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Primary energy and CO₂ emissions implications of different insulation, cladding and frame materials for residential buildings

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Abstract. In this study, we analyse and compare the primary energy use and carbon dioxide (CO_2) emissions associated with different insulation, cladding and frame materials for a constructed concrete frame multi-storey residential building in Sweden. Our approach consists of identifying individual materials giving the lowest primary energy use and CO_2 emissions for each building envelope part and based on that, modelling different material combinations to achieve improved alternatives of the concrete frame building with the same operation energy use based on the Swedish building code or passive house criteria. We analyse the complete materials and energy chains, including material losses as well as conversion and fuel cycle losses. The analysis covers the primary energy use to extract, process, transport, and assemble the materials and the resulting CO_2 emissions to the atmosphere. The results show wide variations in primary energy and CO_2 emissions depending on the choice of building envelope materials. The materials for external walls contribute most to the primary energy and CO_2 emissions, followed by foundation, roof and external cladding materials. The improved building alternatives with wood construction frames, wood external cladding, expanded polystyrene as foundation insulation and cellulose insulation in the external walls and roof result in about 36 - 40% lower production primary energy use and 42 – 49% lower CO_2 emissions than the improved concrete alternative when achieving the same thermal performance. This study suggests that strategies for low-energy buildings should be combined with resource-efficient and low carbon materials in the production phase to mitigate climate change and achieve a sustainable built environment.

1. Introduction

The building sector contributes largely to energy and material use through the construction, operation and end-of-life activities related to buildings. The building and building construction sectors together account for 36% of global final energy use and about 40% of total direct and indirect CO_2 emissions globally [1]. Around 24% of global [2] and 50% the European Union (EU) material extractions are used in the built environment [3]. The operation phase dominates the life cycle energy use, especially in conventional buildings. Currently, about 40% of global final energy demand is for heating and cooling in the building and industrial sectors [4]. Space heating alone constitutes more than 60% of the EU's final energy demand in these sectors [5]. Building envelopes influence the space heating and cooling demands as well as indoor climates in buildings through their thermal performance. Existing energy policies have therefore mainly focused on energy efficiency and renewable energy use within the building sector. The directive on the energy performance of buildings mandates all new buildings

in the EU to be nearly zero-energy buildings from 2021 [6]. However, several studies [7-9] show that the significance of the other life cycle phases increase as more energy efficient buildings are constructed. Stephan et al. [10] noted that the production energy of a Belgian passive house was up to 77% of the production and operational energy use over a 100 year life span. Moran et al. [11] analysed different versions of a semi-detached residential building in Ireland and reported that the production energy and CO_2 emissions of the nearly zero energy building versions were up to 44% and 100% of the total life cycle energy use and CO_2 emissions, respectively. Dimoudi and Tompa [12] studied energy and environmental impacts of different construction materials for multi-storey office buildings in Greece. They showed that the production energy of the buildings' frame materials of concrete and reinforcement steel gives the largest part of the total production energy, while the external walls give the biggest contribution for the building envelope elements. The implication of various material choices for the structural frame, surface components and inner components on the life cycle energy of a hypothetical Finnish building model was studied by Takano et al. [13]. They found that the choice of materials for the structural frame results in the largest impact. Hence, as buildings are constructed to be more energy efficient, strategies for resource efficiency and material use over their life cycle should be addressed.

In this study, we analyse and compare the primary energy use and CO_2 emissions associated with different insulation, cladding and frame materials for a constructed concrete frame multi-storey residential building in Sweden redesigned to meet the Swedish building code of 2015 (BBR) or the passive house criteria (passive). Our approach consists of identifying individual materials giving the lowest primary energy use and CO_2 emissions for each building envelope part and based on that, modelling different material combinations to achieve improved alternatives of the concrete frame building with the same operation energy use.

2. Studied building description

The constructed building used in this study is a recently completed multi-storey residential building in Växjö, Southern Sweden. It is 6 storeys high with prefabricated concrete frame and comprises 24 apartments with a total heated floor area of 1686 m^2. The foundation is made up of 100 mm concrete slab, 300 mm expanded polystyrene (EPS) insulation and 200 mm crushed stone. The external walls consist of 100 mm EPS insulation sandwiched between 100 mm and 230 mm of concrete panels on the outside and inside, respectively. The intermediate floors are 250 mm concrete slabs while the roof consists of 250 mm concrete slab and 500 mm mineral wool insulation with wooden trusses and a roof covering over layers of asphalt-impregnated felt and plywood. The windows and external doors have clear glass double-glazed panels with wood frames, covered with aluminium profiles on the outside. The windows and doors have u- and g-values of 1.2 W/m^2K and 0.6, respectively. The ventilation is based on a balanced mechanical system with a heat recovery (VHR) unit of 76% efficiency. A photograph and floor plan of the reference building is shown in Figure 1.

