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Lifecycle primary energy analysis of low-energy timber building systems for multi-storey residential buildings

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ABSTRACT

A system-wide lifecycle approach is used here to explore the primary energy implications of three timber building systems for a multi-storey building designed to a high energy-efficiency level. The three building systems are: cross laminated timber, beam -and-column, and modular prefabricated systems. The analysis considers the energy and material flows in the production, use and post-use lifecycle stages of the buildings. The effects of insulation material options and the contribution of different building elements to the production energy for the buildings are explored. The results show that external and internal walls account for the biggest share of the production energy for all building systems and its contribution is comparable for the different systems. In contrast, there is significant variation in the production primary energy for the roof-ceilings and intermediate floor-ceilings for the different building systems. Overall, the cross laminated timber building system gives the lowest lifecycle primary energy balance, as this building is insulated with stone wool and has better airtightness in contrast to the other building systems which are insulated with glass wool and have lower airtightness performance. With improved airtightness and insulation substitution, the total primary energy use for the beam-and-column and modular building systems can be reduced by 7% and 9%, respectively.

1. Introduction

Non-renewable fuels currently supply about 87% of the global total primary energy [1], with fossil fuels accounting for 82%, to which oil, coal and fossil gas contribute 32%, 29% and 21%, respectively [2]. Within the European Union (EU), oil, coal and fossil gas provide about 37%, 16%, and 25% of the total primary energy use, respectively [3]. The International Energy Agency global energy system scenarios for 2009–2035 anticipate that fossil fuels may increase in use and remain the dominant energy source [4]. Moreover, long-term energy mix scenarios by the Intergovernmental Panel on Climate Change suggest that fossil fuels are likely to contribute at significant levels in the year 2100 [5].

In the EU where buildings account for 41% of the total final energy use, efforts are ongoing to improve buildings energy efficiency and thereby reduce dependency on fossil fuels [6,7]. Low-energy buildings constitute an important part of the portfolio of measures to improve energy efficiency in buildings in many European countries. Low-energy buildings have much improved operational final energy performance compared to code compliant buildings in a given country. They encompass various standards and criteria including passive house, self-sufficient house and zero energy house. In Sweden, the LÅGAN project documented a classification system for low-energy buildings, and defined such buildings to encompass buildings with at least 25% lower specific purchased energy compared to the requirements of the prevailing building code [8,9]. Generally, low-energy building standards and criteria emphasize the use of both active and passive technologies to minimize heat losses in buildings. Measures typically used to minimize heat losses include improved thermal envelope insulation, reduced thermal bridging, high-performance windows, airtight building envelope and heat recovery of exhaust ventilation air.

Studies from various countries have reported substantial energy savings for buildings designed or built to low-energy standards instead of conventional standards. Dodoo and Gustavsson [10] showed that the final energy use for space heating and ventilation of a Swedish residential building could be reduced by 22% when it is designed to the energy efficiency level of passive house instead of the building code of 2012. Lewandowskaa et al. [11] showed that the overall energy demand of a Polish residential building could be reduced by a factor of 3.6 when it is built as passive house instead of as conventional house. Blengini and Di Carlo [12] reported that space heating demand of an Italian residential building is reduced

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by 91% while lifecycle energy use is reduced by 35% with low-energy instead of conventional building code requirements.

While low-energy buildings result in operational energy reduction, the energy use for building production is increased and becomes more significant [12–14]. Lifecycle studies show that the production stage of a low-energy building may constitute a substantial share of the total lifecycle primary energy use, depending on a building's location, climate, energy supply system and lifespan, as well as on methodological choices. In a hybrid lifecycle analysis of a Belgian residential building, Stephan et al. [15] estimated the production stage of a passive house to represent 77% of the total primary energy for production and operation of the building for 100 years. Thormark [16] found the production stage of a Swedish low-energy house to account for 45% of the total lifecycle energy use for 50 years, based on a bottom-up lifecycle analysis. Dodoo et al. [17,18] performed a process-based lifecycle analysis of Swedish buildings, and found the contribution of the production stage of a passive house to the total primary energy for production, space heating and ventilation for 50 years to range from 20% to 30%. They found that the relative contribution of the production stage depends on the choice of heat supply and is greater when more efficient heat supply systems are used.

Strategies to reduce the primary energy used for production of low-energy buildings are therefore important. Appropriate selection of building materials and structural systems may give significant reductions in lifecycle primary energy use and climate impact of buildings [19–22]. Reviews of lifecycle studies of buildings have underscored the energy and climate benefits of wood-based building materials in contrast to non-wood alternatives [23–25]. Comparatively, wood-based materials require less energy input for manufacture than non-wood alternatives. Significant amounts of biomass residues are generated during the lifecycle of wood-based material and this is increasingly used as bioenergy, and as processing energy for wood-based materials [25–27].

Wood is commonly used for single-family buildings in Sweden, where strong experience exists for such construction [28,29]. However, the Swedish multi-storey building sector is largely dominated by concrete-frame building systems, as the regulatory regime prohibited the construction of multi-storey buildings with timber frames until 1994 [30,31]. Interest in timber-frame multi-storey buildings is now increasing due to growing awareness of environmental impacts of the built environment and the environmental benefits of wood-based materials [32]. Light-framing systems are conventionally used for multi-storey timber buildings in Sweden. In recent times other innovative timber multi-storey building systems are emerging, including those with prefabricated elements, massive timber and engineered timber structural systems. Various studies have been conducted on lifecycle energy and environmental performance of buildings [e.g. 33–42]. While many comparative lifecycle studies have been reported on timber vs. non-timber building systems, few detailed comparative analyses have been reported on the energetic implications of different timber building systems or modern timber construction techniques. Monahan and Powell [43] investigated the lifecycle primary energy use of a low-energy UK building using a modern off-site panellised timber-frame system and compared it to a traditional alternative using on-site masonry construction system. In a US study, Salazar and Meil [44] analysed the primary energy balances of alternative designs for a timber-frame building with different wood intensity and usage. Kim [45] compared the lifecycle energy performance of timber-based buildings constructed with prefabricated modular or on-site conventional building systems in the U.S. John et al. [46] performed an environmental lifecycle analysis including two timber multi-storey building systems using laminated veneer lumber (LVL) in Australia. Beyond these initial studies, little is known about the lifecycle energy implications of innovative timber building systems, considering variations in structural elements, extent of prefabrication and range of wooden materials and components.

In this study we investigate the primary energy balances over the lifecycle of a Swedish multi-storey building designed with three different timber building systems: cross laminated timber (CLT), beam -and-column, and modular volume element. The primary energy analysis includes the entire energy and material chains from the extraction of natural resources to the delivered final energy or

