Primary energy implications for low-energy buildings with different frame construction systems under varying climate scenarios

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life cycle, primary energy use, space heating and cooling, climate change, construction systems, overheating, low-energy building

Abstract
In this study, a 6 storey prefabricated concrete building in Sweden is used as reference to explore life cycle primary energy implications of different frame construction systems under various climate scenarios. The building was redesigned as a low-energy building to the Swedish passive house criteria with frame construction systems in cross laminated timber, prefabricated timber modules and concrete. Using a system perspective approach, we account for relevant energy and material flows linked to the production, construction, operation and end-of-life phases of the building alternatives, including thermal mass effects under recent (2013) as reference and future (2090–2099) climate periods based on representative concentration pathways (RCP) 2.6, 4.5 and 8.5 scenarios. Results show that the buildings' heating and cooling demands vary significantly under the climate scenarios. The timber systems give lower production primary energy and higher biomass residues than the concrete alternative. The concrete system requires slightly lower operation energy due to thermal mass benefits but still, the timber systems give overall lower life cycle primary energy balance. This study shows that low-energy timber buildings with efficient energy supply can play an important role in mitigating climate change for a resource-efficient and sustainable built environment under current and future climate scenarios.

Introduction
The building sector contributes largely to climate change from construction and building related energy use. About 72 % of the total primary energy use in the European Union (EU) came from fossil fuels, while residential and service buildings accounted for around 39 % of the total final energy use in 2016 (Eurostat, 2018). Construction and civil works account for 24 % of global raw material extractions (Zabalza Bribián, Valero Capilla, & Aranda Usón, 2011), which also contribute to greenhouse gas (GHG) emissions and environmental degradation. The concentration of GHG emissions in the atmosphere about doubled in 2010 compared to 1970 levels (IPCC, 2014c), with the building sector accounting for 19 % of the total (IEA, 2012). Average EU outdoor temperature increased by 1.3 °C from 2002–2011 compared to 1850–1899 (IPCC, 2014a). Projections for Sweden show average temperature rise of 2–6 °C by 2100, compared to 1961–1990 (SMHI, 2015).

Buildings are associated with different climate- and environmental-related challenges. Space heating constitutes a significant share of the operation energy use of most EU residential buildings (Saheb, Bódis, Szabó, Ossenbrink, & Panev, 2015). With changing climates, the energy demand profile of buildings may vary, impacting indoor climate and comfort levels, especially in low-energy buildings (Tettey, Dodoo, & Gustavsson, 2018). Previous studies have shown high cooling demands and overheating risks in low-energy buildings (Rohdin, Molin, & Moshfegh, 2014; Tabatabaei Sameni, Gaterell, Montazami, & Ahmed, 2015). (Jakubcionis & Carlsson, 2017) noted that strategies such as proper operation of ventilation systems might mitigate potentially negative impacts of overheating due to building insulation improvement. (Tettey, Dodoo, & Gustavsson, 2017a) analysed different design strategies to minimise both heating and cooling demands for a low-energy Swedish residential building under changing climate. Strategies for low-energy buildings have typically targeted building operation energy reduction through improved thermal envelope insulation, energy-efficient windows and heat exchanger for ventilation heat recovery (VHR). However, these measures also usually lead to increased use of materials and hence highlight the relative significance of building production and end-of-life phases. (Piccardo, Dodoo, Gustavsson, & Tettey, 2019a, 2019b) showed that the production and end-of-life primary energy use for building renovation can be reduced by up to 34 % and 15 %, respectively. The share of production energy was reported to be 26–57 % of the total life cycle energy for low-energy buildings (Chastas, Theodosiou, & Bikas, 2016). (Dodoo, Gustavsson, & Tettey, 2018) showed that the choice of end-of-life management options of building materials influences the life cycle primary energy use and GHG emissions.

The choice of materials for different building envelope components are linked to the thermal performance of buildings and can result in varying energy- and climate-related impacts. (Takano et al., 2015) analysed the impact of material choices for different building components on the life cycle energy use of a model building in Finland and found that the impact was most significant for the structural frame materials. (Skullestad, Bohne, & Lohne, 2016) compared concrete or timber buildings under different scenarios and found that the timber buildings resulted in lower environmental impacts than the concrete alternative. The choice of building frame materials may influence building operation energy through thermal mass depending on the climate. The effect of thermal mass on building operation energy use is reported to be small in cold climates (Dodoo, Gustavsson, & Sathre, 2012; Reilly & Kinnane, 2017). However, the impact of thermal mass may vary under warmer climates due to climate change and should be accounted for to increase understanding of how material choices influence indoor climate, while reducing primary energy use for both building production and operation.