Figure 1. Photograph (left) and floor plan (right) of the reference building.

3. Methodology

Generally, the study approach includes modelling changes to the envelope characteristics of the studied building to achieve building alternatives meeting BBR standard or passive house criteria; considering different insulation, cladding and frame materials in the different parts of the two building alternatives meeting the BBR standard or passive house criteria; analysing and selecting the materials resulting in the lowest production primary energy use in each building envelope part; modelling improved alternatives of the two building alternatives based on a combination of the selected materials; and analysing and comparing the production primary energy use and CO_2 emissions of the alternatives.

Table 1. Thermal characteristics of the different envelope elements for the building alternatives to meet the BBR standard and passive house criteria.

Description	U-values (W/m^{2}K)	
	BBR	Passive
Ground floor	0.11	0.11
External walls	0.22	0.11
Windows	1.2	0.8
Doors	1.2	0.8
Roof	0.08	0.05

3.1. BBR and passive house building alternatives

We modelled changes to the envelope characteristics of the studied building, including the external walls, roof, door and windows to achieve building alternatives with thermal performances of the Swedish building code [14] and passive house criteria [15]. The BBR standard and passive criteria specify maximum limits for specific final energy use for operation of buildings, including space heating, tap water heating and electricity for ventilation but excluding electricity for household appliances and lighting. The specific final energy use depends on climate zones and the heating supply option for the building. The analysed building alternatives are assumed to have the same district heat supply as the constructed building. The constructed building is in climate zone 3 in southern Sweden, where the maximum specific annual final energy use for operation is set to 80 kWh/m^2 and 50 kWh/m^2 for the BBR standard and passive house criteria, respectively. The airtightness of the building alternatives is assumed to be 0.6 l/s m^2 and 0.3 l/s m^2 at 50 Pa for the BBR standard and passive house criteria, respectively. Table 1 shows the thermal characteristics of the building alternatives. The insulation, façade and frame materials in the different building parts of the constructed building and the considered alternatives are shown in Table 2.

The final energy use for operation of the building alternatives, including space and tap water heating as well as electricity for ventilation is calculated with the VIP-Energy software [16]. The VIP-Energy software is validated by the International Energy Agency Building Energy Simulation Test and diagnostic method (IEA BESTEST) and performs dynamic and hour by hour analysis of building operation energy use based on building orientation, geometry, heating and ventilation systems, indoor and outdoor temperature, operation schedule and thermal properties of the building envelope elements. The energy balance calculations are based on the 2013 climate data, which is close to the current average climate, for the city of Växjö and indoor temperature set points of 21°C for living and 18°C for common areas.

Table 2. Insulation, façade and frame materials in constructed concrete building and the considered alternatives.

Building part	Materials in the constructed building	Considered alternatives
Roof	Rock wool	Glass wool, cellulose fiber
External wall	EPS	Glass wool, cellulose fiber, EPS
Ground floor	EPS	Foam glass
Building frame	Concrete	Cross laminated timber (CLT), prefabricated timber modules (Modular)
Façade	-	Stucco, wood cladding, brick tiles, aluminium cladding

3.2. Primary energy and CO_2 emissions analysis

Based on building alternatives with different material choices, we estimated the quantities of the various material inputs required to construct the buildings to meet the BBR standard and passive house criteria. The analysis covers the complete materials and energy chains, including material losses and also, conversion and fuel cycle losses of the energy systems along the entire material production process. We considered the primary energy use for extraction, processing, transport, and assembly of the building envelope materials required for the building alternatives as well as the resulting CO_2 emissions based on methodology presented by Gustavsson et al. [17]. Data for specific end-use energy for material production is from Björklund and Tillman [18]. The specific end-use energy for production of selected materials are given in Table 3.

Table 3. Specific end-use energy (kWh/kg) to produce selected building materials.