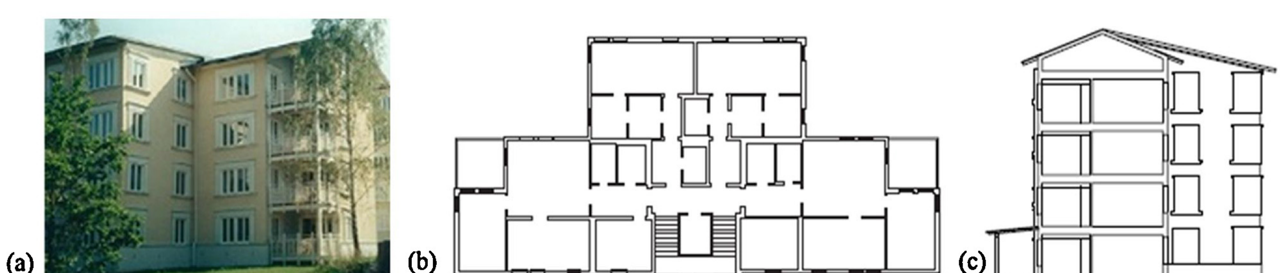
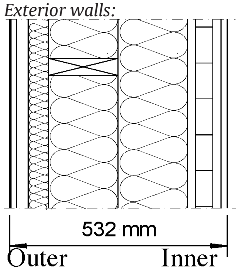
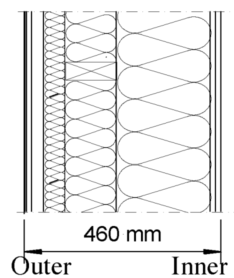
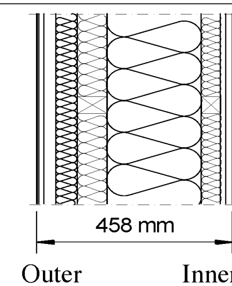
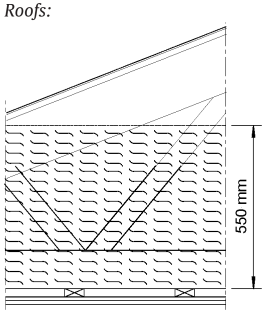
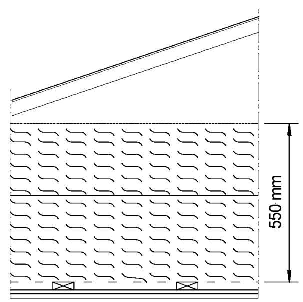
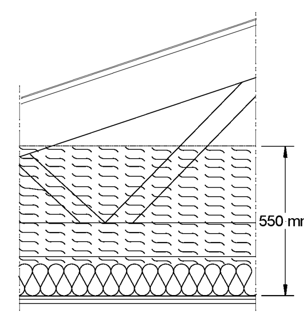
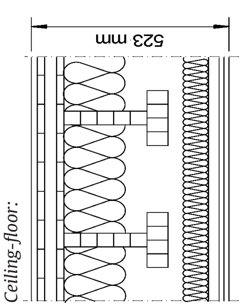
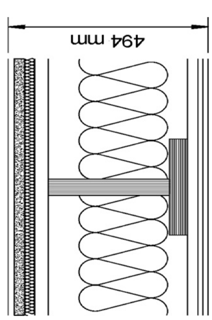
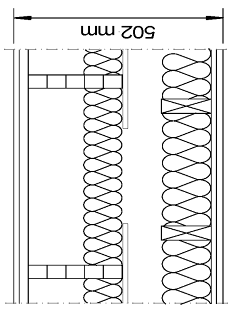
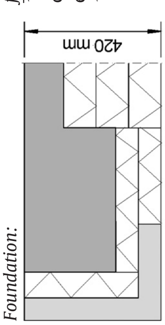


Fig. 1. Photograph (a) and sketch of ground floor plan (b) and vertical section (c) of the reference building.

Fig. 2. Photograph and details of some structural elements of the studied building systems including the (a) CLT building system (b) beam -and-column building system and (c) modular volume element building system.

Table 1
Construction details for the walls, roofs, intermediate floors and foundation of the studied building systems.

CLT system		Beam -and-column system		Modular system	
Details	Layers	Details	Layers (outer to inner)	Details	Layers (outer to inner)
Exterior walls: 	*from outer to inner* Ventilated façade plaster 28 × 70 mm wood lath 50 mm stone wool 170 mm stone wool 45 × 170 mm timber studs 170 mm stone wool 45 × 170 mm timber studs 0.2 mm plastic film 82 mm CLT 15 mm gypsum board		Ventilated façade plaster 28 × 70 mm wood lath 50 mm stone wool 120 mm stone wool 45 × 120 mm timber studs 220 mm stone wool 45 × 220 mm timber studs 0.2 mm plastic film 2 × 13 mm gypsum board		Ventilated facade plaster 28 × 70 mm wood lath 50 mm stone wool, 70 mm glass wool 45 × 70 mm timber studs 220 mm glass wool, 45 × 220 mm timber studs 0.2 mm plastic film 13 mm gypsum board 15 mm gypsum board
Roofs: 	*from top to bottom* Asphalt sheeting (2 layers) 16 mm T&G wood panels Timber trusses 550 mm loose stone wool 0.2 mm plastic film 28 × 70 mm timber battens 2 × 13 mm gypsum board		Asphalt sheeting (2 layers) 45 mm LVL board 45 × 300 mm LVL beams 550 mm loose glass wool 0.2 mm plastic film 28 × 70 mm wood battens 13 mm gypsum board 15 mm gypsum board		Asphalt sheeting (2 layers) 16 mm T&G wood panels Timber trusses 430 mm loose glass wool 45 × 120 mm timber studs 120 mm glass wool 0.2 mm plastic film 13 mm gypsum board 15 mm gypsum board

Ceiling-floor:	 *from top to bottom* 14 mm laminated wood board 2 mm expanded polyethylene 70 mm CLT 45 × 220 mm glulam beams 56 × 180 glulam flange 170 mm stone wool 70 mm stone wool 28 × 70 mm wood panels 2 × 13 mm gypsum board	 14 mm laminated wood board 3 mm expanded polyethylene 25 mm gypsum fibre board 25 mm glass wool board 33 mm LVL board 220 mm glass wool 51 × 300 mm LVL beams 25 mm sound insulation bars 13 mm gypsum board 15 mm gypsum board	 14 mm laminated wood board 2 mm expanded polyethylene 22 mm particle board 42 × 225 mm glulam beams 12 × 300 mm plywood 95 mm glass wool 45 × 120 mm timber studs 120 mm glass wool 15 mm gypsum board 13 mm gypsum board
Foundation:	 *from top to bottom* 120 mm reinforced concrete slab 300 mm extruded polystyrene 150 mm crushed stone	Foundation is designed in a similar manner as the CLT system but with added reinforced concrete footing for columns, to transfer loads to the substructure	Foundation is designed in the same way as the CLT system

product and encompasses the production, operation and end-of-life phases of the building systems.

2. Description of case studies

2.1. Reference building

An existing multi-storey residential building is used as a reference to design and model the three innovative timber building systems explored in this study. The reference building is a light-frame timber residential building situated in Växjö, Sweden. It is a four-storey building and contains a total of 16 apartments with living areas ranging from 42 to 78 m^2. Fig. 1 shows a photograph and ground floor plan and section of the building. An elevator is installed in the building, beside the stairwell.

2.2. Studied building systems

The reference building is used to model three timber-frame building systems designed to the energy efficiency level of the Swedish passive house criteria [47]. The modelled systems are: (i) CLT building system; (ii) beam -and-column building system; (iii) modular volume element building system. All the designs were checked and reviewed by the companies designing and constructing these building systems in Sweden. The building systems each have different structures and construction details but the same architectural layout as the reference building. Fig. 2 presents images of some structural elements and components of the systems.

The building with CLT structural system has walls, intermediate floors and structural systems and load-bearing interior elements constructed with massive timber panels using CLT. For the building with beam -and-column structural system, LVL and glulam columns and beams are used as the main structural frame to transfer all horizontal and vertical loads to the foundation. The building with modular system is based on individual volumetric elements prefabricated off-site. Construction details for the walls, roofs, intermediate floors and foundations for the three building systems are presented in Table 1. The beam -and-column and the modular building systems have double layers of gypsum plasterboard while the CLT building system has a single layer of gypsum plasterboard to comply with fire resistance requirements. The façades of all the buildings are covered with ventilated plaster to make the buildings moisture safe. The foundation for all building systems are similar and consist of 120 mm reinforced concrete floor slab and a 300 mm layer of expanded polystyrene (EPS) insulation laid on 150 mm crushed stones. The walls, intermediate floors and roof for the CLT system are insulated with stone wool. For the beam -and-column system, the walls are insulated with stone wool, the roof with glass wool and the intermediate floors with glass wool and EPS. The walls of the modular system are insulated with a combination of stone wool and glass wool while the intermediate floors and roof are insulated with glass wool.

