Decreasing the carbon footprint of energy efficient buildings, what comes next?

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Abstract

A full LCA was conducted to explore the contribution from each life cycle stage to the carbon footprint of energy efficient buildings, and the role of bio-based materials as future potential alternatives to decrease further carbon emissions in the building sector. Eight different design alternatives with comparable functionality were evaluated for Wälluden, a four-storey multi-family building in Växjö, Sweden. The designs include three different building systems; volumetric modules, massive timber structural elements and a column-beam structure as well as the original design of the building from 1995 both with wood and concrete frame structures. The three new designs were modelled under conventional and passive house energy efficiency categories. A square meter of living area was used as the functional unit, and a service life of one hundred years was assumed. The analysis includes processes from raw material extraction, manufacturing of building materials, construction, energy generation for the use phase, selected maintenance activities, demolition and disposal of the building waste. Concrete carbonation phenomena, carbon storage and end-use benefits from substituting fossil energy effects with wood material waste were also explored. The results show that the benefits of more use phase energy efficient designs are significant, but as the use-phase impact lowers and there is less improvement potential; both the production and end-use phase become more relevant. Indeed, for the passive house design, the production phase carbon footprint is of the same order as for a one hundred years use phase. For the production phase, increasing the share of bio-based products can decrease significantly the carbon footprint of the production phase of a building, no matter which building system is chosen. Bio-based materials have higher potential environmental benefits for the end-use phase, even as there are uncertainties over the fate of materials in future waste management systems.

Keywords: Life Cycle Assessment, Carbon Footprint, Wood Construction, Low-Emission buildings, Passive House

Introduction

Society is heavily dependent on fossil fuels, with rising concerns about environmental impacts such as climate change [IPCC, 2007]. The construction sector is responsible for a large share of society's greenhouse gas emissions. Currently, around 33% of the global greenhouse gas emissions from human activities can be attributed to the building sector [UNEP, 2007]. At the same time safe housing is a basic need for mankind, which means there is a strong need to decrease these emissions while still building enough housing for the growing world population and contributing to economic growth. All this calls for measures towards a more sustainable built environment. There has been a focus on increasing energy efficiency in buildings and eco-efficiency in the energy supply, as many previous studies have pointed to the use stage of the building as the most environmentally and energy intensive [Dodoo, 2011; Gong *et al*, 2012; Adalberth *et al*, 2001; Dixit *et al*, 2012]. This focus has led to substantial reductions of the carbon footprint of buildings, but almost exclusively in the use phase.

Life Cycle Assessment (LCA) is a well-accepted tool for analysing the environmental impact of design alternatives using a life-cycle perspective [Baitz et al, 2013; Guinée et al, 2011]. It provides a fair idea of the environmental impacts related to each life cycle stage of a building, which is often used to identify the environmental "hot spots" of a product's life cycle. One of the environmental impacts that can be analysed is climate change, for which carbon footprint serves as an indicator. Even as there is no universally accepted definition of "Carbon Footprint", it can be defined as the total amount of greenhouse gas emissions of a defined population, system or activity; considering all relevant sources, sinks and storage within the spatial and temporal boundary [Williams et al, 2011].

Objective

Increasing the energy efficiency of buildings is a key aspect in the shift towards a more sustainable building sector. Nevertheless, if the trend towards more energy efficient buildings continues, the operational energy stage will stop being the low-hanging fruit at some point. The purpose of the work described in this paper is to explore in a practical case study the contribution from other life cycle stages to the carbon footprint from energy efficient buildings, and the role of bio-based materials as future potential alternatives to decrease carbon emissions in the building sector.

Methodology

LCA was used to analyse the potential environmental impact from different design alternatives with comparable functionality for Wälluden, a four-storey multi-family building constructed in 1996 in Växjö, Sweden. There are sixteen apartments in the building, with a total of 1190m^2 of heated area and 928 m^2 of living area. The software SimaPro developed by Pré Consultants was used to assess the fossil carbon footprint of each building design through its life cycle, following the Greenhouse gas protocol method [WRI, 2011]. ISO standards were followed for LCA methodology [ISO, 2006].