In this study, a 6-storey prefabricated concrete building is used as reference to explore life cycle primary energy implications of different frame construction systems under various climate scenarios. The building was redesigned as a low-energy building to the Swedish passive house criteria with frame construction systems in cross-laminated timber (CLT), prefabricated timber modules (modular) or concrete. The analysis is based on dynamic hour-by-hour energy balance calculations of the building alternatives, including thermal mass dynamics under current and future climates based on representative concentration pathways (RCP) scenarios (IPCC, 2013).

Construction systems

A prefabricated concrete frame building completed in 2014 in Växjö (latitude 56° 87′ 37″ N; longitude 14° 48′ 33″ E), southern Sweden is used as reference in this study. The reference building (Figure 1) is 6 storeys tall and has 24 apartments, with a total heated floor area of 1686 m^2. The foundation has layers of 200 mm crushed stone, 300 mm expanded polystyrene (EPS) insulation and 100 mm concrete ground floor slab. The external walls consist of 100 mm and 230 mm concrete on the outside and inside respectively, with 100 mm EPS insulation between them. The roof has 250 mm concrete slab and 500 mm loose fill rock wool insulation with wooden trusses and roof covering over layers of roofing felt and plywood. For this analysis, the reference building is remodelled as a low-energy building to the Swedish passive house criteria and redesigned with CLT, modular and concrete frame construction systems.

PREFABRICATED CONCRETE FRAME CONSTRUCTION

The concrete building has outer walls with a layer of EPS insulation sandwiched between precast concrete panel elements. The inner walls have load-bearing concrete wall panels and non-load-bearing walls of plasterboard layers with steel studs spaced at 600 mm and air gaps of 95–145 mm between them. The intermediate floors are concrete slabs with laminated wood floor covering, while the ceiling floor consists of a concrete slab and loose fill stone wool insulation with wooden trusses and roof covering over layers of roofing felt.

CROSS-LAMINATED TIMBER (CLT) FRAME CONSTRUCTION

The framing of the CLT building for the outer and inner walls as well as the intermediate and ceiling floors has CLT panel elements as the main structural components. The outer walls consist of a ventilated façade plaster on the outside with layers of stone wool insulation between timber studs and CLT panel elements clad with gypsum boards on the inside. The inner load-bearing walls have CLT panels clad with gypsum boards on both sides while the non-load-bearing walls are made up of layers of plasterboard with timber studs spaced at 600 mm and air gaps of 95–145 mm between them. The intermediate floors have laminated wood floor covering, CLT panel and glulam beam elements with stone wool insulation and gypsum board as the bottom cover. The ceiling floor has loose stone wool insulation with wooden trusses and roof covering over layers of roofing felt.

PREFABRICATED TIMBER MODULES (MODULAR) CONSTRUCTION

The modular building system is made up of individual light-frame timber volumetric elements, manufactured in the factory and assembled on site. The outer wall elements include ventilated façade plaster on the outside, load-bearing timber stud walls with layers of glass wool insulation between timber studs and gypsum boards on the inside. The inner load-bearing walls are made up of timber stud elements clad with gypsum boards on both sides, while the non-load-bearing walls have layers of plasterboard with timber studs spaced at 600 mm and air gaps of 95–145 mm between them. The intermediate floors consist of laminated wood floor covering over particleboard elements, glulam beam elements with glass wool insulation and plywood as the bottom cover. The ceiling floor has loose stone wool insulation with wooden trusses and a roof covering over layers of roofing felt. The construction details of the outer wall configuration of the buildings to the passive house criteria are presented in Figure 2. The thermal properties of the different envelope elements are given in Table 1.

Method

We calculate the primary energy use over the life cycle of the buildings with the different construction systems, taking into account the production, operation and end-of-life phases. We use a system perspective approach to account for relevant en-

