Greenhouse Gas Emission from Building Construction in a Life-Cycle Perspective - Wood or Concrete Buildings?

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ABSTRACT

The use of different building materials, the kind of primary energy used to produce these building materials, and the treatment of the building materials after the demolition of the building, affect the flow of greenhouse gases to the atmosphere. Here, carbon dioxide (CO_2) and methane (CH_4) emissions from building constructions with either wood or concrete frames are compared in a life-cycle perspective. Emissions of these gases are calculated for a multi-story building with either a wood frame or a concrete frame. The primary energy input, assumed to be mainly based on fossil fuels, in the production of building materials is about 60% higher if concrete is used instead of wood. In a life-cycle perspective, the net CO_2 emission when wood is used instead of concrete is estimated to be reduced by about 6 if natural gravel is used and 8 times if crushed gravel is used. The net emission of CO_2 is released from fossil energy systems and in the chemical processes in the production of cement. The wood waste after demolition, as the timber which is not needed as building materials when a concrete frame is used instead of a wood frame, is assumed to be used for energy purposes, replacing natural gas. If the wood waste is deposited on land-fills, however, the difference in the net emissions of CO_2 and CH_4 expressed as carbon equivalents between construction of wood frames and concrete frames is small, because wood waste decomposes with the emission of CO_2 and CH_4, and CH_4 is a much more potent greenhouse gas than CO_2.

Introduction

There is a growing awareness that in the choice of building materials, the designer must not only consider the traditional requirements of the owner and occupant of the future building, but also the resource base and the effects on the environment of extraction, manufacture and processing of building materials (Buchanan & Honey 1994). The production and use of different building materials, the kind of primary energy used to produce these building materials, and the treatment of the building materials after the demolition of the building, affect the flow of greenhouse gases (GHG) to the atmosphere in different ways over different periods of time. In this paper, we analyse how the flow of carbon dioxide (CO_2) and methane (CH_4) is affected by different construction materials in a life-cycle perspective. The analysis is based on a new, multi-story building (Wälludden) with a wood frame, located in Växjö, southern Sweden. The impact of using a concrete frame instead of a wood frame on the flow of these gases to the atmosphere is calculated, based on theoretical calculations of how the need of different construction materials will change if the building were to be built using a concrete frame. The energy use for operating buildings and the related emissions of GHG are not included in this analysis but are not expected to differ between the existing building with a wood frame and the hypothetical building with a concrete frame. The carbon cycle of wood products, the primary energy use and CO_2 emission to produce the two types of building frames and the different non-structural building materials needed (which, apart from timber and concrete include steel, aluminium, plaster, insulation materials etc.) are considered, as emission of CH_4 from decomposition of wood. The life-time of the building is assumed to be 100 years, based on Swedish conditions.

The Life-Cycle of Wood Products

During a forest rotation cycle of about 100 years, 44 tonnes of carbon (C) will have been fixed by photosynthesis in the biomass used as construction materials in the multi-storey building at Wälludden (Table 1). This calculation includes only the wood products used in the final building, such as timber used for structural purposes, and non-structural purposes (exterior walls, window frames, stairs, balconies etc.). Examples of wood products used are rough timber, treated timber, glue laminated timber, particle-board, and plywood. However, the calculation does not include carbon fixed in logging residues and other waste products generated from the production and final use of different building materials, such as, bark, sawdust, and wood cut-offs.

Instead of using the forest for producing wood products, it can be used for energy purposes, or it can be left untouched and thus function as carbon storage. In the latter case, an equilibrium will be reached as the trees become older, an equilibrium in which there is a balance between the build-up of carbon by photosynthesis and its release in the decomposition of biomass. Thus, the forest will be a carbon sink for as long as it is left untouched.

