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Strategies for energy and resource efficient building systems

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Strategier för energi- och resurseffektiva byggsystem

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E2B2

STRATEGIES FOR ENERGY AND RESOURCE EFFICIENT BUILDING SYSTEMS

Förord

E2B2 Forskning och innovation för energieffektivt byggande och boende är ett program där akademi och näringsliv samverkar för att utveckla ny kunskap, teknik, produkter och tjänster.

I Sverige står bebyggelsen för cirka 35 procent av energianvändningen och det är en samhällsutmaning att åstadkomma verklig energieffektivisering så att vi ska kunna nå våra nationella mål inom klimat och miljö. I E2B2 bidrar vi till energieffektivisering inom byggande och boende på flera sätt. Vi säkerställer långsiktig kompetensförsörjning i form av kunniga människor. Vi bygger ny kunskap i form av nyskapande forskningsprojekt. Vi utvecklar teknik, produkter och tjänster och vi visar att de fungerar i verkligheten.

I programmet samverkar över 200 byggentreprenörer, fastighetsbolag, materialleverantörer, installationsleverantörer, energiföretag, teknikkonsulter, arkitekter etcetera med akademi, institut och andra experter. Tillsammans skapar vi nytta av den kunskap som tas fram i programmet.

Strategier for energi- och resurseffektiva byggsystem är ett av projekten som har genomförts i programmet med hjälp av statligt stöd från Energimyndigheten. Det har letts av Leif Gustavsson och har genomförts i samverkan med Ronneby kommun, Södra Skogsägarnas ekonomiska förening, Växjöbostäder, Växjö energi AB och Växjö Kommun.

Forskarna har identifierat strategier för att minimera primärenergianvändning och utsläpp av växthusgaser vid planering av nya byggnader. Analysen omfattar moderna betong- och träbyggnader och görs utifrån ett system- och livscykelperspektiv med fokus på produktionsfasen. Projektet ger vägledning och rekommendationer för att optimera byggnader under hela livscykeln.

Stockholm, 7 november 2018

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Ordförande i E2B2

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Sammanfattning

Moderna byggnadssystem för flerbostadshus med betong- eller trästomme har utvecklats och kan användas för att bygga mycket energisnåla byggnader, exempelvis passivhus. Men mer kunskap behövs om hur flerbostadshus kan optimeras över hela livscykeln med hänsyn tagen till primärenergianvändning och utsläpp av växthusgaser. I detta projekt studeras olika strategier för att minimera primärenergianvändningen och utsläpp av växthusgaser för moderna flerbostadshus över deras livscykel med focus på byggnaders produktionsfas i ett systemperspektiv. Hela energi- och materialkedjor inklusive förluster beaktas från naturresurs till levererad tjänst.

Analysen baseras på ett nyligen uppfört flerbostadshus i sex våningar med prefabricerad betongstomme. Huset har också utformats för träbyggnadssystem baserat på massivträ eller volymelement, i samverkan med leverantörerna av träbyggnadssystemen, så att energianvändningen för rumsuppvärmning och ventilation är densamma för de olika stomalternativen med bibehållen boendeservice. Husalternativen är också utformade för att uppfylla svensk byggnorm 2015 eller svenskt passivhuskriterium. Olika uppvärmningssystem har studerats inklusive fjärrvärme med kraftvärme-produktion eller enbart hetvattenpannor samt värmepumpslösningar.

Resultaten visar att byggnaders hela livscykel med tillhörande energi- och materialkedjor behöver beaktas för att minimera primärenergianvändningen och utsläpp av växthusgaser. Husalternativen utformade för att uppfylla passivhuskriteriet har väsentligt lägre energibehov än om de är utformade efter svensk byggnorm. Kombinationen passivhus och kraftvärmebaserad fjärrvärme ger låg primärenergianvändning och låga utsläpp av växthusgaser över husalternativens livscykel. Driftsfasen, särskilt hushållselen, dominerar primärenergianvändningen och utsläpp av växthusgaser både om alternativen är utformade efter byggnormen och passivhuskriteriet. Hushållselen ökar också i dominans för passivhus.

Primärenergianvändning för produktion av husalternativen är 31-41% högre för betongalternativet än för trähusalternativen medan utsläppen av växthusgaser är 41-46% högre. Trähusalternativen medför också att stora mängder restprodukter produceras i skogsbruket och i tillverkningsprocesser. Dessa restprodukter kan användas i förnybara energisystem.

Vi har också studerat klimateffekter om Sveriges skogsbruk inriktas på ökad produktion eller skogsavsättning utan avverkning jämfört med dagens skogsbruk under hundra år. Vid ökad skogsproduktion kan mer träbiomassa användas för att uppföra träbyggnader och för bioenergi medan det blir tvärtom vid ökad skogsavsättning. Hög skogsproduktion med effektiv användning av skogsprodukter ger klimatfördelar jämfört med att öka skogsavsättningen och minska avverkningen och därmed minska användningen av träprodukter och bioenergi.

Denna forskning pekar på möjligheter att utnyttja mycket energisnåla träbyggnader för att öka användningen av förnybar energi och förnybara material på ett naturresurseffektivt sätt. För att bättre förstå byggnaders klimatpåverkan behöver hela deras livscykel studeras med tillhörande energi- och materialkedjor från naturresurs till levererad service.

Keywords: Primärenergianvändning; växthusgaser; livscykel; betongstomme; trästomme

Summary

Modern concrete- and timber-frame multi-storey residential building systems have been developed with improved performances. However, research is needed to explore how these systems could be optimised from a system-wide life cycle perspective. In this project, we have explored strategies to minimise primary energy use and greenhouse gas (GHG) emissions of modern multi-storey residential buildings, from system and life cycle perspectives, with a focus on the production phase.

The research involved analysis and optimisation of primary energy use and GHG emissions associated with the life cycle of buildings, including the entire energy and material chains from natural resources to the delivered services. The analyses covered a modern multi-storey residential building redesigned with different building systems of prefabricated concrete, cross laminated timber (CLT), and modular timber-frame as structural systems. Building alternatives meeting the requirements of the Swedish building code or passive house criteria have been analysed, considering the production, operation and end-of-life phases with heat supply based on electric heat pumps or district heat using combined heat and power (CHP) production or heat-only boilers.

The results show that the full life cycle and energy chains should be considered to optimise primary energy use and GHG emissions of buildings. Final energy use is significantly lower when the building systems are constructed as passive houses. The passive house versions of the building systems with CHP-based district heating give low life cycle primary energy use and GHG emissions. The operation phase dominates the life cycle primary energy use and GHG emissions for both the conventional and passive house versions of the building systems. Household electricity constitutes the largest share of the life cycle primary energy use.

The primary energy use for building production is 31-41% higher for the concrete building system compared to the timber building systems. Also, the concrete building system results in 41-46% more GHG emissions for building production compared to the timber alternatives. Large amounts of biomass residues are coproduced for the CLT and modular timber-frame building systems that can be used in renewable-based energy systems.

We analysed the climate effects of directing forest management in Sweden towards enlargement of the set-aside area in forests or towards increased forest production, relative to the current forest management over 100 years. Different building construction and energy system scenarios are considered, assuming that the same services are delivered to society. Active forest management with high harvest and efficient forest product utilization appear to provide significant climate benefits, compared to reducing harvest and storing more carbon in the forest.

This research emphasises the potential of increased use of wood construction materials and energy-efficient buildings and energy supply in achieving a resource efficient low-carbon built environment. To understand the climate implications of building systems, full life cycle accounting must be conducted, including flows from the production, operation and end-of-life phases of buildings.

Keywords: Primary energy use; greenhouse gas emission; life cycle; concrete-frame; timber-frame

CONTENT

1 Introduction

Fossil fuels dominate primary energy use both globally and within the European Union (EU). Despite significant efforts to increase the share of renewables in the global energy mix, fossil coal, gas and oil provided 28.6%, 21.2% and 31.3% of the global primary energy supply in 2014, respectively [1]. The corresponding numbers within the EU are 17.9%, 22.1% and 31.4%, respectively [2]. Medium and long-term scenarios of the global energy system suggest that fossil fuels are likely to remain the dominant energy source [3, 4].

