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Variability in energy and carbon dioxide balances of wood and concrete building materials

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Abstract

A variety of factors affect the energy and CO_2 balances of building materials over their lifecycle. Previous studies have shown that the use of wood for construction generally results in lower energy use and CO_2 emission than does the use of concrete. To determine the uncertainties of this generality, we studied the changes in energy and CO_2 balances caused by variation of key parameters in the manufacture and use of the materials comprising a wood- and a concrete-framed building. Parameters considered were clinker production efficiency, blending of cement, crushing of aggregate, recycling of steel, lumber drying efficiency, material transportation distance, carbon intensity of fossil fuel, recovery of logging, sawmill, construction and demolition residues for biofuel, and growth and exploitation of surplus forest not needed for wood material production. We found the materials of the wood-framed building had lower energy and CO_2 balances than those of the concrete-framed building in all cases but one. Recovery of demolition and wood processing residues for use in place of fossil fuels contributed most significantly to the lower energy and CO_2 balances of wood-framed building materials. We conclude that the use of wood building material instead of concrete, coupled with greater integration of wood by-products into energy systems, would be an effective means of reducing fossil fuel use and net CO_2 emission to the atmosphere.

Keywords: Energy; Carbon dioxide; Variability; Wood; Concrete; Construction

1. Introduction

The building construction sector uses much energy and emits large quantities of carbon dioxide (CO_2) to the atmosphere. Energy is used for extracting, transporting, processing and assembling materials, and CO_2 is emitted by fossil fuel combustion, land-use practices and industrial process reactions. A growing body of knowledge suggests that building with wood-based material can result in lower energy use and CO_2 emission compared to other materials such as concrete, brick or steel. For example, Koch [1] using US data from the 1970s, and Buchanan and Honey [2] using New Zealand data from the 1980s, calculated energy use and CO_2 emission to be lower if wood materials are used for building construction. More recently, CORRIM found two wooden houses to have lower embodied energy and global warming potential than equivalent designs made of steel or concrete [3]. Other studies, while also concluding that wood construction can use less energy and emit less CO_2, have emphasized the spatial, temporal and technological differences that affect the energy and CO_2 balances of material production. UN-HABITAT [4] explored the causes of variability of energy use in building material production introduced by process-specific differences in production methods. Buchanan and Levine [5] found that the energy needed to manufacture building materials decreased between 1983 and 1998, and in both periods the buildings with higher wood content had lower CO_2 emission than those made of concrete or steel.

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Some studies have quantified ranges of possible energy use and CO_2 emission from the manufacture or lifecycle of certain building materials, taking into account various aspects of lifecycle dynamics. For example, Börjesson and Gustavsson [6] quantified the effects of land use and end-of-life alternatives of building materials, and concluded that wood-framed buildings have lower energy use and greenhouse gas emission than concrete-framed buildings. Scharai-Rad and Welling [7] emphasized the importance of using wood waste for energy to improve the CO_2 balance of building construction. In a review of Swedish and Norwegian studies of economic and environmental impacts of wood substitution, Peterson and Solberg [8] found wood construction to consistently result in lower greenhouse gas emission than non-wood material, with the amount depending on material waste management and how forest carbon flows are considered. Gustavsson and Sathre [9] calculated the effect on building material lifecycle CO_2 balances resulting from variation of several process parameters, and found wood-framed buildings to consistently have lower CO_2 balances than concrete-frame buildings.

A variety of factors can affect the energy and CO_2 balances associated with a building material over its lifecycle. Some of these can be described as *uncertainties*, resulting from stochastic variations or from our lack of knowledge of precise parameter values. Examples of sources of uncertainty in CO_2 balance related to building materials include the growth rate of a particular forest stand and the decomposition dynamics of landfilled wood. Uncertainty in energy balance can be caused, for example, by natural differences in physical properties of raw materials such as wood or stone, requiring different amounts of processing energy. Other factors that influence energy and CO_2 balances can be described as *variability*, determined by human decisions and management methods. Examples include the process technology used to manufacture cement, the fuel used to drive production processes, and the choice of using primary or recycled steel. Combinations of uncertainty and variability that may be difficult to separate can also affect energy and CO_2 balances. For example, different factories may produce identical products using physical processes of different efficiency (i.e. with variability), but when aggregated in the marketplace or building stock the differences may be impossible to distinguish (i.e. uncertainty is present).

Separate from these physical factors that influence the actual energy and CO_2 balances resulting from building material production, the methods used and parameters chosen for analysis can also influence the *apparent* energy and CO_2 balances of production [10,11]. For example, Lenzen and Treloar [12] analyzed the data of Börjesson and Gustavsson [6] using energy intensities obtained from input–output analysis that refers to the economic value of materials based on prices in Australia. By using this top-down economic technique they calculated that the embodied energy was twice as high as that found by Börjesson and Gustavsson, though they reached the same conclusion that wood construction uses less energy and emits less CO_2 than concrete construction. They also discussed that variation in energy intensities could depend on differences in production structure between Australia and Sweden and/or the scope of the studies. Nevertheless, when using a top-down economic technique to compare the physical effects of using different construction materials, the results may also be affected by differences in the overall economic system. Furthermore, building practices that vary with climatic conditions, national building codes, as well as geographical conditions that affect e.g. transportation may also influence the comparison.