The building has been re-designed to meet the current building code [Boverket, 2012], but using three different wood-based building systems. Each of these designs was modelled to comply with both the conventional and the passive house energy efficiency standard [Sveriges Centrum för Nollenergihus, 2012]. The analysis includes also an alternative design of the original building with a concrete structure and wood frame in-fill exterior walls, which was obtained from a study performed by Lund Institute of Technology [Persson, 1998]. The number of floors, apartment area (except for the modular system) and architectural details are the same for all the designs. The passive house designs have enhanced air tightness and include efficient water taps, but in general all the designs provide comparable functionality in terms of housing. Further details for the assessed designs are described in SP's research report 2013:07 [Peñaloza et al, 2013].

System description

The scope of the LCA is cradle-to-grave, including the raw material extraction and material production processes, construction, heat and electricity production and supply for the use phase, demolition and end-of-life scenarios. A square meter of living area was assumed as the functional unit. The analysis includes processes from raw material extraction, manufacturing of building materials, construction activities, energy production for the use phase, selected maintenance activities, demolition activities and disposal of the building waste. A service life of one hundred years was assumed for all the designs. An outline of the system process flowchart can be seen in figure 1.

The inventory data used to model the system was obtained from different sources. The production of wood materials was modelled using EPDs inventoried by SP (formerly as Trätek) with the Swedish wood industry. For other materials, external EPDs, literature data [Björklund and Tillman, 1997; IISI, 2001] and existing databases such as Ecoinvent and ELCD were used. Data from the Björklund and Tillman study was used to model the construction and demolition activities. The use stage energy requirements were modelled using the VIP+ dynamic simulation software and environmental data reported by Växjö Energi AB, the local energy supplier.

The effects from concrete carbonation phenomena were also included in the analysis, since when exposed to oxygen, concrete re-absorbs part of the carbon dioxide emitted during the calcination process in production of cement. In order to calculate the amount of carbon dioxide absorbed during the use phase of the building, a methodology developed by the Swedish Cement and Concrete Research Institute – CBI was used [Lagerblad, 2005]. This method calculates the absorbed carbon dioxide as a function of the exposed concrete surface, the time of exposure and a correction factor which depends on the kind of environment that the concrete is exposed to, the quality of the concrete and the kind of surface protection in the concrete.

There are big uncertainties for modelling the end-use stage of products with long life spans such as buildings [Sandin, 2013]. These questions may be out of the scope of this study, but are also an obstacle for having a holistic view of the carbon footprint of wooden buildings. The system model for the end-use stage of the building includes only treatment processes and their environmental impact. However, the environmental benefits from these processes have not been accounted for. Only Ecoinvent data was used to model the waste treatment processes, which represents modern European technology. It was assumed that 70% of the waste is recycled or reused and the remaining waste goes to treatment processes. Nevertheless, 90% of the wood waste was assumed to be reused for energy production. For the analysis of future waste scenarios, the differences between the concrete and wood frame alternatives are of most interest for this study. These carbon implications are explored in an additional module.

It is assumed that the demand for renewable energy will increase in the future, so the wood waste in the building will be used for energy production. Here, a substitution effect is applied, as it is assumed that the energy produced from the wood waste will replace fossil fuels. The total energy potential of the wood waste after the building demolition was calculated assuming a 90% recovery rate of the wood (as explained in the previous section) and an 18,6 MJ/kg dry energy content. The environmental burden from producing this amount of energy from coal, oil and natural gas was modelled using Ecoinvent data. The storage of carbon dioxide in wood products was also calculated assuming a carbon dioxide uptake of 1,87 kg per kilogram of dry mass in the wood and a moisture content of 15%. Rather than accounting them as part of the carbon footprint, these values are calculated to illustrate the possibility of potential additional benefits from the temporal storage of carbon in the building.

Limitations of the analysis

The main limitations for the study are related to assumptions, especially those regarding future energy systems and future end-of-life waste scenarios. These limitations are enhanced by the fact that buildings have such a long life span and long-term future scenarios are more difficult to define. The assumption of the life span of the building also presents a challenge, which was defined as one hundred years. The implications of the life span assumptions were not further explored. The processes excluded from the analysis are summarized in table 1.

Sensitivity analysis

The sensitivity of the results to the choice of the data for the heat supply in the use phase was analysed. For this, a Swedish average mix for heat production was used instead of site-specific data for Växjö, in order to explore the impact of background energy systems in the results.

Results

The results for the greenhouse effect impact category are displayed in figures 2 and 3. The contribution from different kinds of materials to the total carbon footprint of the production phase can be observed in figure 2. The materials were grouped and aggregated to simplify the figure. Furthermore, all bio-based materials are included as part of the “Wood and wood materials” group.