Key thermal characteristics and architectural details for the three building systems are listed in Table 2. The thermal characteristics of the building envelopes were extracted from drawings and specifications from companies making the building systems. The buildings have high levels of insulation and airtight thermal envelopes. The building envelope infiltration values are based on figures currently guaranteed by the companies. The windows are tripled glazed with krypton infill-gas and have composite frame consisting of timber and aluminium. The configuration of the modular system results in a slightly greater floor area compared to the two other systems. Otherwise the building systems have the same architectural details.

Table 2
Thermal characteristics and architectural details of the studied building systems.

Description	CLT system	Beam -and-column system	Modular system
Living area (m^2)	928	928	935
Number of floors	4	4	4
Number of apartments	16	16	16
Common area (m^2)	130	130	130
Room height (m)	2.55	2.55	2.55
U-values (W/m^2 K):			
Roof	0.08	0.08	0.08
External wall	0.10	0.11	0.11
Separating wall	0.16	0.22	0.20
Internal floors	0.13	0.13	0.14
Windows	0.80	0.80	0.80
Doors	0.80	0.80	0.80
Ground floor	0.12	0.12	0.12
Air infiltration (l/s m^2@ 50 Pa)	0.20	0.40	0.40
Mechanical ventilation	Balanced	Balanced	Balanced
Heat recovery (%)	80	80	80
Ventilation rate (l/s m^2)	0.35	0.35	0.35
Water taps	Efficient	Efficient	Efficient

Table 3
Material mass balance for the building systems in tonnes of air-dry material.

Material	CLT system	Beam -and-column system	Modular system
Concrete	114.9	179.8	114.9
Iron/steel	5.2	12.7	3.5
Lumber	47.9	25.1	62.4
Particle board	6.0	2.8	20.5
Plywood	6.7	0.0	9.1
Laminated wood floor	4.9	4.9	4.9
CLT	54.8	4.8	4.8
LVL	0.0	60.7	0.0
Glulam	20.2	24.8	8.2
Stonewool insulation	26.0	16.1	2.3
Glass wool insulation	0.0	6.2	16.5
Plasterboard	72.3	98.5	104.9
PVC	0.7	0.4	0.4
Polyurethane	4.1	4.1	5.1
Expanded polystyrene (EPS)	2.8	2.8	2.8
Crushed stone	315.4	315.4	315.4
Mortar	17.7	11.2	11.2
Aluminium	0.6	0.6	0.6
Zinc and copper	1.4	1.5	1.5
Glass	3.9	10.6	10.4
Paint	1.4	1.3	1.5
Putty and fillers	1.2	1.1	1.3

3. Methods and assumptions

A process-based consequential lifecycle approach with a system perspective methodology is used to evaluate the primary energy implications of the buildings, taking into account processes and activities during the lifetimes of the buildings. The analysis begins with inventory of material mass and then assessment of energy flows from all stages of the building systems.

Consequential lifecycle approach takes into account the consequences of changes in the level of production and aims to characterize all direct and indirect effects that may be associated with changes in output in a system. In contrast, attributional lifecycle analysis characterizes the impacts of processes to produce, consume and dispose an average single unit of a product and does not include induced effects from changes in outputs. According to Plevin et al. [48], the use ofattributional-based approach for estimation of benefits of climate change mitigation options might mislead policy makers due to several limitations of this approach. Typically, historical average data on a product is used in attributional lifecycle analysis and this is less suitable when the effects of marginal changes are to be explored.

3.1. Material mass inventory

The inventory of materials required to construct the buildings (Table 3) was compiled from data supplied by the building systems' companies, including drawings and material specifications. The inventory excludes materials for cabinets, white goods (household appliances, e.g. refrigerator), heating systems and the infrastructure required for production, transportation and distribution of electricity and heat to the buildings. The beam -and-column building system requires greater amounts of concrete and steel reinforcement for the foundation, to transfer the concentrated point loads from the columns. The elevator shaft in this building system is made of reinforced concrete while the elevator shafts for the CLT and modular building systems are made of massive load-bearing timber. Further details on the inventory are given by Peñaloza et al. [49].

3.2. System boundaries

The system boundary of this study encompasses the energy flows during the production, operation and end-of-life stages of the building systems (Fig. 3), including the full energy chains and energy inputs from extraction of raw materials to delivered final energy services.

3.2.1. Production of building systems

The methods used for calculating the primary energy required for building production stage activities are described here. For the production stage, the primary energy required to produce and transport the materials as well as to fabricate and construct the buildings is taken into account. Bioenergy that could potentially be recovered from the wood product chain is also quantified.

3.2.1.1. Material production. A method developed by Gustavsson et al. [50] is applied to calculate the primary energy for production of building material. The method takes into account the energy required for extracting, processing, manufacturing and transporting the materials, and the full energy chains. The method is expressed in Eq. (1) and documented in several lifecycle studies [e.g. 17, 18, 26, 27, 51]. The equation characterizes all energy inputs needed to produce as well as to transport all materials and components comprising the buildings, and is used to calculate the material production energy for the building systems.

$$E_{mp} = \sum_{i} \left\{ \sum_{k} [F_{i,k} \times (1+\alpha_k)] + \frac{L_i}{\eta} + B_i \right\} \quad (1)$$

where E_{mp} is the total material production primary energy; i represents the different types of building materials and their masses; F is the lower heating values of end-use fossil energy used in extraction, processing and transportation of the materials; k represents the different fossil energy: coal, oil, and fossil gas; α is the fuel cycle energy input for the different fossil energy; L is the end-use electricity used in extraction, processing and transportation of the materials; η is the electricity production efficiency; and B is the lower heating value of the bioenergy used for the processing of materials. In this analysis, all energy parameter values are expressed in kilowatt hours (kWh).

In this study, i is based on the mass balance of the buildings (Table 3) with allowance for construction wastage, based on data from Björklund and Tillman [52]. The input values for F and L are based mainly on representative specific material production energy data for Sweden (Table 4) from Björklund and Tillman [52]. This data has been checked and supplemented with data from the

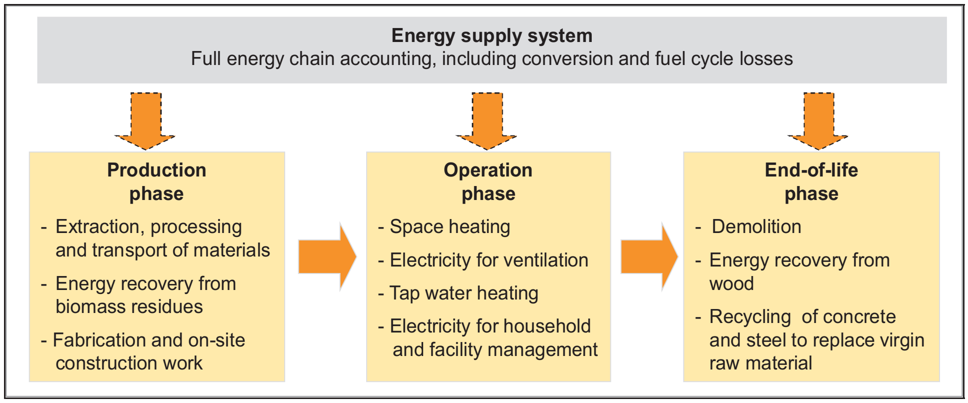


Fig. 3. System boundaries for the primary energy analysis

Table 4
Specific final energy ($kWh_{end-use}/kg$) to extract, process, and transport the selected materials.

Material	Coal	Oil	Fossil gas	Bioenergy	Electricity
Concrete (crushed aggregate)	0.09	0.10	–	–	0.02
EPS (insulation)	0.28	3.9	3.72	–	0.63
Glasswool (insulation)	2.87	0.52	0.03	–	2.00
Gypsum plasterboard	–	0.79	–	–	0.16
Lumber	–	0.15	–	0.70	0.14
Particleboard	–	0.39	–	1.4	0.42
Steel (ore-based)	3.92	0.86	1.34	–	0.91
Steel (scrap-based)	0.06	0.08	0.44	–	0.57
Stonewool (insulation)	2.00	0.36	0.02	–	0.39

Ecoinventv.2.2 database [53], in cooperation with SP Technical Research Institute of Sweden. Some key specific material production energy data are listed in Table 4. For steel we assumed that the production is based on 50% ore and 50% scrap steel. Feedstock energy value is not included in the energy content of the materials.