In the present study, we do not consider the effect of different analytical methods on study results. Instead we apply a single consistent methodology to determine the marginal effects of variation of certain physical parameters related to the manufacture and use of building materials. We focus on variability in energy use and CO_2 emission due to technological choices and managerial decisions in the production process. The objectives of this study are to

- identify factors that have a particularly strong influence on the energy and CO_2 balances resulting from building material production and use,
- determine how these factors differently affect buildings constructed with wood and concrete, and
- determine whether and under what circumstances a wood-framed building might have higher energy and CO_2 balances than a concrete-framed building.

2. Methodology and assumptions

2.1. System description

Gustavsson et al. [13] proposed a method to compare net CO_2 emission from wood-framed and concrete-framed buildings. Factors considered were the CO_2 emission from fossil fuel use during building material production, the substitution of fossil fuels by biomass residues derived from wood production and use, the changes in biomass carbon stocks in forests and buildings, and chemical reactions in the production and use of cement. These were examined in a life-cycle perspective, including the extraction and processing of raw materials, assembling and utilizing the finished product, and demolition and disposal of materials at the end of the usable building life. In the present study, we applied this method to quantify changes in the CO_2 balance that result from the variation of key production parameters, using a case study approach. Using the same method, we calculated changes in energy balances for material production due to variation of the same parameters, taking into account energy used in material production as well as biofuels generated during the production and use of wood-based building materials. We compared changes in energy and CO_2 balances to a reference case comprised of parameters that give the lowest energy and CO_2 balances. Thus the reference case is the ''best case'' scenario, from which deviations cause a higher energy or CO_2 balance.

The analysis is based on a 4-story apartment building containing 16 apartments with a usable floor area of $1190\,m^2$. Calculations were made of materials required to construct functionally equivalent versions of the building with a wood frame and a reinforced concrete frame [14]. We did not consider the energy use and CO_2 emission of the on-site construction of the building, which Cole [15] found to be slightly higher for concrete-framed compared to wood-framed buildings, both in absolute terms and as a percentage of material process and transport energy. We assumed the buildings have a lifespan of 100 years, and that energy inputs for maintenance do not differ between building frame materials [16]. We did not include energy use and CO_2 emission resulting from operation of the buildings because they should not differ significantly between the concrete and wood building. Adalberth [14] has calculated the difference to be less than 1%, and Cole and Kernan [16] found the difference in operating energy between wood and concrete framed office buildings to be negligible.

To address the issue of how forestland should best be used, we included the same area of forestland within the study system boundaries regardless of the building frame material. That area was determined by the extent of forestland required to produce the lumber, plywood and particleboard used in the construction of the wood-framed building. Because the concrete-framed building used less wood materials, some of the forest was not needed for material production. We call this area ''surplus forest''. The utilization or continued growth of this forest can affect the energy and CO_2 balances of the concrete-frame building in various ways, which we explore with two parameter variations.

2.2. Energy balance

We define the energy balance of material production as the primary energy expended to extract, process and transport the materials, minus the lower heating values of the fraction of finished materials and process by-products that can be recovered and made available for external use throughout the lifecycle of the wood building materials. Primary energy use was calculated as the sum of the fossil fuels used directly for building material production and biofuel recovery, the primary energy for electricity used in material production, and sawmill residue used internally for wood processing. Primary fossil fuel use included inputs for fuel extraction and transportation of 5.5%, 10% and 5% for oil, coal and natural gas, respectively. Primary energy use for electricity supply was based on a coal-fired condensing power plant with a conversion efficiency of 40% and distribution loss of 2%.

Our data for specific end-use energy for building material production, expressed as GJ per tonne of material, are primarily based on three European studies: Worrell et al. [17] from the Netherlands, Fossdal [18] from Norway, and Björklund and Tillman [19] from Sweden. Energy data from these studies include extraction, transportation and processing of materials. We used the average of these three studies in order to moderate country-specific differences and methodological peculiarities. Gustavsson and Sathre [20] give further information comparing the three studies. Because our reference case is defined as the parameter values that give the lowest energy and CO_2 balances, some data from these three studies were adjusted when the material or manufacturing process described in the study did not correspond to the best case. For example, a study may contain energy data on ore-based steel or Portland cement, while the best case corresponds to recycled steel or blended cement. In these cases, we adjusted the specific energy values using data from additional studies referred to in Section 3.

The resulting figures for specific end-use energy use for production of selected materials are shown in Table 1, broken down by end-use energy carrier. These eight materials (concrete, plasterboard, insulation, steel, plastic, lumber, plywood, and particleboard) used 85% and 87% of the total primary energy for production of materials for the wood- and concrete-framed versions, respectively.

Assumed recovered fuel production was based on 70% recovery of logging residues (branches and tree-tops), 100% recovery of wood processing residues (bark, sawdust and slabs) not used for particleboard manufacture and fuel for internal process operations, 100% recovery of wood-based construction waste, and 100% recovery of wood-based demolition material. Flow of wood products, and sources of biofuels, are illustrated in Fig. 1 and quantified for the wood- and concrete-frame buildings in Table 2. Division of total tree biomass into components (e.g. stemwood, bark, branches, roots) was based on biomass expansion factors [21] for the dominant forest tree species in Sweden. Recovery of plastic and paper was not considered in this study because the quantities of these materials do not differ significantly between the wood- and concrete-framed buildings. Energy for recovery and transportation of biofuels was assumed to be diesel fuel, calculated as a percentage of the heat value of the recovered biofuel: 5% for forest residue, 1% for sawmill residue and construction waste, and 3% for demolition material.

