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Comparative Life-Cycle Analysis of Building Materials for the Thermal Upgrade of an Existing Building

C Piccardo[1,3], A Dodoo[2,4], L Gustavsson[2,5] and U Y A Tettey[2,6]

[1] Department of Architecture and Design, University of Genoa, 16123 Genoa, Italy
[2] Department of Built Environment and Energy Technology, Linnaeus University, Växjö, SE-35195, Sweden

[3] chiara.piccardo@arch.unige.it, [4] ambrose.dodoo@lnu.se, [5] leif.gustavsson@lnu.se, [6] uniben.tettey@lnu.se

Abstract. The existing building stock is estimated to need major renovations in the near future. At the same time, the EU energy-efficiency strategy entails upgrading the energy performance of renovated buildings to meet the nearly-zero energy standard. To upgrade existing buildings, two main groups of measures can be adopted: thermally-improved building envelope and energy-efficient technical devices. The first measure usually involves additional building materials for thermal insulation and new building cladding, as well as new windows and doors. A number of commercially-available materials can be used to renovate thermal building envelopes. This study compares the life-cycle primary energy use and CO_2 emission when renovating an existing building using different materials, commonly used in renovated buildings. A Swedish building constructed in 1972 is used as a case-study building. The building's envelope is assumed to be renovated to meet the Swedish passive house standard. The entire life cycle of the building envelope renovation is taken into account. The results show that the selection of building materials can significantly reduce the production primary energy and associated CO_2 emissions by up to 62% and 77%, respectively. The results suggest that a careful material choice can significantly contribute to reduce primary energy use and CO_2 emissions associated with energy renovation of buildings, especially when renewable-based materials are used.

Keywords: building renovation, alternative building materials, life cycle, primary energy use, CO_2 emissions, energy-efficiency.

1. Introduction

The European Union's energy performance of buildings directive requires nearly-zero energy performance for all new buildings as well as existing buildings liable to significant renovation, from 2020 [1]. About 49% of existing residential buildings in Europe were built before 1970 [2] and most of them are expected to need significant renovations in the near future.

To renovate a building for energy efficiency purpose, two main groups of measures can be adopted: thermally-improved building envelope and energy-efficient technical devices. The first group of measures increases the use of building materials and hence the energy use of building material production. Refs [3, 4, 5] show that only considering the energy performance in the operation phase may result in potential trade-offs in other life cycle phases of buildings.

The life cycle of a building encompasses production, operation, maintenance and end-of-life phases, which are all interlinked. In the production phase, the selection of building materials has a key role in energy and climate impacts. Comparative life-cycle studies have shown that wood-based materials require less energy and emit less CO_2 during their life cycle than other materials [6, 7, 8, 9, 10, 11, 12, 13]. This is due to the relatively small amount of energy needed to manufacture wood products compared with other materials and the opportunity of replacing fossil fuels with wood by-products. The construction phase, including assembly and transportation, is neglected in the mentioned studies with the exception of Björklund and Tillman [6]. They found that a wood-framed building has higher energy use and CO_2 emission than a concrete-framed building in the construction phase. However, Refs. [3, 14] show no large difference between wood- and concrete-framed buildings in terms of construction energy use, if compared to the total life cycle energy use. The weight of building materials [15], as well as the construction method [16], can affect the construction energy use and hence the results.

Few studies have focused on primary energy and CO_2 emissions implications of the end-of-life phase of buildings. Adalberth [17] and Adalberth et al. [3] analysed the complete life cycle of different types of buildings, finding that demolition activities account for less than 4% of the buildings' production energy. Thormark [18] compared the use of different building materials in a passive house, and found that the energy benefits from the recycle of demolished materials are comparable between materials with high and low production energy use. End-of-life energy and climate impacts can vary significantly depending on the assumed post-use management of the demolished materials [19, 20].

This study compares the life-cycle primary energy use and CO_2 emissions of different material options for retrofit of an existing building to meet the passive house standard. We focus on additional materials used for thermal insulation and new building cladding, as well as new windows.