In this analysis, 95% of the electricity to produce the materials is assumed to be produced from a stand-alone biomass-fired steam turbine (BST) plant, with light-oil gas turbines generating the remaining. The BST plant and the light-oil gas turbines plants are assumed to have conversion efficiencies of 40% and 34%, respectively. Electricity distribution loss is assumed to be 2% [26]. The fuel cycle energy inputs are taken to be 10%, 5% and 5% of the delivered fossil energy for coal, oil and fossil gas, respectively [26].

3.2.1.2. Construction. The calculated primary energy for building construction, including fabrication and assembly, may also vary depending on parameters included, e.g. fuel use to transport construction equipment, workers and off-site fabricated components, etc. In contrast to site-built systems, modular building systems are typically prefabricated off-site as volume elements, and then transported and assembled on site-built foundations. The energy for building construction is typically small compared to the energy for material production. Adalberth et al. [54] estimated the construction energy to constitute 4% of the material production primary energy for the reference building. This percentage is applied to the building systems due to challenges in obtaining specific data for each system.

3.2.1.3. Bioenergy recovery. A diagram of system-wide flow of residues during the life cycle of a wooden material is illustrated in Fig. 4. Residues are generated during forest management activities, during primary processing when logs are sawn into lumber, and in secondary processing for products such as doors, windows and glue-laminated beams. Residues are used as bioenergy, redirected to non-wood product streams such as pulp and paper, or used as raw material for particleboard and other composite wood products [44,50,55]. In Sweden, 90% of recovered wood is used as bioenergy [56]. In this analysis the heat content of woody biomass residues that can be recovered for external use as bioenergy is calculated using a method reported by Sathre [57] and Gustavsson et al. [50]. This method is expressed in Eq. (2) and is used to calculate the energy of the recoverable biomass residues due to use of wood-based materials.

$$E_{re} = \sum_j \left\{ m_j \times H_j \times \left[1 - \beta_j \times (1 + \alpha_{\text{diesel}}) \right] \right\} \quad (2)$$

where E_{re} is the net lower heating value of recoverable residues; j is the various types of biomass residues from forest, wood processing and construction sites; M is the oven dry mass of the recoverable residue; H is the lower heating value of the oven dry biomass residue; β is the fossil fuel energy required to recover and transport the residue, expressed as a proportion of the heat energy contained in the residue; α is the fuel cycle energy requirement of the fossil fuel. The mass of the potential biomass residues that can be recovered during production and construction stages of the building is calculated based on the amount of wood materials in the ready buildings, using the method of Gustavsson et al. [50] and biomass expansion factors from Lehtonen [58]. All other data for the input

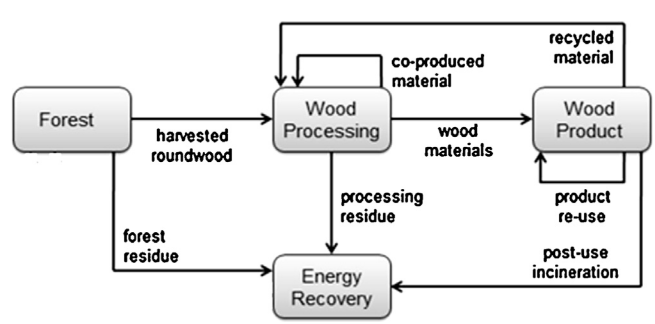


Fig. 4. Schematic diagram of system-wide material flows of wood-based products.

Table 5
List of key climate data of locations in Sweden considered for the final energy simulation, from the Meteonorm database.

Description	Växjö (South)	Östersund (Middle)	Kiruna (North)
Latitude	56°9′ N	63°2′ N	67°8′ N
Longitude	14°5′ E	14°4′ E	20°0′ E
Average annual ambient temperature, °C	7	4	0
Maximum annual ambient temperature, °C	28	25	26
Minimum annual ambient temperature, °C	−17	−26	−31
Average horizontal solar radiation, W/m^2	105	101	91
Average annual relative humidity, %	81	81	73
Average annual wind speed, m/s	3	4	4

parameters for the present analysis are as reported by Dodoo et al. [10].

3.2.2. Operation of building systems

3.2.2.1. Final energy simulation. The final energy demands for space and tap water heating, ventilation electricity and household and facility electricity are analysed for the operation stage of the building systems. The annual final energy demands are modelled using the VIP+ (version 2.1.0) dynamic hourly-based simulation program [59]. This simulation program calculates whole-building final energy balance and load based on several building energy-related parameters including envelope thermal properties of buildings, orientation, glass area, heating and ventilation systems, heat gains from lighting, appliances, human bodies and solar radiation, and operation schedule, indoor temperature, geographical location and outdoor climate. The program considers the interactions between a building's geometry, thermal properties, climate parameters and operational schedule. It allows for one, two and three dimensional modelling of thermal transmissions in a building's components and for detailed thermal bridge modelling. VIP+ is increasingly used for whole-building energy simulation by consultants and researchers in Sweden and is also validated by the building energy simulation test and diagnostic method (BESTEST). The BESTEST method was developed by the IEA model evaluation and improvement expert group to evaluate numerical heat transfer models in simulation software and is elaborated by Neymark et al. [60].

To explore the impact of climatic location on the energy performance of the building systems, the space heat demands for the building systems are modelled for three cities in different climate zones in Sweden: Växjö, Östersund and Kiruna. Hourly climate data representative of the cities for 1996–2005 are used for the calculations. Some key annual average climate values during this period are presented in Table 5. For the space heat demand calculations, set-point temperature of 22 °C and 18 °C are assumed for the living and for the common areas of the buildings, respectively.

3.2.2.2. Primary energy analysis. The operational final energy for space and tap water heating, ventilation electricity and household and facility electricity are converted to primary energy using the energy systems modelling program ENSYST, developed by Karlsson [61]. The spreadsheet-based program evaluates the primary energy required for delivered energy or final energy services in the Swedish context, considering the full energy chains. In this study, cases where end-use heating for the buildings is based on either ground-source electric heat pump or district heating are explored. Stand-alone electric power is assumed to be used for the heat pump, with 95% of the power supplied from BST plant and the remaining from light-oil gas turbine. The district heating is assumed to be supplied from combined heat and power (CHP) plant and heat-only boilers (HOB). 80% of the district heat is assumed to be supplied from the CHP plant using BST technology, and for the remaining, 16% and 4% are assumed to be supplied by biomass and light-oil HOB, respectively [62]. To avoid the issue of allocation due to the co-products of the CHP plant, the subtraction method [63] is used to calculate the primary energy use for heat. Based on this method, the coproduced electricity is considered to replace electricity that would instead have been produced in a stand-alone plant using the same fuel and technology as the CHP plant. The primary energy used for the replaced electricity in the stand-alone plant is subtracted from the CHP plant to obtain the primary energy for the heat.

3.2.3. End-of-life of building systems

A scenario where the buildings are disassembled after service life with dominant recyclable material recovered is analysed. The end-of-life calculation is based on a method developed by Dodoo et al. [64,65]. The net end-of-life primary energy use is calculated as the primary energy used to disassemble and transport the building materials, minus the primary energy benefits from using the recovered wood, concrete and steel. Adalberth et al. [54] found the demolition energy of different multi-storey buildings in Sweden not to exceed 10 kWh/m^2 [usable area]. For the current analysis, this value is assumed, independent of the building systems. Based on Dodoo et al. [65] we assume that 90% of the demolished concrete, steel and wood materials are recovered or recycled.

3.2.4. Complete lifecycle and unit of analysis

Total lifecycle primary energy balances are calculated for the buildings for a 50-year period including the production, operation and end-of-life stages. The scope of analysis encompasses the entire buildings, and the results are expressed in units of kWh primary energy per square metre of living floor area of the buildings.