The International Energy Agency (IEA) anticipates that global carbon dioxide (CO_2) emissions may increase by 20% by 2035 with the current trends in energy use and planned measures to mitigate climate change [5]. This might result in global average temperature rise of about 3.6°C relative to pre-industrial levels. The Paris climate agreement suggested limiting global temperature rise to well below 2° C [6]. This will require radical changes in the global energy and material systems.

The building sector accounted for about 32% of the global final energy use and 19% of the global greenhouse gas (GHG) emissions in 2010 [7, 8]. Concrete, a common material for structural applications in the building sector, typically includes cement and reinforcing steel which are energy intensive materials. The steel and cement industries together accounted for 15% of the global CO_2 emissions in 2012 [9] of which cement production accounts for about 5% [10].

Improved energy and material efficiency in the building sector is increasingly suggested to offer significant reduction of GHG emissions at low mitigation costs [7]. Energy is used during different life cycle phases of buildings for material production, transport, construction, operation, maintenance and demolition. The complete life cycle of buildings must be considered if the climatic impacts of buildings are to be addressed effectively [11].

The development of modern concrete- and wood-frame building systems allows the design and construction of more energy efficient multi-storey buildings with improved performances [12-14]. While several comparative life cycle studies (e.g. [15-18]) have been reported for timber and concrete construction, little information is available on complete life cycle optimisation of modern building systems considering both primary energy use and GHG emissions.

This project involved analysis and optimisation of primary energy use and GHG emissions associated with the life cycle of buildings, including the entire energy chains from natural resources to the delivered services, with a focus on the production phase. The analyses cover modern concrete- and wood-based building systems heated with different technologies.

2 Assumptions and methods

A typical multi-storey building constructed with modern prefabricated concrete frame is used as reference to design building alternatives fulfilling the Swedish building code or passive house criteria with structural frames of prefabricated concrete, cross laminated timber (CLT) or modular timber constructions. Based on these alternatives, life cycle primary energy use and GHG emission flows associated with the production, operation and end-of-life phases of the building alternatives are estimated, including the complete material chains from natural resources to delivered services (figure 1). The fuel cycle energy requirements of the fossil fuels and bioenergy are considered in the calculations.

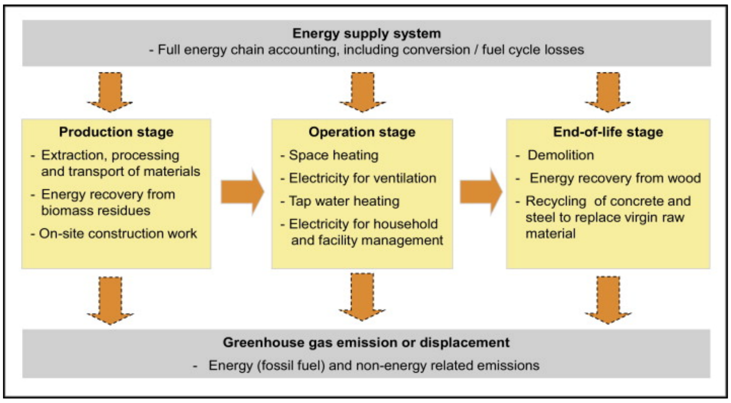


Figure 1. Main processes and activities included in the analysis.

2.1 Production

The production primary energy balance is calculated as the primary energy use for material and component production and transportation and on-site construction for assembly. The net energy (based on lower heating values) of biomass residues that can be recovered and made available for external use is calculated and shown separately.

The production primary energy balance is estimated based on methodology and data presented in [19]. The specific final energy use for production of the different building materials is based on a study of building materials industries in Sweden [20] and a similar study in Norway [21]. The specific final energy use for production of selected building materials is listed in table 1. The on-site construction primary energy use includes the primary energy use for on-site fabrication and assembly of the materials and components into the complete building.

Biomass residues can be recovered from forest thinning and final fellings, wood processing industries and construction sites. The quantities of available biomass residues are calculated based on [19] and by applying biomass expansion factors from [22]. Particleboard needed for building production alternatives is assumed to be produced from processing residues from lumber production.

The GHG balance is calculated based on CO_2 emissions from material production and the net CO_2 emissions from cement reactions. Net cement reaction is the calcination emission during the production minus carbonation uptake during the service life of the cement-based products. The carbonation process occurs throughout the life cycle of concrete products and the absorbed CO_2 is calculated based on data from Dodoo et al. [23].

Table 1. Specific final energy use to produce selected building materials ($kWh_{end\text{-}use}/kg$) [based on 20, 21].

Material	Coal	Oil	Fossil gas	Biofuel	Electricity
Concrete	0.09	0.10	–	–	0.02
Plasterboard	–	0.79	–	–	0.16
Rock wool	2.00	0.36	0.02	–	0.39
Glass wool	2.87	0.52	0.03	–	2.00
EPS	0.28	3.9	3.72	–	0.63
Lumber	–	0.15	–	0.70	0.14
Particleboard	–	0.39	–	1.39	0.42
Steel (ore-based)	3.92	0.86	1.34	–	0.91
Steel (scrap-based)	0.06	0.08	0.44	–	0.57

2.2 Operation

The activities analysed during the operation of the buildings are space heating, domestic hot water heating, electricity for ventilation fans and pump, and electricity for household purposes. The final energy for the operation activities are modelled with VIP-Energy software [24], a dynamic hourly energy balance program. The VIP-Energy software takes into account thermal storage capacity of a building's mass, envelope thermal properties, orientation, glass area, heating and ventilation systems, heat gains from lighting, appliances, human bodies and solar radiation, operation schedule, indoor temperature, geographical location and outdoor climate. The software is validated by the International Energy Agency building energy simulation test [25].

The calculations are based on the 2013 hourly weather data for Växjö, where the reference building is located, obtained from the Meteonorm database [26], including profiles of outdoor air temperature, relative humility, solar radiation and wind speed. Indoor temperatures are assumed to be 21^{o} C and 18^{o} C for the living and common areas of the buildings, respectively. Uncertainties related to key input parameter values and assumptions may influence building energy balance calculations. To reduce the effect of these uncertainties, input parameters and assumptions have been selected to reflect the specific thermal characteristics and surroundings of the reference building as suggested in [27, 28].

The primary energy needed to provide the final energy for the operation activities, and associated CO_2 emissions, are calculated with the ENSYST program [29]. The program calculates primary energy use considering the system-wide energy chain, from natural resources acquisition, transport, refinement and conversion to produce the final energy services.

The implications of district heating systems of different scales as well as ground-source electric heat pumps with or without solar water heating are analysed. The district heat production systems (DHS) considered are those of Ronneby with several heat-only boilers (HOBs), and of Växjö with a

combination of combined heat and power (CHP) unit and HOBs, mainly based on woody biomass. We considered the heat load profiles in 2013 for the district heating systems. The system in Ronneby produced 110 GWh_{heat} at a peak capacity of 35MW while that in Växjö produced 630 GWh_{heat} at a peak capacity of 180MW in 2013. Hourly district heat load duration curves of the district heating systems in Ronneby and Växjö in 2013 are documented in [30, 31]. Data and assumptions of costs and performances of district heating systems are based on and explained in [30]. Allocation between the heat and cogenerated electricity in the CHP plant is avoided by the subtraction method, where the cogenerated electricity is assumed to replace electricity from a standalone power plant with similar technology and fuel input as the CHP plant [32].

For the estimation of primary energy use, changes of electricity use are assumed to be balanced by standalone power plants based on fossil coal or fossil gas with EU-average conversion efficiencies, as these power plants are assumed to give the lowest short-and long-term marginal costs, respectively [33]. A transmission and distribution loss of 8% based on the Swedish average during 2007-2016 [34] is assumed for the electricity use.

