Greenhouse gas emission from the construction stage of wooden buildings

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Abstract

This study reports on a detailed investigation into the greenhouse gas emissions associated with the construction process of multi-story wooden buildings relative to the other life cycle stages – the material production and operation stages. The results showed that the construction stage accounts for 20-30% of the initial embodied emissions and 6-10% of the total emission of the included life cycle stages. Especially the transport process of building components seems to have higher potential to mitigate the emissions than the actual construction work. In addition, the emissions from different construction systems were studied based on the reference buildings. Although definitive conclusion would be difficult to be drawn from this study alone due to the small sample size and the assumptions made, prefabrication work seems to be a more efficient construction method compared to on-site work for wooden buildings.

Keywords: Life cycle assessment, Greenhouse gas emission, Wooden building, Construction

1. Introduction

In the life cycle assessment (LCA) of a building most attention has been paid to the operation phase, mainly because it accounts for a large proportion of the environmental impacts over the whole life cycle. Reducing the operational environmental impact of a building has thus far been the main target and, as a result of efforts in this part, the impact from the use phase has been mitigated and the relative importance of the other life cycle stages has increased (Verbeeck and Hens 2007). Sartori and Hestnes (2007) reported that the share of embodied energy in the life cycle energy use (service life 50 years) accounts for up to 46% in the case of low energy building and up to 38% in the case of conventional buildings, although there were the methodological differences between the reviewed case studies. In general, the production phase of construction materials has been regarded as the next target for mitigation. It has been reported by several researchers that the construction phase accounts for a small proportion of the life cycle energy use of a building; in many cases it is less than 10% depending on the case in question (Adalberth 1997; Cole 1996; 1999; Keoleian et al. 2000; Junnila et al. 2006; Junnila and Horvath, 2003; Scheurer et al. 2003).However, recent research has highlighted the importance of the construction phase. For instance, Gangolells et al. (2009) stated that transportation, construction machinery, waste production and water consumption have significant environmental consequences, implying that any improvements in these areas could be priority targets for reducing the overall life cycle impact of a building.

There has been discussion about the implications of off-site construction systems as opposed to traditional on-site construction. For instance, Quale et al. (2012) carried out a comparative analysis of two different construction methods - a modular system and conventional on-site construction - considering different scenarios and transportation distances. The results showed that the greenhouse gas (GHG) emission from the modular system, which includes many prefabrication processes, is lower than that of conventional construction due to the limited duration of on-site activities, leading to less waste and worker transportation.

Data collection from the construction phase has been also an issue. Ahn et al. (2009) found that the decentralization of construction processes, which often involves several subcontractors, leads to critical issues in measuring the significance of GHG emissions from construction processes. Furthermore, the uniqueness of each project and the fragmented nature of the industrial building sector make improvements difficult to implement. Peña-Mora et al. (2009) pointed out that efforts to manage the construction process have not been developed sufficiently and proposed a management system for GHG and other air pollutant emissions from construction equipment.

This paper reports on a detailed investigation into the GHG emissions associated with the construction process of multi-story wooden buildings. GHG emissions from the materials production, construction and operation phases of three wooden reference buildings were assessed in order to examine the features and proportions of the construction phase relative to the other phases. In addition, based on these reference buildings, an environmental profile of different construction methods - prefabrication and conventional on-site construction - was undertaken. For comparison purpose the assessment was limited to wooden building elements, thus the manufacturing and installation of all building service equipment, such as the basements, steel staircases and furniture were excluded from the study.

2. Methodology

2.1 Reference buildings

Three multi-story wooden residential buildings were assessed as case studies. Basic information about the reference buildings is summarized in Table 1. The functional unit was 1 m^2 of living area, which is an area enclosed by the inside of the walls excluding technical space and maintenance space (e.g. machine room and storage). Although the contexts of the buildings (e.g. location and size) differ from each other, for the purpose of this study the assessments were carried out with the same methodology and accuracy. The ground floor plan and section of the buildings are shown in figure 1.

2.2 Impact assessment and system boundary

According to normative standard EN15978 (2011), the life cycle phases studied in this paper are defined as shown in table 2. GHG emission values for the material production, construction, and operational energy use of the reference buildings were calculated with the ecoinvent database V2.2. (ecoinvent centre 2010). The CML 2001 method: global warming potential 100 years (Frischknecht et al. 2007), was used to quantify GHG emissions from both fossil fuel use (fossil GHG) and biomass fuel use (biogenic GHG). From ecoinvent, European average data were applied to the assessment of module A1-3 and country average data were applied to the module A4-5 and B6.