Meanwhile, figure 3 shows the carbon footprint for the whole life cycle of each of the analysed designs. The results are distributed per life cycle stage, a distribution which is aligned with the module division in the EN 15978 standard [CEN, 2011]. The results displayed under “Module D” correspond to the environmental benefits from the end-of-life scenario in which all the bio-based products are incinerated to produce energy, and this energy replaces energy from coal described in the previous section.

The results of the sensitivity analysis are displayed in Figure 4. The figure shows the carbon footprint from the use phase for each design alternative, both modelled using local data and the Swedish average. For every design alternative, the carbon footprint was around 30% higher if modelled with a Swedish average.

Discussion

It is noticeable in figure 3 that for the conventional building designs most of the greenhouse gas emissions occur during the operation phase, more specifically from the operational energy use of the building. The key aspect that influences the greenhouse gas emissions from the operation phase is the energy efficiency category for which the building is designed. This means that with more strict energy efficiency requirements for buildings, other stages shall become more influential to the total carbon footprint of the building. For these other stages, the role of wood is more important and using wood materials brings higher potential for decreasing greenhouse gas emissions. It can be observed in the same figure that the shift to more energy-efficient designs makes the operation phase less dominant.

It can be observed in the results that the shift to a more energy efficient passive house design has a very small carbon cost in the production phase. Going from a standard design to a passive house design implies a rise of about 3% of the carbon footprint in the production phase, but at the same time reduces around 50% the carbon footprint in the operation stage. Other studies have reached similar conclusions [Erlandsson et al, 1997; Mazor et al, 2011].

The energy supply system influences greatly the carbon footprint from the use stage. This was confirmed in the sensitivity analysis, where using an average country mix instead of local data caused a 30% difference in the results. This difference in the operational use stage is quite important, as it is the major contributor to the total carbon footprint. The use phase maintenance activities do not largely influence the carbon footprint in the use stage, being only around 20% of the greenhouse gas emissions from the production phase and 5% of the emissions from the operational energy use. The carbon emissions from these activities were very similar for every design, which means that the use of wood in the building structure has little influence in this life cycle stage. On the other hand, the use stage maintenance activities are surrounded by big uncertainties and subjective assumptions as it is influenced by many other factors than the durability of the materials used such as customer behaviour, the real service life of the building or good practices during the construction activities. This is why further research is needed to analyse the environmental impacts of this stage.

By only having a passive house design decreases greatly the greenhouse gas emissions in the use stage. For such a design, the background processes for energy production have the biggest influence in the results. These processes are beyond a designer's control, which means that for decreasing further greenhouse gas emissions after changing to energy efficient buildings, designers must look at other life cycle stages.

Looking at the production phase in figure 2, there is almost a 60% increase in the carbon footprint from the production of a concrete-design building. It should also be noted that the concrete design analysed in this study contains wood-frame in-fill exterior walls, which means that this difference would increase with steel stud in-fill walls or concrete sandwich panel walls that are increasingly used today. The difference between different building systems for wood construction is minimal, with the column-beam system being the one with a higher carbon footprint. This is mainly because the column-beam design modelled in this study includes more concrete than the others for the elevator-stairs structure and in the ground slab.

Wood materials account for around 10% of the total carbon footprint of the production phase, while their share of the total material mass in the building is higher, but this differs for each building system. Figure 2 shows that mineral-based materials such as concrete, gypsum board, mineral insulation and glass contribute most to the total carbon footprint of the production phase. As an example, the mineral insulation accounts for only 1,5% of the total material mass but for 15-20% of the carbon footprint depending on building system and energy efficiency category.

The re-absorption of carbon dioxide by the concrete during the operational stage via carbonation processes can be regarded as relatively small, as it is only around 26% of the carbon dioxide emissions of the calcination emissions during concrete production and 13% of the total emissions from concrete production. The main reason for this low value is the fact that only the concrete surfaces which are exposed to air can absorb carbon dioxide, meaning that in most of the surfaces in the building carbonation cannot be expected to take place.

Since buildings are long-lasting products and their service life might go as long as one hundred years or more, the end of life stage is full of uncertainties regarding the prediction of future systems. Modelling of waste management systems for building materials is one challenge, as it is not clear whether the materials will be recycled, reused or used for energy production; or if the current technologies and the inventory data available for them are representative of the processes that will take place. Moreover, for scenarios where waste is used to produce energy, it is unclear what kind of energy system will be replaced, and what will be the marginal change in these systems.