The annual produced heat from solar water heating is estimated based on solar irradiation, ambient temperature and fluid entering the collector [35] using the hourly average global solar radiation and ambient temperature for Växjö during 2013 [36].

2.3 End-of-life

After end of service life, the buildings are assumed to be demolished with 90% recovery of concrete, steel and wooden materials. The primary energy use and GHG emissions avoided due to end-of-life materials management options are considered in the calculations based on [23]. Demolished concrete is assumed to be crushed into aggregate followed by exposure to air for a 4-month period to increase carbonation uptake of CO_2. The recycled aggregate is assumed to be used for below-ground filling applications, substituting virgin aggregate for such purpose. Post-use steel is assumed to be recycled as feedstock for production of new scrap-based steel reinforcement. For demolished wood, different scenarios are analysed, including combustion for energy recovery, recycling into particleboard and landfilling with and without recovery and use of methane landfill gas (LFG).

3 Studied building systems

The reference as-built concrete-frame building is 6 storeys high and has 24 apartments of 1-3 rooms with a total heated floor area of 1686 m^2. The foundation comprises layers of 200 mm crushed stones, 300 mm expanded polystyrene (EPS) insulation and 100 mm ground floor concrete slab. The outer walls have a 150 mm layer of EPS insulation sandwiched between 100 mm and 230 mm precast concrete panels. The inner walls are made of 200 mm concrete load bearing walls and non-load bearing walls of 30 mm thick plasterboard layers with steel studs spaced at 600 mm and air gaps of 95–145 mm between them. The intermediate floors are 250 mm concrete slabs whiles the ceiling floor is of 250 mm concrete slab and 500 mm loose fill rock wool insulation with wooden trusses and a roof covering over layers of asphalt-impregnated felt and plywood. The windows and external doors have clear glass double-glazed panels with wood frames, clad with aluminium profiles on the outside. A photograph, floor plan and section of the building are shown in figure 2.

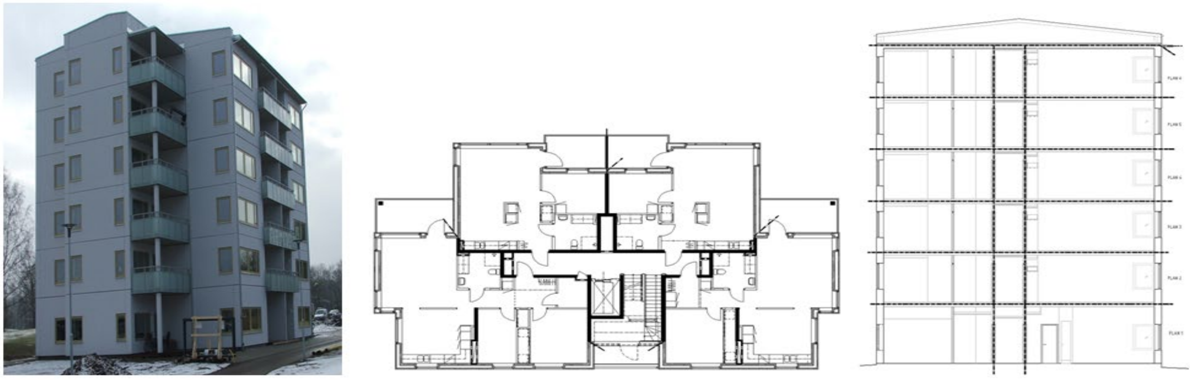


Figure 2. Photograph (left), floor plan (middle) and section (right) of the reference concrete building.

Based on the architectural layout of the prefabricated concrete building, two functionally equivalent alternatives were designed with CLT panels and timber modules in collaboration with the respective Swedish companies which produce them. The main framing elements of the CLT building, including the outer wall, inner load bearing walls, inner and ceiling floors consist of CLT panel elements. The modular building system is made up of light-frame individual volumetric elements which are produced at the manufacturing factory and delivered to the construction site to be assembled. The construction details of the foundation for the wood frame buildings are similar to that of the concrete alternative, except that they have been designed taking into account the lighter weight of the wood building system compared to that of the concrete building.

The three building alternatives were then designed to meet the Swedish building code (BBR 2012 or 2015) [37] and passive house criteria [38]. The buildings meeting the passive house criteria have improved airtightness and thermal performance, more efficient water taps and shower heads, and household appliances and technical installations based on today’s best available technology (BAT).

4 Prefabricated concrete building

4.1 Building design strategies

Design strategies to minimize primary energy use and CO_2 emissions for the prefabricated concrete building alternative meeting the BBR 2012 or passive house criteria are explored in paper 3. The design strategies considered to minimise the production primary energy use and space heating and cooling demands of the building alternatives are varying proportions of glazed window areas, different façade orientations and different combinations of window thermal and solar transmittances.

The increased primary energy use for production of more energy efficient buildings are mainly due to the increased insulation material thicknesses that is required in the envelope (figure 3). The production primary energy increased from 1340 to 1461 kWh per m^2 heated floor area when going from BBR 2012 to passive house criteria buildings.

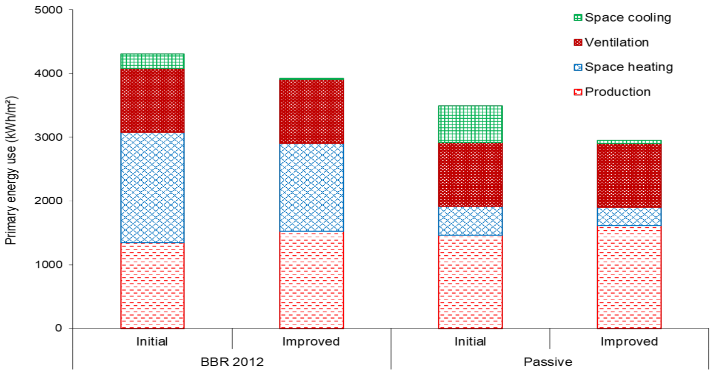


Figure 3. Primary energy use for building production and for space heating, space cooling and ventilation over 50 years for the initial and improved concrete building alternatives based on combination of strategies giving lowest space heating (based on district heat with CHP) and cooling demand.

The overall primary energy use for production, space heating, space cooling and ventilation decreased by 387-537 kWh/m^2 (9–15%) for the improved building compared to the initial alternatives over 50 years. However, the production primary energy use after implementing the different design strategies increased by 186 kWh/m^2 (14%) and 149 kWh/m^2 (10%) for the BBR 2012 and passive house building versions, respectively compared to their respective initial versions.

4.2 Heat supply combined with solar energy

The primary energy use as well as GHG emissions associated with the operation of the prefabricated concrete building alternatives when designed to the BBR 2015 or passive house criteria and heated with district heating or electric heat pump with or without solar water heating are shown in table 2. District heat with CHP units is the most primary energy efficient while ground-source electric heat pump is more primary energy efficient than district heat with HOBs. Primary energy use for heating with the electric heat pump depends strongly on how electricity is produced. The primary energy use

is reduced by about 13% if electricity is produced by fossil gas- instead of coal-based standalone power plant. The primary energy use for electricity production is reduced by about 10% and 20% for the BBR 2015 and passive house alternative, respectively, with solar water heating. The CO_2 emissions when using district heat is much lower compared to the electric heat pump alternatives (table 3). Total CO_2 emission is reduced by about 36% if electricity is produced by fossil gas- instead of coal-based standalone power plant.

Table 2. Annual primary energy use (MWh) when the BBR 2015 and passive house building alternatives are heated with district heating or electric heat pump and the electricity is produced with coal-fired or fossil gas (brackets) standalone power plants.