Since the specifications of the basements differed significantly between the buildings and there were several uncertainties in the non-wooden building element (e.g. prefabrication of steel staircase), the results of the assessment for module A are limited to the wood-based building element of the buildings in order to make the results comparable.

2.3 Data collection

2.3.1 Module A1-3: Product stage

The inventory was carried out from the working drawings of the architects and structural engineers. Material losses during the construction process were taken into account. The quantity (volume) of each building component was calculated and cross-checked with the material order list provided by the constructor. The components were converted to mass using the specific density of the materials. Due to lack of information, building service equipment and furniture were excluded from the inventory, even if they were integrated into the building element. The inventories are summarized in Table 3.

2.3.2 Module A4: Transport

All information regarding the construction stage was collected by monitoring the construction works and interviewing the constructors. The transport of building components and elements was modelled according to the real case. The GHG emissions from the processes were calculated by multiplying distance (km) and mass of deliverable (ton), taking vehicle type into account. In the case of buildings A and C, most of the materials were delivered from domestic plants so that the conveyancing distance was generally less than 400km by truck. The cross-laminated timber (CLT) panels used in building C were delivered from Austria, which was a relatively longer distance. In building B, all materials were transported from locations within Finland except for the CLT, which was delivered by truck and ferry from Austria, a distance of over 2300km. The transport of the construction crew was not included due to lack of information.

2.3.3 Module A5: Construction and installation

Energy consumption during the prefabrication of the wood-based building elements in the factory and on-site assembly of the elements was monitored. For the prefabrication process, the inventory included electricity for the production line (e.g. operation of machinery, lighting and ventilation systems), space heating energy and fuel for construction machinery. For on-site work, the inventory included electricity for the operation of the construction infrastructure and equipment, and fuel for construction machinery. Data collection methods were determined on a case-by-case basis due to the different working systems adapted by the constructors. The most relevant methods were determined after discussion with the constructors. In building A, the information was collected mainly with electrical instruments installed on the construction machines in the prefabrication factory and by interviewing the constructors. In building B, a researcher was stationed on the construction site and monitored the processes everyday with the constructors. Energy consumption data from the prefabrication factory and the working time spent on the project were monitored by the prefabrication company as well. In the case of building C, a special agreement was made between the client and constructors regarding the construction schedule. Therefore, each constructor had a detailed working activities plan in advance, which helped in the collection of the relevant data by the constructors themselves. Where only aggregated data (e.g. monthly electricity consumption) was available, allocation was applied on a physical basis (e.g. production volume or the floor area of each section in the factory).

2.3.4 Module A5: Waste management

Waste from prefabrication and on-site construction work was considered based on the real case and on literature (Peurifoy and Oberlender 2002; Holm et al. 2005; Popescu 2005). Waste management methods and transportation to waste treatment facilities were taken into account based on interviews.

2.3.5 Module B6: Operational energy use

The calculation of operational energy use was based on the electricity and heating/cooling energy demand of the buildings estimated by the designers for the purpose of energy performance certification. The service life of the building was assumed to be 50 years. The aggregated annual operational energy demand is summarized in Table 1. The energy mix at each location for the year 2012 was applied to the calculation (IEA 2012).

2.4 Prefabrication and on-site construction

Although an environmental profile of different construction methods would be of interest to stakeholders from industry and government, scientific research on this topic is still limited (Quale 2012). In order to tackle this question, GHG emissions from different construction systems - prefabrication-oriented construction processes and on-site oriented construction processes - were also observed. In the case of building C, the level of prefabrication was much lower than in the other two cases, only the cutting and drilling of CLT panels and fixing metal connectors to the panels was done in the factory. In the case of buildings A and B, basically all building elements had been prefabricated in the factory. Thus an environmental profile of the different construction systems could be seen by comparison of building C with the other buildings. In addition, the different systems were studied further by using the reference building A. The original construction data of building A was regarded as an example of the prefabrication-oriented system and compared with an on-site oriented system. The possible construction duration, number of workers, the construction machines required, construction waste factors and waste management methods for the on-site oriented system were modelled based on the original data and interviews with the constructors. The waste factors for the on-site oriented system was estimated to be one and a half times as large for insulation materials and twice as large for boarding materials and ancillary materials as the waste factors for the prefabrication oriented system. It was assumed that wooden waste from the prefabrication was reused as a thermal energy source for factory space heating and the other waste was fully recycled. On the other hand 90% of plastic, 50% of steel and 90% of wood from the on-site system was assumed to be disposed of. Temporary on-site construction office and workshop ($40m^2$, $10kWh\ m^{-2}$ of electricity consumption per month) was assumed for the on-site oriented system. All these assumptions were made based on interviews with the constructors.