Material	Coal	Oil	Fossil gas	Bioenergy	Electricity
Concrete	0.09	0.10	–	–	0.02
Plasterboard	–	0.79	–	–	0.16
Rock wool	2.00	0.36	0.02	–	0.39
Glasswool	2.87	0.52	0.03	–	2.00
EPS	0.28	3.9	3.72	–	0.63
Lumber	–	0.15	–	0.70	0.14
Particleboard	–	0.39	–	1.39	0.42
Stucco (plaster)	0.05	0.05	–	–	0.04
Brick	–	0.003	0.46	–	0.15
Steel	1.99	0.47	0.89	–	0.74
Aluminium	–	11.8	–	–	17.8

We assumed fossil fuel cycle energy inputs of 10, 5 and 5% as well as specific fuel-cycle carbon emissions of 0.11, 0.08 and 0.06 kg C/kWh for fossil coal, oil and gas, respectively based on Gustavsson and Sathre [19]. End-use electricity for building material production is taken to be from a coal based power plant with conversion efficiency of 40% and distribution losses of 2% based on Gustavsson et al. [17].

4. Results and discussion

The required quantities of insulation materials in the various building envelope parts when the building alternatives are constructed with different frame materials to meet the BBR standard and passive house criteria are given in Table 4. Glass wool and EPS result in the lowest thickness for external wall insulation, whiles cellulose fiber results in the highest for all the building alternatives. For the ground floor insulation, EPS gives a lower thickness compared to foam glass insulation. The passive building alternatives require about 56-60% and 113-158% more insulation materials for the roof and external walls, respectively compared to the BBR alternatives.
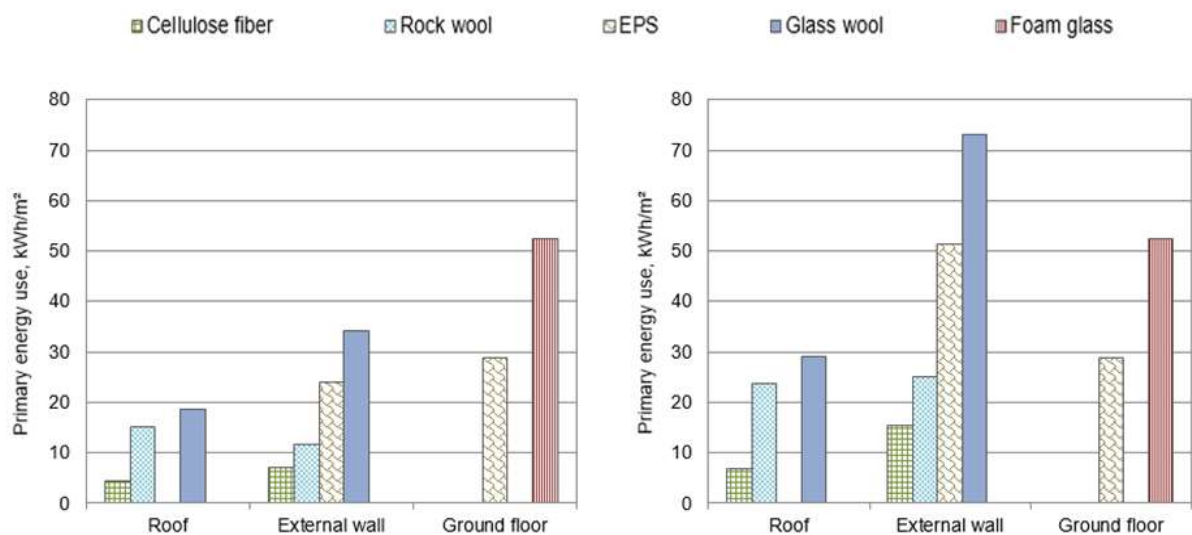
Table 4. Quantities of insulation materials required in the different building envelope parts to meet the BBR standard and passive house criteria.

Building parts	Insulation materials	BBR			Passive		
		Concrete	CLT	Modular	Concrete	CLT	Modular
Roof	Rock wool	500	465	465	780	745	745
	Glass wool	500	465	465	780	745	745
	Cellulose fiber	500	465	465	780	745	745
External walls	Rock wool	158	124	154	337	320	332
	Glass wool	150	117	146	320	286	315
	Cellulose fiber	166	130	162	355	320	350
	EPS	150	117	146	320	286	315
Ground floor	EPS	300	300	300	300	300	300
	Foam glass	315	315	315	315	315	315