2.3. Carbon dioxide balance

We define the CO_2 balance of material production as CO_2 emissions to the atmosphere due to fossil fuel combustion and industrial process reactions, minus CO_2 emission avoided by replacing fossil fuel with recovered biofuels, minus increased (or plus decreased) carbon stock in materials and forests. Combustion of fossil fuels produced positive CO_2 emission, in quantities that depend on the carbon intensity and fuel-cycle characteristics of the fuel. Fuel-cycle specific carbon emission values used in this study were 30 kg C/GJ coal, 22 kg C/GJ oil, and 18 kg C/GJ natural gas. Cement production accounting included positive CO_2 emission from calcination reaction during manufacture, and negative emission due to carbonation reaction during the building lifecycle. Combustion of biofuel obtained from sustainably managed forests was assumed to have zero emission, because CO_2 emitted during combustion is balanced by CO_2 fixed during forest growth. Biofuel available for external use was assumed to replace fossil fuel that otherwise would have been burned. In our reference case the recovered biofuel replaces coal, using appropriate combustion efficiency conversion factors to relate the heat value of the biofuel to the avoided fossil CO_2 emission.

Carbon stock in building materials was considered to have zero change over the 100-year building lifecycle, because all wood material put into the building at the beginning of the lifecycle was assumed to be burned at the end of the lifecycle. Carbon stock in the forest used for materials for the wood-frame building was considered to have zero change over the building lifecycle, because the forest harvested at the beginning of the lifecycle was assumed to completely re-grow over a 100-year rotation period. The portion of forest land harvested to produce wood products for the concrete-frame building also had zero carbon stock change over

Table 1
Specific end-use energy use (GJ/tonne) for reference case production of eight building materials

Material	Coal	Oil	NG	Biofuel	Electricity
Concrete	0.20	0.21	—	—	0.08
Steel	0.28	0.36	1.95	—	2.19
Lumber	—	0.62	—	0.99	0.58
Particleboard	—	2.94	—	1.09	1.41
Plywood	—	5.58	—	2.07	1.62
Insulation	7.88	1.42	0.08	—	1.25
Plasterboard	—	3.73	—	—	0.55
Plastic PVC	—	19.44	11.99	—	6.93

Data include extraction of natural resources (except steel which is recycled from scrap), transportation, and processing into finished building materials.

Table 2
Flows of wood-based materials (tonnes of oven-dry material, and percent of biomass removed from forest) from forest to sawmill to building to demolition

Source	Wood-frame		Concrete-frame	
	Tonnes	Percent	Tonnes	Percent
Total tree biomass	288.5	139.0	186.2	139.0
Biomass removed from forest	207.5	100.0	133.9	100.0
Harvested roundwood	166.8	80.4	107.6	80.4
Recovered forest residue	40.7	19.6	26.3	19.6
Sawmill residue burned internally	8.2	4.0	6.2	4.6
Sawmill residue available externally	69.1	33.3	38.7	28.9
Recovered construction waste	8.9	4.3	6.3	4.7
Wood material in building	80.5	38.8	56.4	42.1
Recovered demolition wood	80.5	38.8	56.4	42.1

Biomass left in forest includes stumps, roots and non-recovered branches of harvested trees, but does not include surplus forest not harvested in the concrete-frame case.

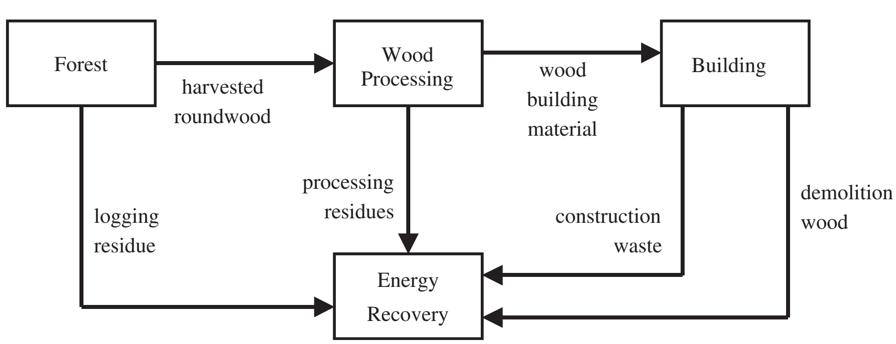

Fig. 1. Schematic flow chart of wood materials during the building lifecycle. Quantities for the wood- and concrete-framed buildings are shown in Table 1.

the building lifecycle, but the surplus forest not required for building material production was assumed in our reference case to grow by 50% over the 100-year lifecycle, resulting in an increased forest carbon stock for the concrete-frame building.

3. Description of parameter variations

Variations of system parameters that are encountered due to technological choices and managerial decisions are described below. The effects of these variations on energy and CO_2 balances are quantified and discussed in Section 4.

3.1. Cement and concrete aggregate

During cement manufacture, mineral raw materials are heated in a kiln to produce clinker. Fuel combustion for kiln firing is the largest single source of energy use and CO_2 emission during cement manufacture. The energy required for clinker production depends on the kiln design and the moisture content of the raw materials. The moisture content of kiln feed material can vary from about 0.5% when using the dry process to about 38% when using the wet process, with less energy being needed at lower moisture content. Using exhaust gas to pre-heat feed material also reduces energy requirement. We compare the most efficient process using a short dry rotary kiln with preheater and precalciner to the least efficient, wet rotary kiln process that uses an average of 3.2 GJ more kiln fuel per tonne of clinker [22]. Electricity consumption for grinding and other uses is similar in both processes. We assume that coal is used for kiln fuel.