If the forest is cut and used for timber or energy purposes, carbon will be fixed and stored in new biomass during the increment of the new forest which can, after a rotation period, be cut again. A minor share of the carbon, about 10%, may be transformed into stable humus in the soil. If the biomass is used in building constructions, the carbon will be conserved in the building materials for about 100 years. The way the building materials of wood are treated after the demolition of a building, will greatly affect the emissions of GHG. If the wood waste is deposited as landfills, CO_2 will be produced during the decomposition of the wood waste. How much CO_2 is produced depends on the degree of decomposition. If the degree of decomposition under aerobic conditions reaches 100%, the amount of CO_2 produced will be equivalent to the amount of CO_2 originally fixed by the trees by photosynthesis. The degree of decomposition is normally less than 100%, usually varying between 20% and 80% (Pingoud et al. 1996). During decomposition under anaerobic conditions, CH_4 is emitted. In a well-covered land-fill, equal amounts of CO_2 and CH_4 could be produced. CH_4 is nine times more potent as a GHG than CO_2, on a volume basis. Thus, if the degree of decomposition varies between 20% to 80%, the emissions of GHG from a well-covered land-fill, expressed as CO_2 equivalents, could be equivalent to 90-360% of the CO_2 fixed by photosynthesis.

If the forest is used directly in the energy sector for energy purposes replacing fossil fuels, the net CO_2 emission will be reduced. When biomass equivalent to the amount of timber used for the wood frame construction in the case of Wälludden is used instead to replace natural gas, oil or coal, CO_2 emission will be reduced equivalent to 50-80% of the CO_2 fixed by photosynthesis. An equivalent reduction of CO_2 emission will be achieved when the wood waste after the demolition of the building is used for energy production instead of being deposited in landfills. This reduction will, however, occur about 100 years later than the reduction attained if the forest is used directly for energy purposes. Another option of wood waste treatment is to reuse the waste for producing building materials such as in particle-board. This option is not considered in this paper.

To calculate how the utilisation of forest for building materials is affecting GHG emissions, the utilisation must be related to a reference case of land use. In this study, we assume that no forest was originally growing on the site. This means that if the wood products used in the building at Wälludden after utilisation decomposes without producing CH_4, the net balance of carbon will be unchanged during the life-cycle. If, however, the wood waste is used to replace fossil fuels, there will be a net reduction in CO_2 emission. On the other hand, if the wood waste is deposited in landfills, there would be a net increase in GHG, expressed as CO_2 equivalents, if CH_4 is produced during decomposition.

Table 1. Flow of carbon equivalents (tonne C) to the atmosphere of CO_2 and CH_4 over different periods of time assuming various options for the utilisation of the wood needed as construction materials (including wood for structural and non-structural purposes) in the multi-storey building at Wälludden. The options are (i) direct use of the wood for energy purposes instead of as building materials, (ii) utilisation as building materials and thereafter indirect use for energy purposes in the form of wood waste after the demolition of the building, and (iii) utilisation as building materials and thereafter deposition in landfills after demolition. CO_2 emission from the production of building materials is not included.

	Period of Time (year)			
	- 100 to 0	0 (final felling)	100	100 to 200
Photosynthesis[1]	- 44			
(i) Biomass equivalent to the biomass used for the wood frame replaces fossil fuels (Concrete frames are used)[2]				
Natural Gas		22		
Oil		18		
Coal		8		
(ii) Wood waste after demolition replaces fossil fuels[2]				
Natural Gas			22	
Oil			18	
Coal			8	
(iii) Wood waste after demolition is deposited in landfills[3]				
20% Decomposition				40
40% Decomposition				80
80% Decomposition				160

[1] The carbon content in wood is assumed to be 50%.
[2] Referring to the net CO_2 emissions, where the reduction of CO_2 emissions when biomass is replacing fossil fuels, has been taken into account. The energy content in wood is assumed to be 15.8 MJ/kg, which gives a CO_2 emission of 32 g C/MJ wood. The fuel-cycle emissions, which include end-use emissions and emissions from energy use for fuel extraction, conversion, and distribution, are assumed to be 18, 22, and 30 g C/MJ for natural gas, oil and coal, respectively (Gustavsson et al. 1995).
[3] Equivalent amounts of CO_2 and CH_4 are assumed to be produced.

