Carbon Dioxide Implications of Building Materials

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ABSTRACT

The concern over environmental issues, such as global warming, is growing and will influence consumers in the market place. A significant proportion of our forest is used to manufacture wood building materials.

Carbon dioxide (CO_2) emissions of two representative constructions using wood building materials were compared to emissions for non-wood building materials. The energy required to extract the raw materials, to manufacture and distribute the building materials was used to estimate CO_2 emissions.

The study showed that wooden structures require the least amount of energy and emit less CO_2 than other building materials. This finding should be included by consumers, designers and builders in comparative evaluation of building materials at the design stage, when decisions are made regarding the type of materials to be used.

Key words: *Carbon dioxide (CO_2) emissions, global warming, wood building materials, non-wood building materials, energy content, energy sources.*

INTRODUCTION

The rising of the earth's temperature, suspected to result from excessive emissions of carbon dioxide (CO_2) and other gases, is a major global concern.

CO_2 is emitted by chemical reactions (e.g. calcination), burning renewable fuels (e.g. wood) or burning fossil fuels (e.g. coal and oil). Fossil fuels are the common source of energy for the manufacture of building materials.

CO_2 is taken from the atmosphere by growing forests, plants and other forms of living organisms, and is emitted to the atmosphere by decay of forest litter and residues, and with decay of organic products including wood when they are discarded after the useful life of the products. Wood is different from other building materials in that 50% of its dry weight is carbon. However, quantitative methods for carbon budgeting through forest growth and decay cycles are still under development. These aspects are not considered in this paper, which concentrates on the energy input and CO_2 emissions in converting wood to components of buildings in comparison with other building materials.

CO_2 is a result of human activities such as raw material extraction, manufacture and distribution of both wood and non-wood building materials; therefore, CO_2 emissions can be used as one of the relative measures of the environmental friendliness of a building product and help determine its desirability in construction. Wood building materials consume a large percentage of the harvested forest and their relative environmental friendliness may ultimately affect forest utilization.

Reported energy analyses of building materials [1,7] indicated that a building constructed with wood consumed less energy than a building constructed with other building materials. The CO_2 emissions from the manufacture of building materials for a structure are proportional to the total energy consumed in the production of the building materials; therefore the CO_2 emissions associated with a wood construction would also be expected to be less.

The objective of this study was to quantify and compare the energy consumption and CO_2 emission of building in wood as opposed to materials such as brick, concrete, steel or aluminum.

METHOD

This paper uses the energy approach to estimate CO_2 emissions, taking into account the energy sources used in Canada to manufacture the building materials required in two representative constructions:

1. a two-storey, 215 m^2 (2,000 ft^2) residential house with full basement
2. the new 11,000 m^2 (101,600 ft^2) Forintek Research facility in Vancouver, British Columbia.

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The energy requirements to transform raw materials into useful building materials, including the energy spent on the construction site for erection, were based on data compiled by the US Department of Energy [9], as data for Canada was not available, and the industrial technology in the two countries is similar. Table 1 shows the energy requirements for the main building materials and elements used in this study.

The first step in determining the CO_2 emissions per unit of energy for the building material was to identify the energy sources [3,4] used in the manufacture of the material and to break down these sources as percentages. Table 2 shows the calculated energy source percentages for the building materials considered.

Table 1. Energy consumption of building materials.

BUILDING MATERIALS	ENERGY CONTENTS (MJ per)
Concrete	3,574 m^3
101 mm (4") Concrete Slab	365 m^2
203 mm (8") Concrete Block	542 m^2
Framing Lumber	3,407 m^3
Plywood	6,903 m^3
12 mm (1/2") Exterior Plywood	88 m^2
16 mm (5/8") Exterior Plywood	110 m^2
19 mm (3/4") Exterior Plywood	132 m^2
Exterior Finish	
Cedar Siding	83 m^2
0.61 mm (0.024") thick Aluminum Siding	606 m^2
0.63 mm (0.025") thick Vinyl Siding	114 m^2
101 mm (4") Brick & Masonry	1,488 m^2
Roofing	
Cedar Shingles	83 m^2
0.81 mm (0.032") thick Aluminum Ribbed	962 m^2
Tile	487 m^2
Floor Finish	
Hardwood Floor	108 m^2
2.4 mm (0.093") thick Vinyl Floor	426 m^2
Glazed Ceramic Tile	780 m^2
Wood Window Sash & Frame	
610 x 915 mm (2' x 3')	976 ea
1220 x 1220 mm (4' x 4')	1,424 ea
1220 x 1830 mm (4' x 6')	1,720 ea
Aluminum Window Sash & Frame	
610 x 915 mm (2' x 3')	1,014 ea
1220 x 1220 mm (4' x 4')	1,698 ea
1220 x 1830 mm (4' x 6')	2,289 ea
Glazing (double glazed)	350 m^2
Wood Door	
813 x 2032 mm (2'8" x 6'8") Hollow Core	844 ea
1016 x 2032 mm (3'4" x 6'8") Panel	1,298 ea
Miscellaneous	
Nails & Steel	79 kg
Building Paper (2 ply)	12 m^2
Exterior Oil-Base Paint	16 m^2
Interior Water-Base Paint	10 m^2
10 mm (3/8") Gypsum	60 m^2
12 mm (1/2") Gypsum	79 m^2
89 mm (3 1/2") Fiberglass Insulation	78 m^2