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

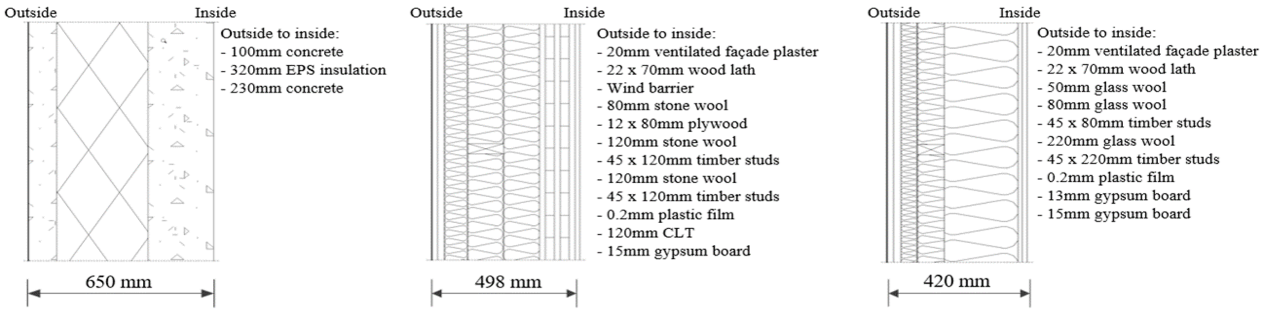


Figure 2. Outer wall details of buildings with the concrete (left), CLT (middle) and modular (right) construction frames to the passive criteria.

Table 1. Thermal properties of different frame construction systems to the Swedish passive house criteria.

Building version	U-value (W/m²K)					Air leakage at 50 Pa (l/s m²)	Mechanical ventilation
	Ground floor	External walls	Windows	Doors	Roof		
Passivhus 2012	0.11	0.11	0.80	0.80	0.05	0.3	Balanced with (76 %) heat recovery

ergy and material flows linked to the various life cycle phases as well as dynamic hour-by-hour energy balance calculations, including thermal mass effects under current and future climates.

PRODUCTION PHASE

Analysis of the production primary energy use covers the energy to extract, process, transport, and assemble the building materials for the different construction systems as well as the potential bioenergy recovery from biomass residues in the wood product chain. We take into account material losses during production and construction. The specific final energy use to manufacture the building materials is based on (Björklund & Tillman, 1997) for building material production in Sweden. We assume fuel cycle loss values of 10 % for coal, 5 % for oil and 5 % for natural gas (Leif Gustavsson, Pingoud, & Sathre, 2006). Electricity for material production is assumed to be from a biomass-fired condensing plant, with conversion efficiency of 40 % and distribution losses of 2 % (Leif Gustavsson & Sathre, 2006). The primary energy use to assemble the building material is taken to be 80 kWh/m², comprising 50 % electricity and 50 % diesel fuel for the CLT and modular building systems (Leif Gustavsson, Joelsson, & Sathre, 2010) and assumed to be doubled for the concrete alternative (Adalberth, 2000; Dodoo et al., 2012). Assessment of the distribution of biomass residues from the wood product chain is based on (Lehtonen, Mäkipää, Heikkinen, Sievänen, & Liski, 2004).

OPERATION PHASE

The annual operation final energy use, including space heating and cooling, tap water heating, ventilation electricity and household and facility electricity were calculated with VIP-Energy (StruSoft). VIP-Energy is validated commercially available energy simulation software with dynamic hour-by-hour and multi-zone whole-building calculation features. The energy balance calculations are performed using 2013 climate data for Växjö as reference and 2090–2099 (2090s) as future climate periods. The 2013 climate data is fairly representative of the Swedish normal climate for the 1961–1990 (SMHI, 2013). The future climate data are based on the global climate model (GCM) of the HadGEM2 Earth system for the county of Kronoberg, where the city of Växjö is situated and were obtained from the regional climate model RCA4 (SMHI, 2011). The climate data from the RCA4 model are based on monthly resolutions and to obtain hourly resolution datasets for the future climate periods, they were downscaled using the morphing approach (Belcher, Hacker, & Powell, 2005) with 1961–1990 as the baseline period. The downscaled data for the future climate scenarios are based on the Representative Concentration Pathways (RCPs) scenarios of RCPs 2.6, 4.5 and 8.5 (IPCC, 2014b) and take into account variations in ambient temperature, solar radiation, wind speed and relative humidity. Variations in ambient temperature and solar radiation are shown in Table 2. Input parameters and assumptions for the energy balance calculations are given in Table 3.

Based on the simulated final energy use, the operation primary energy use is calculated with the ENSYST software (Karlsson, 2003). ENSYST calculates primary energy use based on detailed analysis of the entire energy chains from natural resources extraction to supply of final energy services. The analysed building alternatives are assumed to be heated with a biomass-based district heating system, comprising a combined heat and power (CHP) plant using wood chips and heat only boilers (HOB) using wood chips or wood powder producing 68, 30.5, and 1.5 %, respectively, of the total district heat. The cogenerated electricity from the CHP plant is assumed to replace electricity from a stand-alone plant with similar fuel and technology as the CHP plant using the substitution method to avoid co-products allocation (L. Gustavsson & Karlsson, 2006). Individual room air conditioners are assumed to meet the cooling demand with electricity to operate the air conditioners as well as ventilation and household equipment assumed to be from a stand-alone biomass-based steam turbine (BST) plant. The efficiencies and capacities of the energy supply systems are given in Table 4.