2.5 Uncertainty

In each case study, where certain data were not available a number of assumptions were made regarding the energy use during the construction process. This uncertainty would affect the result to some extent, although it was not estimated. However, every assumption was made based on monthly factory data, data from similar production lines or from information obtained from interviews. Thus it is expected that the associated error was not significant in this case. On the other hand, the on-site oriented construction system mentioned in section 2.4 was based entirely on assumptions. With these assumptions, although based on discussion with experienced constructors, the uncertainty in the calculation would be expected to be rather high compared to the other cases, where the assumptions were based on the real construction process.

3. Results and discussion

3.1 Dominance analysis of the module A

Figure 2 shows both the fossil and biogenic GHG emissions for each phase in module A of the reference buildings. Although the GHG emission value as such differs significantly on a case-by-case basis, similar trends between the cases can be observed. Module A1-3 accounts for 70-80% and module A4-5 for 20-30% of the total GHG emission. In addition, module A4 has a relatively high share in module A4-5, approximately 30% in the case of building A and more than 50% in the case of buildings B and C. It is remarkable that the transportation of building components results in higher GHG emission than the actual construction work, module A5, in these two cases. This result mainly stems from the long delivery distance, as mentioned before, of the CLT.

Module A5: the prefabrication and waste management process also show relevant emissions. However, as shown in the figure, the GHG emissions from those phases consist of mainly biogenic GHG. Thus, the emissions from the phases decrease significantly when biogenic GHG emission is regarded as zero based on the idea of carbon neutrality. This would be the main environmental feature of the wood-based construction process, which would also indicate the importance of module A4. Actually the dominance of module A4 increases greatly, 60-83% in module A4-5, when only fossil GHG is compared.

3.2 Share of the construction stage in a life cycle emission

Figure 3 shows GHG emissions for module A and B6 of the reference buildings as a positive number and temporal carbon storage in the buildings as a negative number. Modules A1-3, A4-5 and B6 account for 16-35%, 6-10% and 55-78% of total emission, respectively. The construction stage (A4-5), accounts for up to 10% of the total emission. Naturally this share will increase for buildings with lower operational energy demand. Since the reference buildings are not the highest energy standard buildings, this result deserves further consideration. This result will also change when the other life cycle phases (e.g. maintenance and deconstruction process) and excluded construction materials and works (e.g. foundation and building services) are included in the assessment. In addition, the transport of the construction crew to and from the construction site might have a significant influence on the result, as Cole (1999) mentioned.

All the buildings have a significant carbon storage capacity, which is an environmental benefit of wood construction. In the case of building A, carbon storage is larger than the GHG emissions from module A, and in the case of buildings B and C, it corresponds to more-or-less the same amount as the emissions from module A1-3.

3.3 Emission of different construction systems

Although there are no major differences between building C and the other two buildings with regard to the trend in GHG emissions from the construction phase, a clear gap can be seen in module A4. As shown in figure 2, the transportation of building components from factories to the construction site (G to S) results in much higher emissions than the emissions arising from the transportation of the wood products from the mill to the prefabrication factory (G to G) in the case of building C, whereas in buildings A and B the opposite is true. Figure 4 shows the difference between the prefabrication oriented system and on-site oriented system with regard to the GHG emissions for module A1-5 of building A. The differences in modules A1-3, A4 and A5: Waste management process, originate from the construction waste factors used for prefabrication and on-site construction work. The on-site construction process tends to generate more waste than prefabrication, which means more building components are required for the on-site oriented system. In module A5: Prefabrication and On-site, the prefabrication system shows slightly smaller emission than the on-site system on the basis of fossil GHG emission. This result is consistent with a previous study (Quale 2012).

In the prefabrication system, electricity for machine operation, lighting and the ventilation system was the major source of energy. But space heating energy for the factory, which was generated by a biomass boiler, also had a significant share. On the other hand, diesel for operating construction machines was the dominant energy source in the on-site system. This difference in the energy source between the systems is a notable point. The possible use of biomass fuel seems to be a positive feature of the prefabrication of wood-based building elements, since residues from the wood process can be utilized directly.