Building alternative	District heat		Electric heat pump	
	Växjö	Ronneby	without SWH	with SWH
BBR 2015	100 (109)	180 (180)	135 (112)	120 (99.3)
Passive house	47.0 (51.8)	86.1 (86.1)	72.2 (60.0)	59.0 (49.0)

Table 3. Annual CO_2 emission (ton) when the BBR 2015 and passive house building alternatives are heated with district heating or electric heat pump and the electricity is produced with coal-fired or fossil gas (brackets) standalone power plants.

Building alternative	District heat		Electric heat pump	
	Växjö	Ronneby	without SWH	with SWH
BBR 2015	5.42 (5.43)	5.67 (5.67)	47.2 (30.4)	41.9 (27.0)
Passive house	2.24 (2.25)	2.43 (2.43)	25.3 (16.3)	20.7 (13.3)

5 Varied frame materials

Material mass has been analysed for the prefabricated concrete, CLT and modular timber building alternatives and the major materials are presented in table 4. The passive house building alternatives have more insulation materials, and also lumber for the CLT and modular building alternatives than BBR 2015 alternatives. Concrete and crushed stone represent the largest shares of the total mass of all building alternatives. The concrete in the CLT and modular building systems is used in the foundation and constitutes 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, respectively.

Table 4. Mass (tonnes) of major materials in the finished building for the different building alternatives.

Materials	BBR 2015			Passive house		
	Concrete	CLT	Modular	Concrete	CLT	Modular
Concrete	2870	229	229	2870	229	229
Steel	95.2	12.5	14.2	95.2	12.6	14.2
Lumber	50.9	115	145	50.9	127	154
Particleboard	20.8	0.00	22.8	20.8	0.00	22.8
Plywood	2.99	20.9	29.0	2.99	20.9	29.0
CLT	0.00	176	0.00	0.00	176	0.00
Glue-laminated wood	0.00	40.3	7.77	0.00	40.3	7.77
Stone wool insulation	7.14	18.7	5.86	11.1	31.7	10.6
Glass wool insulation	0.00	0.00	15.2	0.00	0.00	23.6
EPS insulation	8.99	4.54	4.54	13.6	4.54	4.54
Plasterboard	22.6	110	116	22.6	110	116.
Plastic (PVC)	2.31	2.31	2.31	2.31	2.31	2.31
Marmoleum	0.40	0.40	0.40	0.40	0.40	0.40
Crushed stone	202	202	202	202	202	202
Mortar	4.40	4.40	4.40	4.40	4.40	4.40
Aluminium	2.25	2.25	2.25	2.25	2.25	2.25
Copper	0.60	0.60	0.60	0.60	0.60	0.60
Glass	20.9	20.9	20.9	29.8	29.8	29.8
Tar paper	1.20	1.20	1.20	1.20	1.20	1.20
Paint	1.09	1.09	1.09	1.09	1.09	1.09
Putty /fillers	4.82	4.82	4.82	4.82	4.82	4.82
Asphalt	0.21	0.21	0.21	0.21	0.21	0.21
Porcelain	0.70	0.70	0.70	0.70	0.70	0.70
Ceramics	13.2	13.2	13.2	13.2	13.2	13.2

5.1 Production of building alternatives

Tables 5 and 6 show the primary energy use and carbon balances for the production of the different building systems. Electricity for material production is assumed to be from a coal-based standalone power plant. In paper 4, the implication of fossil gas-based electricity is also shown. Positive numbers

denote energy use or emission to the atmosphere while negative numbers denote energy benefits or GHG emission avoided.

Table 5. Primary energy balances (kWh/m^2) for the production of the building systems. Electricity is produced in coal-fired standalone power plants.

Description	BBR 2015			Passive house		
	Concrete	CLT	Modular	Concrete	CLT	Modular
Material production:						
Fossil fuels	717	300	306	759	334	345
Electricity	363	313	280	373	327	316
Bioenergy	45	214	119	45	219	123
Total	*1125*	*826*	*705*	*1177*	*880*	*784*
Building construction:						
Fossil fuels	80	40	40	84	43	45
Electricity	80	40	40	84	43	45
Total	*160*	*80*	*80*	*167*	*85*	*85*
Total material production & building construction	1285	906	785	1344	965	873
Biomass residues:						
Forest harvest[a]	-56	-418	-189	-56	-431	-199
Wood processing[b]	-76	-1160	-400	-76	-1193	-424
Construction	-21	-100	-57	-21	-103	-59
Total	-153	-1678	-646	-153	-1727	-682
Balance	1132	-771	138	1192	-762	191

[a] Includes branches and foliage; [b] Includes chips, sawdust and bark.

Table 6. Carbon balances (kg CO$_{2\text{-eqv}}$/m^2) for the production of the building systems. Electricity is produced in coal-fired standalone power plants.

Description	BBR 2015			Passive house		
	Concrete	CLT	Modular	Concrete	CLT	Modular
Material production:						
Fossil fuels	233	91	94	245	103	108
Electricity	140	121	108	144	126	122
Net cement reactions	58	6	6	58	6	6
Total	*431*	*217*	*208*	*447*	*234*	*235*
Building construction:						
Fossil fuels	23	12	12	24	12	13
Electricity	31	15	15	32	16	17
Total	*54*	*27*	*27*	*56*	*29*	*30*
Total material production & building construction	485	244	235	504	263	265
Carbon in wood materials	-67	-323	-184	-67	-334	-192
Substitution of fossil coal:						
Forest harvest	-22	-161	-73	-22	-166	-76
Wood processing	-29	-447	-154	-29	-460	-163
Construction	-8	-38	-22	-8	-40	-23
Total	-60	-646	-249	-59	-665	-263
Balance	359	-738	-198	378	-737	-189

Electricity accounts for 32, 38 and 40% of the total primary energy use for material production for the concrete, CLT and modular building systems, respectively. The BBR 2015 concrete building alternative requires 27 and 37% more primary energy for material production than the CLT and modular BBR 2015 building alternatives, respectively. The corresponding numbers are 25 and 33% when the building systems are designed to meet the passive criteria. The primary energy use for material production of the buildings to the passive house criteria is 5% more than that of the BBR 2015 for the concrete and CLT building systems, and 11% more for the modular building system.

The CLT and modular buildings give lower CO_2 emissions for building production and construction, compared to the concrete building. The production CO_2 emissions for the concrete frame building are nearly double those of the timber-frame building. The carbon balances for the production phase of the building systems including benefits from available biomass residues and carbon in wooden materials is negative for the timber-based buildings.

5.2 Operation of building alternatives

Figure 4 shows the annual profiles of final space heating demands of the building alternatives arranged in descending order. The difference in space heating demand between the concrete- and timber-frame alternatives is very minor and can be noticeable in spring and autumn seasons.

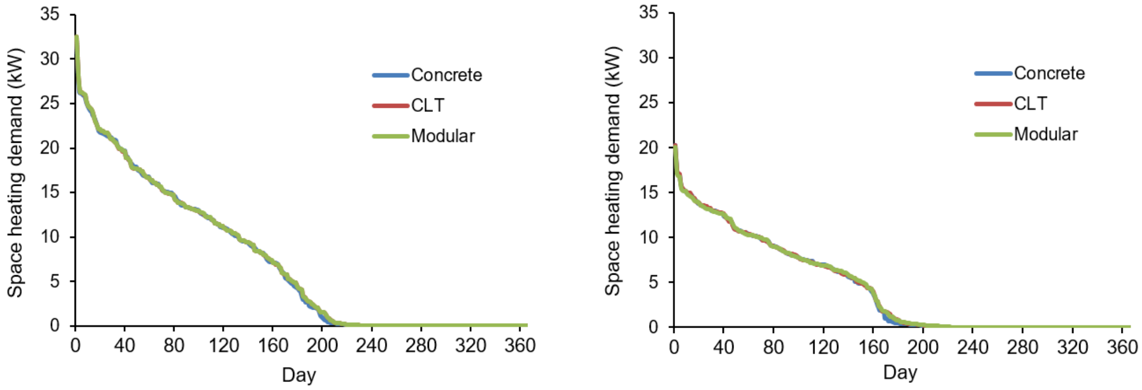


Figure 4. Annual profiles of space heating demand of the building alternatives to the BBR 2015 standard (left) and passive house criteria (right) arranged in descending order.