END-OF-LIFE PHASE

The buildings are assumed to be demolished after a service life of 80 years and the concrete, steel and wood materials recovered. We calculate the net end-of-life primary energy use as the primary energy used to disassemble and transport the demolished building materials, minus the primary energy benefits from the recovered concrete, steel and wood, assuming that 90 % of the demolished materials are recovered based on (Dodoo, Gustavsson, & Sathre, 2009). The primary energy use for demolition is taken to be 10 kWh/m^2 for the CLT and modular building systems and assumed to be doubled for the concrete alternative (Adalberth, 2000; Dodoo et al., 2012). The recovered concrete is assumed to be crushed into aggregate for below ground application in road construction while the recovered steel is assumed to be used as feedstock for new steel production, replacing ore-based raw materials. The recovered wood-based materials are assumed to be used as bioenergy.

Table 2. Annual variations in the climate datasets for the energy balance calculations.

Description	Växjö_2013	RCP2.6	RCP4.5	RCP8.5
Outdoor temperature, °C				
Maximum	28	28	31	33
Average	7	8	10	12
Minimum	-17	-14	-13	-12
Solar radiation, W/m2				
Maximum	912	834	902	910
Average	105	100	105	104
Minimum	0	0	0	0

Table 3. Key input parameters and assumptions for the energy balance calculations based on (Dodoo, Tettey, & Gustavsson, 2017).

Description	Parameter	Values/assumptions	Comments
Indoor temperature set points	Heating	21 ºC/18 ºC	Living area/common area
	Cooling	26 ºC	Estimated
Heat gains	Lighting and appliance	1.35 W/m^2	Efficient equipment. Average values with annual variations considered in simulation. Estimated based on data from (Aníbal de Almeida et al., 2008).
	Hot water circulation	0.68 W/ m^2 (average)	Efficient equipment. Average values with annual variations considered in simulation. Estimated based on data from (Isover, 2016).
	Sun		Based on climate file.
Hot water	Annual average intensity	1.75 W/m^2	Efficient taps and shower heads based on (Swedish Energy Agency, 2015).
Electric power use	Annual average intensity	1.69 W/m^2	Efficient electric equipment and lighting. Estimated based on data from (Aníbal de Almeida et al., 2008).
Ventilation, pumps, heat exchanger and fans	Heat recovery	80 %	Based on (Rohdin et al., 2014; Smeds & Wall, 2007; Swedish Energy Agency, 2010)
	Fan pressure	200 Pa	Estimated
	Fan efficiency	50 %	Based on (Camfil, 2014).

Table 4. Efficiencies and capacities of considered energy supply technologies based on (Truong, Dodoo, & Gustavsson, 2014).

Description	Capacity	Efficiency
Stand-alone power plant:	(MW_{elec})	(η_{elec})
Biomass steam turbine (BST)	400	0.40
Cogeneration plants:	(MW_{heat})	(η_{elec}/η_{heat})
CHP-BST	81	0.29/0.78
Heat-only boilers:	(MW_{heat})	(η_{heat})
Wood powder	50	0.88
Wood chip	50	1.08
End-use heating and cooling:		(η)
District heating heat exchanger		0.95
Room air conditioners		3

Table 5. Mass (tonnes of oven dry tonnes) of major materials in the analysed buildings with the different frame construction systems.

Materials	Concrete	CLT	Modular
Concrete	2,867.8	229.1	229.1
Steel	95.2	12.6	14.2
Lumber	50.9	127.4	153.5
Particleboard	20.8	0.0	22.8
Plywood	3.0	20.9	29.0
CLT	0.0	175.7	0.0
Glue-laminated wood	0.0	40.3	7.8
Stone wool insulation	11.1	26.8	5.9
Glass wool insulation	0.0	0.0	19.3
EPS insulation	13.6	1.8	1.8
Plasterboard	22.6	109.7	116.1

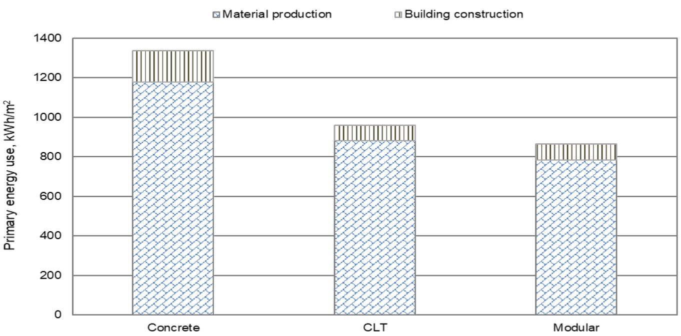


Figure 3. Primary energy for material production and building construction for the different frame construction systems.