4. Results

Relative dominance of the construction materials for the building systems in terms of mass and primary energy are summarized in Fig. 5a and b. The wooden materials include CLT, lumber, LVL, glulam, plywood, particleboard and laminated wood flooring. The steel reinforcement bars in the concrete are aggregated with other iron/steel materials used in the buildings. For all building systems, crushed stone is the dominant material by mass, while wooden materials are dominant on a primary energy basis. Crushed stone accounts for 40–45% of the total mass of the buildings, but its contribution to the total material production primary energy is about 1% for all building systems. In contrast, EPS insulation, aluminium and polyurethane jointly account for about 1% of the total building mass but their combined contribution to the total material production primary energy for the buildings ranges from 11% to 13%. The contribution of concrete to the building mass and material production primary energy use is significant. The insulation material used has significant influence on the buildings' materials production primary energy. The CLT building system has13% and 21% more wooden material compared to the beam -and-column and modular building systems, respectively. However, the CLT building system require 36% and 44% less plasterboard compared to the beam -and-column and modular building systems, respectively. Besides wooden materials, the main contributors to the material production primary energy for the building systems are glass wool and stone wool insulations, plasterboard, and iron/steel. These four materials together with the wooden material account for 76%, 76% and 75% of the material production primary energy for the CLT, beam -and-column and modular building systems, respectively.

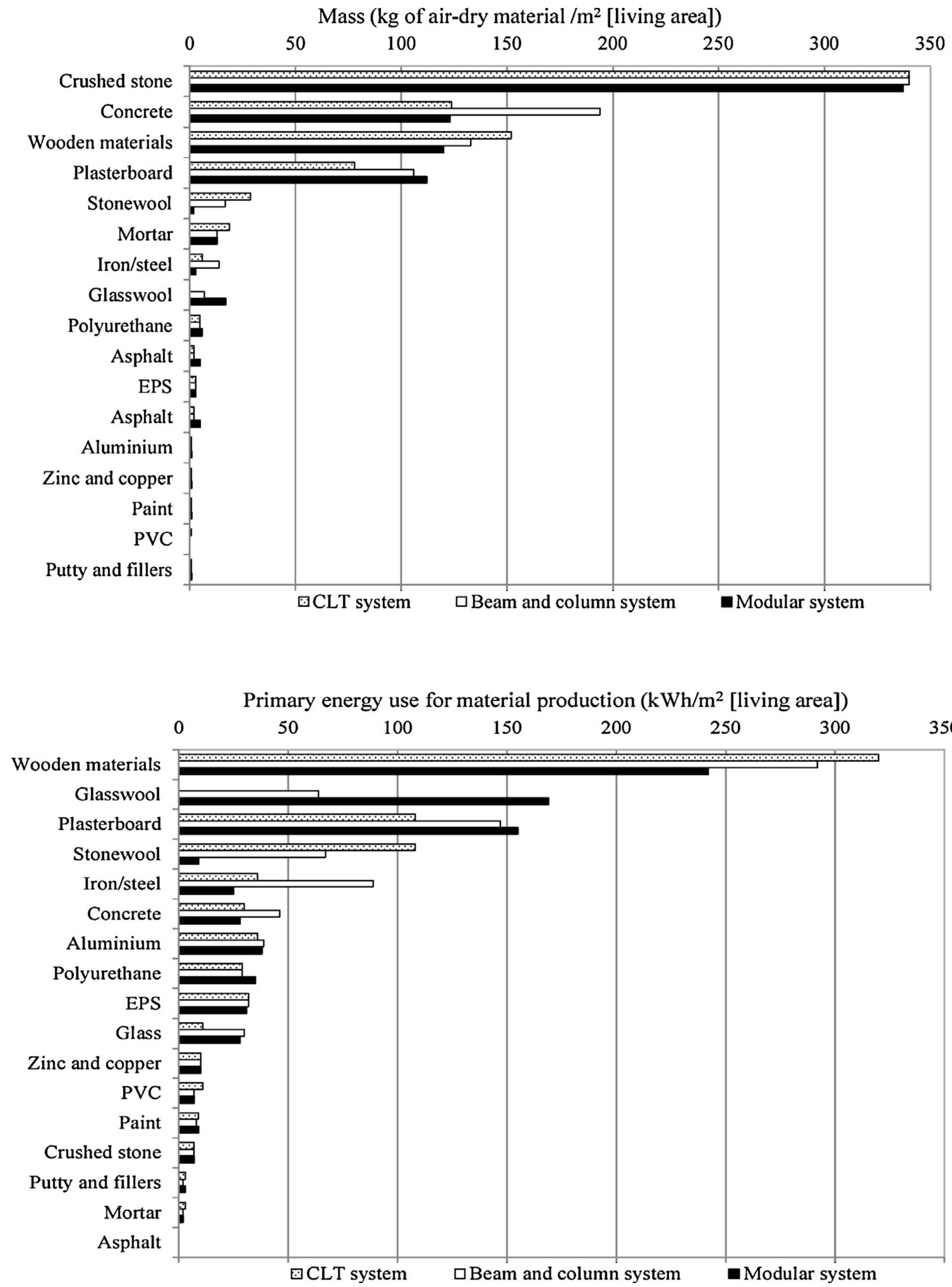


Fig. 5. (a) Mass balance of principal construction materials used in the building systems [top]. (b) Primary energy use for construction material production for the building systems [bottom].

Fig. 6 presents a breakdown of the material production primary energy for the systems in terms of building elements. External and internal walls dominate for all building systems, accounting for 38–40% of the total material production primary energy. Intermediate floors and roof-ceilings account for a large share of the total material production primary energy, and their primary energy intensity varies significantly for the different building systems.

Table 6 gives a breakdown of the production stage primary energy for the building systems in terms of end-use energy carriers including bioenergy, fossil fuels, and electricity. The total production primary energy use is lowest for the CLT building system, followed by the modular and the beam -and-column systems. The greater production primary energy use for the beam -and-column building system is somewhat linked to the large amounts of steel and concrete used in this building system for the elevator shaft, besides the foundation. Based on the energy supply and productions systems used, fossil fuel energy carriers dominate the primary energy use for the materials production, accounting for 46–48% of the overall material production energy. Bioenergy accounts for 15–21% of the material production primary energy for the buildings and is mainly used for processing of wood-based materials. The bioenergy available from the CLT and beam -and-column building systems are significantly larger than the primary energy required for material production for these systems.

Fig. 7 shows the annual final energy use for space heating of the building systems. The differences in the final energy for space heating of the buildings range from 17 to 21% within the same climatic location. The CLT building system gives a significantly lower final space heating demand compared to the beam -and-column or the modular building systems, due mainly to its improved airtightness. With the climate conditions of Östersund, the buildings have 35–36% more space heating demand compared

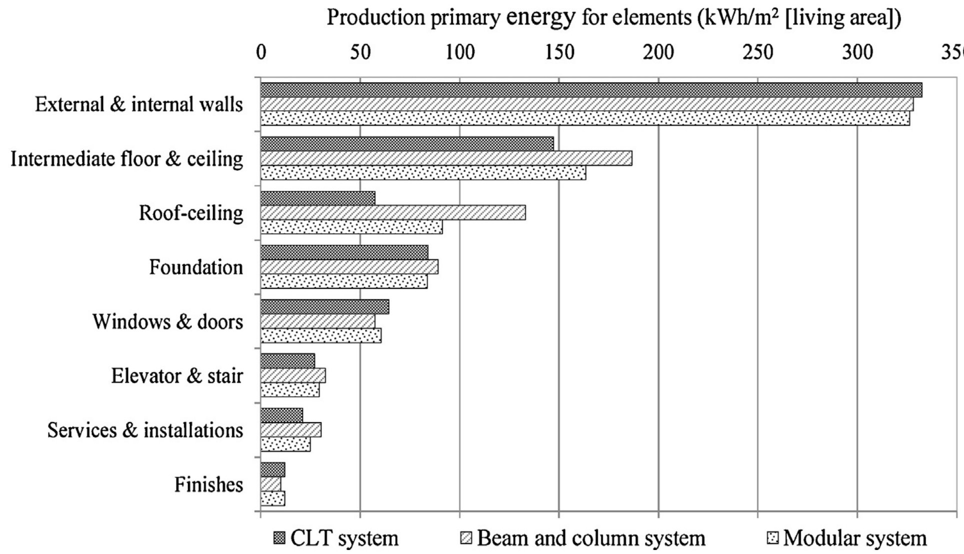


Fig. 6. Primary energy for production of various elements of the building systems.

