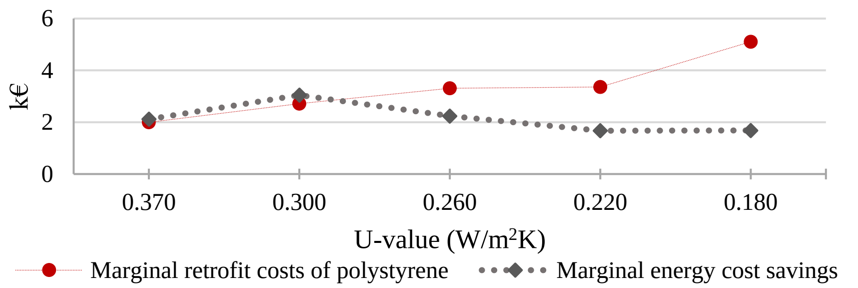

Figure 5. Marginal energy cost savings and marginal retrofit costs of extra insulation on basement walls using polystyrene (XPS).

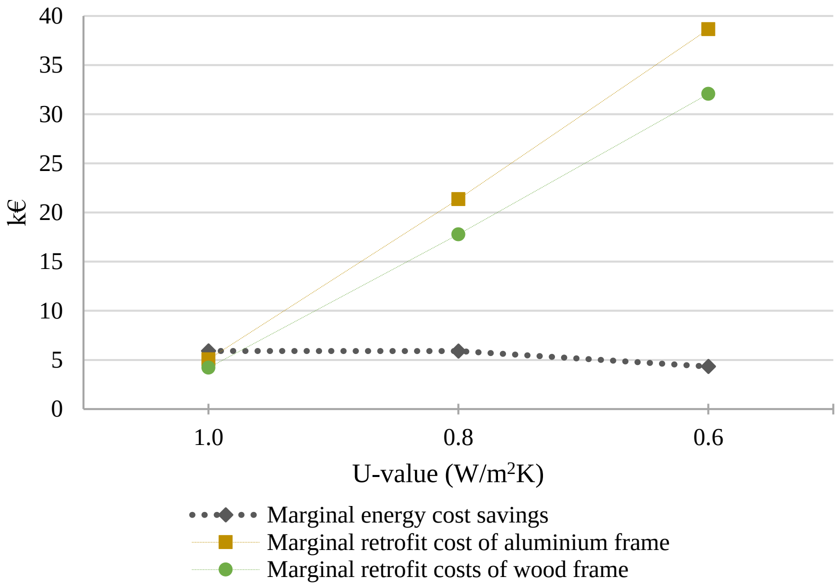

Figure 6. Marginal energy cost savings and marginal retrofit costs of new thermally-efficient windows using aluminum and wood frames.

4.2. Sensitivity Analyses

The sensitivity of cost-optimal retrofit measures to different discount rates and energy price increases is shown in Tables 6 and 7. Compared to the Reference scenario, previously analyzed, the cost-optimal U-values increase in the BAU scenario and decrease in the Sustainability scenario. Different discount rates and energy price increases influence the energy cost savings as well as the costs to dispose of retrofit materials. The costs to build retrofit materials are not influenced as they occur in year zero. Both energy cost savings and retrofit costs decrease in the BAU scenario and increase in the Sustainability scenario. However, energy cost savings vary significantly between BAU and Sustainability scenarios, due to different energy price increase and discount rates.

Table 6. U-values (W/m^{2}K) of cost-optimal extra insulation, using different materials, under different economic scenarios.

	Attic Floor			External Walls			Basement Walls
	Glass Wool	**Rock Wool**	**Wood Fibre**	**Glass Wool**	**Rock Wool**	**Wood Fibre**	**XPS**
Reference	0.130	0.110	0.150	0.120	0.110	0.140	0.370
BAU	0.140	0.140	0.160	0.130	0.140	0.160	0
Sustainability	0.090	0.090	0.110	0.080	0.080	0.100	0.220

Table 7. U-values (W/m^{2}K) of cost-optimal windows, using different frame materials, under different economic scenarios.

	Windows	
	Aluminum	**Wood**
Reference	1.00	1.00
BAU	1.00	1.00
Sustainability	0.90	0.90

The sensitivity of cost-optimal retrofit measures to the price of district heat in different scales, in the Reference economic scenario, is shown in Tables 8 and 9. The DH system of Ronneby is representative of a small-scale system in Sweden. The DH systems of Växjö and Helsingborg represent medium- and large-scale systems, respectively, having an annual heat production of 630 and 1100 GWh and peak heat demand of 180 and 340 MW, respectively, based on 2013 data. The district heat production of Växjö and Helsingborg includes combined heat and power (CHP) units for base-load production and heat-only boilers (HOBs) for peak- and medium-load productions. The HOBs in Växjö amd Helsingborg are assumed to be fueled by oil and biomass and by oil and biogas, respectively. The conversion efficiency of HOBs based on biogas is 97% [45]. The district heat tariff of Helsingborg is based on an annual fixed charge of 268.58 € and a variable charge of 0.069, 0.038, 0.010 €/kWh in winter, spring/autumn, and summer, respectively. The district heat tariff of Växjö is based on a capacity cost of about 90 €/kW for buildings having a peak heat demand below 100 kW, a heat flow cost of 0.38 €/m^3, and a seasonal energy price of 0.033 and 0.019 €/kWh in winter and summer, respectively. The results show no significant variations in the cost-optimal level of retrofit measures and material options.