For the scenarios modelled in this study, the greenhouse gas emissions from the disposal processes of the building materials are fairly similar among all the designs analysed. However, the environmental benefits beyond the system boundaries are more of interest, as the structural elements system design (which use more wood materials) represent almost twice the benefits compared to the concrete design. In this case, the bioenergy potential in the end of life was assumed to substitute energy from coal, representing the worst case scenario. Whatever the case, there is for sure more renewable energy stored in wooden buildings, which will be available at the end of life no matter which energy system it substitutes. This means that the potential carbon benefits beyond the end of life is higher for wood constructions.

Finally, the amount of carbon stored temporally in the building is visibly higher for all the wood-based designs. Since this amount does not represent a tangible carbon flow, it should not be compared with the actual emissions from the life cycle stages. There are methodologies to quantify the climate benefits from this temporal storage proposed in existing and coming standards which have not been applied in this study, but result in a negative carbon value in the use phase [BSI, 2011].

Conclusions

For more energy efficient building designs or buildings supplied from energy systems with lower carbon footprint, the production and end of life stages are highly relevant. Thus, the potential relative carbon footprint reduction from using more wood in the design is high. The operational stage results dominate the carbon footprint due to the operational energy supply, and the use of wood materials in the design and the choice of building system do not influence this outcome significantly. It is mostly influenced by the energy efficiency standard followed and the energy supply system modelled in the use phase. Moreover, the results show that the additional emissions in the production phase caused from the shift from the standard to the passive house design are quite low, compared with the reduction of the emissions in the operational stage.

The use of wood and bio-based materials can significantly decrease further the carbon footprint of energy-efficient buildings. This potential can be seen in the production stage, the construction activities and the end-of-life stage. Furthermore, buildings with a higher content of wood materials have higher potential environmental benefits beyond the end-of-life from using them for energy recovery. Lastly, an additional benefit of increased use of wood in building structures is the long-term temporal storage of CO_2 in the built-in wood products, which has an effect on climate change. The choice of wood building system does not seem to have a major influence in the carbon footprint of the building.

Finally, mineral-based and fossil-based materials contribute more to the carbon footprint of the production phase than wood and bio-based materials even in the wood structure buildings. Materials such as gypsum board, concrete and mineral wool present higher contributions to the carbon footprint of the production phase for every design; which means they present the highest potential for lowering further the carbon emissions from production, either by substitution or process optimization.

Figures and tables

Figure 1 Outline of the system boundaries for the analysis

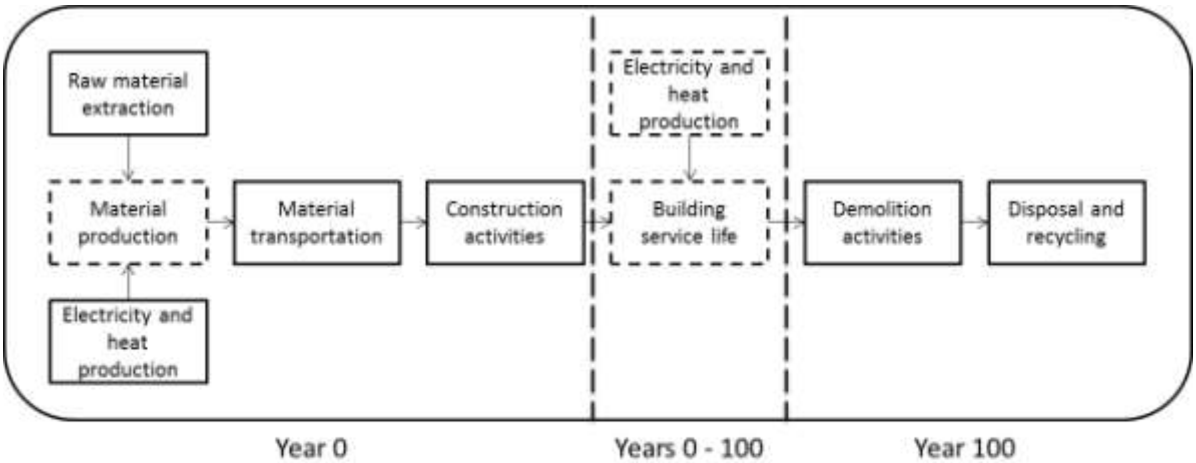

Figure 2 Greenhouse effect for the production phase of the eight design alternatives, measured in kg CO2 equivalents per m2 of living area.