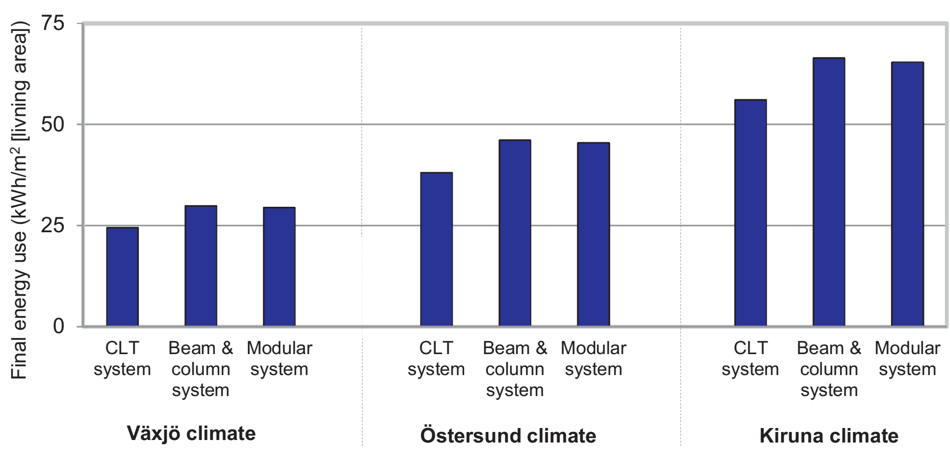


Fig. 7. Annual final energy use for space heating for the buildings in different climates.

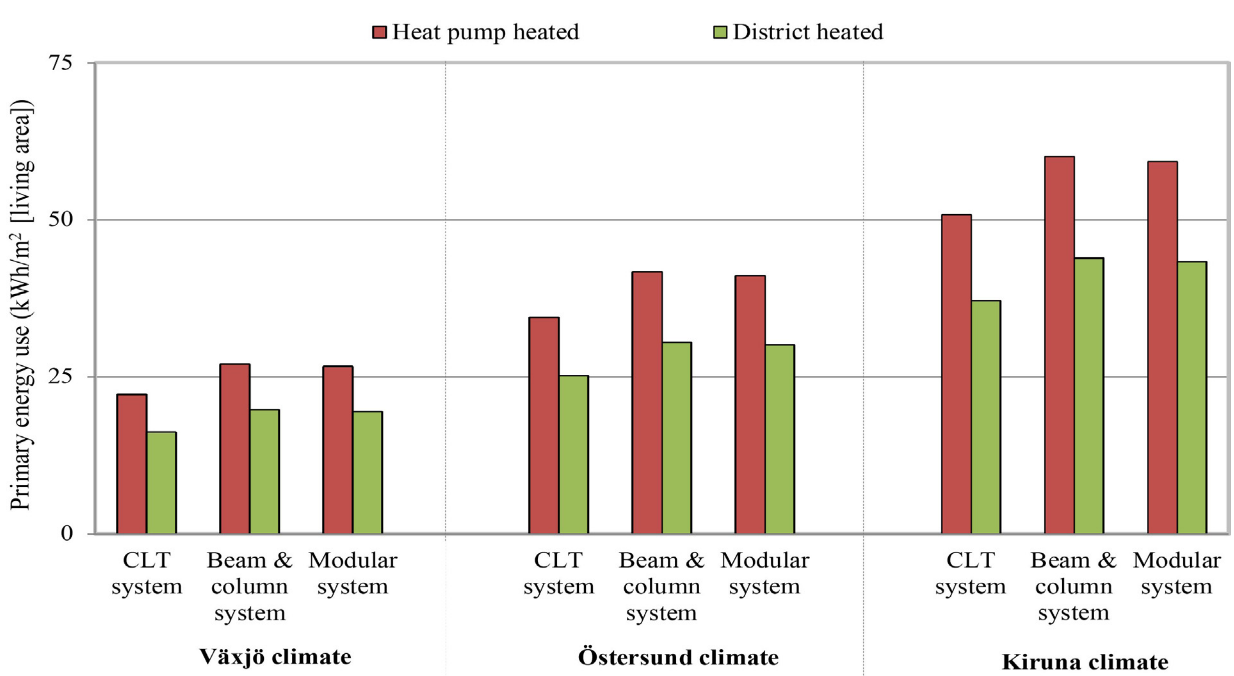


Fig. 8. Annual primary energy use for space heating of the buildings in various locations in Sweden with different end-use heating systems.

Table 6
Breakdown of primary energy balance during the production phase of the building systems in terms of fossil fuels, bioenergy and electricity.

Description	Primary energy (kWh/m² [living area])		
	CLT system	Beam -and-column system	Modular system
Energy use			
Material production			
Fossil fuels	341	418	370
Electricity	252	307	306
Bioenergy	156	139	122
Total	749	864	798
Building construction			
Fossil fuel	15	17	16
Electricity	15	17	16
Total	30	34	32
Total	779	898	830
Biomass residues[a]			
Forest harvest	−287	−267	−174
Wood processing industries	−759	−744	−335
Construction site	−72	−63	−55
Total	−1118	−1074	−564
Overall balance	−339	−176	266

[a] Lower heating value.

with the climate conditions of Växjö. Also, space heating demands of the buildings are more than doubled with the climate conditions of Kiruna compared to that of Växjö.

Fig. 8 shows the variation in the annual primary energy for space heating of the buildings with different end-use heating systems in the three varied climates. The end-use heating technology has a major impact on the operational primary energy use of the buildings. The heat pump heated buildings have higher primary energy use than the district heated alternatives, due largely to the higher conversion losses in stand-alone power plants.

Table 7 shows the annual operation primary energy for the building systems for Växjö, including space heating, tap water heating, ventilation electricity and household and facility electricity. Electricity used for ventilation, household and facility management are the same for all buildings. Household electricity largely dominates the operation primary energy use and the overall operation primary energy use is lowest when the buildings are district heated.

Table 8 shows the primary energy for the end-of-life phase of the buildings. The primary energy benefits from recovery of demolished wood and recycling of steel varies significantly for

Table 7
Annual primary energy use for operation of buildings located in Växjö, with biomass−based energy supply using steam turbine technology.

Description	Primary energy (kWh/m² [living area])		
	CLT system	Beam -and-column system	Modular system
Heat pump heated:			
Space heating	22	27	27
Tap water heating	16	16	16
Ventilation electricity	15	15	15
Household electricity	94	94	94
Facility electricity	40	40	40
Total for Operation	187	192	192
District heated:			
Space heating	16	20	20
Tap water heating	11	11	11
Ventilation electricity	15	15	15
Household electricity	94	94	94
Facility electricity	40	40	40
Total for Operation	176	180	180

Table 8
Primary energy balance for the end-of-life stage of the buildings.

Description	Primary energy (kWh/m² [living area])		
	CLT system	Beam -and-column system	Modular system
Demolition energy use	11	11	11
End-of-life benefits:			
Concrete recycling	−2	−2	−2
Steel recycling	−16	−40	−11
Wood recovery for bioenergy	−572	−503	−439
Total for End-of-life	−579	−534	−441

the buildings. The energy benefits of demolished wood are most significant, due to the use of wooden materials for the buildings production.