Results

The mass of major materials distinguishing the building alternatives with different frame construction systems are given in Table 5. Concrete and crushed stone form the largest shares of the total mass of building materials for all the building systems. The concrete in the CLT and modular building systems are used in the foundation and constitute about 23 and 27 %, respectively of their total building mass while the share of wooden materials is 36 and 25 %, respectively. For the concrete building system, concrete and wooden materials constitute about 86 and 2 % of the total building material mass balance.

Figure 3 shows that the concrete building requires 28 and 35 % more primary energy for material production and construction than the CLT and modular buildings, respectively. The primary energy for production and construction for the CLT building is 10 % more than that for the modular alternative.

Table 6 gives the primary energy balance for the production phase for the different frame construction systems, including various end-use energy supply systems as well as recoverable biomass residues from forest harvest, wood material processing and on-site construction activities. Fossil fuels account for the largest share of the primary energy use for material production for all the building systems, followed by electricity and bioenergy. The CLT and modular buildings give significant biomass residues over the production phase.

Table 6. Primary energy balance, kWh/m² for the production phase of the different frame construction systems.

Description	Concrete	CLT	Modular
Material production:			
Fossil fuels	759	334	345
Electricity	373	327	316
Bioenergy	45	219	123
Total	*1,177*	*880*	*784*
Building construction:			
Fossil fuels	80	40	40
Electricity	80	40	40
Total	*160*	*80*	*80*
Total material production and building construction	*1,337*	*960*	*864*
Biomass residues (Energy content based on lower heating value)			
Forest harvest (includes branches and foliage)	-56	-431	-199
Wood processing	-76	-1,193	-424
Construction	-21	-103	-59
Total	*-153*	*-1,727*	*-682*
Primary energy balance for production phase	***1,184***	***-767***	***183***

Table 7. Variations in annual space heating and cooling demands, kWh/m² for the different frame construction systems under the considered climate scenarios. Numbers in brackets show differences due to thermal mass between concrete and modular building alternatives.

Description	Växjö_2013			RCP2.6			RCP4.5			RCP8.5		
	Concrete	CLT	Difference	Concrete	CLT	Difference	Concrete	CLT	Difference	Concrete	CLT	Difference
Space heating	22.2	22.4	0.2 (0.2)	19.4	19.4	0.1 (0.1)	17.4	17.5	0.1 (0.1)	12.8	12.9	0.1 (0.1)
Space cooling	11.0	11.4	0.4 (0.3)	9.5	9.9	0.4 (0.3)	13.8	14.1	0.3 (0.3)	17.2	17.6	0.3 (0.3)

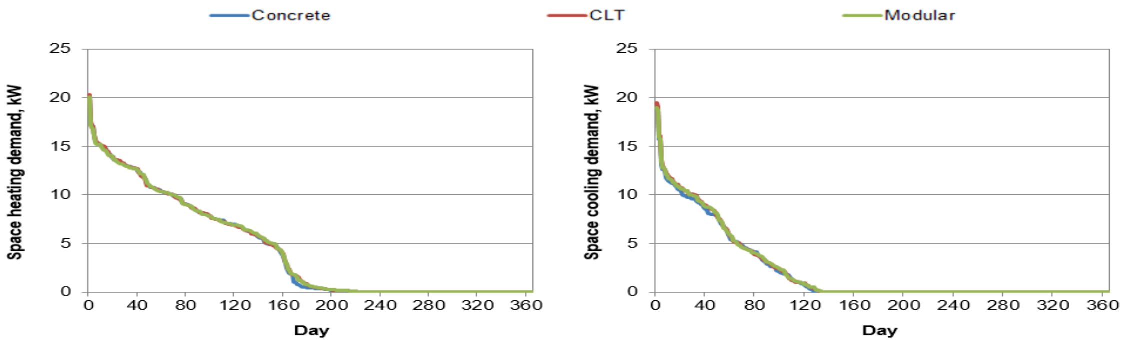
Table 7 shows annual variations in space heating and cooling demands due to the thermal mass of different frame construction systems under the considered climate scenarios and indoor temperature set points. The effect of thermal mass is small, accounting for about 0.2 kWh/m² lower space heating demand for the concrete building system compared to the CLT alternative under the reference climate of 2013 and 0.1 kWh/m² under future scenarios. The effect of thermal mass is however, greater for space cooling under both reference and future climate scenarios.