Table 8. U-values (W/m^{2}K) of cost-optimal extra insulation, using different materials, under different scales of district heating systems and district heat price.

	Attic Floor			External Walls			Basement Walls
	Glass Wool	**Rock Wool**	**Wood Fibre**	**Glass Wool**	**Rock Wool**	**Wood Fibre**	**XPS**
Ronneby	0.130	0.110	0.150	0.120	0.110	0.140	0.370
Växjö	0.130	0.120	0.150	0.120	0.100	0.140	0.370
Helsingborg	0.130	0.120	0.150	0.120	0.110	0.140	0.370

Table 9. U-values (W/m^{2}K) of cost-optimal windows, using different frame materials, under different scales of district heating systems and district heat price.

	Windows	
	Aluminum	**Wood**
Ronneby	1.00	1.00
Växjö	1.00	1.00
Helsingborg	1.00	1.00

Finally, the sensitivity of primary energy savings due to retrofit measures when assuming different scales of DH systems is shown in Tables 10–12. The DH systems of Växjö and Helsingborg are compared with Ronneby. The calculation of primary energy savings follows the method described in Section 3.2.1. The results show a significant decrease in primary energy savings when assuming a medium- or large-scale DH system instead of a small-scale DH system. When the primary energy savings decrease, the respective primary energy use due to retrofit materials is more relevant.

Table 10. Primary energy savings (kWh/m^2/year) of extra insulation on the attic floor and external walls under different scales of district heating systems.

U-Value W/m^{2}K	Attic Floor			External Walls		
	Ronneby	**Växjö**	**Helsingborg**	**Ronneby**	**Växjö**	**Helsingborg**
0.180	49.7	34.1	29.4	58.2	40.2	34.2
0.160	50.2	34.5	29.7	59.6	41.2	35.0
0.140	50.8	34.9	30.0	61.1	42.3	35.8
0.120	51.2	35.2	30.3	61.9	42.9	36.3
0.100	51.8	35.7	30.6	63.1	43.7	36.9
0.080	52.4	36.1	30.9	64.2	44.5	37.5

Table 11. Primary energy savings (kWh/m^2/year) of extra insulation on basement walls under different scales of district heating systems.

U-Value W/m^{2}K	Basement Walls		
	Ronneby	**Växjö**	**Helsingborg**
0.420	7.8	5.3	4.5
0.370	8.2	5.7	4.7
0.300	8.9	6.1	5.1
0.260	9.4	6.4	5.4
0.220	9.7	6.7	5.6
0.180	10.1	6.9	5.8

Table 12. Primary energy savings (kWh/m^2/year) of new windows under different scales of district heating systems.

U-Value W/m^{2}K	Windows		
	Ronneby	**Växjö**	**Helsingborg**
1.2	61.6	42.6	36.1
1.0	62.9	43.6	36.8
0.8	64.2	44.5	37.5
0.6	65.1	45.2	38.0

5. Discussion

In this study, we perform an hourly-based energy balance analysis of an existing building assuming different retrofit measures and materials for the thermal building envelope. Next, we calculate the cost-optimal level of retrofit measures and material options using the marginal cost difference method. The cost-optimal level is expressed in terms of the U-value.

All the analyzed retrofit measures and material options are cost-efficient, as the retrofit costs are lower than the respective energy cost savings calculated over a service life of 50 years. However, only cost-optimal retrofit measures lead to the highest energy cost savings with the lowest retrofit costs in the estimated service life. Differently from the life cycle cost (LCC) method, the marginal cost difference method allows us to identify the energy performance level where these retrofit measures and material options have the highest profitability.

The results show that decreasing the U-value of the thermal building envelope increases the energy cost savings, even though different retrofit measures show significantly different contributions. The energy cost savings per unit of retrofit cost are larger for the extra insulation of the attic floor, followed by the extra insulation of external and basement walls, and the substitution of old windows with new thermally-efficient windows. However, in absolute numbers, the extra insulation on external walls has the highest retrofit cost and gives the highest energy cost savings, whereas attic floor and basement walls give 16 and 83% less energy cost savings, respectively. The substitution of old windows with new windows having a U-value of 1.0 W/m^{2}K gives energy cost savings similar to extra insulation on external walls having a U-value of 0.1 W/m^{2}K.