CO_2 Emission from Primary Energy Use in the Production of Building Materials

The primary energy use for the production of the different building materials used in the construction of the wood frame house at Wälludden (including concrete, iron, aluminium, plastics, insulation materials, plaster etc.), has here been calculated to result in CO_2 emission equivalent to 55% of the carbon fixed by photosynthesis, if the electricity used for production is assumed to be based on GHG-neutral energy sources and other energy sources are fossil fuels (Fig. 1) (Adalberth & Persson 1997; Fossdal 1995). Based on information supplied by Fossdal (1995) of different energy carriers used in the production of different building materials, electricity is here calculated to amount to about 17% of the total final energy use for the production of the building materials, while the remaining primary energy use, equivalent to 83%, is assumed to be based on fossil fuels. However, if the electricity used for the production of the building materials is based on fossil fuels, the CO_2 emission will increase from 55% to 70-90% of the CO_2 fixed by photosynthesis, depending on whether the electricity production is based on natural gas, oil or coal. The emissions factors are assumed to be 18 g C/MJ for natural gas, 22 g C/MJ for oil, and 30 g C/MJ for coal, considering fuel-cycle CO_2 emissions, including end-use emissions and emissions from the energy used for fuel extraction, conversion, and distribution (Gustavsson et al. 1995). The efficiency factors for electricity conversion are assumed to be 0.50, 0.41, and 0.40, when the production is based on natural gas, oil and coal, respectively (Gustavsson & Johansson 1994). The net emission of CO_2 from the energy used for the production of the building materials could be low or zero, if renewable energy is use instead of fossil fuels for the production of the building materials.

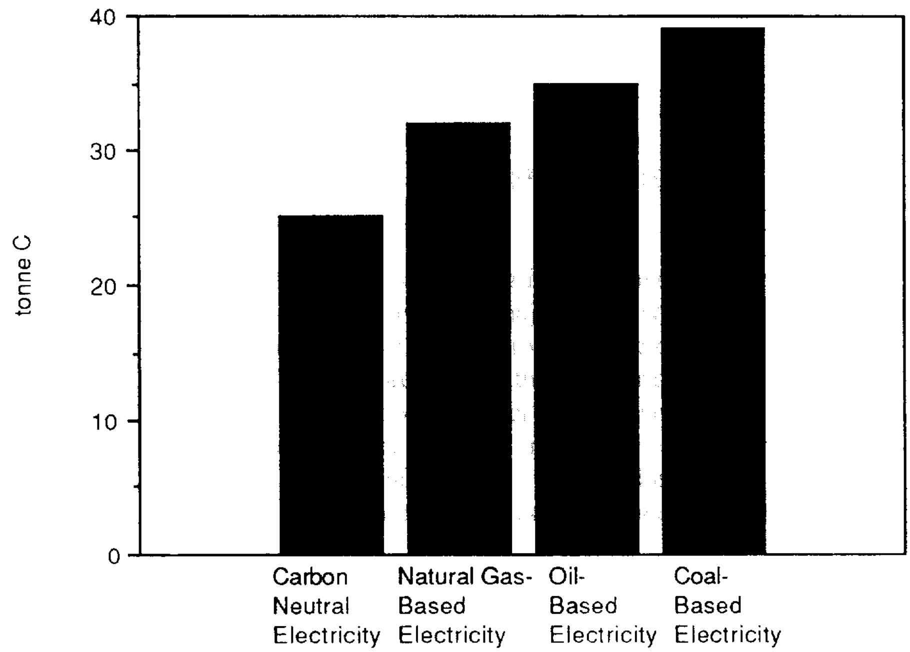

Figure 1. Carbon dioxide emission from primary energy use in the production of the building materials used at Wälludden, depending on how the electricity is produced, when other energy sources are fossil fuels. Examples of electricity production with low or zero GHG emission are hydro and wind power.