Even though the effect of thermal mass is minor between the building alternatives, the external wall insulation for the CLT and modular building alternatives are increased to adjust for this difference. Thus, all the building systems are modelled to the same annual final energy demand for space heating, ventilation electricity, tap water heating and household electricity of 37, 5, 21 and 32 kWh/m^2, respectively, for BBR 2015 building alternatives. The corresponding numbers for the passive house criteria are 22, 2, 13 and 16 kWh/m^2. In total the annual final energy use is reduced by 45%, from 95 to 53 kWh/m^2, for the passive building alternatives compared to BBR 2015 alternatives.

Table 7 shows annual primary energy use for operation of the building alternatives with different heat supply systems with electricity produced in coal-based standalone power plants. Household electricity

dominates the operation primary energy use for all alternatives, accounting for 48-63% of the total primary energy use depending on the thermal performance of the building and heat supply option. This is followed by space heating, making up 17-30% of the total operation primary energy use. Among the considered heat supply options, district heating with CHP gives the lowest operation primary energy, followed by electric heat pump and then district heating with HOBs.

Table 7. Annual primary energy use (kWh/m^2) for operation of building alternatives with different heat supply. Electricity is produced in coal-based standalone power plants. The implication of gas-based electricity is shown in paper 4.

Description	BBR 2015			Passive house		
	DHS-CHP	DH-HOB	EHP	DHS-CHP	DHS-HOB	EHP
Space heating	23.7	45.6	33.8	14.2	27.2	20.2
Ventilation electricity	14.2	14.2	14.2	4.7	4.7	4.7
Tap water heating	13.4	25.8	19.1	8.0	15.4	11.4
Household electricity	86.1	86.1	86.1	44.3	44.3	44.3
Total	137.5	171.7	153.2	71.2	91.6	80.6

5.3 End-of-life of building alternatives

The primary energy balance for the end-of-life of the different building systems, including benefits from concrete and steel recycling as well as recovery of wood-based demolition materials for energy is shown in table 8 (see also paper 1). The CLT building system gives the largest end-of-life primary energy benefits, followed by the modular and then the concrete alternative. The passive CLT and modular building systems give slightly greater end-of-life primary energy benefits than the BBR alternatives, mainly due to increased wood recovery for energy.

Table 8. End-of-life primary energy balance (kWh/m^2) of the building alternatives.

Description	BBR 2015			Passive house		
	Concrete	CLT	Modular	Concrete	CLT	Modular
Demolition	20	10	10	21	11	11
Concrete recycling and carbonation	-30	-2	-2	-30	-2	-2
Steel recycling	-251	-33	-37	-251	-33	-37
Heating value for wood residues	-169	-818	-465	-169	-846	-486

5.4 Life cycle of building alternatives

The complete life cycle primary energy balance, assuming an 80 year life span with space heating based on CHP and coal-based electricity for the building systems is given in table 9. The production primary energy use of the building alternatives ranges between 7% and 22% of the total life cycle primary energy balance but the operation phase dominates the life cycle primary energy use. Overall, the CLT and modular building alternatives give about 20 and 9% lower life cycle primary energy use than the concrete alternative for the BBR alternatives. The corresponding numbers are 37 and 17%, respectively, when the building systems are designed to the passive house criteria. The CLT building system gives the largest end-of-life primary energy benefits, followed by the modular compared to the concrete building system. The energy use for maintenance and repairs over the life span is not considered as the analysed building systems are assumed to have similar designs and mechanical installations and the differences due to the different frame materials are expected to be minor.

Table 9. Annual life cycle primary energy balance (kWh/m^2) of the building alternatives assuming an 80 year life span. Space and tap water heating from district heating with CHP and electricity from coal-based standalone power plants.

Description	BBR 2015			Passive house		
	Concrete	CLT	Modular	Concrete	CLT	Modular
Production phase	14.2	-9.65	1.74	14.9	-9.53	2.39
Operation phase	137	137	137	71.2	71.2	71.2
End of life phase	-5.38	-10.5	-6.18	-5.36	-10.9	-6.43
Life cycle balance	146	117	133	80.7	50.8	67.2

The life cycle primary energy balances of the building systems based on different heat supply options and building lifespans of 80, 100 or 150 years are shown in table 10. The life cycle primary energy balances for the building systems vary widely depending on the choice of building life span.

Table 10. Variations in total life cycle primary energy balance (kWh/m^2) of the different building alternatives for different heat supply options and life spans with coal-based electricity.

Description	BBR 2015			Passive house		
	Concrete	CLT	Modular	Concrete	CLT	Modular
80 year life span:						
CHP	11700	9380	10600	6460	4060	5370
HOB	14400	12100	13400	8100	5700	7010
Heat pump	13000	10600	11900	7210	4810	6120
100 year life span:						
CHP	14400	12100	13400	7880	5480	6790
HOB	17900	15600	16800	9920	7530	8840
Heat pump	16000	13700	15000	8820	6430	7740
150 year life span:						
CHP	21300	19000	20300	11400	9040	10400
HOB	26500	24100	25400	14500	12100	13400
Heat pump	23700	21400	22600	12900	10400	11800

The overall carbon balances over the different life cycle phases of the buildings assuming an 80-year lifespan are presented in table 11. Positive carbon balance values indicate emissions to the atmosphere while negative values indicate avoided emissions. The operation phase dominates the life cycle carbon balances for the building alternatives. The timber-frame building system results in significantly lower life cycle carbon emissions among for the building systems analysed. During the end-of-life phase, the benefits from steel and concrete recycling are greatest for the concrete building system. However, the benefits from the recovered wood materials for CLT and modular building systems are significantly higher.

Table 11. Annual life cycle carbon balances (kg $CO_{2\text{-eqv}}/m^2$) for the building alternatives assuming an 80 year life span. Space and tap water heating from DHS with CHP and electricity from coal-based standalone power plants. Biomass residues replace coal.

Description	BBR 2015			Passive		
	Concrete	CLT	Modular	Concrete	CLT	Modular
Production phase	5.33	-5.01	-0.18	5.55	-5.01	0.03
Operation phase	36.3	36.3	36.3	17.8	17.8	17.8
End of life phase	-1.96	-4.06	-2.38	-1.96	-4.20)	-2.48)
Life cycle balance	39.6	27.2	33.7	21.4)	8.55	15.3

5.5 Life cycle effects of material and end-of-life options

In paper 5, the impacts of different end-of-life material management options on the life cycle primary energy use and GHG balance of building alternatives designed to the BBR 2015 are analysed. We explored end-of-life scenarios where demolished concrete and steel are recycled, and where demolished wood is recycled, used for energy or landfilled with or without landfill gas (LFG) recovery.

Tables 12 and 13 summarize the primary energy and GHG balances for the building alternatives for the production and end-of-life phases when recovered energy from the LFG or combustion of the wood is assumed to replace fossil coal or fossil gas. Positive numbers denote energy use or emission to the atmosphere. Negative numbers denote energy benefits or GHG emission avoided. Also, substitution factors, based on carbon in wood materials in the finished building or in harvest forest biomass, are given in these tables.

The substitution factors are the difference between GHG emissions divided by the difference between wood in finished building or harvest forest biomass in the timber building alternatives (CLT or modular) and the reference alternative (concrete). Substitution factors are expressed in carbon equivalent emissions and mass units of carbon contained in the wood material in the finished building or harvest forest biomass. Positive substitution factors show that the CO_2 emissions of the timber building alternatives are lower than that of the reference concrete alternative, while negative numbers show the opposite.