Emission factors for the energy sources in Canada were based on data published by Environment Canada [6] or calculated based on a given set of assumptions. These factors (Table 3) were used to convert energy expended to CO_2 cost.

The following assumptions were used to determine the CO_2 emissions for each building material:

1. The sources of electrical energy are 64.9% hydro-power, 15.12% nuclear, 16.65% coal-fired, 1.80% oil-fired and 1.47% natural gas [6]. Nuclear energy and hydroelectric energy were assumed not to emit CO_2.

   Other environmental impacts of the construction of hydro-electric dams and nuclear-power plants were not considered in this analysis.

2. The energy contents of building materials listed in Table 1 were used. These energy contents were US national averages, compiled from data collected in 1976 and 1977.

3. The CO_2 emissions factor for cement of 0.499 Kg/Kg, published by Environment Canada [6] which accounts for the chemical reactions that take place in a kiln, was increased to 0.513 Kg/Kg to include emissions from the industrial process of cement production [8]. It was assumed that concrete consists of one part of cement and four parts of gravel and sand (i.e. 20% of the concrete by weight is cement). Carbon dioxide emissions from the handling of gravel and sand were assumed to be negligible compared to cement production.

4. Heat and steam for the production of wood products are generated from hog fuel combustion.

5. The average life of a North American building is 50 years. The energy consumed for expected maintenance and material replacement, for example, exterior painting and roof shingle replacement, was included in the analyses.

6. Direct energy and business overhead energy expended in construction were not included in

Table 2. Energy sources in the manufacture of building materials.

Building Materials	Electric Power %	Carbon Based Fuels: Gasoline %	Diesel %	Coal %	N. Gas* %	LPG** %	Hog Fuel %
Lumber	23.86	38.89	5.84	0	10.29	0.42	20.70
Concrete	8.24	8.14	21.76	52.36	9.40	0.10	0
Building Paper	14.29	2.26	17.45	0	64.44	1.56	0
Gypsum	6.75	8.53	8.53	0	76.19	0	0
Fibre Glass	16.52	0.37	0.63	8.71	72.92	0.85	0
Glazing	8.19	0.37	0.64	3.42	87.35	0.03	0
Vinyl	18.58	0.89	7.61	34.27	38.59	0.06	0
Steel	15.63	0.93	6.15	30.56	46.55	0.18	0
Aluminum	75.95	0.28	13.22	4.38	6.15	0.02	0
Brick/Tile	5.35	2.13	5.08	15.23	71.53	0.68	0
Paints	18.38	4.57	2.90	0	39.47	34.68	0
Plywood	40.83	1.96	0.37	0	28.42	1.09	27.33
Hardwood Floor	48.87	25.57	25.56	0	0	0	0
Cedar Shingle	39.75	25.00	25.00	0	0	0	10.25
Stucco	5.60	8.86	1.86	55.93	27.42	0.33	0

* Natural gas
** Liquefied petroleum gas

the comparison, since they would generally be the same for a building of the same size constructed in wood or other materials.

7. The logs used to manufacture all wood building materials were harvested from a mature forest that reached a steady state in its CO_2 O_2 exchange process.

CALCULATION OF ENERGY CONSUMPTION AND CO_2 EMISSION OF BUILDINGS

The energy and the CO_2 cost of a building were calculated based on a detailed "material take off" (Table 4). The following describes the buildings and their respective assemblies as used in this study:

Table 3. Carbon dioxide emlissions factors by fuel type.

FUEL TYPE	EMISSIONS FACTORS Kg/GJ
Electricity	24.6
Gasoline	68.0
Diesel	70.7
Coal	94.4
Natural Gas	49.7
LPG	59.8
Hog Fuel	81.4

Residential Building

A typical two-storey single-family house with a 11 x 8.5 m (36 x 28 ft) footprint and full basement was used in this analysis. The material quantity profile was obtained from MIT [2].