In normal Portland cement, clinker is ground and mixed with 5% gypsum to produce the finished product. Other materials whose reactivity has been increased through thermal processing, such as fossil fuel fly ash and blast furnace slag, can also be used as cement binders instead of clinker. Construction cement made of a blend of clinker and other additives is becoming more commonly used [23]. When cement is made with a blend of clinker and by-products of other industrial processes, total energy use is reduced because less clinker must be produced. CO_2 emission is reduced in two ways: less fossil energy is needed for the production of the lower quantity of clinker, and lower clinker production means less CO_2 emission from the chemical reaction of limestone calcination. We compare a clinker/cement ratio of 65% to the 95% used in normal Portland cement. This reduces kiln fuel consumption by 1.4 GJ/tonne of blended cement [24]. The electricity use increases by 0.06 GJ/tonne due to the need for grinding of the blending materials. The decrease in clinker manufacture reduces CO_2 emission from process chemical reactions by 32%.

Stone aggregate in the form of sand and gravel is an essential component of concrete, composing over 80% by weight of a typical concrete mix. Aggregate of suitable size and quality occurs naturally in some places, requiring only extraction, washing, and transportation. Where natural aggregate is not available or cannot be extracted, large stone is quarried, crushed and graded to the required sizes. Demolished concrete structures can also be crushed to produce aggregate. Extraction of one tonne of natural aggregate requires 20 MJ oil and 9 MJ electricity, while one tonne of crushed gravel requires 120 MJ oil and 50 MJ electricity [17]. These figures do not include transport energy, which will depend on the locations of the resource and the batching site, and which we assume will not vary between natural and crushed aggregate. The use of crushed aggregate instead of natural aggregate may require minor adjustments in concrete mixture due to differences in aggregate texture and porosity, a factor not considered in this study.

3.2. Recycled steel

Production of steel for concrete reinforcement, wood connectors and other construction material requires substantial energy. Less energy is required to produce finished steel products using secondary, recycled steel than by mining and reducing iron ore. Our reference case uses steel products made entirely from recycled steel. While this is the best-case scenario in terms of energy and CO_2 balances of new construction, in a lifecycle perspective the impacts of primary steel production from ore must be considered. Various methods exist to allocate the impacts of primary production throughout the lifecycle(s) of recycled products [25]. In this study, we take a simplified approach assuming that an adequate quantity of steel scrap is available, hence our reference case considers only the energy use and CO_2 emissions to upgrade the scrap to new, usable construction materials. Using best practices, production of one tonne of hot rolled steel product recycled from 100% scrap using the electric arc furnace process requires 2.6 GJ coal and 2.9 GJ electricity, while one tonne of a similar product made from 90% ore and 10% scrap using the basic oxygen furnace process requires 16.1 GJ coal and 0.7 GJ electricity [26].

3.3. Wood drying efficiency

Trees are living organisms and contain large amounts of water. Moisture content of wood in freshly harvested trees ranges from about 50 to 200% (weight of water per weight of dry matter). For reasons of dimensional stability, physical strength and resistance to biological decay organisms, it is necessary to reduce the moisture content of finished wood products to below 25%. This was traditionally achieved through air-drying under shelter for several months or years. Air-drying is still employed in some situations, though almost all industrial wood production now uses heated kilns for drying. Presently, the largest single use of energy in the manufacture of wood-based products is thermal energy for drying of the wood. Kiln drying accounts for 70–90% of the total energy for sawn lumber conversion [27]. A large proportion of the total energy required for plywood and particleboard manufacture is also heat energy used for drying veneer and particles. Various drying technologies exist, some more energy efficient than others. Progressive type kilns employing a continuous process use 10–35% less energy than compartment type kilns using a batch process. We compare a high-efficiency progressive kiln fueled by sawmill residues to a less efficient kiln that uses 35% more fuel.

3.4. Transportation of materials

Transportation of materials, both raw and finished, contributes to the energy use and CO_2 emission of building construction. The data used in this study for specific energy use in material production include appropriate local transportation distances. The distances and transport modes assumed by Fossdal [18] and Björklund and Tillman [19] are shown in Table 3. Worrell [17] does not report details of distances and modes but claims to include transport of raw materials to the processing facilities, but not transport of finished materials to the consumer. To determine the impact of longer transportation distances on energy and CO_2 balances, we increased the transport distance of selected materials as shown in Table 3. We assumed specific energy requirements of 1.5 MJ oil/tonne-km for truck transportation and 0.50 MJ oil/tonne-km for train transportation, based on approximate averages of the specific transport energy figures used in the above three studies.

3.5. Carbon intensity of fossil fuel

Different fossil fuels have different conversion efficiencies and emit different amounts of carbon per unit of heat energy. Our reference case assumes that coal is used to generate electricity needed for material production, and that recovered biofuel replaces coal. To determine the significance of the carbon intensity of fossil fuel, we calculated the energy and CO_2 balances assuming natural gas was used instead of coal for electricity generation, and that recovered biofuel replaces natural gas instead of coal.

3.6. Recovery of wood residues

By-products from the harvesting of trees, such as branches, foliage and treetops, can be used to substitute fossil fuel. Commonly this material is left in the forest, but it is increasingly viewed as a valuable energy source. Utilization of logging residue is subject to ecological constraints involving nutrient cycling and organic matter content of soils, but can make a potentially significant contribution to energy supply [28,29]. It also requires the logistical capability to efficiently collect and transport the residue, which is currently being developed in several countries. Our reference case assumes that 70% of forest residues are recovered as biofuels, and accounts for fossil fuel needed for recovery and transportation.