3.4 Construction greenhouse gas emissions

In module A4-5, there seems to be greater potential to mitigate GHG emission from the transport of building components and elements (A4) than in the actual construction work (A5). This tendency has been noted previously (Cole 1999). Normally loading is optimized from an economic standpoint; however, transport distance is not always in proportion to the price of a product. Thus it can sometimes happen that a product is bought from a distant country due to cheaper price, even though the same product might be available in a neighbouring city. In the construction industry, this trend seems to be more conspicuous for wooden products compared to other materials such as concrete and steel. Concrete consists of cement, aggregates and water, which are globally available. Cement is primarily consumed close to the production area because of the availability of raw materials and the high cost of transport relative to its value, particularly over land. Only 5.8% of world production is traded, with 40% of this trade between regions. In the steel market, about 30% of world production is traded. But the major proportion of trade is between neighbouring regions (Watson et al. 2005). Since these are very common construction materials, concrete and steel mills can be found in many parts of the world. Thus, secondary processing of those materials is normally carried out near to the construction site. On the other hand wood is, in general, a location dependent material because the availability of suitable wood species differs from region to region. Trade in wood-based products has been active mainly between Europe, North-America and Asia and recently the global trade volume of wood products has been growing as well. About 30% of sawn timber produced is nowadays traded. In addition, international trade in secondary processed wood products (SPWPs) is increasing rapidly (FAO 2007). For instance, about 25% of the world production of wood-based panel products are traded (FAOSTAT 2012), and this figure is likely to increase even more in the future because of increasing demand and higher profits of SPWPs to manufactures (FAO 2007). SPWPs require greater manufacturing skills than primary products (e.g. logs and sawn timber). Thus the mills for SPWPs tend to be unevenly distributed to certain regions. In this study, CLT was in fact delivered from Austria to Finland or Italy in the case of buildings B and C. As shown before, this long transport distance accounts for the major emissions in the construction stages of the buildings.

4. Conclusions

This study provided a detailed examination of GHG emissions associated with the construction process of multi-story wooden buildings relative to the other life cycle stages - the material production and operation stages. The results showed that the construction stage had a significant impact: 20-30% of the initial embodied emissions and 6-10% of the total emission of the included life cycle stages. In particular, the transport process of the wooden building components considered seemed to have higher potential to mitigate the emissions than the actual construction work. Moreover, the emissions from different construction systems were studied based on the reference buildings. Although it would be difficult to draw definitive conclusions from this study alone due to the small sample size and the assumptions made, prefabrication seems to be a more efficient construction method compared to on-site work.

Optimization of the construction stage may not have a significant effect on the overall life cycle impact of a building in some cases yet, but it would have a major impact at an industrial (aggregated) level. The environmental impact of the process should be known, to enable constructors and designers to optimise the process. The construction work is case specific and not standardised like the material production process. Further study is required to collect sufficient samples and accumulate experience for the purpose of understanding the environmental features of different construction systems.

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Figure captions

1. Basic plan and section of the reference buildings

2. Greenhouse gas emissions for module A. A1-3: Product stage, A4 G to G: Transport of building components from product factory to prefabrication factory, A4 G to S: Transport of building components from prefabrication factory to construction site, A5 Prefabrication: Prefabrication work in the factory, A5 On-site: Construction work on the site, A5 Waste: Waste management process

3. Greenhouse gas emissions for module A1-3 (Product stage), A4-5(construction stage) and B6 (Operation)

4. Comparison of the prefabrication oriented system (P) and the on-site oriented system (O) in terms of greenhouse gas emission for module A1-5 based on building A. A1-3: Product stage, A4 G to G: Transport of building components from product factory to prefabrication factory, A4 G to S: Transport of building components from prefabrication factory to construction site, A5 Prefabrication: Prefabrication work in the factory, A5 On-site: Construction work on the site, A5 Waste: Waste management process

Tables

Table 1 Basic information of the reference buildings

Name	**Location**	**Structure frame**	**Gross area (m^2)**	**Living area (m^2)**	**Floors**	**Operative energy use* (kwh m^{-2} of living area/ year)**
Building A	Germany	Sawn timber panels	726	488	5	63
Building B	Finland	Cross laminated timber	730	548	3	59
Building C	Italy	Cross laminated timber	1840	1398	5	43