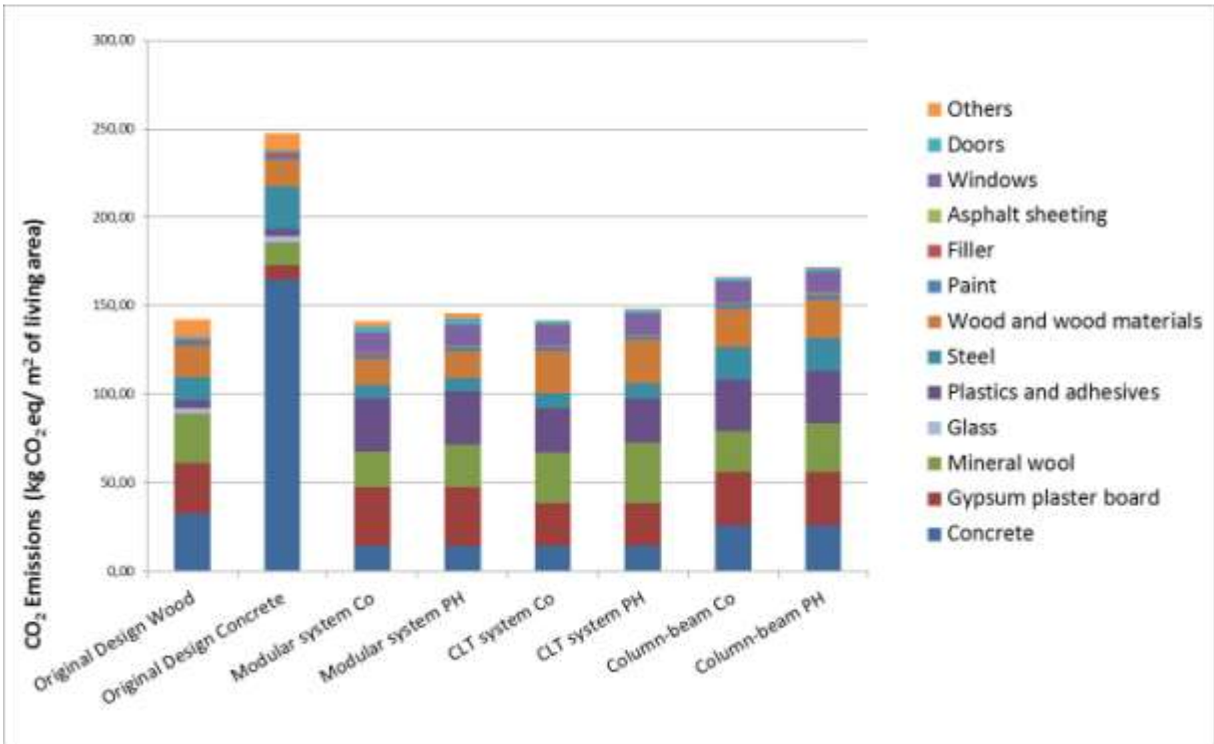

Figure 3 Greenhouse effect for the whole life cycle of the eight design alternatives, measured in kg CO_2 equivalents per m^2 of living area and calculated using the Greenhouse Gas Protocol