Conversion of harvested logs to finished wood products results in sawmill by-products such as bark, slabs and sawdust. Traditionally this was regarded as a waste product that was dumped and allowed to decay

Table 3
Transportation distance (km) of selected building materials accounted in Fossdal [18] and Björklund and Tillman [19], and additional increased transportation distances assumed in this scenario

Material	Fossdal [18]			Björklund and Tillman [19]		Increase	
	Truck	Train	Ship	Truck	Ship	Truck	Train
Cement	50	—	450	160–250	—	200	1000
Aggregate	49[a]	—	—	40	—	200	—
Concrete	55	—	—	15–30	—	—	—
Logs	45[a]	—	—	—	—	200	—
Wood products	200–250[a]	—	—	250–350	—	200	1000
Steel[b]	120	800	1100	80	350	200	1000
Plasterboard	225[a]	—	—	250	—	200	1000
Insulation	300[a]	—	—	350	—	200	1000
Plastic	—	—	—	—	—	200	1000

[a]Mode of transport not specified; we assume truck.
[b]Total transport distance including both scrap and finished steel.

naturally, or was burned without energy recovery. In Sweden, this resource is now commonly used as fuel for sawmill process energy or for other energy purposes such as district heating. Some types of sawmill residue can also be used as raw material for particleboard and other engineered wood products. In the buildings analyzed in this study, particleboard was produced from sawmill residue and composed 18% and 22% by dry weight of all wood products used in the wood- and concrete-frame buildings, respectively. Some sawmill residue was also burned within the sawmill as process heat for wood product manufacture (see Table 2). After subtracting sawmill residue used as raw material for particleboard production and as fuel for internal sawmill process heat, there still remained 56 and 32 tonne dry weight of sawmill residue available for external use as biofuel, for the wood- and concrete-framed buildings, respectively.

Wood waste is generated at the construction site as standard-sized boards and panels are cut into smaller sizes required in the building. The amount of construction waste depends on a variety of factors including the design of the building, the characteristics of the materials supplied to the construction site, and the craftsmanship of the construction personnel. Additional waste material can be produced by secondary material processing industries that provide manufactured products to the building site. In this study we assume that the quantity of wood waste generated is equal to 10% of the total wood-based material in the finished building [19]. Appropriate waste percentages of other materials were also included in calculations of energy use and CO_2 emission of material manufacture, but recovery of non-wood waste materials is not considered in this study. Our reference case assumes that all wood-based construction waste is recovered as biofuels.

Recovery of wood from demolished buildings is becoming increasingly common. Reasons for this practice include the value of recovered wood for material or energy purposes, and ordinances against landfilling of organic material that are entering into force in Sweden and the European Union. Our reference case assumes that all wood-based materials in the buildings are recovered and burned as biofuel in place of coal.

3.7. Growth and use of surplus forest

Our reference case assumes the surplus forest of the concrete-framed building (described in Section 2.1) is untouched and increases in biomass by 50% over the 100-year lifespan of the building. Actual forest growth and utilization can affect the energy and CO_2 balances in various ways, including carbon storage in biomass and wood products, and replacement of fossil fuels by forest biofuels. Forest growth and biological carbon storage is highly uncertain, and depends on tree species, climate, soil conditions, alternative uses for the forest and other factors [30]. We explore these uncertainties with two parameter variations, one assuming zero growth of the surplus forest during the building lifecycle and the other assuming that the surplus forest is harvested at the time of building construction and used for biofuel to replace fossil fuel.

4. Results and discussion

4.1. Reference energy balance

Contributions to the energy balances of the reference case production of materials for the wood- and concrete-framed buildings are shown in Fig. 2. Primary energy for end-use fossil and electrical energy for material production is slightly higher for the concrete-framed building, and biofuel used internally for sawmill processes is slightly higher for the wood-framed building. Substantially more biofuel available for external use is created during the lifecycle of the materials for the wood-framed building, compared to the concrete-framed building. The overall energy balance is 260 GJ for the concrete-frame building and −1110 GJ for the wood-framed building. The negative energy balance for the wood-frame building means that more usable energy in the form of biofuel is made available during the lifecycle of the materials, than is used during the production of materials.

4.2. Reference CO_2 balance

The CO_2 balances of the reference case production of materials for the two building types are shown in Fig. 3. The greater end-use fossil fuel and electricity use in the concrete-frame building is reflected in the higher CO_2 emission from these sources in the concrete-frame building. Emission due to chemical process reactions during cement manufacture is also greater in the concrete-frame building. The greater quantity of biofuels generated as residues from the production and use of wood-based materials for the wood-framed building, results in the greater negative emission due to replacement of fossil fuels by biofuel. The surplus forest in the concrete case, due to the need for less wood-based building materials, is assumed to increase in biomass during the building lifecycle resulting in a negative emission. The overall CO_2 balance is the sum of these separate contributions, and is −44.2 tonne C for the wood-frame building and −16.5 tonne C for the concrete-frame building. It is more negative for the wood-frame building, due to the lower emission during material manufacture and the greater replacement of fossil fuel by biomass residues.