Table 5 shows the mass balances while Figure 2 shows the primary energy use for production of the various insulation materials for the different building envelope parts to meet the BBR standard and passive house criteria. EPS gives a lower production primary energy use than foam glass for the foundation insulation of the building alternatives. For the roof and external walls, cellulose fiber insulation consistently results in the lowest primary energy use for production compared to the other insulation alternatives both for the BBR standard and passive house criteria, while glass wool gives the highest. The differences in production primary energy use of the insulation materials are linked to variations in manufacturing processes as well as fuel resources. Tettey et al. [20] considered different insulation materials for a Swedish residential building and found that their production process is typically fossil fuel intensive.
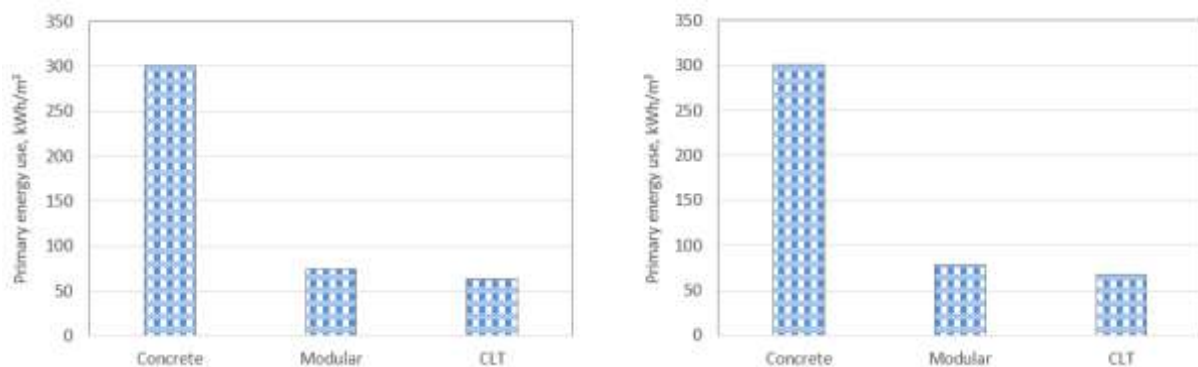
Table 5. Mass (kg) of insulation materials required in different building parts to meet the BBR standard and passive house criteria.

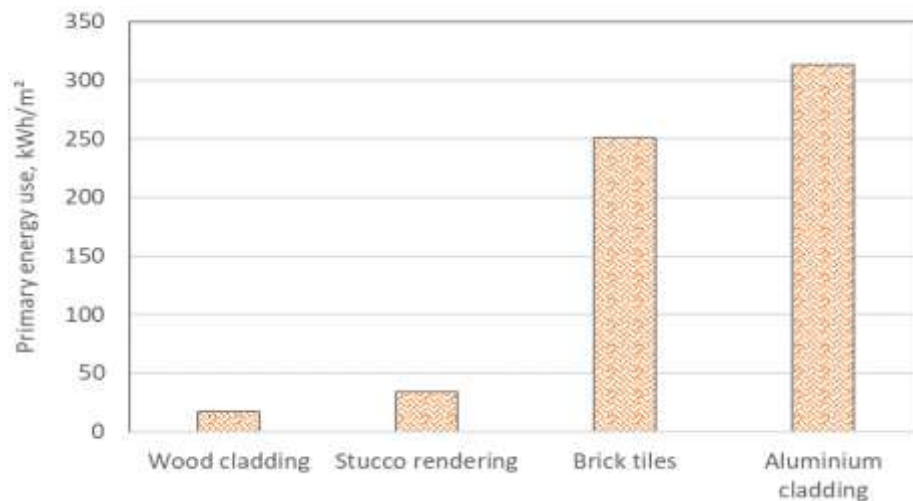| Building parts	Insulation materials	BBR			Passive		
		Concrete	CLT	Modular	Concrete	CLT	Modular
Roof	Rock wool	7140	6640	6640	11140	10640	10640
	Glass wool	3570	3320	3320	5570	5320	5320
	Cellulose fiber	7140	6640	6640	11140	10640	10640
External walls	Rock wool	5520	4330	5380	11770	11170	11590
	Glass wool	6550	5110	6370	13960	12480	13750
	Cellulose fiber	11770	9220	11490	25170	22690	24820
	EPS	4090	3190	3980	8730	7800	8590
Ground floor	EPS	4900	4900	4900	4900	4900	4900
	Foam glass	19700	19700	19700	19700	19700	19700

Figures 2. Primary energy use for production of the various insulation materials in the different building envelope parts to the BBR standard (left) and passive criteria (right).