Retrofit costs include the cost of materials and construction works, as well as disposal costs of non-recycled materials excluding wood materials. However, initial costs for materials and construction works are significantly higher than disposal costs due to the discount rate applied to future costs.

Different insulation materials (i.e., rock wool, glass wool, wood fiber) can influence the cost-optimal level of extra insulation on the attic floor and external walls. For example, using rock wool instead of glass wool and wood fiber decreases the cost-optimal U-value by 11% and 22% for the attic floor and by 13% and 24% for the external walls, respectively. Lower cost-optimal U-value results in higher final energy savings, which account for a maximum of 1.8 and 2.5 MWh/year for attic floor and external walls, respectively. However, the respective energy cost savings and retrofit costs calculated for different materials show minor variations, assuming a remaining service of the building of 50 years. Different frame materials (i.e., aluminum, wood) do not influence the cost-optimal U-values of new windows, nor the final energy savings due to cost-optimal windows.

Different economic scenarios can influence the cost-optimal level of extra insulation and new windows. In general, the BAU scenario gives cost-optimal U-values 3–4% and 10–34% higher than the Reference scenario for new windows and extra insulation, respectively, resulting in lower energy savings. The Sustainability scenario gives cost-optimal U-values 8–10% and 24–47% lower than the Reference scenario for new windows and extra insulation, respectively, resulting in higher energy savings.

The price of district heat in different scales of DH systems has a minor impact on the cost-optimal level of retrofit measures and material options. The DH systems of Växjö and Helsingborg, as a medium- and large-scale systems, give fairly lower energy cost savings compared to the DH system of Ronneby. However, the scale of DH systems can affect the primary energy savings of retrofit measures significantly. The DH systems of Växjö and Helsingborg give about 30 and 40% lower primary energy savings compared to the DH system of Ronneby, respectively, with minor variations among the retrofit measures. This is due to the higher efficiency level of biomass-based medium- and large-scale DH systems using CHP units, compared to small-scale DH systems using only heat boilers. The primary energy use of different retrofit measures and material options vary significantly but is always minor compared to respective primary energy savings, especially when retrofit U-values of walls and floors are higher than 0.1 W/m^2K. Assuming different DH supply scenarios, the primary energy use due to retrofit materials is more relevant when the primary energy savings decrease, as in the case of medium- and high-scale DH systems.

6. Conclusions

The marginal cost difference method adopted in the present study allows us to identify cost-optimal U-values for different retrofit measures and material options in different economic and energy supply scenarios. This method is different from other cost optimum calculation methods based on life cycle cost or payback time. The cost optimum calculations show that the cost-optimal insulation and windows materials have an almost linear increase of marginal retrofit costs when increasing the marginal energy cost savings. Cost optimality of retrofit measures is mostly affected by economic parameters such as real discount rate and energy price increase. Retrofit materials can influence the retrofit costs of envelope retrofits during the life cycle and mostly by the material and work costs. The disposal costs of retrofit materials, even considering the future increase of landfill and incineration taxes, are negligible. A careful selection of retrofit materials could somewhat increase the cost efficiency of retrofit measures, especially in the Business-as-usual (BAU) scenario, when the real discount rate is higher. The choice of retrofit material can strongly reduce the primary energy use of envelope retrofits. However, the primary energy reduction due to retrofit materials is much lower than the primary energy reduction due to different scales of DH systems.

Wood-based materials give lower primary energy use than non-renewable materials. Wood-based materials are also more profitable than aluminum in window frames. However, wood-based insulation is less profitable than glass and rock wool insulation, especially when U-values are higher than 1.2 W/m^2K. This suggests that, to increase the use of wood-based materials in envelope retrofits in a way that can be profitable for users, incentives may be considered. Also, modern wood insulation materials are in an early phase of implementation and increased use of such materials and further development is expected to decrease the production cost and increase the profitability of wood-based materials.

In previous studies considering the same building [36,37], we analyzed retrofit measures needed to achieve passive house standards. We considered two standards having a final energy use for space and tap water heating of 50 and 30 kWh/m^2 per year, respectively, of which tap water heating accounting for 15 kWh/m^2 per year. The first passive house level implies a reduction of 85 kWh/m^2 per year by reducing the U-value of the attic floor, basement walls, and windows to 0.07, 0.12, and 0.8 W/m^2K, respectively. We conclude that the cost-optimal retrofit measures identified here are close but do not meet the U-values required to meet the requirements of the passive standard of 50 kWh/m^2 per year. This is consistent with previous studies [17,18] showing that envelope retrofit measures in cold climates are usually close to being, but not, profitable if we consider passive house standards.

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