2. Building description

2.1. Existing building

This study is based on a multi-storey residential building in Ronneby municipality, Southern Sweden. The concrete-framed building was built in 1972, before energy efficiency was emphasized in the Swedish building code. The building is composed of a 3-storey living area above ground level with a total heated floor area of 2000 m^2, and an unheated basement below ground level. The foundation is 230 mm concrete slab on 150 mm layer of crushed stone. The northern and southern external walls consist of 95 mm mineral wool insulation sandwiched between 85 mm brick cladding and 120 mm concrete panels on the outside and inside, respectively. The eastern and western external walls consist of 25 mm polystyrene plus 45 mm or 95 mm mineral wool insulation clad with brick or wood, alternatively. The intermediate floors are 190 mm concrete slabs, with a 70 mm additional layer of wood fibre insulation over the basement. The ceiling floor consists of 160 mm concrete slab and 120 mm mineral wool insulation with wooden trusses and roof covering over a layer of asphalt impregnated felt. The windows and external doors have clear glass double-glazed panels with wood frames clad with aluminium profiles on the outside. The building has mechanical exhaust ventilation system.

2.2. Retrofitted building

In Sweden, a maximum specific annual final energy use for heating and ventilation of a passive house is set to 50 kWh/m^2 (50PH) and 30 kWh/m^2 (30PH), according to the SCNH (Sveriges Centrum för Nollenergihus) [21] and the Passive House Institute [22], respectively. We apply energy efficiency measures to the existing building so as to fulfil these two standards. The 50PH standard is achievable with cost-effective retrofitting measures and exhaust air ventilation heat recovery (VHR) unit [23]. The

50PH version requires extra insulation in the basement walls and attic floor, as well as new energy-efficient windows. The 30PH version also requires extra insulation in the external walls and hence a new external building cladding.

We select different building materials for: thermal insulation, building cladding and window (frame). Six and eighteen retrofitted building envelopes are modelled by combining different material options (Table 1) for the 50PH and 30PH versions, respectively. The retrofitting works are assumed to be carried out forty years after the building construction and to have a lifespan of 50 years.

Table 1. Material categories, material options (with abbreviations) and U-values (W/m^{2}K) of the 50PH and 30PH retrofitted building elements.

	Building envelope elements				
	Basement wall	**Attic floor**	**External wall**		**Windows**
Material category	Insulation	Insulation	Insulation	Cladding	Window (frame)
Material options	Extruded polystyrene (XPS)	Wood fibre (W) Rock wool (R) Glass wool (G)	Wood fibre (W) Rock wool (R) Glass wool (G)	Wood (W) Brick (B) Aluminium (A)	Wood (W) Aluminium (A)
U-value of 50PH (30PH) (W/m^{2}K)	0,11 (0,14)	0,6 (0,9)	(0,14)		0,8 (0,6)

The existing technical devices are assumed to be upgraded based on [24]. The efficiencies of fans and VHR unit are increased from 33% to 50% and from 76% to 85, respectively. Resource efficient water taps are assumed to be used, reducing tap water heating energy use by 40%.

3. Method

The study adopts a bottom-up approach to analyse the primary energy use and CO_2 emissions for material production, construction, maintenance and end-of-life phases of thermally-equivalent retrofitted building envelopes. The analysis is based on material and energy flows over the retrofitted building envelopes' life cycle.

3.1. Final energy calculations

We perform dynamic hour-by-hour energy balance calculations of the retrofitted building under the different passive house standards (50PH and 30PH), including modelling different material options. The dynamic energy modelling allowed comparison of equivalent building envelopes in the 50PH or 30PH versions of the building. The final energy calculations include space and tap water heating, as well as electricity for ventilation and household appliances.

The analysis is based on the following input data:

- hourly weather data for the city of Ronneby in 2013, taken from Meteonorm database;
- indoor air temperatures of 22°C for the living areas and to 18°C for common areas;
- internal heat gains from building occupants and electrical appliances of 2,16 W/m^2 and 3 W/m^2 respectively, assuming a constant profile over the year;
- tap water heating (kWh) use based on standard equation (1800 × number of apartments + 18 × heated area [m^2]) from the Swedish National Board of Housing, Building and Planning [25].

We used the VIP Energy simulation software [26], which is validated by the International Energy Agency's BESTEST, ANSI/ ASHRAE Standard 140 and CEN 15265 for the final energy calculations.

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3.2. Primary energy use and CO_2 emission calculation

We assume that the electricity is produced in coal-fired stand-alone plants. The conversion efficiency of coal-fired condensing plant is taken to be 40% [5] and the specific fuel-cycle carbon intensity of coal is taken to be 0.11 kg CO_2/kWh [5]. The distribution losses for high-voltage electricity is assumed to be 2% [27]. Woody biomass residues are assumed to replace fossil coal and biogenic CO_2 emissions is excluded in the analysis. The conversion efficiency is assumed not to change when coal is replaced by biomass [16]. The fuel-cycle carbon intensity of motor diesel is assumed to be 0.29 kg CO_2/kWh [28].