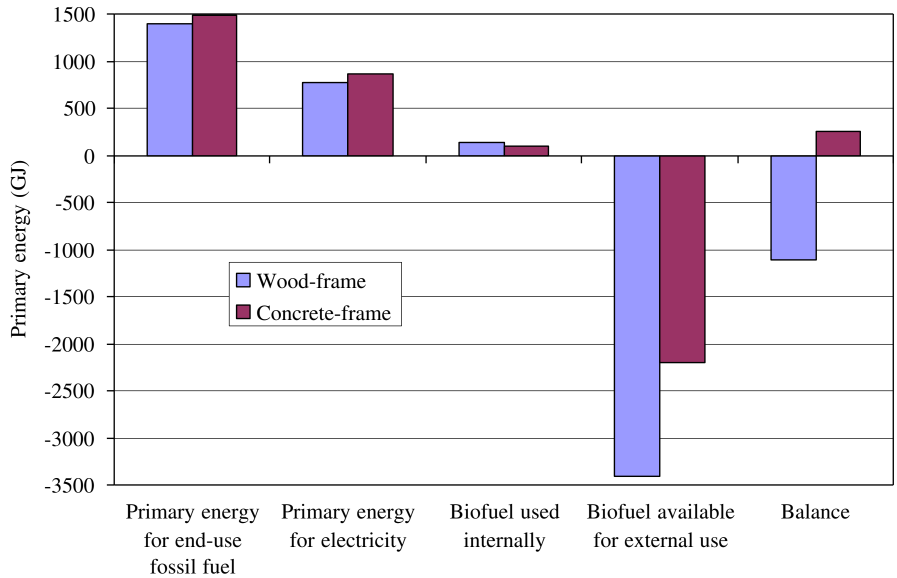

Fig. 2. Contributions to the energy balances (GJ) of the reference case production of all materials for the wood- and concrete-frame buildings. Biofuel used internally is for process heat for wood product manufacture. Biofuel available for external use is total biomass residues recovered from logging, processing, construction and demolition, minus biofuel used internally.

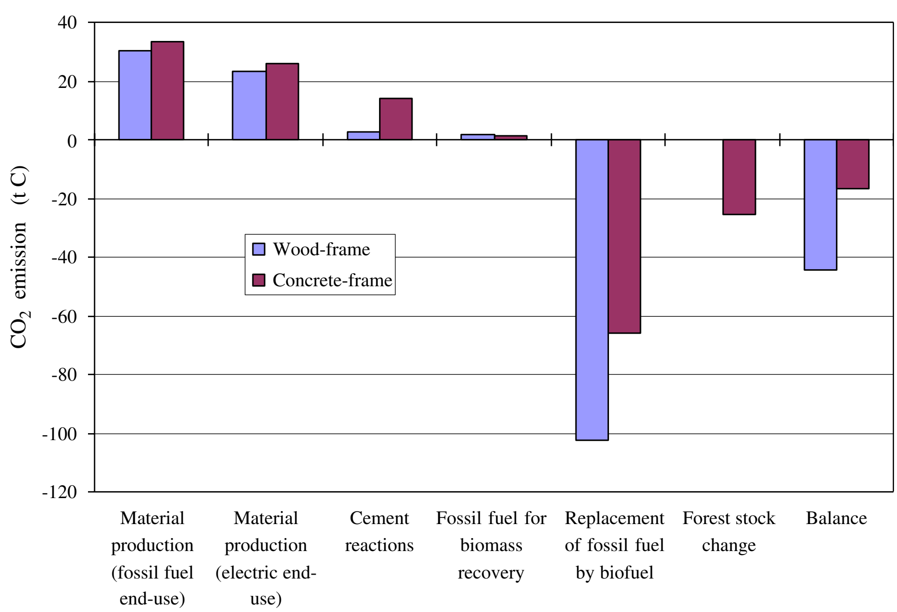

Fig. 3. Contributions to CO_2 balances (tC) of the reference case production of materials for the wood- and concrete-frame buildings. End-use electricity for material production is based on coal-fired generation. Recovered biofuel replaces coal. Stock change of surplus forest is assumed to be 50% over the 100-year lifecycle.

4.3. Effect of parameter variation

The energy and CO_2 balances of the wood- and concrete-frame building, for the reference case and for each parameter variation, are presented in Table 4. Recovery of demolition wood has the single greatest effect on both the wood- and concrete-framed buildings. Non-recovery of demolition residue is the only parameter variation that makes the energy balance of the wood-frame building to be positive. Note that the effects of demolition wood recovery are experienced at the *end* of the building life cycle, distinct from other parameters considered in this study that are felt at the beginning of the building lifecycle. Besides burning for energy recovery, other management options for wood-based demolition material that were not quantified in this study include reuse and landfilling. Reuse of recovered wood as material for new construction may result in a

Table 4
Energy balance (GJ) and CO_2 balance (tonnes of C), and changes in balance compared to the reference case, of production of materials for buildings with a wood-frame and concrete-frame when selected system parameters are varied. See text for description of reference case and variation of parameters