The GHG emission substitution factors for the timber-based building systems vary widely, depending on the end-of-life management option for the wood products and the assumed fossil fuel replaced by the demolished wood or LFG. If fossil coal is assumed to be replaced, the substitution factors are in a range of 0.0 to 3.3 t and 0.0 to 1.3 t of C_{eqv} emission per t of C in wood product or harvest forest biomass, respectively. The corresponding factors if fossil gas is assumed to be replaced are -0.8 to 2.4 t and -0.3 to 1.0 t, respectively. The GHG substitution factors are slightly higher for the modular timber-frame building system compared to cross laminated timber-frame building system. Wood for energy recovery gives large end-of-life primary energy and GHG benefits for all the building systems, in contrast to concrete recycling and carbonation in the post-use phase. The primary energy and GHG benefits for steel recycling are somewhat significant.

Overall, the assumed end-of-life option for post-use wood has significant impacts on the life cycle primary energy use and GHG balances of the building systems. The buildings' total life cycle primary energy use and GHG balances are lowest when wood is recovered for energy and highest when wood is landfilled without LFG recovery. Compared to landfilling with LFG recovery, wood recycling into

particleboard gives lower GHG balances and higher primary energy balances for all the building systems.

Table 12: Primary energy and GHG balances, and substitution factors for the buildings with various end-of-life options. The substitution factors are shown when considering carbon in wood materials (outside brackets) or in harvest forest biomass (inside brackets). Recovered energy replaces fossil coal.

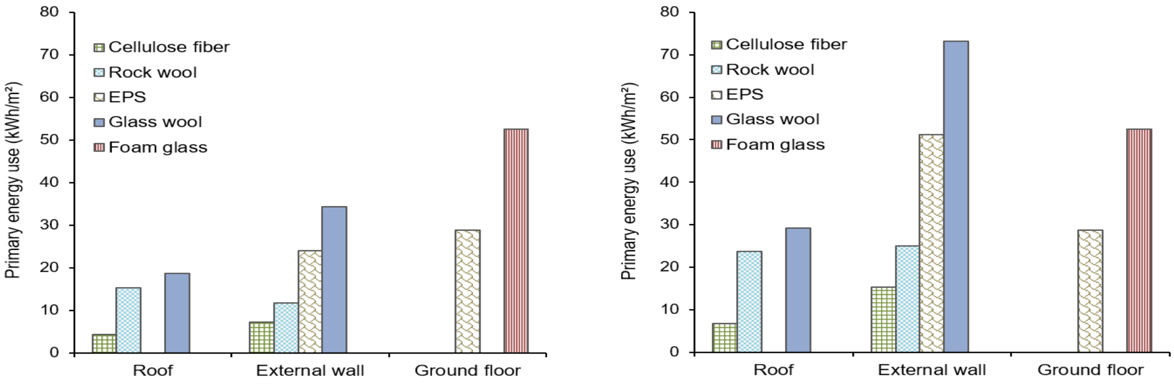
Description	Primary energy (MWh)			GHG balance (tCO_2-eqv)			Substitution factor	
	Concrete	CLT	Modular	Concrete	CLT	Modular	CLT	Modular
Building production:								
Material production	1900	1390	1190	629	357	341		
Net cement reaction				97.8	10.1	10.1		
On-site construction	270	135	135	91.0	45.5	45.5		
Sub-total	2170	1530	1320	818	413	396	0.8 (0.3)	1.8 (0.7)
Harvest and processing residues:								
Heating value of residues	-258.0	-2830	-1090					
Substitution of fossil coal				-99.5	-1090	-420		
Sub-total	-258.0	-2830	-1090	-99.5	-1090	-420	1.9 (0.6)	1.3 (0.5)
Building disassembly	33.7	16.9	16.9	10.1	5.1	5.1	0.0 (0.0)	0.0 (0.0)
Concrete and steel management options:								
Concrete recycling and carbonation	-51.4	-4.1	-4.1	-17.1	-1.4	-1.4		
Steel recycling	-422	-55.4	-62.9	-149	-19.5	-22.1		
Sub-total	-474	-59.5	-67.0	-166	-20.9	-23.5	-0.3 (-0.1)	-0.6 (-0.2)
Wood management options:								
A. Energy recovery of wood								
Heating value of residues	-276	-1300	-756					
Substitution of fossil coal				-101	-478	-277.0		
Sub-total	-276	-1300	-756	-101	-478	-277.0	0.7 (0.2)	0.7 (0.3)
B. Cascading wood	-328	-1550	-896	-108	-508.0	-295	0.8 (0.3)	0.8 (0.3)
C. Landfill with LFG recovery								
LFG to atmosphere				43.4	205	119		
Heating value of LFG	-72.3	-341	-198					
Substitution of fossil coal				-28.9	-137	-79.2		
Sub-total	-72.3	-341	-198	14.5	68.2	39.5	-0.1 (0.0)	-0.1 (0.0)
D. Landfill without LFG recovery								
LFG emissions				333	1570	910		
Sub-total				333	1570	910	-2.4 (-0.8)	-2.4 (-1.0)
Totals:								
Option A: Energy recovery from wood	1190	-2650	-572	461	-1170	-319	3.2 (1.0)	3.3 (1.3)
Option B: Cascading wood	1140	-2890	-712	455	-1200	-337	3.3 (1.0)	3.3 (1.3)
Option C: Landfill with LFG recovery	1400	-1690	-13.6	577	-624	-2.5	2.4 (0.8)	2.4 (1.0)
Option D: Landfill without LFG recovery	1470	-1340	184	895	878	868	0.0 (0.0)	0.1 (0.0)

Table 13: GHG balances, and substitution factors for the buildings with various end-of-life options. The substitution factors are shown when considering carbon in wood materials (outside brackets) or in harvest forest biomass (inside brackets). Recovered energy replaces fossil gas.

Description	GHG balance (tCO$_2$-eqv)			Substitution factor	
	Concrete	CLT	Modular	CLT	Modular
Building production:					
Material production	629	357	341		
Net cement reaction	97.8	10.1	10.1		
On-site construction	91.0	45.5	45.5		
Sub-total	818	413	396	0.8 (0.3)	1.8 (0.7)
Harvest and processing residues:					
Heating value of residues					
Substitution of fossil gas	-57.3	-627	-242		
Sub-total	-57.3	-627	-242	1.1 (0.4)	0.8 (0.3)
Building disassembly	10.1	5.1	5.1	0.0 (0.0)	0.0 (0.0)
Concrete and steel management options:					
Concrete recycling and carbonation	-17.1	-1.4	-1.4		
Steel recycling	-149	-19.5	-22.1		
Sub-total	-166	-20.9	-23.5	-0.3 (-0.1)	-0.6 (-0.2)
Wood management options:					
A. Energy recovery of wood					
Heating value of residues					
Substitution of fossil gas	-58.3	-275	-160		
Sub-total	-58.3	-275	-160	0.4 (0.1)	0.4 (0.2)
B. Cascading wood	-64.7	-306	-177	0.5 (0.2)	0.5 (0.2)
C. Landfill of wood with recovery of LFG					
Net landfill GHG emissions to atmosphere	43.4	205	119		
Heating value of LFG					
Substitution of fossil gas	-16.6	-78.6	-45.6		
Sub-total	26.8	126	73.1	-0.2 (-0.1)	-0.2 (-0.1)
D. Landfill of wood without recovery of gas					
Landfill gas emissions	333	1570	910		
Sub-total	333	1570	910	-2.4 (-0.8)	-2.4 (-1.0)
Totals:					
Option A: Energy recovery from wood	546	-505	-23.6	2.1 (0.7)	2.4 (1.0)
Option B: Cascading wood	540	-536	-41.2	2.1 (0.7)	2.4 (1.0)
Option C: Landfill with LFG recovery	631	-104	209	1.4 (0.5)	1.8 (0.7)
Option D: Landfill without LFG recovery	937	1340	1050	-0.8 (-0.3)	-0.5 (-0.2)