3.2.1. Production phase. The calculation consists of the net primary energy and CO_2 emissions to manufacture building materials used in the retrofitted building envelope. The production energy is calculated as the primary energy used to manufacture the materials, minus the net energy recovered from woody process waste. The primary energy to manufacture building materials is calculated based on Ecoinvent data [29], adjusted in order to account for coal used for the production of electricity. The production CO_2 emission is calculated as the CO_2 emission due to the manufacture of materials, minus the CO_2 emission avoided by replacing fossil coal with recovered woody biomass. The manufacture CO_2 emission is calculated based on Ecoinvent data adjusted in order to account for the CO_2 emission from coal-sourced electricity and excluding the carbon stock in wood material. We take into account the wastage of materials on the construction site by increasing the amount of materials in the finished renovated building by typical wastage percentage values in Sweden, based on Ref. [6]: 7% insulation waste, 10% plasterboard and wood waste, 5% for all other materials.

Bioenergy recovery and avoided fossil emissions. Woody biomass is assumed to be recovered for energy purposes, substituting fossil coal. The biomass waste rate is calculated based on Ecoinvent flow data [30], resulting in: 55% from thinning, 38% from sawing and 7% from planing. The net energy from biomass recovery is calculated as the heating value of the overall biomass residues, minus the energy used to transport and process the residues. The lower heating values of the processing residues are based on [31] but adjusted according to the Swedish context [16], resulting in: 3.09 kWh/kg for thinning residues, 4.17 kWh/kg for sawing residues and 5.39 kWh/kg for planing residues. The fuel-cycle energy use is 7% for thinning and 1% for other activities [16]. The net CO_2 emission is calculated as the avoided CO_2 emission from fossil coal substitution, minus the CO_2 emission of the fossil fuel used to recover and transport the biomass residues.

3.2.2. Construction phase. The construction primary energy use and CO_2 emissions include transport and assembly of building materials. Construction primary energy calculation is based on average energy data for multi-family buildings in Sweden [3], with a final energy use of 40 kWh/m^2 and 80 kWh/m^2 for transport and assembly, respectively. Diesel, assumed to be used for transportation, dominates the road transport in Sweden [32]. Coal-based electricity is assumed to be used for assembly.

3.2.3. Maintenance phase. The maintenance primary energy use and CO_2 emissions include manufacture, transport and assembly of the building materials used to replace or renovate the worn-out ones throughout the life cycle of the retrofitted building envelopes. The number of maintenance cycle is based on standard service lives of building materials from Ref. [33] and on the life-span of the retrofitted building envelopes. The calculation formula is taken from Refs. [17, 34]

3.2.4. End-of-life phase. The calculation consists of the net primary energy use and CO_2 emissions to transport and dispose demolished materials of the retrofitted building envelopes, both at the construction (current scenario) and demolition (future scenario) phases. The end-of-life energy is calculated as the primary energy use for demolition and transportation of construction and demolition waste (CDW), minus the net energy from the recovery of CDW. The primary energy use for demolition activities is neglected according to Ecoinvent data, since non-structural building material are mainly disassembled by handheld tools [35]. The primary energy use and CO_2 emissions to transport CDW take into account site-specific haul distances, based on the Swedish waste management system [36] and the current production system (10 km for landfill and processing; 90 km for incineration; 100 km for aluminium recycling; 200 km for mineral wool and gypsum board recycling; and 1000 km for glass recycling).

Based on [19], we assume that transportation is by a diesel-fuelled truck of 26 tons with a capacity of 70%. Fuel consumption of truck is assumed to be 32 l/100 km [37].

CDW recovery and avoided fossil emissions. We maximise the recycling potential of building materials complying with Swedish waste management regulations. For building materials recycled in the demolition phase (i.e. glass, mineral wool), we assume recycling efficiency rates based on current best available technology (BAT) based on [38]. The destination, recovery rate and recycling efficiency per type of CDW are summarized in Table 2. The net energy from CDW recovery is calculated as the energy saved by substituting primary materials or fossil fuel, minus the energy used to sort the recover CDW. The conversion efficiency of a municipal incineration plant producing electricity is taken to be 30% [39]. The energy use from landfilling is neglected. The net CO_2 emission from CDW recovery is calculated as the avoided CO_2 emission from primary material or fossil fuel substitution, minus the CO_2 emission from sorting. For energy recovery purpose, the calculation is described in Subsection 3.2.1.1. Ecoinvent database provides specific primary energy use and CO_2 emissions for CDW sorting and transport. However, Ecoinvent data are adjusted in order to consider only sorting of the CDW and account for coal-based electricity.