Variations in annual profiles of final space heating and cooling demands of the building systems arranged in descending order are also shown for the considered climate scenarios in Figure 4 a-d.

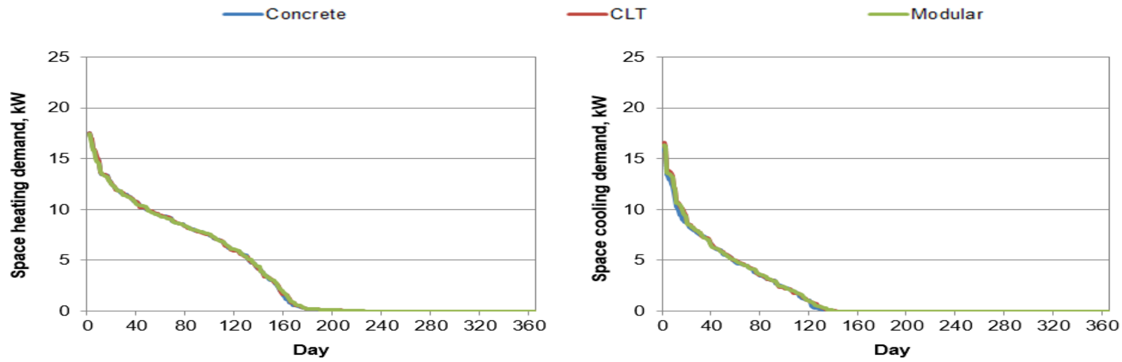
Table 8 shows the annual operation final and primary energy use for the analysed frame construction systems under different climate scenarios. Space heating accounts for the largest share of the operation final energy use, followed by household electricity and tap water heating except for RCP8.5 where space cooling dominates. Space cooling demand decreases slightly under RCP2.5 and increases slightly under RCP4.5 and even more under RCP8.5, compared to the reference climate of Växjö_2013. Household electricity dominates the operation primary energy use for the building systems under all the consideered climate scenarios, accounting for about 55 % of the total primary energy use, followed by space heating for the reference climate and RCP2.6. The primary energy use for space cooling is about 14 % and 93 % more than the primary energy use for space heating under RCP4.5 and RCP8.5, respectively. The primary energy use for space cooling is about 14 % and 93 % more than the primary energy use for space heating under RCP4.5 and RCP8.5, respectively. The lowest operation final and primary energy energy use are observed under RCP2.5.

The primary energy balance for the end-of-life phase, including the benefits from concrete and steel recycling as well as the recovery of wood based demolition materials for energy is shown in Table 9. The CLT building system gives the largest end of life primary energy benefits, followed by the modular and concrete alternatives, mainly due to increased wood recovery for energy.

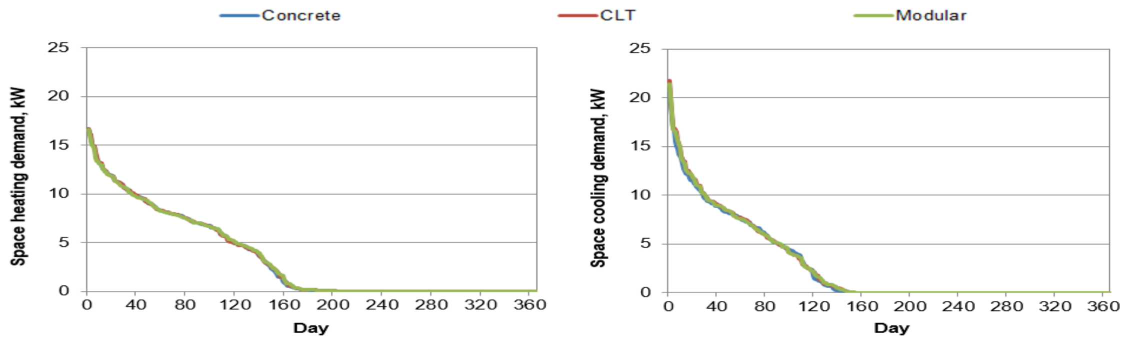
The complete life cycle primary energy balance, assuming an 80 year life span for the analysed buildings for the climate of Växjö_2013 is given in Table 10. Variations in total life cycle primary energy balance of the analysed building systems due to



