EMBODIED ENERGY AND CO_2 EMISSION OF WOOD- AND CONCRETE-FRAMED BUILDINGS IN SWEDEN

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ABSTRACT: We studied the contribution of embodied energy of building materials to overall carbon dioxide (CO_2) balance of wood- and concrete-framed buildings. Using data from three European process analyses, we compared embodied energy values of lumber and concrete materials, and of the total materials comprising a wood-framed and concrete-framed apartment building. We estimated the net CO_2 emission resulting from this embodied energy based on fuel-cycle carbon emission of the fossil fuels used. To place this emission in the context of the overall CO_2 balance of the buildings, we estimated the net emissions from cement process reactions, carbon stock in the buildings, the potential to replace fossil fuel with biomass residues, and emission from landfilled demolition wastes.
Keywords: embodied energy, CO_2 balance, construction material

1 INTRODUCTION

Efforts are ongoing in Sweden to reduce the usage of fossil fuels, and hence the net emission of carbon dioxide (CO_2). Choice of materials in the building construction sector may contribute to such a reduction. Various studies have recognized the low embodied energy of wood products, and some have suggested that building with wood results in lower net CO_2 emission than with other materials such as concrete or steel. Beyond establishing a link between energy use in material manufacture and CO_2 emission, few studies have examined the net CO_2 emission from building material production from a system-wide perspective. The purpose of this study is to gain insight into the significance of material embodied energy to overall net CO_2 emission from construction of wood- and concrete-framed buildings, considering all significant carbon fluxes.

Various factors determine the overall CO_2 balance of a building material or system. One important factor is the embodied energy of the materials, which is the focus of this paper and is discussed in Section 2. Other important factors include the characteristics of the systems that supply the required energy, carbon fluxes inherent to product manufacturing processes, the potential to replace fossil fuel by wood residues, and emission dynamics from biomass decomposition. These are discussed in Section 3, to provide a context for analyses of CO_2 emission due to embodied energy of construction materials.

2 EMBODIED ENERGY OF MATERIALS

A general definitions of embodied energy is the total energy used to produce a product, including the energy required to extract, transport and process material inputs. Pears [1] has pointed out the inappropriateness of assigning a single "correct" number for the embodied energy of a building material, and discussed the possible causes of variation in material embodied energy. These include technological differences between industrial processes, so that identical material can be produced in various ways, each with a different energy requirement. Geographic variation exists between regions, due to differences in raw material availability and local traditions. The diffusion of new technology also adds temporal variation to the embodied energy of a building material.

2.1 Measuring embodied energy

Various approaches to measure embodied energy employ different system boundaries and collect data from different sources, which could result in significantly different values of embodied energy for the same product. System boundaries may range from a restrictive analysis of direct energy required for a particular process, to an expansive analysis including energy used by entire industrial input chains and society as a whole. Analyses may consider only purchased fossil fuel energy inputs, or may include renewable sources or combustible process by-products. Data may be direct measurements of energy used by a particular machine or factory, or may be aggregated for an entire industrial sector.

A common method to analyze embodied energy is the *process* analysis. This method begins with the final production process and works backward to determine the energy need of each contributing material or energy input. As the analysis expands to include the energy consumed by higher order indirect inputs, the contribution of additional factors becomes less significant and more cumbersome to determine. System boundaries of the analysis are drawn at an appropriate level, beyond which the energy use is ignored. While giving detailed information on the particular process studied, this method allows truncation error outside of the system boundaries.

In *input-output* analyses, macro-economic data are used on monetary transactions between entire industrial sectors, including flows of commercial energy. Data on energy use by particular industries are coupled with information on physical production, yielding approximate figures of the embodied energy of the materials produced. Truncation error is avoided because contributions from the entire economy are considered, by definition accounting for 100% of commercial energy use. However, this method has very limited detail of particular processes because the data are highly aggregated. It does not account for non-commercial energy sources such as biomass residue used internally in wood production processes, and this method is not further discussed here.

A *hybrid* analysis attempts to utilize the strengths of both process and input-output methods. It begins with a process analysis of the energy consumption and material inputs of a particular production process. Instead of truncating the analysis at a certain point, however, aggregated data from an input-output calculation are substituted for higher-order inputs.