Concrete or Wood Frames?

The use of concrete frames (cast-in-situ floors and walls) instead of wood frames will, in the case of Wälludden, increase the primary energy used for the production of the building materials by about 60% (see Fig. 2) (Adalberth & Persson 1997; Fossdal 1995). The primary energy use includes the complete production chain, from the extraction or mining of the raw materials to the manufacture of the final building materials, including transportation. When concrete frames are used, not only will the demand for concrete increase but also the demand for iron for reinforcement. On the other hand, the demand for plaster and acoustic insulation materials is estimated to be reduced in the case of Wälludden (Adalberth & Persson 1997). Energy used in the construction process, directly or indirectly in the form of materials consumed such as timber as formwork, is not included here in the analysis of wood or concrete frames, nor is the energy used for the demolition or transportation of the demolition waste.

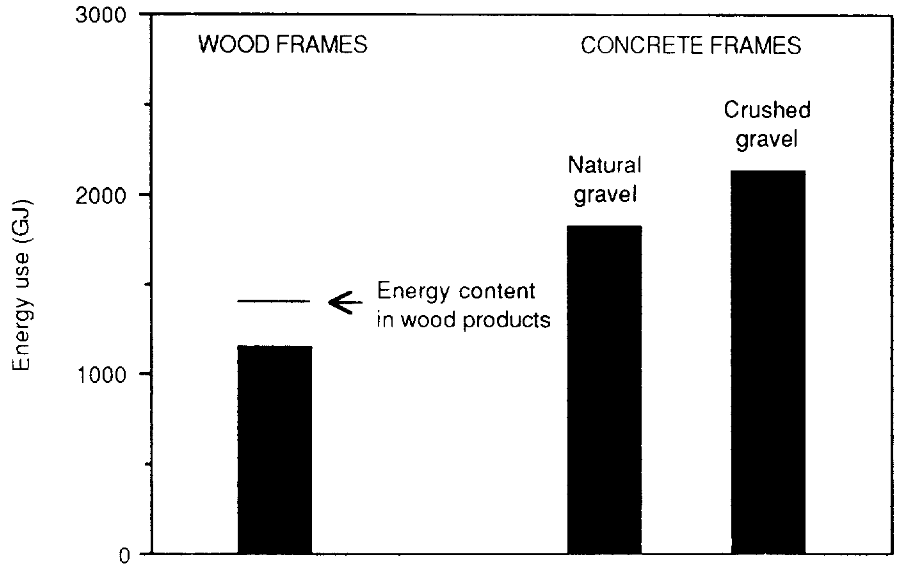

Figure 2. Energy input in the production of building materials used in the multi-storey building at Wälludden, taking into consideration whether wood frames or concrete frames are used. Concerning concrete frames, the change in energy inputs are shown when natural gravel or crushed gravel is used.

The increase in CO_2 emission will be greater than the increase in energy use when concrete frames are used instead of wood frames, as CO_2 is released, not only from the fossil fuel used in the production of concrete, but also in the chemical process taking place in the production of cement. An estimate is that an equal amount of CO_2 is released from the chemical process as from the fossil fuel used in the production of cement (Fossdal 1995). The amount energy used in concrete production may, however, vary greatly (Worrell et al. 1994b).

Another factor affecting the energy use and thus the emission of CO_2 in the production of concrete is whether natural gravel or crushed gravel is used, as the energy demand for the production of crushed gravel is about three times higher than for extracting natural gravel (Worrell et al. 1994a). The total energy demand for the production of concrete is estimated to increase by 20-30% when crushed instead of natural gravel is used (Fossdal 1995). Other aspects affecting the energy demand in the use of concrete frames are how the concrete waste is treated after demolition and whether the waste is reused in new concrete production. The energy used in concrete production utilising concrete waste is here assumed to be about the same as when crushed gravel is used, as the energy needed to crush concrete is estimated to be similar to the energy needed to crush gravel.