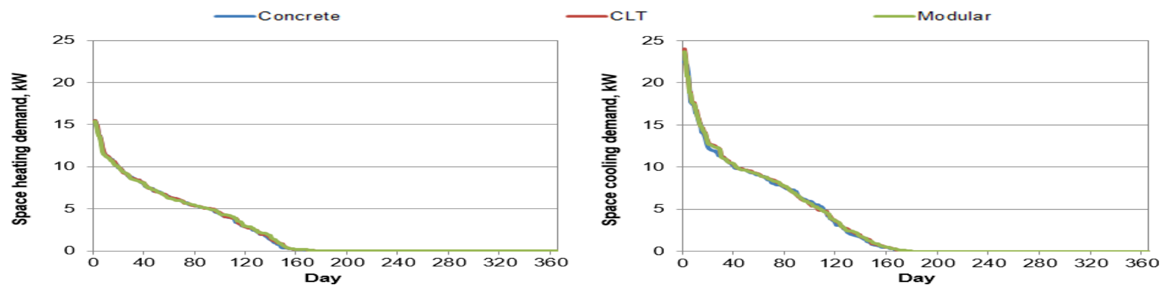
(a) Växjö 2013



(b) RCP2.6



(c) RCP4.5



(d) RCP8.5

Figure 4. Annual profiles of space heating (left) and space cooling (right) demands of the analysed building systems under different climate scenarios arranged in descending order.

Table 8. Annual final and primary energy use, kWh/m² for operation of the analysed frame construction systems under different climate scenarios.

Description	Final energy use, kWh/m²			Primary energy use, kWh/m²		
	Concrete	CLT	Modular	Concrete	CLT	Modular
Växjö_2013						
Space heating	22.2	22.4	22.4	14.2	14.3	14.3
Space cooling	11.0	11.4	11.3	10.0	10.3	10.3
Ventilation electricity	1.7	1.7	1.7	4.7	4.7	4.7
Tap water heating	12.6	12.6	12.6	8.0	8.0	8.0
Household electricity	16.2	16.2	16.2	44.3	44.3	44.3
Total	63.7	64.2	64.2	81.2	81.6	81.6
RCP2.6						
Space heating	19.4	19.4	19.4	12.4	12.4	12.4
Space cooling	9.5	9.9	9.8	8.6	9.0	8.9
Ventilation electricity	1.7	1.7	1.7	4.7	4.7	4.7
Tap water heating	12.6	12.6	12.6	8.0	8.0	8.0
Household electricity	16.2	16.2	16.2	44.3	44.3	44.3
Total	59.4	59.8	59.7	78.0	78.4	78.3
RCP4.5						
Space heating	17.4	17.5	17.5	11.1	11.2	11.2
Space cooling	13.8	14.1	14.0	12.5	12.8	12.8
Ventilation electricity	1.7	1.7	1.7	4.7	4.7	4.7
Tap water heating	12.6	12.6	12.6	8.0	8.0	8.0
Household electricity	16.2	16.2	16.2	44.3	44.3	44.3
Total	61.7	62.1	62.0	80.6	81.0	80.9
RCP8.5						
Space heating	12.8	12.9	12.9	8.2	8.2	8.2
Space cooling	17.2	17.6	17.5	15.7	16.0	15.9
Ventilation electricity	1.7	1.7	1.7	4.7	4.7	4.7
Tap water heating	12.6	12.6	12.6	8.0	8.0	8.0
Household electricity	16.2	16.2	16.2	44.3	44.3	44.3
Total	60.5	61.0	60.9	80.8	81.2	81.1

the different climate scenarios are also shown in Table 11. The production primary energy use of the building systems, taking into account the recoverable biomass residues ranges between 14, 19 and 20 % of the total life cycle primary energy balance for the modular, concrete and CLT buildings, respectively. The operation phase dominates the life cycle primary energy use of the building systems. Overall, the CLT and Modular building systems give about 34 % and 15 % lower life cycle primary energy balance than the concrete alternative.