In contrast to other activities during the operation stage of a building, the demand for space heating and ventilation is essentially linked to the building's construction system and energy efficiency level. The demands for tap water heating and household and facility electricity depend to a large extent on a building's users and not on the construction system. In Fig. 9 the total primary energy flows linked to the choice of building systems are presented, including production, space heating and ventilation (for a 50-year period) and end-of-life of the buildings, with end-use heating based on cogenerated district heating. Space heating and ventilation dominate the total primary energy use and the production stage represents a large share of the total primary energy. Material production and construction account for one-third of the total primary energy for production, space heating and ventilation, and demolition for the buildings. The total primary energy for the CLT building including material production, construction, space heating, ventilation, and demolition is 12% and 9% lower compared to that for the beam -and-column and modular building systems, respectively. All the building systems give some benefits from recycling steel or concrete (shown as negative values in Fig. 9) at end-of-life. However, the benefits from recoverable biomass may be large at end-of-life as well as in the production phase.

Fig. 10 shows the lower heating value of recoverable biomass residues from forest harvest, wood processing and construction for the buildings as well as of wood in the buildings recoverable at end-of-life of the building. The total heating value of the biomass residues available for external use including from forest harvest, wood processing industries and construction site are 1563, 1458 and 930 MWh for the CLT, beam -and-column and the modular building systems, respectively. These heating values are about 5–8 times more than the bioenergy used for production processing of the wood-based material for the respective buildings. The total mass of residues generated for the CLT and beam -and-column building systems exceeds the mass of biomass fuel required to provide district heating (excluding cogenerated electricity) for space heating these buildings for a 50-year period.

5. Sensitivity analysis

A sensitivity analysis is conducted to assess the impact of input parameter variations and uncertainties on the analysis. The parameters included in the sensitivity analysis and their effects are discussed as follows.

5.1. Description of parameter variations

5.1.1. Choice of insulation

The results in Fig. 5a and b show that the choice of insulation material has significant impact on the production primary energy use of the buildings. Proportionally, stone wool resulted in less

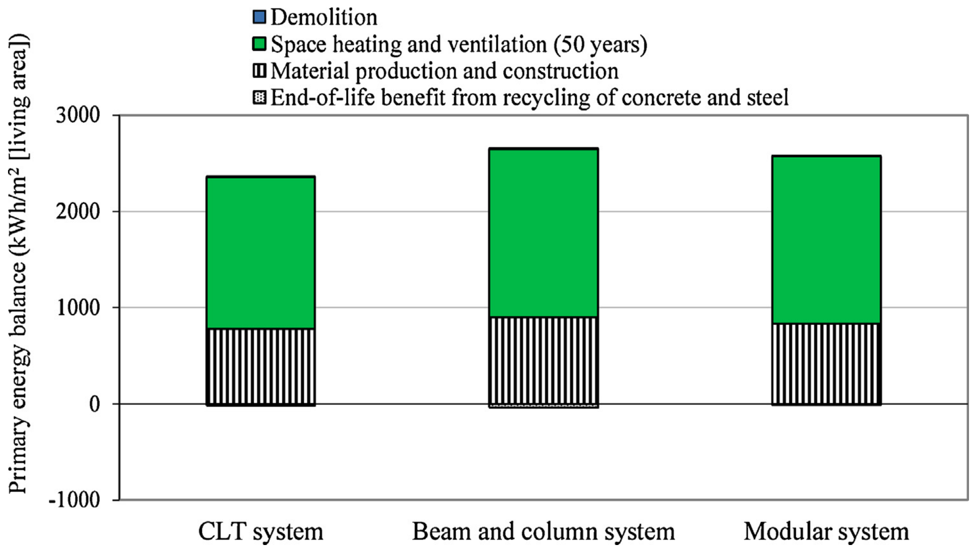


Fig. 9. Primary energy use for material production, construction, space heating and ventilation (50 years) and end-of-life stages of the buildings located in Växjö, with cogenerated district heating. Negative values denote benefits from recycling steel or concrete.

material production energy compared to glass wool. For the superstructure, the CLT building system is based on stone wool insulation while the beam and column and the modular building systems are based mainly on a combination of glass wool and stone wool. To explore the significance of the choice of insulation material, the glass wool insulation in the beam and column and the modular building systems are substituted with stone wool.

5.1.2. Building lifespan

A building's lifespan is an uncertain parameter, and is linked to various factors including the quality of materials, construction and maintenance. The lifespan of a building is largely independent of the construction materials used [66]. The IEA [67] reported typical lifespans of energy-related capital stock and noted the typical lifespan of buildings to range from 50 to 150 years, with 80 years as average. In this study, an assumed 50 years building lifespan is used in the base calculation, and this is varied to 80, 100 and 150 years in the sensitivity analysis.

5.1.3. Air infiltration rate

The air infiltration rates used for the calculations are based on values presently guaranteed by the companies making the studied building systems. Currently, infiltration of 0.4 l/s m^2 is achievable for the beam and column and the modular building systems, in contrast with 0.2 l/s m^2 for the CLT building system. The airtightness of the beam and column and the modular systems may be further improved. To demonstrate the effects of improved thermal envelope infiltration rates for the beam and column and the modular building systems, their envelope infiltration is varied to 0.2 l/s m^2. We also explore the implications of variations of the initial infiltration rate for the building systems by ±20%.

5.1.4. Ventilation heat recovery (VHR) efficiency

Actual performance of heat exchangers in ventilation systems may vary depending on several factors including the type of heat exchanger installed and climate conditions. For example, the efficiency of heat exchangers may be reduced when frost accumulates in the VHR units, which could possibly occur in colder winters. In the sensitivity analysis, the efficiency of VHR equipment is varied from the initial 80% to 50%, 60 and 70%.

5.2. Effects of parameter variations

Table 9 summarizes the effects of the parameter variations for the building systems. Insulating with stone wool instead of glass wool reduces the material production primary energy for

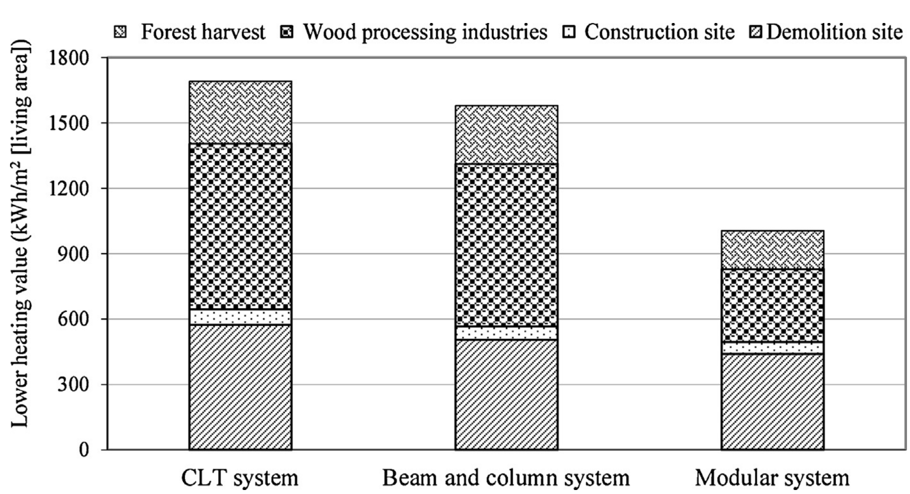


Fig. 10. Lower heating value of recoverable biomass residues from forest harvest, wood processing industries, construction site and end-of-life (demolition site).

Table 9
Effects of varying parameters on the primary energy use of the buildings. In the reference case, the buildings are located in Växjö and district heated for a period of 50 years.