The primary energy use for production of the different building frame materials are presented in Figure 3 for the building alternatives to the BBR standard and passive house criteria. The CLT building frame requires the least while the concrete frame alternative requires the most primary energy use for production. The modular and CLT building frames to the passive house criteria have about 6 and 8% more primary energy use for production than the BBR alternatives. Figure 4 shows the

primary energy use for production of the different building façade alternatives. Wood cladding results in the lowest production primary energy use, followed by stucco rendering, brick and aluminium cladding. The choice of façade materials is not directly linked to the thermal performance of buildings but influences the production energy use. Façade materials such as brick and aluminium may have longer service life spans than wooden alternatives leading to variations in maintenance and repair needs [21]. The primary energy for maintenance and repairs can constitute a large share of the life cycle primary energy use, depending on the choice of façade material and the exposure conditions [22]. Hence the choice of façade materials should be combined with appropriate design strategies to minimise primary energy use for maintenance and repairs.
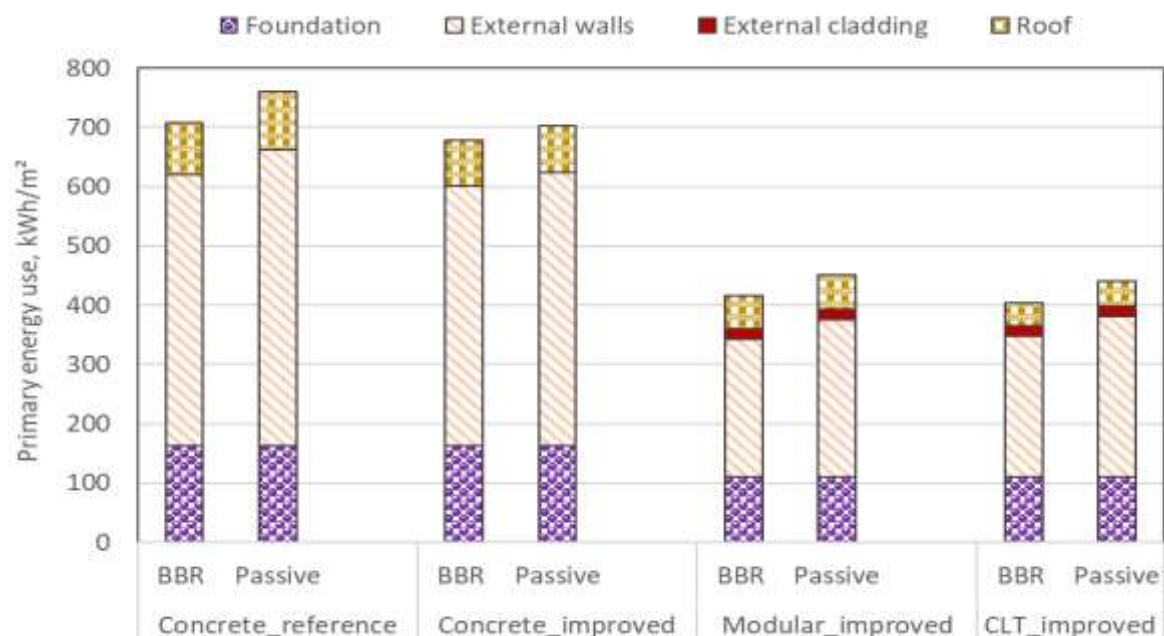

Figures 3. Primary energy use for production of the different building frame alternatives to the BBR standard (left) and passive criteria (right).
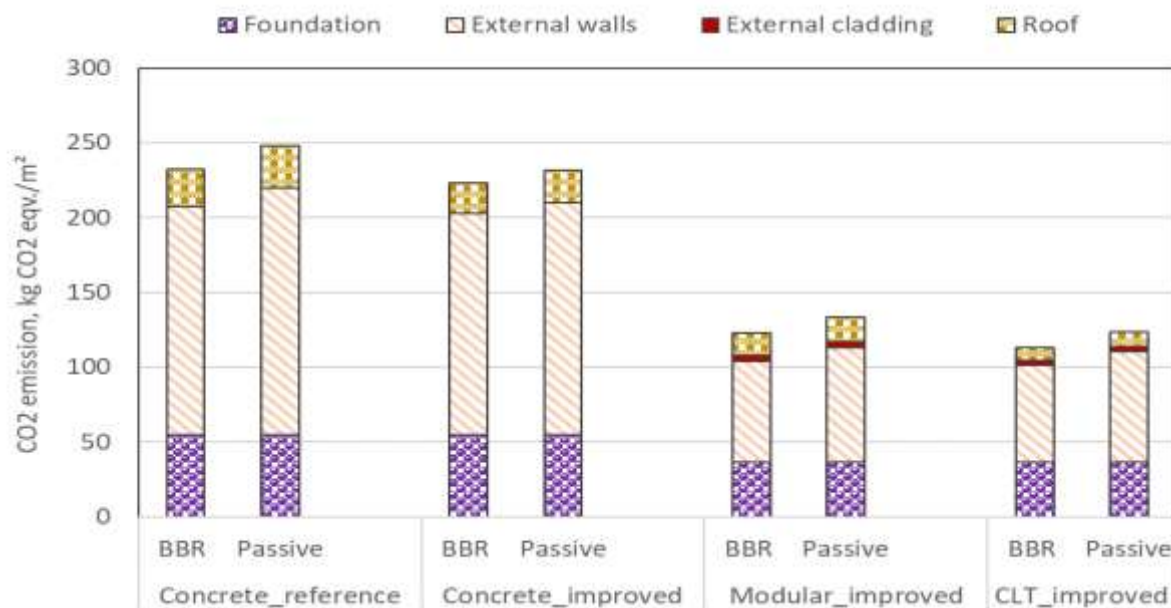