Four residential assemblies similar in performance were considered; the thermal resistivity (R-values) of the wall assemblies were about R15-16 (°F-ft^2-hr/Btu-in). All four assemblies used wood frame construction; this would be typical for a small-scale, single family house.

The first assembly had a preserved wood foundation, 51 mm x 140 mm (2 x 6 in) exterior wood frame, 51 mm x 89 mm (2 x 4 in) interior wood frame, wood windows, cedar siding and cedar shingle roof. The analysis included painting the exterior siding five times and replacing the roof shingles once over the 50 year life of the building.

The second assembly had a concrete foundation wall, 51 mm x 140 mm (2 x 6 in) exterior wood frame, 51 mm x 89 mm (2 x 4 in) interior wood frame, 89 mm ($3^{1/2}$ in) thick brick veneer, tile roof, glazed floor tiles for kitchen and bathrooms, and aluminum windows.

The third assembly had a concrete block foundation wall, 51 mm x 140 mm (2 x 6 in) exterior wood

Table 4. Material takeoff for the four assemblies of the residential building.

Description	Material	Assembly	Area m^2(ft^2)	Volume m^3(ft^3)	Comments
Footing	Concrete	All	16 (170)	3.20 (113)	
Basement Slab	Concrete	All	94 (1008)		101mm (4") slab
Foundation Wall	Concrete	2	95 (1024)	24.15 (853)	
	Concrete block	3,4	95 (1024)	19.14 (676)	203mm (8") thick block
	Lumber	1		4.76 (168)	
	Plywood	1	95 (1024)		19mm (3/4") thick plywood
Exterior Wall Structure	Wood (2x6)	1,2,3	196 (2112)	9.51 (336)	38 x 140mm (2x6") construction
	Wood (2x4)	4	196 (2112)	6.34 (224)	38 x 89 mm (2x4") construction
	Concrete block	4	196 (2112)		203mm (8") thick block
	Plywood	1,3		2.49 (88)	12mm (1/2") thick sheathing
	Plywood	2		1.87 (66)	10mm (3/8") thick sheathing
Exterior Wall Surface	Cedar Siding	1	196 (2112)		19mm (3/4") siding
	Brick	2	196 (2112)		89mm 1,900kg/m^3 (3 1/2" 120#/cu.ft.)
	Aluminum Siding	3	196 (2112)		0.5mm (0.019") thick
	Stucco	4	196 (2112)	0.62 (22)	3mm (1/8") thick
	Building Paper	1	291 (3136)		2 ply
	Building Paper	2,3,4	196 (2112)		2 ply
Inside Surface Exterior Wall	Gypsum	1,3	196 (2112)		12mm (1/2") thick
	Gypsum	2,4	196 (2112)		10mm (3/8") thick
Exterior Wall Insulation	Fiberglass	All	196 (2112)		89mm 8 kg/m^3 (3 1/2" thick 0.5#/cu.ft.)
Interior Wall Structure	Wood (2x4)	All	171 (1840)	5.38 (190)	38 x 89mm (2x4") wood frame
Interior Wall Finish	Gypsum	All	342 (3680)		12mm (1/2") thick
Windows	Wood	1			Eight 610 x 915mm (2x3') windows Six 1220 x 1220mm (4x4') windows One 1220 x 1830mm (4x6') window
	Aluminum	2,3,4			Quantity & size same as above
Doors	Wood	All			One 1016 x 2032mm (3'4" x 6'8") panel door Thirteen 813 x 2032 mm (2'8" x 6'8") hollow core doors
Floor Structure	Wood	All	187 (2016)	9.91 (350)	Wood joist 7.53m^3 (266 cu.ft.) and sheathing 2.38m^3 (84 cu.ft.)
Floor Finish	Hardwood	All	94 (1008)		
	Vinyl	1,3	28 (302)		
	Tile	2,4	28 (302)		
Ceiling	Gypsum	All	187 (2016)		12mm (1/2") thick
Roof Structure	Wood	1,2,4		4.81 (170)	
	Wood	3		4.08 (144)	
	Plywood	3	113 (1216)		16mm (5/8") thick
Roofing	Cedar Shingles	1	113 (1216)		
	Tile	2,4	113 (1216)		
	Aluminum	3	113 (1216)		
	Building Paper	3	113 (1216)		2 ply
Roof Insulation	Fiberglass	All	94 (1008)		
Nails		All			227kg (500 lbs)
Paints	Interior	All	529 (5696)		
	Exterior	1	196 (2112)		

Table 5. Energy consumption of the four assemblies of the residential building (GJ).