Parameter			Energy balance (GJ)					Carbon dioxide balance (tonne C)				
Description	Reference condition	Changed condition	Wood frame		Concrete frame		Difference	Wood frame		Concrete frame		Difference
			Energy balance	Change from ref.	Energy balance	Change from ref.	(Concrete—wood)	CO_2 balance	Change from ref.	CO_2 balance	Change from ref.	(Concrete—wood)
Reference case	—	—	−1110	0	260	0	1370	−44.2	0.0	−16.5	0.0	27.7
Cement clinker process	Dry	Wet	−1050	+60	640	+380	1690	−42.3	+1.9	−5.0	+11.5	37.3
Cement content	Blended	Portland	−1080	+30	480	+220	1560	−41.9	+2.3	−3.2	+13.3	38.7
Concrete aggregate	Natural	Crushed	−1070	+40	500	+240	1570	−43.2	+1.0	−10.2	+6.3	33.0
Steel	Recycled	Ore-based	−950	+160	520	+260	1470	−39.4	+4.8	−8.8	+7.7	30.6
Wood-drying efficiency	High	Low	−970	+140	370	+110	1340	−42.0	+2.2	−14.9	+1.6	27.1
Material transportation	Short	Long distance	−770	+340	880	+620	1650	−36.7	+7.5	−2.8	+13.7	33.9
Carbon intensity of fuel	Coal	NG	−1270	−160	90	−170	1360	−12.8	+31.4	−2.0	+14.5	10.8
Logging residue	Recovered	Not recovered	−520	+590	630	+370	1150	−26.2	+18.0	−4.8	+11.7	21.4
Wood processing residue	Recovered	Not recovered	0	+1110	880	+620	880	−10.7	+33.5	2.2	+18.7	12.9
Construction waste	Recovered	Not recovered	−950	+160	370	+110	1320	−39.3	+4.9	−13.0	+3.5	26.3
Demolition wood	Recovered	Not recovered	340	+1450	1260	+1000	920	−0.4	+43.8	14.3	+30.8	14.7
Surplus forest	50% growth	0% growth	−1110	0	260	0	1370	−44.2	0.0	9.1	+25.6	53.3
Surplus forest	50% growth	Bioenergy	−1110	0	−830	−1090	280	−44.2	0.0	−23.3	−6.8	20.9
Worst-case for concrete-frame	—	See text	−470	+640	1980	+1720	2450	−26.6	+17.6	61.6	+78.1	88.2
Worst-case for wood-frame	—	See text	2130	+3240	1160	+900	−970	56.2	+100.4	55.0	+71.5	−1.2

CO_2 balance similar to that of burning for energy, and landfilling of demolition wood will likely result in a CO_2 balance substantially higher than that of burning for energy [31].

Recovery of logging residue, wood processing residue and construction waste also make a large impact on the energy and CO_2 balances of the constructions. If these residues are not recovered and used as fuel, the energy balance would increase by 1860 and 1100 GJ in the wood- and concrete-frame buildings, respectively. If the residues were not used to replace coal but instead were incinerated without energy recovery or allowed to decompose aerobically, the CO_2 balance would increase by 56.4 and 33.9 tonne C in the wood- and concrete-frame buildings, respectively. Taken together, these parameters have a greater impact than recovery of demolition wood.

The growth or utilization of the surplus forest has a large impact on the energy and CO_2 balances of the concrete-frame building. If the surplus forest does not increase in biomass, the CO_2 balance increases because less atmospheric carbon is fixed in growing biomass. No change occurs in the CO_2 balance of the wood-frame building, as no surplus of forest exists in that case. Growth of surplus forest has no effect on energy balance. Leaving surplus forest untouched may not be the best-case scenario in terms of energy and CO_2 balance calculations. Forest growth is a dynamic process, and trees increase in biomass at different rates during their lives. This varies with tree species, climatic conditions and many other factors. Under Nordic conditions, forest rotation periods of around 100 years are common. Trees older than 100 years grow only slowly, and if left unharvested will eventually die and decompose naturally, releasing the energy and CO_2 accumulated through photosynthesis during their lifetimes.

If the surplus forest is not left standing at the time of building construction, but instead harvested and used for bioenergy to replace coal, the energy balance of the concrete-frame building would decrease substantially due to the greater supply of biofuel, and hence the CO_2 balance would decrease. The energy and CO_2 balances for the concrete-frame building are lower in this scenario than in any other scenario considered in this study. This parameter has no effect on the energy or CO_2 balances of the wood-frame building. Harvesting the surplus forest may be more beneficial from an energy and CO_2 balance point of view, although the burning of timber-grade trees as biofuel could be considered an inappropriate use of a high quality economic resource. In general, cascading of forest products may be the most efficient way to use trees and the forestland on which they grow [32]. More detailed study will be required to accurately capture the dynamics of forest growth vis-à-vis wood product use.

The material transportation distance has a substantial impact on the energy and CO_2 balances of both the wood- and concrete-frame buildings. This is due to the fossil energy used to transport both raw materials (logs, aggregate, etc) to processing facilities, and finished building materials from the factories to the construction sites. The exact values obtained in the study depend on the assumptions made of transport distances of the various materials, but the implication is clear that local sourcing of materials can help to reduce energy use and CO_2 emission.

The cement clinker production efficiency, blending of cement and source of concrete aggregate have greater impact on the concrete-frame building than the wood-frame building, due to its higher use of concrete. These three parameters taken together affect the energy balance by 130 and 840 GJ in the wood- and concrete-frame buildings, respectively. They affect the CO_2 balance by 5.2 and 31.1 tonne C in the wood- and concrete-frame buildings, respectively. High efficiency clinker production and use of blended cement is expected to continue increasing in the future, while the use of natural aggregate is not. In Sweden, the use of natural sand and gravel decreased from 70 to 23 million tonnes per year during the period 1990–2002, while the use of crushed stone increased during the same period from 25 to 38 million tonnes per year [33,34]. Total aggregate use declined during the period because of decreased activity in the construction sector. The Swedish Parliament has established, as an interim target of an environmental quality objective, a limit of 12 million tonnes of natural gravel extraction per year, to be achieved by 2010. Policy measures implemented to reach this target include licensing of gravel pits and taxation of natural gravel extraction.