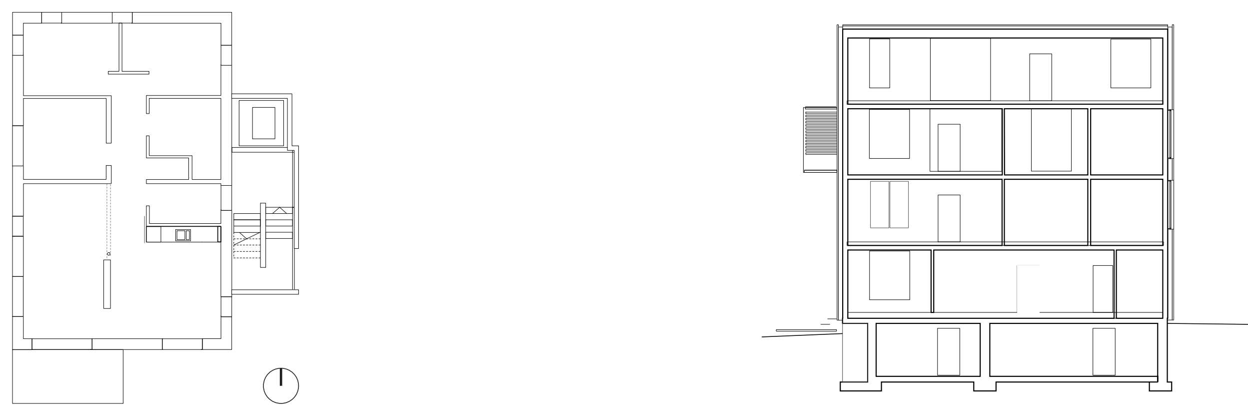
*Operative energy use is the aggregated secondary energy including electricity and space heating energy

Table 2 Included life cycle phases and its abbreviation according to EN15978

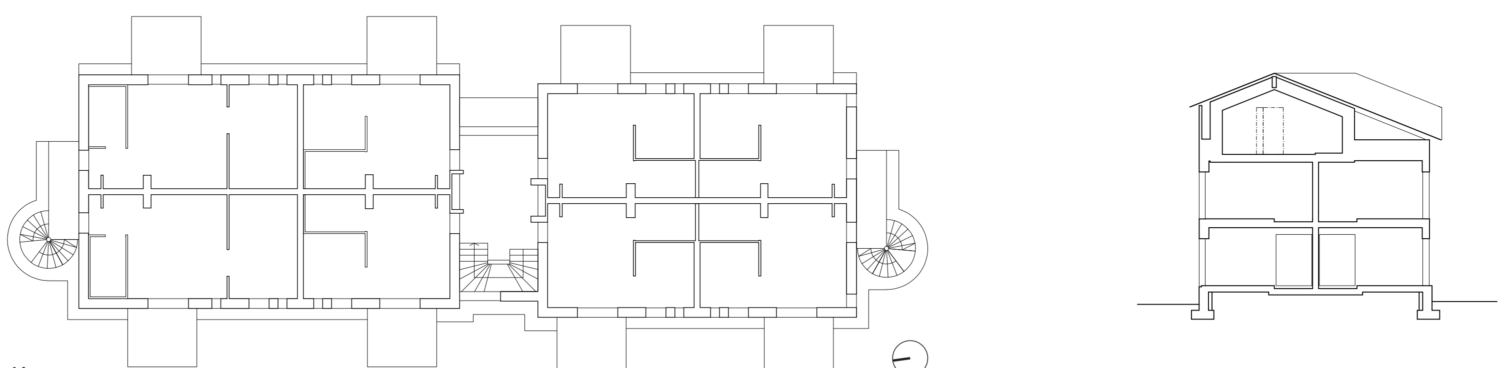
Product stage (Module A1-3)			**Construction process stage (Module A4-5)**		**Use stage (Module B)**
A1	**A2**	**A3**	**A4**	**A5**	**B6**
Raw material supply	Transport	Manufacturing	Transport	Construction and Installation	Operational energy use

Table 3 Mass of used materials in wood-based building elements (kg m^{-2} of living area)