When concrete frames are used, the forest needed for the production of wood frames can be used in an alternative way, for example, to replace fossil fuels and thus reduce CO_2 emission. We assume that the forest is used to replace natural gas when concrete frames are used.

In Figure 3, the net life-cycle emissions of CO_2 and CH_4, expressed as carbon equivalents, from the building materials used at Wälludden are shown, when either wood frames or concrete frames are used. The time perspective is 200 to 300 years, including fixation of CO_2 by photosynthesis during the growth of the trees, emission of CO_2 from the fossil fuel used in the production of building materials and from the chemical processes in the production of cement, the emission of CO_2 and CH_4 from the decomposition of wood waste deposited in landfills after the demolition of the building, alternatively reduced CO_2 emission when the wood waste is used for energy purposes replacing natural gas. The wood waste in land-fills is assumed to produce equal amounts of CO_2 and CH_4 with a decomposition of 40%. The difference in of CO_2 and CH_4 emissions expressed as carbon equivalents between wood and concrete frames is not significant when wood waste is deposited in land-fills. If wood waste is used to replace natural gas, the differences in carbon equivalents between concrete and wood frames will be about 60 tonnes for the Wälludden building, or equal to the difference in carbon equivalents in the production of wood frames and concrete frames.

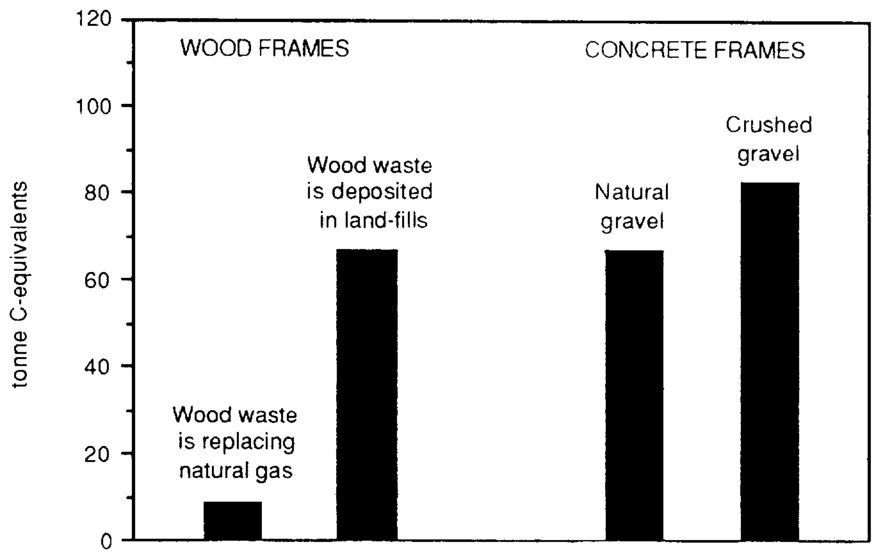

Figure 3. Net life-cycle emissions of CO_2 and CH_4 expressed as carbon equivalents from the building materials used at Wälludden, when either wood or concrete frames are used. For wood frames, two alternatives are shown: one in which the wood waste after demolition is used to replace natural gas, and one in which the wood waste is deposited in land-fills producing equal amounts of CO_2 and CH_4 at a decomposition of 40%. For concrete frames, two alternatives are shown: one in which natural gravel is used, and one in which crushed gravel is used. The energy input is based on fossil fuels where the electricity produced is based on natural gas.

The CO_2 will be emitted when the building is demolished about 100 years after its construction if wood frames are used, and the credit of reduced CO_2 emission due to the substitution of fossil fuel will also be counted 100 years after the emissions from the concrete frame. Thus, the life-cycle emissions of CO_2 from concrete frames of about 70 to 90 tonnes of carbon arise when the building is being constructed; 90 to 110 tonnes from building materials, and about - 20 tonnes from the credit of replacing natural gas when the timber equal to the amount used for the wood frames in the wood building are used for energy purposes. The emissions from wood frames are from construction, 32 tonnes, and from the credit of replacing natural gas when wood waste after demolition is used for energy production, - 22 tonnes, or from decomposition, 36 tonnes. Thus, the net life-cycle emissions of CO_2 are estimated to increase six to eight times if concrete frames are used instead of wood frames when the wood waste is used for energy purposes, depending on whether natural gravel or crushed gravel is used in the concrete. If the wood waste is deposited on land-fills, the differences in net life-cycle emissions of CO_2 and CH_4 expressed as carbon equivalents between wood frames and concrete frames are small.