The carbon intensity of fossil fuels has a significant impact on the CO_2 balance, particularly when large amounts of biofuel are recovered to replace fossil fuel. If natural gas were used instead of coal for electricity generation, the energy balance would decrease due to higher conversion efficiency in electricity generation and differences in fuel-cycles between the two fuels. The energy balance of the wood-frame building in this scenario is the lowest of all studied scenarios. However, if natural gas were used for electricity generation and if the recovered biofuels replace natural gas instead of coal, the CO_2 balance would increase. Although using natural gas for electricity generation emits less CO_2 than coal, replacing natural gas with biofuel avoids less CO_2 emission than would have been avoided had coal been the fossil fuel replaced.

4.4. Worst-case combinations of parameter changes

The analyses above considered the effects of varying one parameter at a time, and determined the changes in energy and CO_2 balances resulting from the change of each parameter while keeping all other parameters constant. In all cases, the wood-frame building had lower energy and CO_2 balances than the concrete-frame building. While almost all the parameter variations increased the energy and CO_2 balances compared to the reference case, some parameter variations had a greater effect on one of the building-frame materials compared to the other material. Some parameter variations make the wood-frame building more advantageous compared to the concrete-frame buildings: low clinker process efficiency, unblended cement, crushed aggregate, ore-based steel, long transportation distances, and zero growth of surplus forest. Other parameter variations improve the situation of the concrete-frame building relative to the wood-frame building, and reduce the difference between the two building types: low wood drying efficiency, no recovery of logging residue, no recovery of wood processing residue, no recovery of construction waste, no recovery of demolition wood, lower carbon intensity of fossil fuels, and use of surplus forest as biofuel.

To determine the effects of combinations of parameter variations, particularly those combinations that could most affect the relative energy and CO_2 balances of the two building types, we varied parameters to make worst-case situations for both the wood- and concrete-frame buildings. With the worst-case combination of parameters for the concrete-frame building, the energy balance of the concrete-frame building increased by 1720 GJ compared to the reference case. The energy balance of the wood-frame building increased by 640 GJ, but still remained negative. The CO_2 balance of the concrete-frame building increased by 78.1 tonne C and produced the highest CO_2 balance encountered in this study. The CO_2 balance of the wood-frame building increased by 17.6 tonne C.

With the worst-case combination of parameters for the wood-frame building, the energy balance of the wood-frame building increased by 3240 GJ, giving the highest energy balance encountered in this study. The energy balance of the concrete-frame building increased by 900 GJ. The CO_2 balance of the wood-frame building increased by 100.4 tonne C. The CO_2 balance of the concrete-frame building increased by 71.5 tonne C. This was the only scenario in this study in which the energy and CO_2 balances of the wood-frame building were higher than those of the concrete-frame building.

5. Conclusions

We conducted this study to identify factors that contribute most significantly to the variation of energy and CO_2 balances of building material lifecycles, and to compare the energy and CO_2 balances of buildings made with wood and concrete frames. The reference case that we considered generally represents the most efficient methods in use today. Because of temporal and spatial dynamics of the diffusion of new technologies, less efficient practices are still in use in many areas. There may, however, be other reasons besides energy and CO_2 balance considerations why more efficient parameter conditions are not preferred. For example, using natural gravel as concrete aggregate uses less fossil fuel and emits less CO_2 than using crushed gravel, but may not be preferred due to the local unavailability of natural gravel or the environmental impacts of gravel extraction. There may also be economic forces that compel the choice of parameter conditions that result in higher energy and CO_2 balances.

We found that the recovery of wood-based by-products for use as biofuel to replace fossil fuel, especially demolition wood and sawmill and logging residues, has the most significant impact on the energy and CO_2 balances of both the wood- and concrete-framed buildings. Parameters affecting concrete production, such as clinker production efficiency, blended cement additives, and source of concrete aggregate, also have substantial effects on the energy and CO_2 balances of the concrete building, but smaller effects on the wood-framed building. Material transportation distance affects the balances of both buildings. The status of the surplus forest not required for production of building materials for the concrete-framed version influences the CO_2 balance of the concrete-framed building. The assumptions of forest growth rate used in this study were rough, and further analyses of the effects of surplus forest development will be conducted using more sophisticated forest models.

Regardless of the variations of different parameters, we found that the wood-framed building had lower energy and CO_2 balances than the concrete-framed building in all cases except the worst-case combination of parameters that was most unfavorable for the wood-frame building. The energy balance of the wood-framed building was negative in all cases except when wood processing residue or demolition wood was not recovered and used as fuel. The concrete-framed building generally had a positive energy balance. The CO_2 balance of the wood-frame building was negative regardless of the variation of any single parameter.

The precise values of the energy and CO_2 balances of building materials depend upon many factors, but we conclude that the use of wood construction material will, in general, result in lower energy and CO_2 balances than when concrete is used. Our results are in agreement with, and provide contextual support to, previous studies, e.g. [1–9]. The use of wood building material instead of concrete, coupled with the greater integration of wood by-products into energy supply systems, could be an effective means of reducing fossil fuel use and net CO_2 emission to the atmosphere.

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