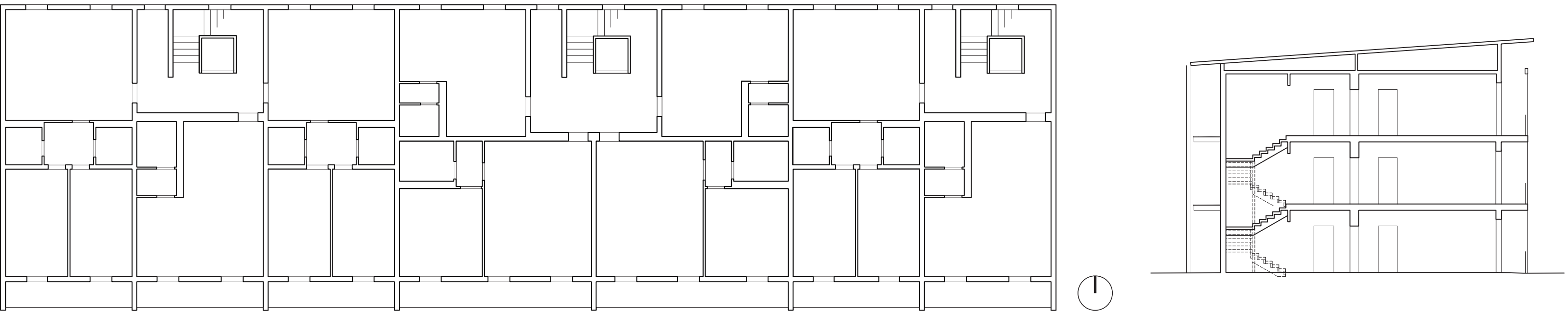
Material	**Density (kg m^{-3})**	**Building A**	**Building B**	**Building C**
Sawn timber (soft wood, MC12%)	480	133	40	19
Cross laminated timber (MC12%)	470	20	151	241
Laminated veneer lumber (MC10%)	470	16	5	2
Glulam (MC10%)	400	82	40	
Plywood (MC9%)	450		7	
OSB	615		7	
Wood fibre board	300		16	
Gypsum board	930	82	60	78
Rock wool	40	12	33	10
Cork	120			4
Cellulose fibre	40		5	
Particle board	700	8		28
Ancillary material		23	2	11
Vapour barrier sheet			0,4	
Water proof sheet		1	3	6
Cement fibre board	1700			14
Window and door		39	57	43