6 Insulation and facade materials

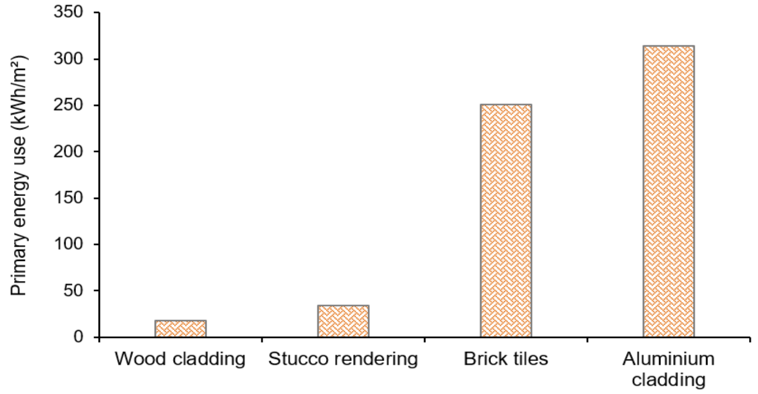
The implications of different insulation and façade materials for production primary energy use and GHG emissions of building alternatives are analysed (paper 2). Figure 5 shows the primary energy required for production of various insulation materials for different building elements of the reference as-built prefabricated concrete building designed to fulfill the BBR 2015 and passive house criteria. EPS gives a lower production primary energy-use compared to foam glass for the building's foundation insulation. For the roof and external walls, cellulose fiber insulation consistently results in the lowest while glass wool gives the highest primary energy use for production compared to the other insulation alternatives for both the BBR 2015 and passive house criteria.



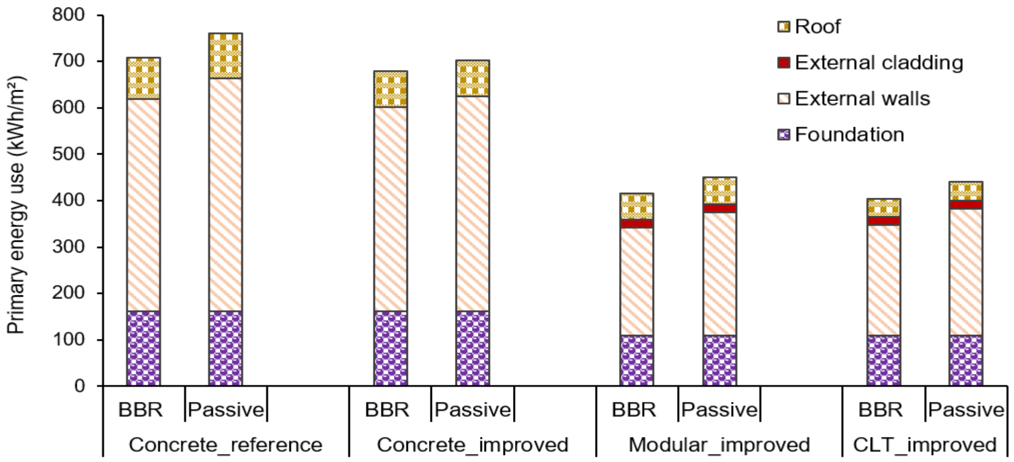
Figures 5. Production primary energy use for various insulation materials for the prefabricated concrete frame BBR 2015 (left) and passive house (right) building alternatives.

Figure 6 shows primary energy use required for production of building façade alternatives for the as-built building. Wood cladding results in the lowest production primary energy use, compared to the other façade alternatives. The lifetime and required maintenance vary between the facade materials and that may influence the ranking of the facade materials and should be further analysed although the production energy is 7 to 18 times higher for brick tile and aluminum cladding, compared to stucco rendering and wood cladding.

Figure 7 shows the implications of the choice of insulation, façade and structural frame materials for primary energy use for the production of foundation, external walls and cladding as well as roof of the building alternatives designed to fulfill the BBR 2015 or passive house criteria. The reference alternatives show as-built versions of the building, constructed with concrete framework and façades, rockwool insulation for the roof, and EPS insulation for the exterior walls as well as ground floor. The improved alternatives show when the insulation materials resulting in the lowest production primary energy for each building part (figure 5) replace those in the corresponding parts of the reference building, and also when the concrete framework and façades are replaced with wooden alternatives. The improved building alternatives all have wood external wall cladding, EPS as foundation insulation and cellulose insulation in the external walls and roof. The external wall materials dominate the production primary energy use of the external envelope elements. The improved CLT and modular building systems give significantly lower production primary energy use for the building envelope compared to the concrete alternatives.



Figures 6. Production primary energy use for façade alternatives for the as-built building.



Figures 7. Production primary energy use of envelope elements for the reference and improved BBR 2015 and passive house alternatives with different frame alternatives.

7 Forest management

We have analysed the climate effects of directing forest management in Sweden towards enlargement of the set-aside area in forests or towards increased forest production, relative to the current forest management over 100 years (paper 6). We considered various scenarios of forest management and biomass use, and we estimate the carbon balances of the forest systems and their climate effects in term of radiative forcing.

The analysis is built on three general forest management scenarios: Business as usual (BAU), Set-aside, and Production. The BAU scenario reflects current forestry practices. In the Set-aside scenario, the protected area is doubled at the starting year of the simulations and then kept constant while all other settings are equal to BAU. In the Production scenario, a higher forest productivity is assumed. Each combination of forest management and harvest extraction scenario provides a specific quantity of biomass raw materials to be used in the building and energy sectors.

We assume that the same services are delivered to society in the different forest management scenarios. In the Production scenario, more biomass is harvested compared to the BAU scenario, increasing the potential production of timber buildings and bioenergy. In the Set-aside scenario, the harvest is less compared to BAU, decreasing the potential production of timber buildings and bioenergy. With less production of timber buildings and bioenergy, the construction of concrete buildings and use of fossil fuels need to increase to deliver the same amount of service to society.

The building construction scenarios include the prefabricated concrete-frame, CLT and modular timber-frame building alternatives designed to meet the passive house criteria. The full life cycle implications of the building versions are considered excluding the operation phase as the building versions are designed to have the same operating energy use. The service life of each building is assumed to be 80 years. In the end-of-life management of the building, steel is assumed to be recycled as scrap for production of new steel, concrete is crushed into aggregate and exposed to the atmosphere to increase carbonation during four months.

Harvest residues from forest thinning and final fellings as well as residues from wood processing and building construction and demolition are assumed to be used for bioenergy. Net CO_2 emissions from bioenergy systems are compared to those from fossil energy systems that provide the same services. Each bioenergy scenario has a corresponding fossil energy system that makes equivalent products based on coal or fossil gas for cogeneration of heat and electricity or diesel oil for transportation. For biomass used for bioenergy an international transport of 1000 km is included in the analysis.

In the first 20 years of the analysis, the net CO_2 emission differences between the scenarios are small when bioenergy is assumed to replace fossil coal. After this initial period, the Production scenario with high residue recovery rate give most climatic benefits which also increased over time. At the end of the analysed period, the effect of more set-aside forest area for carbon storage in Set-aside scenario results in higher total net CO_2 emissions due to lower forest harvests leading to higher CO_2 emissions from the energy and material systems.

The climate benefits are significantly reduced if bioenergy replaces fossil gas and the Set-aside scenario give climate benefits during 20-50 years compared to the Production scenario. However, after

50 years, the Production scenario with high residue recovery rate gives clear climate benefits that increased over time compared to the Set-aside scenario. Using biomass to replace motorfuels in the transport sector instead of fossil gas in the electricity and heat sector further reduced the climate benefits of the Production scenario compared to the Set-aside scenario. The type of wood building system has a rather small impact on the results.

All significant annual flows of CO_2 to and from the atmosphere are considered, but not other climate effects such as albedo. Hence, the cumulative radiative forcing is calculated based on annual net CO_2 emissions to the atmosphere. The timespan of 100 years appears to be long and technological development may change the results, but still mainly only one forest rotation period is included in the analyses. In longer timespans the climate benefit of the Production scenario is expected to further increase compared to the Set-aside scenario, as the carbon stock in the set-aside forest may reach a dynamic steady state, while the forest in the Production scenario continues to produce biomass that can be harvested and used for bioenergy and materials.