Figures 4. Primary energy use for production of the various façade alternatives.

The insulation, cladding and frame materials resulting in the lowest production primary energy and CO_2 emissions for each building part are given in figures 5 and 6 compared to the material choices in the constructed building for the BBR standard and passive house criteria. The lowest production primary energy use and CO_2 emissions for insulation is when EPS is used in the foundation and cellulose insulation in the external walls and roof. In addition, the best wall cladding choices is wood for the modular and CLT building alternatives while the concrete building alternatives do not need any

external cladding, similar to the constructed building. The primary energy use and CO_2 emissions for production of the external wall materials are large compared to those of the other building envelope parts. The production primary energy use for the external wall elements constitutes 56 – 65% and 59 – 66% of the total primary energy use for the building alternatives to meet the BBR standard and passive house criteria, respectively. The best CLT and modular building alternatives give significantly lower production primary energy use and CO_2 emissions for the building envelope parts compared to the best concrete alternatives. The total primary energy use for production of the building envelope materials to meet either the BBR standard or passive house criteria are about 4%, 41% and 42% lower for the best concrete, modular and CLT building alternatives, respectively, compared to the material choices in the constructed building. Similarly, the CO_2 emissions are reduced by 4%, 47% and 51% for the best building alternatives meeting the BBR standard and 7%, 46% and 50% when meeting the passive house criteria, compared to the material choices in the constructed building.

Figures 5. Production primary energy use of the different building envelope parts for material choices in the constructed building (reference) and for the combination resulting in the lowest production primary energy (improved) for the building alternatives.

Figures 6. CO_2 emission of the different building envelope parts for material choices in the constructed building (reference) and for the combination resulting in the lowest production primary energy (improved) for the building alternatives.

5. Conclusion

We have analysed the impacts of different building envelope materials on the primary energy use and CO_2 emissions for a multi-storey residential building meeting the BBR standard or passive house criteria and explored how combinations of the building envelope materials could minimise production primary energy use and CO_2 emissions. Our results show that the choice of building envelope materials significantly influences the primary energy use and CO_2 emissions of the analysed alternatives. The materials for the external walls contribute most to the primary energy use and CO_2 emissions, followed by foundation, roof and external cladding materials. The building alternatives with wood construction frames, wood external cladding, EPS as foundation insulation and cellulose insulation in the external wall and roof were found to give significantly lower production primary energy use and CO_2 emissions than the material choices in the constructed building both for the BBR standard and passive house criteria building alternatives. The choice of building envelope materials such as insulation and frame construction systems may result in varying energy- and climate-related impacts over the full life cycle of buildings. In this study, we have focused on the primary energy use and CO_2 emissions implications of different building envelope materials during the production phase. However, the choice of building envelope materials may also influence the maintenance needs and end-of-life related impacts. Moreover, several studies [23-25] report climate and environmental benefits for timber frame buildings mainly due to significant wood material recovery over the production and end-of-life phases for energy purposes. Further studies should consider these aspects in a life cycle perspective.

Overall, the improved CLT and modular building alternatives result in about 36 - 40% and 42 – 49% lower primary energy use and CO_2 emissions, respectively, compared to the improved concrete alternative. This study suggests that strategies for low-energy buildings should be combined with resource-efficient and low-carbon materials in the production phase to mitigate climate change and for a sustainable built environment.

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