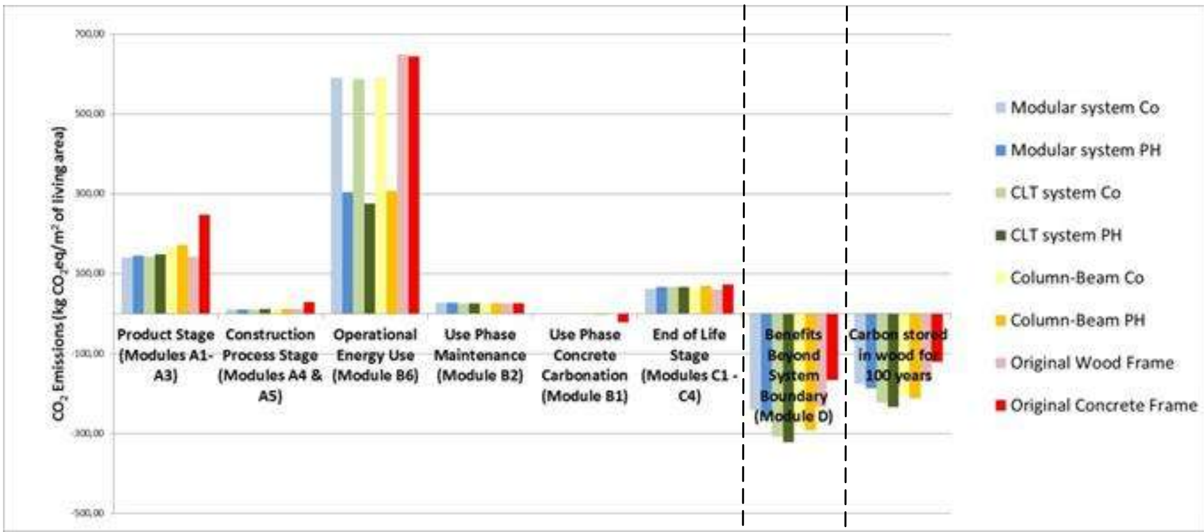

Figure 4 Results from the sensitivity analysis, greenhouse gas emissions from the use phase operational energy using local data and a Swedish supply mix for heat production

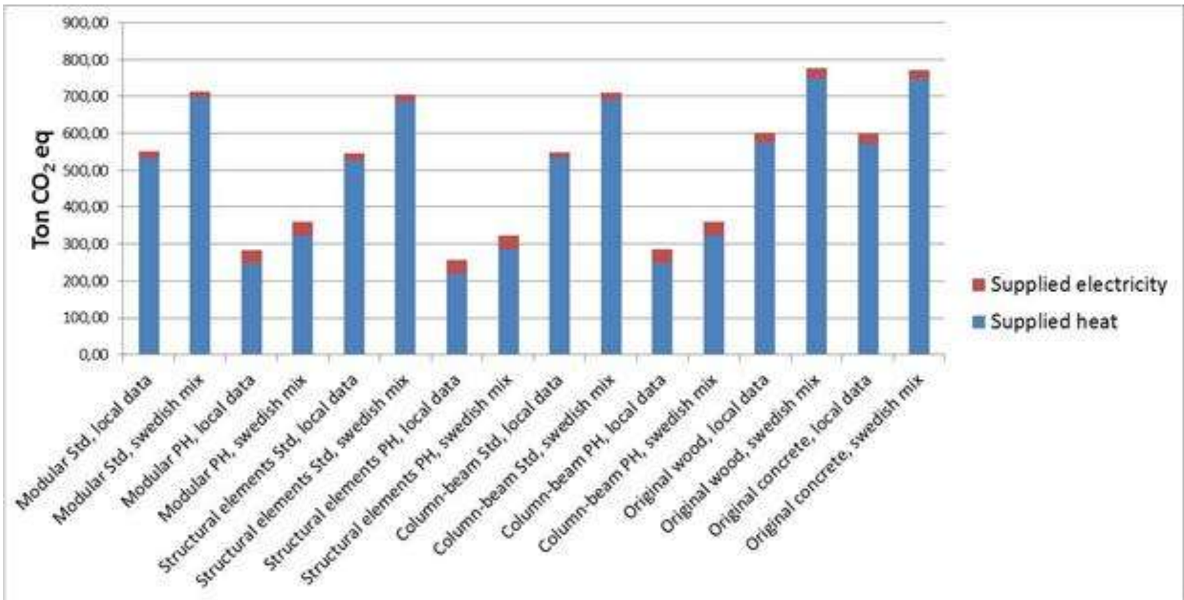

Table 1 Summary of the processes excluded from the analysis

Life cycle stage	Excluded processes
Production phase	Hydro sanitary equipment and system, such as water pumps, pipes and tanks. Elevator and elevator motor. White goods for laundry areas and kitchen. Domestic electronic equipment such as TV-sets, computer, etc. Electric equipment such as transformers and electric station. Lighting equipment. Domestic furniture, such as kitchen cabinets, closets, living room furniture, beds and tables.
Construction phase	Ground works and landscaping. Storage of products and provision of heating. Transport of materials within the site. Temporary works. Water use for cooling of construction machinery. Temporary facilities for personnel.
Use phase	Repairing and refurbishing activities. Operational water use.
End-use phase	Waste separation or transport to sorting stations.

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Glossary

LCA	Life Cycle Assessment
ISO	International Organisation for Standardization
EPD	Environmental Product Declarations
SP	Technical Research Institute of Sweden

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