8 Discussion

In this project, we have explored strategies to minimise primary energy use and GHG emissions of new buildings, from system and life cycle perspectives, with a focus on the production phase. The research involved analysis of primary energy use and GHG emissions associated with the life cycle of buildings.

The analyses covered a modern multi-storey apartment building redesigned with different building systems including prefabricated concrete, cross laminated timber, and modular timber-frame as structural systems. Cases where the building systems are built as conventional houses to meet the requirements of Swedish building code or as low-energy building to meet passive house criteria have been analysed, considering the production, operation and end-of-life phases of the buildings as well as different heat supply systems. Complete materials and energy chains, including the primary energy use to extract, process, and transport the required materials are considered, and material losses, efficiencies of fuel cycles and conversion and distribution systems as well as calcination and carbonation carbon flows linked to cement-based materials are considered.

The calculations show that the primary energy use for building production is 31-41% higher for the concrete building system compared to the timber alternatives. Also, the concrete building system results in 41-46% more GHG emissions for building production compared to the timber alternatives. The operation phase dominates the life cycle primary energy use and carbon emissions for both the conventional and passive house versions of the building systems. Household electricity constitutes the largest share of the life cycle primary energy use. The passive house versions of the building systems with cogeneration-based district heating give low life cycle primary energy use and GHG emissions.

Large amounts of biomass residues are produced due to the use of wood framing material for the case of timber-frame building systems. The energy content of the residues is significant relative to the primary energy used for production of the buildings. The primary energy use and GHG emissions for demolition and processing of the post-use material is minor in relation to the primary energy and GHG benefits from recovery of the materials.

In summary this research shows that that a timber-frame building gives lower life cycle primary energy use and carbon emissions than a concrete-frame alternative. Efficient end-of-life management options for building materials can offer opportunities to further reduce the life cycle energy use and GHG emissions in the built environment. The findings show the importance of a system-wide life cycle perspective and the choice of heating system in reducing primary energy use and GHG emissions in the built environment.

9 Publication list

The research has been documented in a scientific journal article and six conference papers in international conferences in France, Hong Kong, Portugal, Finland and Sweden. The project publications are listed below.

Journal articles:

1. Tettey, U. Y. A., Dodoo, A., & Gustavsson, L. (2019). Effect of different frame materials on the primary energy use of a multi storey residential building in a life cycle perspective. Energy and Buildings 185: 259-271.

Conference papers:

2. Tettey, U. Y. A. & Gustavsson, L. (2019). Primary energy and CO_2 emissions implications of different insulation, cladding and frame materials for residential buildings. SBE19 Sustainable Built Environment Conference. Helsinki, Finland.
3. Tettey, U. Y. A., Dodoo, A., & Gustavsson, L. (2016). Design strategies for a Swedish residential building to minimize primary energy use and CO_2 emission. The 11th Conference on Sustainable Development of Energy, Water and Environment Systems. Lisbon, Portugal.
4. Tettey, U.Y.A., Dodoo, A., Gustavsson, L. (2018). Carbon balances for a low energy apartment building with different structural frame materials. 10th International Conference on Applied Energy. Hong Kong, China
5. Dodoo, A., Gustavsson, L. & Tettey, U. Y. A., (2018). Effects of end-of-life management options for materials on primary energy and greenhouse gas balances of building systems. 10th International Conference on Applied Energy. Hong Kong, China
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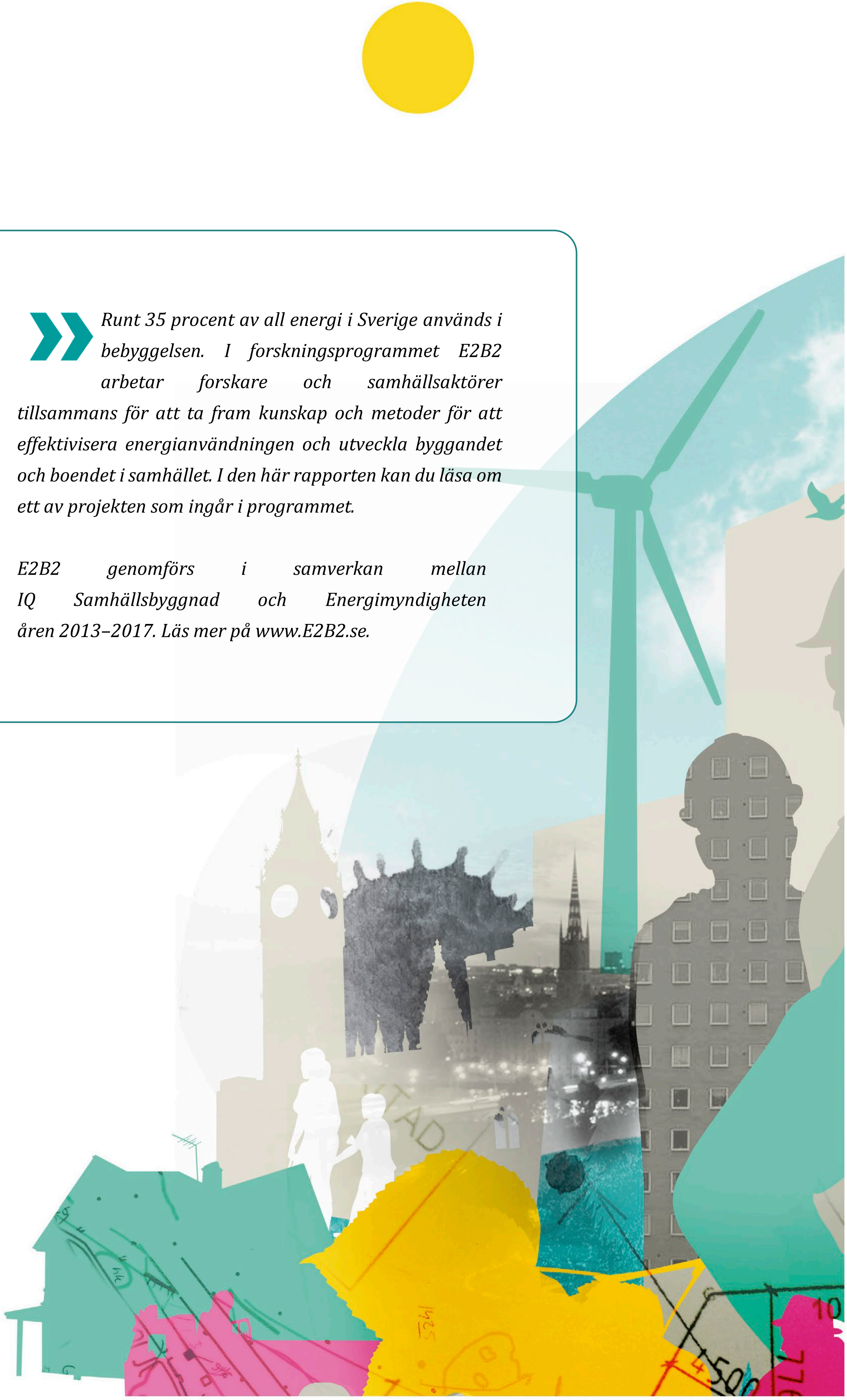

Runt 35 procent av all energi i Sverige används i bebyggelsen. I forskningsprogrammet E2B2 arbetar forskare och samhällsaktörer tillsammans för att ta fram kunskap och metoder för att effektivisera energianvändningen och utveckla byggandet och boendet i samhället. I den här rapporten kan du läsa om ett av projekten som ingår i programmet.

E2B2 genomförs i samverkan mellan IQ Samhällsbyggnad och Energimyndigheten åren 2013–2017. Läs mer på www.E2B2.se.