2.2 Comparison of three process analyses

Three European studies of energy use in building material production were compared in this study: Worrell et al. from the Netherlands, Fossdal from Norway, and Björklund et al. from Sweden [2, 3, 4]. Hereafter these studies will be referred to simply by the primary authors' names. We used specific energy use data from these studies to estimate the total primary energy used, and fossil CO_2 emitted, in manufacturing materials for construction of wood-framed and concrete-framed versions of a multi-story apartment building. Our calculations are based on materials lists for the Wälludden building, a 4-story structure built in Sweden containing 16 apartments and a usable floor area of 1190 m^2. The original building was constructed with a wooden structural frame, and calculations have been made of the materials needed to make a functionally equivalent building with a concrete frame [5].

We based initial computations on the Fossdal study because it includes data on almost all the materials comprising the case study building. Details of assumptions and results of this calculation are described by Gustavsson et al. [6]. The eight materials contributing most to the total energy use were then identified: concrete, plasterboard, insulation, steel, plastic, lumber, plywood, and particleboard. These eight materials used 85% and 88% of the total primary energy for production of materials for the wood- and concrete-framed versions, respectively.

Embodied energy data for these eight materials were then tabulated from the other two studies, Worrell and Björklund. Data on plasterboard, insulation and plastic were lacking in one study, and in those cases data from the other two studies were averaged and used in place of the missing data. Due to incomplete data on plywood, we assumed plywood manufacture to use 15% more electricity and 90% more end-use fossil and biomass fuel than particleboard [7]. Two of the studies broke down fossil fuel use into coal, oil, and natural gas fuels. The other study (Fossdal) included all fossil fuel together as a single category, and we disaggregated this category assuming the same average proportional breakdown of different fossil fuel used in the other two studies. We assumed Worrell's category of "transport energy" to use petroleum as fuel.

Using these data from Fossdal, Worrell and Björklund for the eight most energy intensive materials in the building, and data from Fossdal for the remaining materials, we produced three data sets for embodied primary energy of the case study building. These are summarized in Figure 1. Electricity was assumed to come from coal-fired condensing plants with a conversion efficiency of 40% and distribution loss of 2%. In all the studies the concrete-framed building materials used more primary energy than those of the wood-framed building. Significant differences between the studies include the energy use in steel production (ore-based or scrap-based) and the use of biofuels for drying of wood products.

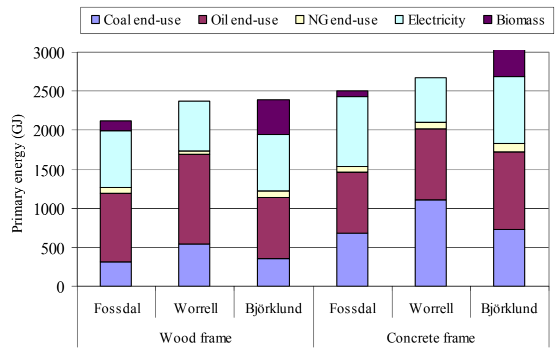

Figure 1. Primary energy needed for production of construction materials for wood-framed and concrete-framed versions of the case-study building, using specific energy use data from three European studies.

2.3 Truncation error of process analyses

As discussed above, process analyses suffer from truncation error of higher order energy requirements. Depending on the purpose of the study, if the truncation error in process analyses were the same for all materials it could be either ignored, or compensated for by increasing the calculated embodied energy of all materials by a certain percentage. However, higher order energy consumption may be proportionally higher for natural materials like wood than for other materials that require more intense processing [2]. The more energy needed for direct processing of raw materials into a usable product, the less significant may be the contribution of indirect energy use such as transportation and equipment upkeep. It has been estimated [8] that second order process analyses of metal and cement industries have 80% system completeness, i.e. a truncation error of 20%. Analyses of agricultural industry, here assumed to represent the forestry sector, may have truncation error as high as 50%. As a simplified illustration of the impact that such truncation error could introduce, we increased the specific embodied energy of the wood-based materials by 50%, and the other building materials by 20%. Total primary fossil energy demand for the wood-frame building increased 33% from 2.1 TJ to 2.8 TJ, and that for the concrete-frame building increased 31% from 2.6 TJ to 3.4 TJ.

2.4 Absolute vs. relative embodied energy

Given that a building is to be constructed, the relative embodied energies of different materials can be used to compare materials that fulfill the same function. Information on relative embodied energy of alternative materials may assist the designer in creating a building with satisfactory function and low total embodied energy. We compared the embodied energies of lumber and concrete in the three studies, and calculated the lumber/concrete ratios (Table I). We did not include feedstock heat value of the lumber in its embodied energy. Substantial variation exists between the lumber embodied energy reported in the three studies, with the largest being 58% greater than the smallest. Similarly, a 53% difference in concrete embodied energy exists between the three studies. However, we found that the ratios of the lumber and concrete embodied energies show a smaller difference, with the largest being 7% greater than the smallest. Thus, although results of absolute embodied energy vary depending on the assumptions and methodologies of a particular study, the embodied energy values of different materials can be quite consistently compared within a given study when analyzed using consistent assumptions and methodology.