Table 2. Destination and recovery rate in the current and future scenario, respectively, and recycling efficiency of CDWs (I=incineration facility; L=landfill; R=recycling facility).

CDW material	Destination		Recovery rate [%weight]		Recycling efficiency [%weight]
	Current scenario	Future scenario	Current scenario	Future scenario	
Aluminium	R	R	90	98	96
Clay	R	R	90	95	15
Glass	R	R	0	50	120
Gypsum board	L	R	10	95	100
Mineral wool	L	R	0	90	9
Wood	I	I	90	90	100
XPS	I	I	90	90	100

4. Results

In the 50PH-retrofitted building envelopes, the production energy of the new building envelopes dominates the life-cycle primary energy, as shown in Table 3. It ranges between 709 MWh and 1163 MWh, where the low-energy option has wood fibre insulation and wood-framed windows (WW) and the high-energy option has glass wool insulation and aluminium-framed windows (GA). Production CO_2 emissions follow similar trends, ranging between 98 tCO_2 (WW) and 218 tCO_2 (GA), though the deviation between wood-based envelopes (WA and WW) and other envelopes is higher. This is due to the lower carbon intensity of wood fibre insulation compared to rock and glass wool insulations. Construction and maintenance primary energy are minor, together ranging between 4% and 9% of the production primary energy and between 7% and 15% of the production CO_2 emissions. End-of-life primary energy is negative and accounts for 18% and 16% of the production primary energy in the WW and WA options, respectively, and for a maximum of 5% in the other options. End-of-life CO_2 emission is negative and reduces the production CO_2 emissions by 41% and 32% in the WW and WA options, respectively, and by a maximum of 6% in the other options. Burnable insulation materials (XPS and wood) contribute to the end-of-life energy by 84% and 88% and to the end-of-life carbon benefits by 81% and 95% in WW and WA, with a small contribution by aluminium recycling process.

Table 3. Primary energy – PE (MWh) and CO_2 emission – CO_2 (tCO_2) of the 50PH and 30PH retrofitted building versions (acronyms are composed by the abbreviations of the materials used in: attic thermal insulation and window frame, respectively, in 50PH; attic and external walls' thermal insulation, cladding and window frame, respectively, in 30PH – e.g. GGWA, where GG=glass wool in attic and external walls' thermal insulation, W=wood in cladding, A=aluminium in window frame).

	Production phase		**Construction phase**		**Maintenance phase**		**End-of-life phase**		**Total**	
	PE	CO_2	PE	CO_2	PE	CO_2	PE	CO_2	PE	CO_2
50PH standard										
GA	1163	218	14	5	56	11	-42	-4	1190	230
GW	1090	209	14	5	33	8	-48	-10	1089	213
RA	1018	162	14	5	56	11	-42	-4	1046	175
RW	946	153	14	5	33	8	-47	-10	946	157
WA	782	108	14	5	56	11	-122	-35	730	90
WW	709	98	14	5	33	8	-127	-40	629	71
30PH standard										
GGWA	2541	662	36	13	790	229	-364	-102	3003	802
GGWW	2466	653	36	13	767	225	-369	-107	2900	784
GGBA	2827	606	36	13	272	51	-134	-13	3001	657
GGBW	2752	595	36	13	249	48	-140	-18	2897	638
GGAA	2862	615	36	13	1101	221	-201	-21	3798	828
GGAW	2786	605	36	13	1079	218	-207	-27	3694	809
RRWA	2326	590	36	13	789	228	-356	-100	2795	731
RRWW	2251	579	36	13	767	225	-362	-105	2692	712
RRBA	2613	536	36	13	272	51	-135	-13	2786	587
RRBW	2538	525	36	13	249	48	-141	-19	2682	567
RRAA	2649	545	36	13	1101	221	-205	-21	3581	758
RRAW	2574	535	36	13	1078	218	-210	-27	3478	739
WWWA	2090	535	36	13	789	228	-412	-121	2503	655
WWWW	2015	525	36	13	767	225	-417	-126	2401	637
WWBA	2377	481	36	13	272	51	-210	-43	2475	502
WWBW	2302	471	36	13	249	48	-216	-49	2371	483
WWAA	2413	491	36	13	1101	221	-277	-51	3273	674
WWAW	2338	480	36	13	1078	218	-283	-57	3169	654