Building Material	Assembly 1 Wood	Assembly 2 Brick	Assembly 3 Aluminum	Assembly 4 Concrete
Lumber	140	98	83	88
Concrete	46	132	97	203
Building Paper	3	2	4	2
Gypsum	58	54	57	54
Insulation	23	23	23	23
Glazing	5	5	5	5
Steel	18	18	18	18
Vinyl	12	-	12	-
Aluminum	-	15	248	15
Brick & Tile	-	369	-	77
Paints	23	8	8	8
Plywood	34	30	36	17
Hardwood Floor	17	17	17	17
Stucco	-	-	-	2
Cedar Shingles	35	-	-	-
TOTAL	414	771	618	529

Table 6. CO_2 emission of the four assemblies of the residential building (tonnes).

Building Material	Assembly 1 Wood	Assembly 2 Brick	Assembly 3 Aluminum	Assembly 4 Concrete
Lumber	8.2	5.8	4.9	5.1
Concrete	3.5	10.2	7.5	15.7
Building Paper	0.2	0.1	0.2	0.1
Gypsum	3.0	2.8	2.9	2.8
Insulation	1.1	1.1	1.1	1.1
Glazing	0.3	0.3	0.3	0.3
Steel	1.1	1.1	1.1	1.1
Vinyl	0.7	-	0.7	-
Aluminum	-	0.5	8.8	0.5
Brick & Tile	-	20.9	-	4.4
Paints	1.2	0.4	0.4	0.4
Plywood	1.6	1.4	2.3	0.8
Hardwood Floor	0.8	0.8	0.8	0.8
Stucco	-	-	-	0.2
Cedar Shingles	1.9	-	-	-
TOTAL	23.6	45.4	31.0	33.3

frame, 51 mm x 89 mm (2 x 4 in) interior wood frame, aluminum windows, aluminum siding and roofing.

The fourth assembly had a concrete block foundation wall, 203 mm (8 in) exterior concrete block wall, 51 mm x 89 mm (2 x 4 8 in) exterior and interior wood frames and tile roof.

Forintek Building

The existing wood frame structure of the Forintek Western research facility formed a reliable basis for our analyses. It was not practical to reengineer the entire building in steel. Instead three typical sample areas; office, laboratory and pilot plant, representing structural conditions that apply to 90% of the building, were selected. The analysis was based on the material quantity profiles for steel and wood assemblies of these representative portions of the building provided by Hanscomb Consultants Inc., project managers for the Forintek building [5]. Energy and CO_2 costs per unit area for these sections were calculated and used to estimate the total energy anc CO_2 costs of the entire building following the same approach as the Forintek cost comparison study [5]. While the results of this approach are not as certain as those which would have been obtained by completely redesigning the project in steel, they are considered accurate within a margin of ±5%. Even at extreme of this range, the conclusion of this study would not change.

RESULTS

The results are shown in Tables 5 through 8.

Residential Building

The wood assembly consumed 414 GJ and emitted 23.6 tonnes CO_2. In comparison: the brick assembly emitted 1.92 times, the concrete assembly emitted 1.41 times and the aluminum assembly emitted 1.31 times more CO_2 than the wood assembly (Figure 1).

Table 7. Energy consumption of the wood and steel assemblies of the Forintek facility (GJ).

Location	Wood Assembly	Steel Assembly
Office/Lab Floor	2,837	9,458
Office/Lab Roof	3,653	7,648
Pilot Plant	1,646	5,818
TOTAL	8,136	22,924

Table 8. CO_2 emission of the wood and steel assemblies of the Forintek facility (tonnes).

Location	Wood Assembly	Steel Assembly
Office/Lab Floor	157	581
Office/Lab Roof	197	463
Pilot Plant	94	352
TOTAL	448	1,396