Uncertainties

The input data used in the calculations in this study are uncertain, as the estimation of the amount of building materials used at Wälludden is based on one type of building only. Also, data on the energy input and CO_2 emission for the production of different building materials differ in different studies. For example, the energy used in plywood production is estimated to be much higher in a Dutch study (Worrell et al. 1994a), than data used in this study based on Fossdal (1995). The data on the energy use for the production of other wood products, as well as of steel, concrete, and aluminium, also vary in the literature (see e.g. Buchanan & Honey 1994; Fossdal 1995; Worrell et al. 1994a; Østergaard et al. 1993). Thus, to achieve more comprehensive results, the quality of the input data should be analysed and if needed, improved. However, the data will also depend on the production techniques used.

Future Energy System

The analysis in this study is based on a fossil fuel system, with the exception of production of the electricity. Other types of energy systems will affect the energy demand and emission of GHG for the production of building materials and thus the analysis should be extended to consider such systems, because the current energy system may change in the future. For example, an increased use of renewable energy systems such as systems based on biomass, would reduce the net emissions of GHG but could lead to an increased demand for primary energy due to the energy losses in processing and conversion, e.g. in the processing of solid biomass into liquid transportation fuels. There is also a continuous technological development, leading to increased energy efficiency in the production of building materials, which is affecting GHG emissions (Worrell et al. 1994b). However, the amount of CO_2 released in the chemical process of the production of cement will not depend on the energy systems being used.

Discussion

The Intergovernmental Panel of Climate Change (IPCC) states that the production of wood products normally requires less energy than the production of alternative products (IPCC 1996). This is in agreement with our results in this study. IPCC also states that the utilisation of wood products must be analysed in a life-cycle perspective, taking into account the net changes in carbon storage in biological materials and net emission of CO_2. The importance of doing so is evident from this study, see e.g. Table 1.

How efficiently wood products will reduce GHG emissions by the replacement of energy intensive materials, depends, not only on differences in the production process, but also on how the wood waste after utilisation is treated (e.g. reuse, combustion with energy recovery, or deposition) and how the forest is used in an alternative way if it is not used for the production of wood products. According to IPCC, replacing fossil fuels by biomass, directly or indirectly by using wood products instead of more energy intensive materials, is a more efficient method to reduce CO_2 emission than leaving forests untouched as carbon sinks (IPCC 1996).

More knowledge about energy balances of the production in wood products and alternative products is needed. Future changes in waste treatment systems, towards increased reuse and more closed material cycles, and changes in energy systems, imply that the use of wood products as a measure to reduce GHG emissions must be analysed in a wide perspective. Examples of scenarios that should be interesting to analyse are those which are based on current energy systems, or a biomass-based energy system where the wood waste is (i) deposited, (ii) combusted, or (iii) reused. Other products than building frames, such as facades and window materials, should also be included in such analyses, as well as all GHG emissions.

In this study, no economic considerations have been taken regarding the costs of reducing GHG emissions by material substitution. Future studies should include such economic analyses so that the GHG mitigation cost of material substitution can be compared with GHG mitigation costs of different measures in the energy sector. Furthermore, the GHG mitigation potential of material substitution should be estimated and compared with the potential in the energy sector. The importance of a postponed CO_2 release when using wood products should also be clarified.

Acknowledgements

We gratefully acknowledge the economic support provided by the Swedish National Board for Industrial and Technical Development and by SÖDRA AB.

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