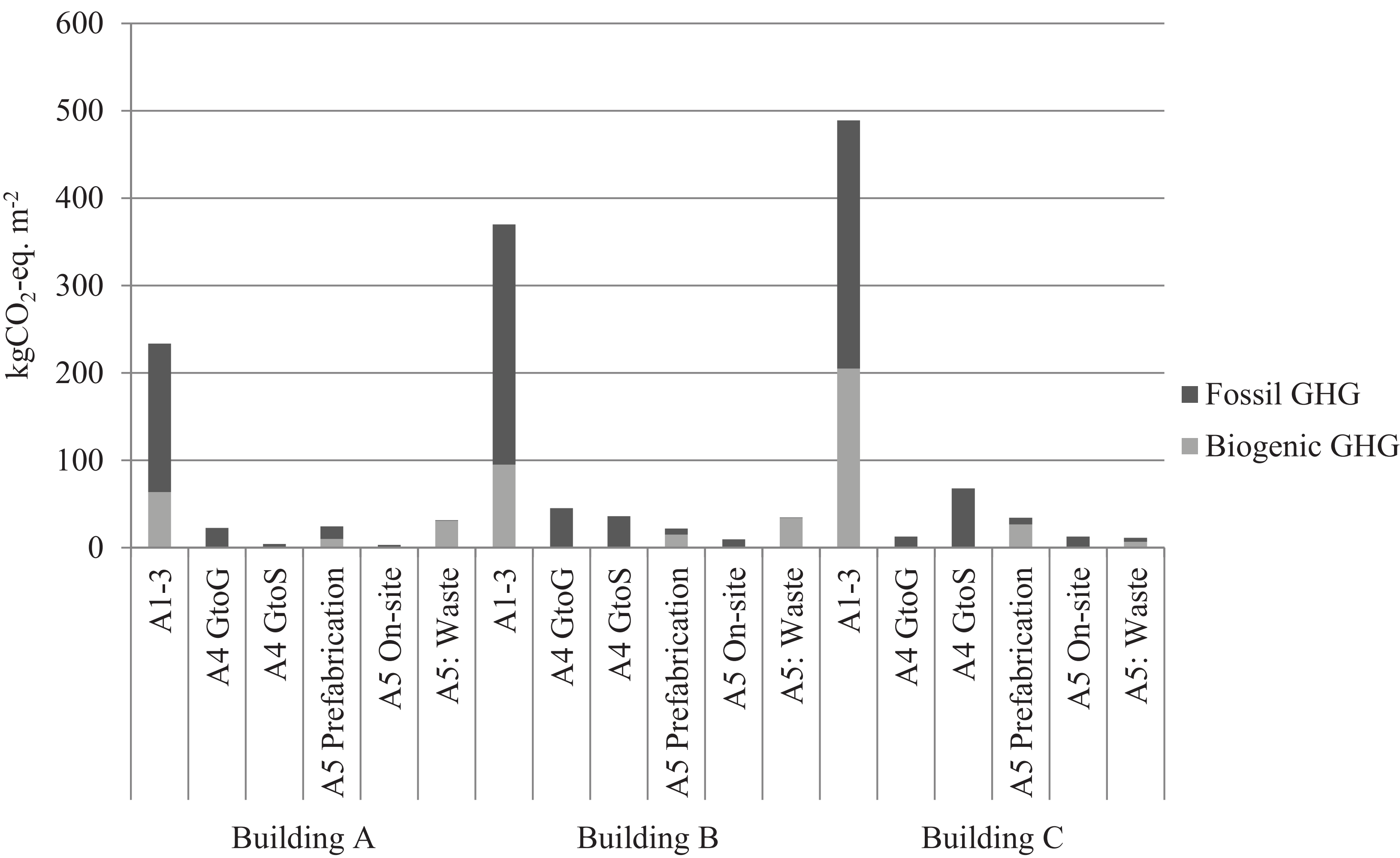
Building A



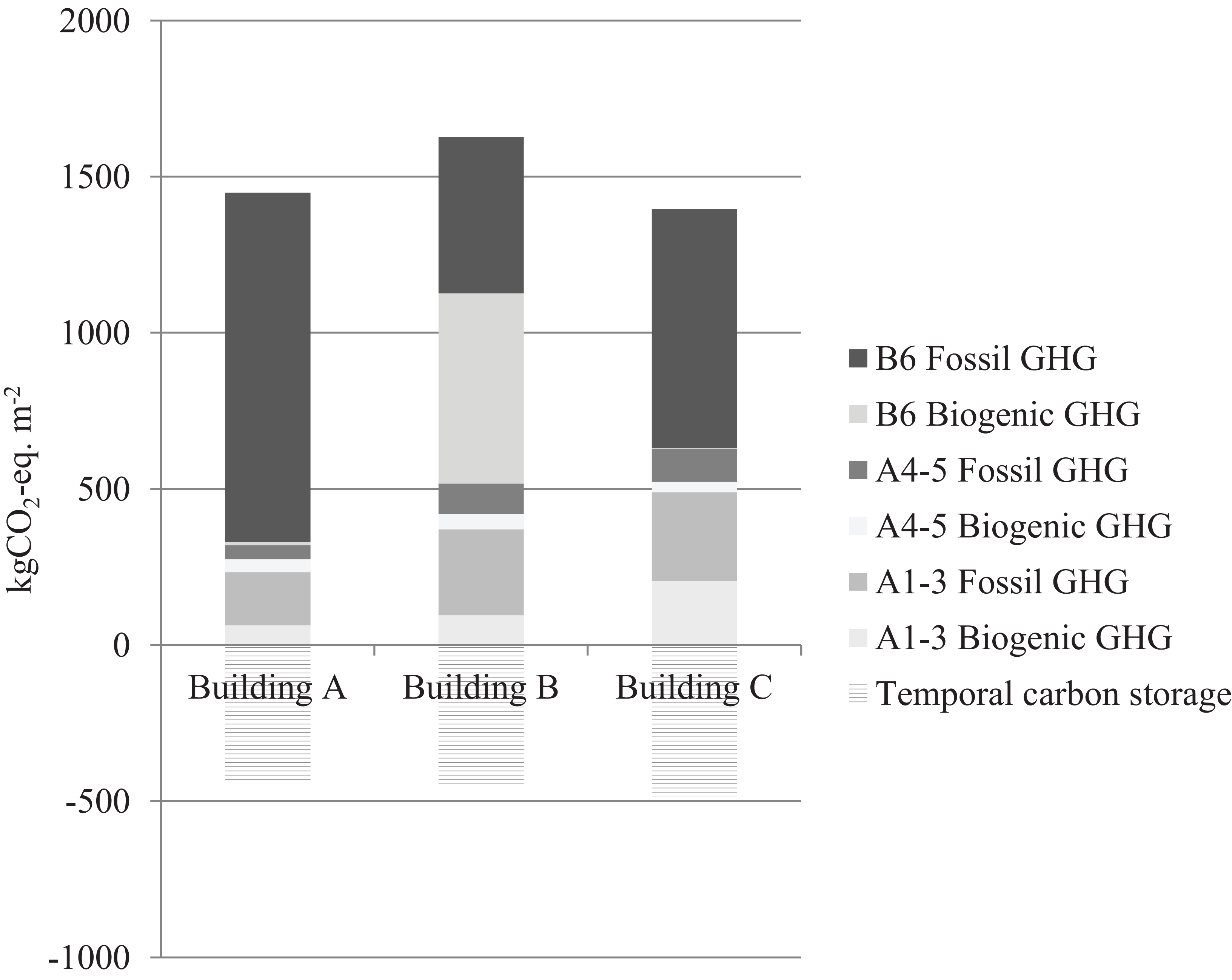
Building B

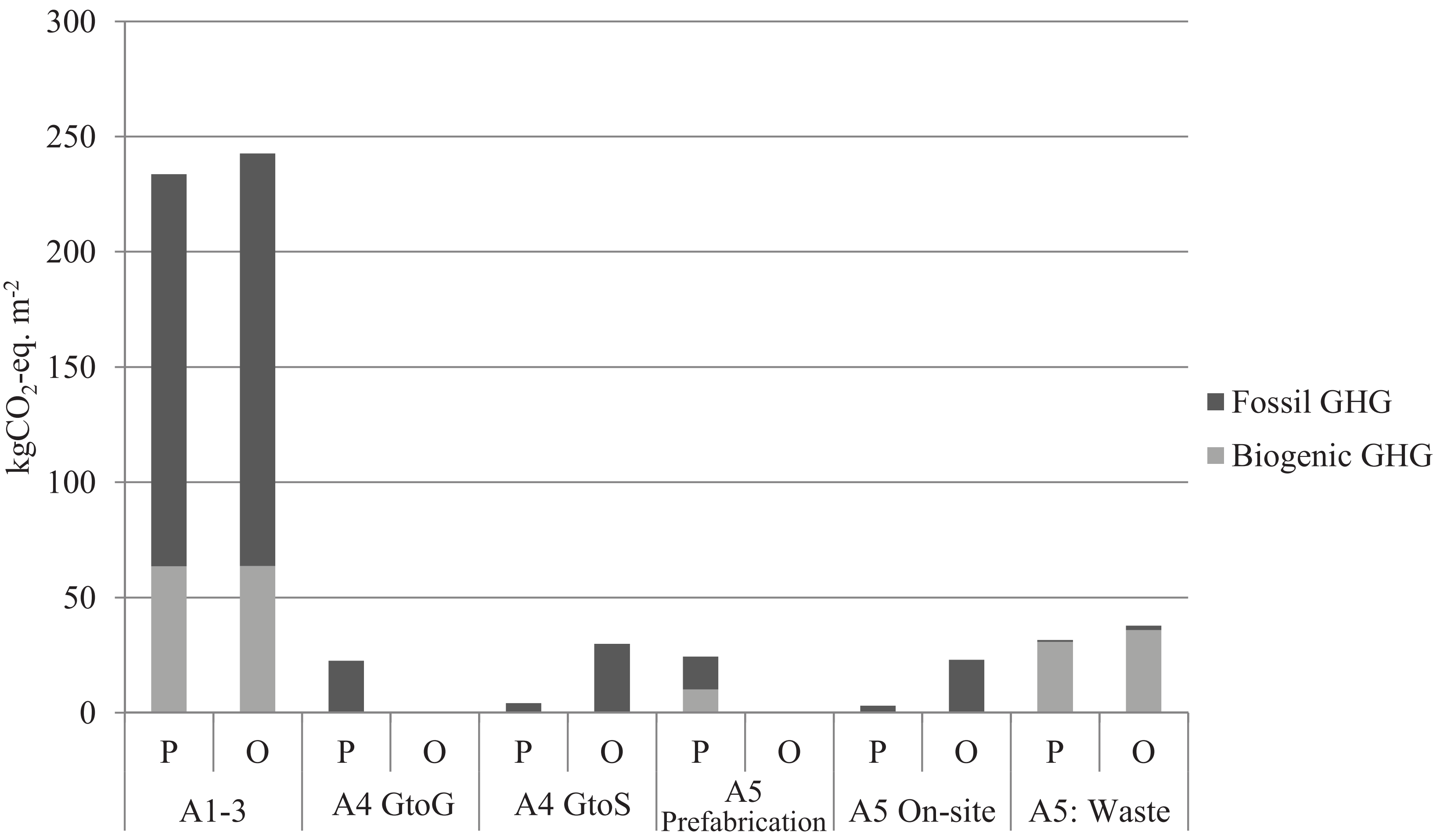


Building C



600
500
400
300
200
100
0
$kgCO_2$-eq. m^{-2}
Fossil GHG
Biogenic GHG
A1-3
A4 GtoG
A4 GtoS
A5 Prefabrication
A5 On-site
A5: Waste
Building A
Building B
Building C


2000
1500
1000
500
0
-500
-1000
kgCO2-eq. m-2
Building A
Building B
Building C
B6 Fossil GHG
B6 Biogenic GHG
A4-5 Fossil GHG
A4-5 Biogenic GHG
A1-3 Fossil GHG
A1-3 Biogenic GHG
Temporal carbon storage



300
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kgCO2-eq. m-2
P
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A1-3
A4 GtoG
A4 GtoS
A5 Prefabrication
A5 On-site
A5: Waste
Fossil GHG
Biogenic GHG