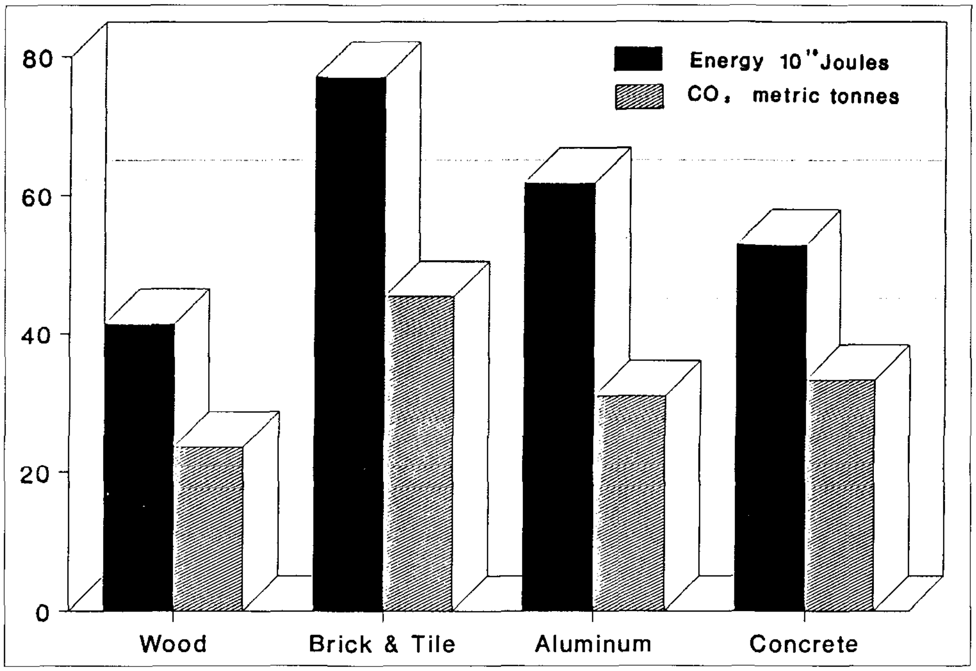

Figure 1. Energy and CO_2 cost comparison of the four residential buildings.

Although the aluminum assembly consumed 1.17 times more energy than the concrete assembly, the CO_2 emitted was less. This was because 75% of the energy spent in the aluminum assembly was electrical energy which emits little CO_2 under the assumptions of this study.

The Forintek Building

The steel Forintek building would have consumed 2.82 times more energy than the wood Forintek building and emitted 3.12 times more CO_2 (Figure 2).

Steel structures are common for commercial buildings. This case showed that wood commercial constructions would consume less energy and emit significantly less CO_2 than steel ones.

CONCLUSIONS

This is a preliminary study with approximate results, but realistic for comparison purposes. It shows that with existing technologies in North America, the CO_2 emissions associated with wood construction are lower than those for similar construction using other building materials.

Thus wood is an environmentally desirable building material offering economies in fuel consumption and CO_2 emissions. This should encourage designers, builders and consumers to consider the incorporation of more wood in residential and industrial buildings, and to evaluate the economic costs of such changes.

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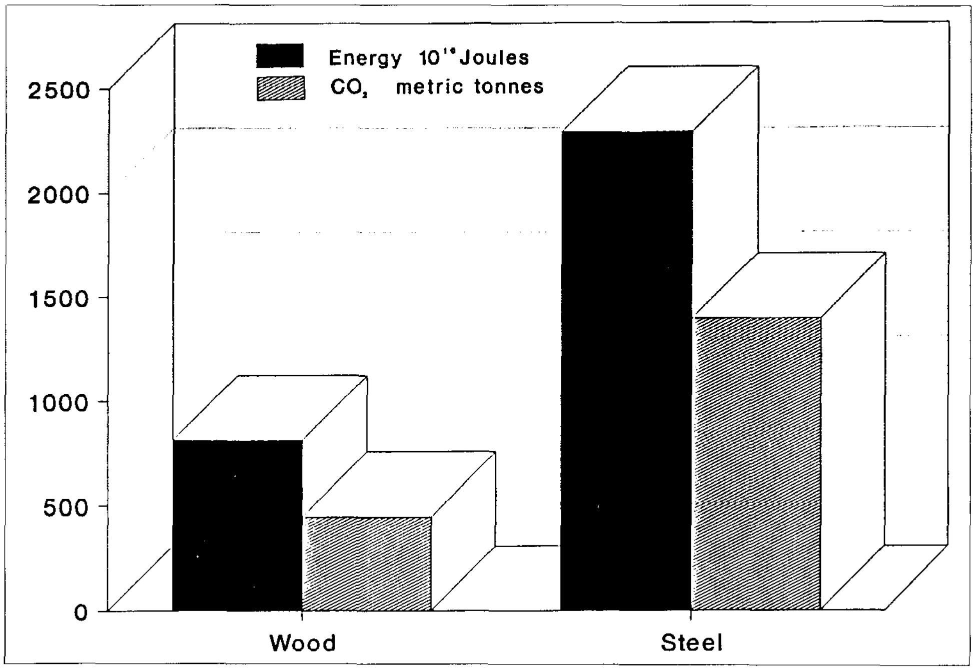

Figure 2. Energy and CO_2 cost comparison of the wood and steel assemblies of the Forintek Research Facility.

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