Description	Base case	Variation	Primary energy (kWh/m^2 [living area])					
			CLT system		Beam and column system		Modular system	
			Balance	Change from Ref	Balance	Change from Ref	Balance	Change from Ref
Material production and construction:								
Reference	–	–	779	0	898	0	830	0
Insulation material	Glasswool	Stonewool	–	–	860	−38	731	−99
Space heating and ventilation:								
Reference	–	–	1575	0	1750	0	1740	0
Building lifespan	50	80 years	2520	945	2800	1050	2784	1044
Building lifespan	50	100 years	3150	1575	3500	1750	3480	1740
Building lifespan	50	150 years	4725	3150	5250	3500	5220	3480
Air infiltration	0.4	0.2 $l/s\,m^2$	–	–	1600	−150	1595	−145
Air infiltration	0.2[a]/0.4[b]	−20%	1533	−42	1732	−18	1720	−20
Air infiltration	0.2[a]/0.4[b]	+20%	1617	42	1908	158	1891	151
VHR efficiency	80	50%	2027	452	2215	465	2199	459
VHR efficiency	80	60%	1871	296	2057	307	2045	305
VHR efficiency	80	70%	1722	147	1904	154	1889	149

[a] Value (in $l/s\,m^2$) for the CLT building system.
[b] Value (in $l/s\,m^2$) for the beam and column, and for modular building systems.

the beam and column and the modular building systems by 4 and 12% compared to the base case. The primary energy use for operation increases proportionally as the lifespan of the buildings is changed from 50 to 80, 100 and 150 years. Variation of the infiltration rates for the beam and column and the modular buildings to 0.2 $l/s\,m^2$ reduces the space heating and ventilation primary energy demands of the buildings by 9 and 8%, respectively. Reduction by 20% of the initial envelope infiltration rates of all the building systems results in 1–3% reduction in primary energy use for space heating and ventilation of the buildings. In contrast, a 20% increase in the initial envelope infiltration results in 3–9% increase in primary energy use for space heating and ventilation of the buildings. Change of the base case VHR efficiency to 70% results in 9% increase in the primary energy use for space heating and ventilation, for all buildings. The primary energy use for space heating and ventilation for the buildings increase, ranging from 18 to 19% if the efficiency of VHR is 60% instead of the 80% assumed in the base case. Variation of the efficiency of VHR from 80 to 50% resulted in 29–26% increase in the primary energy use for space heating and ventilation for the buildings.

6. Discussion and conclusions

In this paper, the primary energy implications of three innovative timber building systems for a multi-storey building have been explored using a system-wide lifecycle perspective approach. The buildings have structural systems or components made of massive wood using CLT, beam and columns using glulam and LVL, and prefabricated modules using light-frame volume elements. All the buildings are designed to high energy efficiency levels. The results suggest that the CLT building system gives lower production and operation primary energy and greater end-of-life benefit among the building systems. The CLT building system results in 16% and 6% reduction in material production primary energy use compared to the beam and column and the modular building systems, respectively. Over a 50-year period, the CLT building system has 11% and 10% lower space heating and ventilation primary energy demand compared to the beam and column and the modular building systems, respectively. Further, the CLT building results in 8% and 24% more end-of-life primary energy benefit compared to the beam and column and the modular building systems, respectively.

Previous process-based lifecycle studies of low-energy buildings [e.g. 10, 13, 16] found the operation stage to dominate the lifecycle impacts, and this trend is observed in this study. The primary energy for space heating the buildings varies considerably for different end-use heating options, with cogenerated district heating giving the lowest primary energy use, followed by ground-source heat pumps. Space heating and ventilation account for 66–67% of the total primary energy use for the buildings, including material production, construction, space heating, ventilation and demolition, considering a 50-year lifespan. The beam and column and modular building systems each use about 22–25% more primary energy for space heating compared to the CLT building system. This demonstrates the importance of envelope air infiltration rate for the building systems. The lower space heating demand of the CLT building system is largely due to its air infiltration rate of 0.2 $l/s\,m^2$, in contrast to 0.4 $l/s\,m^2$ for each of the other building systems. When the air infiltration of the beam and column and modular building systems are varied to 0.2 $l/s\,m^2$, the primary energy for space heating for each building is reduced by 15%. Hence, significant primary energy reductions can be achieved with improved airtightness. Electricity for household purposes including lighting and appliances accounts for the single greatest share of the primary energy use during the operation stage of the buildings. However, this plays an inconsequential role in the choice and performance of building systems, and in this study conventional appliances and lightings are assumed to be used. Still, reducing household electricity is important and studies have reported electricity savings ranging from 44% to 50% when conventional lighting and appliances are changed to efficient types [68,69]. Efficient electric appliances and lighting may lead to increased space heating demands due to decrease in process heat gains but this may be small compared to the gains from electricity reduction [70].

The choice of insulation material has significant impact on primary energy use for building production, with stone wool resulting in lower production energy relative to glass wool. The primary energy for material production for the beam and column and modular building systems are reduced by 4% and 9% when the glasswool insulation used is varied to stonewool, respectively. Hence, the selection of insulation presents further opportunity to improve resource efficiency of timber-based buildings. Nevertheless, the choice of insulation for a building system may be governed by the interplay of several factors besides the need to fulfil thermal performance requirements. Different insulations may vary in acoustical, fire protection, mechanical and water resistance performance, and varying a particular insulation material might have impact on other functions. This study illustrates the impact of insulation substitution from a resource efficiency perspective, and a more holistic evaluation might be needed before implementing such substitution. A comparison of the various elements of the building systems shows that there is a significant variation in the production primary energy for the roof-ceiling and intermediate floor-ceiling for the different systems. In contrast, there is small variation in the production primary energy for the external and internal walls, which account for the biggest share of the material production energy for all building systems. The large amount of bioenergy obtained from wood residues over the lifecycle of the buildings is a further benefit of timber-based buildings [26,50,51].

Besides energy performance, other factors may influence the choice of building systems including those related to technical issues, e.g. structural performance, and those related to non-technical issues, e.g. perceptions. Hemström et al. [32] carried out a survey of Swedish architects' views on the choice of framing material for multi-storey buildings and found that most ranked timber frames less suitable for buildings of 3–8 storeys, though the respondents acknowledged the environmental benefits of timber-based buildings. Reasons often cited for low interest in the use of timber frames include acoustics, structural and fire resistance issues, risk of moisture damage and mould growth in highly insulated timber building [31,32,71,72]. Recent experience shows that these issues can be addressed with modern construction techniques for multi-storey timber buildings. For example, four 8-storey timber-frame low-energy apartment buildings and two 8-storey timber frame passive houses have recently been constructed using CLT building system, similar to the type analysed here, in the city of Växjö in southern Sweden. Overviews and experience from these projects describe how the issues of fire safety requirements and stability were addressed in these buildings [73,74]. These include the installation of residential fire sprinklers in the buildings, besides gypsum plasterboard cladding to give adequate fire resistance. The stabilization of the buildings is provided by combination of internal walls and tension rods. Arfvidsson [75] and Mundt-Petersen [76] documented moisture safety plans and measures to minimize mould risk during the planning, designing and construction of timber buildings, and emphasize the use of interior vapour barriers and well ventilated air gaps behind facades. In the present study, the moisture risk and safety of the various building systems considered were reviewed by a team of researchers from the Moisture Centre of the Department of Building Physics, Lund University, Sweden. Still, there are important issues to address to improve the diffusion of timber-based building systems. Mahapatra et al. [31] studied the influence of legislations, perceptions and promotions on the diffusion of timber-frame buildings and suggested that market intervention may be needed to encourage the diffusion of such buildings.

In summary, this study shows that the CLT building system results in a low primary energy balance from a lifecycle perspective. With improved airtightness and insulation substitution, the total primary energy use (for material production and construction, space heating and ventilation for 50 years, and demolition) for the beam and column and modular building systems can be reduced by 7% and 9%, respectively. Further studies may consider the implications of the building systems for greenhouse gas emission and for biomass use, as the buildings require significantly different amounts of wooden materials and hence land-use. Overall, this study shows that low-energy timber building systems with energy-efficient heat supply can contribute to improving resource efficiency of the built environment.

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