Table I. Specific primary energy use for production of lumber and concrete, and ratio of lumber/concrete energy use, based on three European studies.

Source	Lumber (MJ/kg)	Concrete (MJ/kg)	Ratio (L/C)
Fossdal	3.8	0.82	4.6
Worrell	2.7	0.57	4.8
Björklund	4.3	0.87	4.9

A simple ratio of the embodied energies of two building materials, for example the wood/concrete ratio, is however of limited use. Buildings are composed of many different materials, not just wood and concrete. The question remains of adequately expressing the functional unit of the building materials, because one kg of concrete does not provide the same service as one kg of wood. Furthermore, because embodied energy is but one of several factors that determine the net CO_2 balance of building materials, it is necessary to consider embodied energy-related emissions within the context of the overall CO_2 balance of a material.

2.5 CO_2 emission from embodied energy

The use of fossil fuels to provide the energy embodied in construction material results in net CO_2 emission. Figure 2 shows CO_2 emissions based on primary energy use shown in Figure 1 and fuel-cycle specific carbon emission values of 30 kg C/GJ coal, 22 kg C/MJ oil, and 18 kg C/MJ natural gas. Emissions based on the different embodied energy studies range from 51.3 to 61.5 t C for the wood-framed building and 65.8 to 72.0 t C for the concrete-framed building. The average CO_2 emission is 54.9 t C and 69.6 t C for the wood- and concrete-framed buildings, respectively.

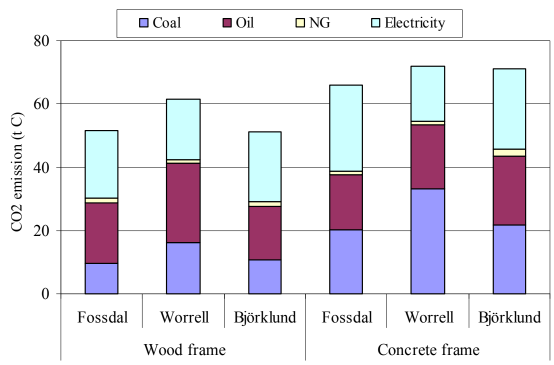

Figure 2: CO_2 emission from production of construction materials for wood-framed and concrete-framed versions of the case-study building, using specific energy use data from three European studies. Emissions from fuel combustion account for full fuel cycle of energy carriers. Emission from electricity is based on coal fuel.

2.6 Energy supply system

CO_2 emission from an industrial process depends on the carbon intensity of the fuels used and the efficiency of conversion of energy to its form of final use. Different fossil fuels emit different amounts of CO_2 per unit of heat released in combustion. Differences in energy conversion and distribution efficiencies mean that more fuel may need to be burned to provide the same end-use service. The above calculations assumed the electricity used in material production was generated in a coal-fired condensing plant. If the electricity were instead generated in a natural gas-fired plant with a conversion efficiency of 50%, the CO_2 emission would decrease by 10.9 t C (20%) and 12.0 t C (17%) for the wood- and concrete-framed building, respectively.

3 CO_2 BALANCE OF MATERIALS

Besides embodied energy there are several other factors that determine the net CO_2 emission of building material production. In this section we examine these other factors, and compare their impacts on CO_2 balance to that of embodied energy. Our reference in these comparisons is based on average specific energy use data from the Fossdal, Worrell and Björklund studies, assuming coal is used for electricity generation. The results are summarized in Table II and described below.

3.1 Emission from cement manufacture

CO_2 is emitted during cement manufacture due to the chemical reaction of calcination of limestone during clinker production. Normal Portland cement contains 95% clinker, and emits 0.136 t C per ton of cement produced [9]. For the buildings considered in this study this corresponds to 4.3 t C (8%) and 22.7 t C (33%) for the wood- and concrete-framed versions, respectively. This emission can be reduced by blending the clinker with other ingredients such as fly ash, pozzolan or blast furnace slag to reduce CO_2 reaction emission per unit of cement produced. In addition, part of the CO_2 emitted during clinker calcination will be re-fixed over time due to carbonation reaction in the concrete matrix.