In the 30PH-retrofitted building envelopes, the production primary energy of the new building envelopes ranges between 2015 MWh and 2862 MWh, where the low-energy option has wood fibre insulation, wood cladding and wood-framed windows (WWWW) and the high-energy option has glass wool insulation, aluminium cladding and aluminium-framed windows (GGAA). Retrofitted envelopes with wood cladding result in lower production primary energy use than brick and aluminium claddings. Production CO_2 emission ranges between 471 tCO_2 and 662 tCO_2, where the low-emission option has wood fibre insulation, brick cladding and wood-framed windows (WWBW) and the high-emission option has glass wool insulation, wood cladding and aluminium-framed windows (GGWA). Brick cladding in retrofitted envelopes has less production CO_2 emissions than aluminium and wood cladding, according to Ecoinvent specific CO_2 emission. The construction phase has minor impact, accounting for between 1.3% and 1.8% of the production primary energy and between 1.9% and 2.7% of the production CO_2 emission. The maintenance phase affects the results significantly, ranging between 9% and 46% of the production primary energy, as well as between 8% and 45% of the production CO_2 emissions. Retrofitting envelopes with wood cladding give higher primary energy use and CO_2 emission than brick cladding, because of higher maintenance need. End-of-life primary energy ranges between -134 MWh (GGBA) and -417 MWh (WWWW). The highest energy benefits are in retrofitted envelopes with wood cladding and window frames, ranging between 14% and 21% of the production primary energy depending on the material options. End-of-life CO_2 emissions range between -13 tCO_2 (GGBA) and -126 tCO_2 (WWWW). In the end-of-life phase, the retrofitted envelopes with wood cladding achieve the highest carbon benefits, reducing the production CO_2 emissions by between 15% (GGWA) and 24% (WWWW), followed by those with aluminium and brick claddings.

5. Discussion and conclusions

The 30PH retrofitted envelopes use up to 3243 MWh and recover up to 376 MWh (production bioenergy recovery excluded) more than the 50PH alternatives. Furthermore, the 30PH retrofitted envelopes release up to 793 tCO_2 and avoid up to 123 tCO_2 more than the 50PH alternatives. The production phase accounts for the highest share of life cycle primary energy, excluding impacts from the operation phase, that are equal for the 50PH- and 30PH-retrofitted buildings, respectively. The options maximising the use of wood materials in the 50PH building (WW) and the use of wood and brick materials in the 30PH building (WWBW) have the lowest primary energy balance, due to the low production energy of wood and brick products and to the energy recovery of woody biomass from manufacture, construction and demolition activities. In the 50PH retrofitted building envelopes, the choice of the insulation materials significantly affects the production primary energy use and CO_2 emissions, as well as the life cycle balances. In the 30PH retrofitted building envelopes, cladding materials affect the energy and climate impacts more than insulation materials, mainly due to their weight. Construction primary energy use and CO_2 emission of the building envelopes do not show significant variations and account for a negligible share of life cycle primary energy and CO_2 emission as also showed by Refs [3, 14]. The maintenance phase accounts for a significant share of primary energy use, trading off those options with the lowest production energy (e.g. WWWW and WWWA). Maintenance primary energy and CO_2 emission essentially depend on the service lives of building elements and on the assumed exposure conditions, especially for cladding materials. Based on Ref. [33], the expected service life of wood cladding is shorter than brick and aluminium ones. Finally, the end-of-life phase can contribute to primary energy and carbon benefits due to the recovery of CDW. The findings show that maximising CDW recovery for recycling or energy purposes is advantageous in a life cycle perspective. The highest carbon benefits can be obtained in retrofitted envelopes using wood cladding, because of the significant quantity of biomass residues recoverable.

We conclude that the overall primary energy can vary significantly according to the choice of materials for thermal insulation, cladding systems and energy-efficient windows, also within the same energy-efficiency standard (50PH or 30PH). The results showed that the lowest primary energy and carbon balances were achieved by maximising the use of wood materials and using brick in building cladding. Furthermore, the entire remaining life cycle should be considered when analysing the energy and climate impacts of retrofitting buildings. Design strategies should pay attention to the durability of building materials to reduce maintenance need, as well as to future disassembly of building parts to optimise the efficiency of CDW recovery.

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