Discussion and conclusions

In this study, we analysed the life cycle primary energy implications of low-energy multi-storey residential buildings with concrete and timber frame constructions under climate change. We considered energy and materials flows over the entire life cycle phases of the analysed buildings, using a system perspective approach and dynamic hour-by-hour energy balance calculations, including thermal mass effects under current and future climate scenarios. The timber building systems give lower production primary energy use and higher biomass residues compared to the concrete alternative. The primary energy use for material production and construction of the building systems constitutes 14–20 % of the total primary energy use for material production, construction, space heating and cooling, ventilation and demolition. The space heating and cooling demands for the concrete building are slightly lower than that of the CLT and modular building systems due to thermal mass. This follows trends observed by (Dodoo et al., 2012) who found the advantages of thermal mass to be small in cold climates and for high-energy performance buildings. The effect of thermal mass is more evident for the cooling than heating demand under the considered climate scenarios. The heating and cooling demands of the building systems vary under the climate scenarios. Generally, space heating decreased while space cooling increased considerably under future climate scenarios, except for RCP2.6 where both space heating and cooling demands decreased compared to the reference climate. RCP2.6 scenario is reported as closest to the 2 °C global temperature target in line with ambitions of the Paris agreement (UNFCCC, 2015). These findings suggest that under warmer climates, space cooling may be more significant than heating demand. Appropriate design strategies may thus be necessary to mitigate high cooling demand and overheating risks as legislations lead to the construction of more low-energy buildings. (Tettey, Dodoo, & Gustavsson, 2017b) showed that high cooling demands and overheating risk can be significantly reduced with different design strategies. The operation phase dominates the life cycle primary energy use of the analysed building systems. The timber building systems give significant end-of-life primary energy benefits than the concrete alternative corresponding with findings from a previous study (Dodoo et al., 2012), that energy recovery from demolished wood materials and products generally give larger primary energy benefits, compared to recycling of steel and concrete. In practice, most wood products that may have been reused and/or recycled will be combusted with or without energy recovery or landfilled at their end-of-life. EU regulations suggest that landfilling should not be a future option. As part of development of a more sustainable society, end-of-life of wood products may be combusted for energy recovery to substitute fossil fuels. Depending on future circumstances the replacement may vary. In addition, changes in recycling and re-use of wood and non-wood alternatives may also vary. Overall, the CLT building system results in the lowest life cycle primary energy balance, followed by the modular and then the concrete alternatives. The life cycle primary energy balance of the building systems vary slightly depending on climate scenario with RCP2.6 giving about 4 % lower life cycle primary energy balance under than the other climate scenarios. Different alternatives of forest utilisation such as for direct energy purposes and carbon storage may influence the analysis in this study. Still, the CLT building gives better climate benefits if timber is not considered as a limited forest resource, otherwise the modular alternative gives a better climate benefit. This is in line with conclusion by an earlier study that active forest management and efficient forest product use can result in significant climate benefits (Leif Gustavsson et al., 2017).

Table 9. End of life primary energy balance, kWh/m² for the different frame construction systems.

Description	Concrete	CLT	Modular
Demolition	21	11	11
Concrete recycling	-30	-2	-2
Steel recycling	-251	-33	-37
Wood recovery for energy	-169	-846	-486
Primary energy balance for end of life phase	***-429***	***-871***	***-514***

Table 10. Life cycle primary energy balance, kWh/m² of the different frame construction systems.

Description	Concrete	CLT	Modular
Production and construction	*1,184*	*-767*	*183*
Material production	1,177	880	784
Building construction	160	80	80
Available biomass residues from production	-132	-1,624	-622
Available biomass residues from construction	-21	-103	-59
Operation (80) years[a]	*6,494*	*6,528*	*6,525*
Space heating	1,133	1,142	1,142
Space cooling	800	827	824
Ventilation electricity	375	375	375
Tap water heating	642	642	642
Household electricity	3,543	3,543	3,543
End-of-life	*-429*	*-870*	*-514*
Energy use for building demolition	21	11	11
Concrete recycling benefits	-30	-2	-2
Steel recycling benefits	-251	-33	-37
Wood recovery for energy	-169	-846	-486
Life cycle primary energy balance	***7,249***	***4,891***	***6,194***

[a] *Under 2013 climate data for Växjö.*

Table 11. Variations in total life cycle primary energy balance, kWh/m² for the analysed frame construction systems, under the considered climate scenarios.

Description	Concrete	CLT	Modular
Växjö_2013	7,249	4,891	6,194
RCP2.6	6,995	4,632	5,934
RCP4.5	7,206	4,841	6,143
RCP8.5	7,222	4,859	6,160

The efficiency of energy supply systems and COP of air conditioners as considered here may improve over time and this may influence the primary energy benefits of the analysed buildings. The share of solar and wind power in the energy supply continues to increase globally and this may influence future energy supply and should be further studied. In this study the electricity production is based on stand-alone fuel-based plants giving high primary energy use for electricity production. This study emphasises the importance of adopting a life cycle perspective covering production, construction, operation and end-of-life activities as well as the potential of wood construction materials for low energy buildings in achieving resource efficiency for a sustainable built environment under climate change.

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