3.2 Fossil fuel substitution by wood residues

Biomass byproducts from the manufacture and use of wood-based materials, such as logging and sawmill residues and wood demolition waste, can substitute for fossil fuels and result in lower net CO_2 emission. While biofuels are not completely carbon-neutral because of fossil fuel used for biofuel recovery and transportation, they result in substantially lower net CO_2 emission compared to the use of fossil fuels. Logging residues include branches, foliage and tree tops left over from the harvest of sawlogs. If 70% of logging residues resulting

Table II: CO_2 emissions from various sources, expressed in tonnes C and as percentage of fossil fuel emission from embodied energy of building materials of wood- and concrete-framed versions of case-study building.

Source	Emission (t C)	% of Reference	Emission (t C)	% of Reference
Fossil emission from reference embodied energy	54.9	100%	69.6	100%
Carbon emission from cement chemical reactions	4.3	8%	22.7	33%
Logging residues substituting coal	-16.3	30%	-10.5	15%
Sawmill residues substituting coal	-30.1	55%	-17.6	25%
Demolition material substituting coal	-39.5	72%	-27.7	40%
Net emission from landfilled wood (CO_2 equiv)	43.5	63%	30.5	56%

from the production of the wood-based materials used in the wood- and concrete-framed building were recovered and used in place of coal, 16.3 t C (30%) and 10.5 t C (15%) of CO_2 emissions would be avoided, respectively. These figures take into account the emissions of diesel used for recovery and transportation of the residues. If 100% of the sawmill residues, such as bark and sawdust, were used in place of coal, 30.1 t C (55%) and 17.6 t C (25%) of CO_2 emissions would be avoided for the wood- and concrete-framed buildings, respectively. If 90% of wood-based demolition material were recovered and used in place of coal, 39.5 t C (72%) and 27.7 t C (40%) of CO_2 emissions would be avoided for the wood- and concrete-framed buildings, respectively. In total, the replacement of coal by wood-based residues avoids CO_2 emissions of 85.9 t C and 55.8 t C for the wood- and concrete-framed buildings, respectively. If natural gas is replaced instead of coal, total avoided emissions are 50.8 t C and 32.9 t C for the two buildings.

3.3 Net landfill emission

Landfilling has been a common method of disposing of building demolition waste, though this option is becoming less favored. Great uncertainty exists about decomposition dynamics of landfilled biomass. We use the IPCC Tier 1 default method, a zero-order model using simplified parameters characterising the material and the landfill environment [9,10]. We assume that 70% of methane gas is recovered and replaces coal, and use a Global Warming Potential of 23 times that of CO_2 for the unrecovered methane, corresponding to a time horizon of 100 years. Landfilling all the wood-based building materials results in a net emission of 43.5 t C as CO_2 equivalent for the wood-framed building (63%), and 30.5 t C as CO_2 equivalent for the wood-framed building (56%).

3.4 Temporary carbon stock in buildings and forests

During tree growth, CO_2 is taken up from the atmosphere and fixed in biomass through photosynthesis, and later released again to the atmosphere during wood combustion or decomposition. Over a long time frame this results in zero net emission. Over shorter time frames, for example the lifespan of a building or the regrowth time of a harvested forest, these carbon fluxes and sinks can be significant. Consideration of these fluxes must recognize their time-dependency, because analyses over different time scales will result in different conclusions. The carbon incorporated into the wood-based materials in the building in this study amounts to 80.5 t C (147%) and 56.4 t C (81%) for the wood- and concrete-framed versions, respectively.

4 CONCLUSIONS

Embodied energy values of building materials can vary because of differences in physical production processes and because of different analytical methodologies. The three studies we compared had widely varying values for the same products. Using consistent methodologies within each study, however, the relative embodied energies of lumber and concrete showed less variation. The same result was found in a comparison of the total embodied energy of all the materials in the wood- and concrete-framed buildings.

Various factors influence and determine the overall CO_2 balance of a building material. Several of these factors have impacts that are comparable in magnitude to that of embodied energy, and taken together have a greater effect on CO_2 balance than embodied energy. This suggests that focus should not be placed exclusively on the embodied energy of a building material, but instead the CO_2 balance should be studied from a system-wide perspective. Our analysis of embodied energy-related CO_2 emission shows the wood-framed building to have lower emission than the concrete-framed building. Inclusion in the analysis of other significant carbon fluxes makes the wood-framed building still more favorable than the concrete-framed building, from the point of view of net CO_2 emission reduction.

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