Saving Energy versus Saving Materials

Life-Cycle Inventory Analysis of Housing in a Cold-Climate Region of Japan

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Summary

To reduce energy consumption and carbon dioxide (CO_2) emissions in housing construction, the energy-intensive processes and life-cycle stages should be identified and integrated. The environmental impact of vertically integrated factory-built homes (VIHs) constructed with increased material inputs in Japan's northern island of Hokkaido was assessed using life-cycle inventory (LCI) analysis methods. Manufacturing process energy and CO_2 intensities of the homes were evaluated based on the material inputs. They were compared with those of a counterpart home hypothetically built using the vertically integrated construction methods, but in accordance with the specifications of a less material-intensive conventional home (CH) in Hokkaido today. Cumulative household energy consumption and CO_2 emissions were evaluated and compared with those of the production stages. The annual household energy consumption was compared among a VIH, a CH, and an average home in Hokkaido. The energy intensity of the VIH was 3.9 GJ production energy per m² of floor area, 59% higher than that of the CH. Net CO_2 emissions during VIH manufacturing processes were 293 kg/m², after discounting the carbon fixation during tree growth. The cumulative use-phase household energy consumption and CO_2 emissions of a VIH will exceed energy consumption and CO_2 emissions during the initial production stage in less than six years. Although VIHs housed 21% more residents on average, the energy consumption per m² was 17% lower than that of a CH.This may indicate that using more materials initially can lead to better energy efficiency.

Introduction

In Japan, between 1.2 and 1.5 million housing units are constructed yearly, a total exceeding that of the United States. The typical existing Japanese house has a projected life span of thirty years, after which it is demolished and replaced (Japan Housing Loan Progress Association 1997). In 1985, housing construction consumed 416,000 TJ (terajoules, 10^{12} J or about 395 trillion BTU) of energy, representing 4% of Japan's domestic energy use (Ministry of International Trade and Industries 1985). Strategies to reduce energy consumption and CO_2 emissions associated with housing construction need to be identified in order to minimize the environmental impact of housing construction. In Japan, the design and construction of longer-lasting homes may lessen the industry's environmental burden. In Japan's competitive housing market, however, innovations by individual home builders that improve the longevity of houses are not feasible if the prices are not comparable to those of their competitors.

Wood has been the favored material for both structural and decorative features in Japanese houses for millennia (Cohen et al. 1996). By adapting construction techniques used in Japanese historical wooden buildings, a vertically integrated construction company in Hokkaido, a northern island of Japan, has developed and applied unique design concepts aimed at increasing the longevity of its homes, as well as attaining a sustainable manufacturing process. These concepts include optimization of resource use and home designs suited to the unique climate and culture of Hokkaido. The vertically integrated housing construction company analyzed here differs from conventional factory-built house construction in that a substantial fraction of its lumber is milled from logs and cut to specifications in the factory and shipped as components for assembly at the home construction site. After-sale maintenance assures the performance and longevity of the home. By optimizing resource use, reducing waste, and facilitating recycling, vertically integrated construction techniques permit the builder to use materials more efficiently in constructing homes that last longer while maintaining competitive pricing.

The environmental impacts of the vertically integrated company's factory-built (VIH) homes were evaluated and compared to those of a conventional home (CH) using a life-cycle inventory (LCI) analysis method. The conventional house in the comparison was hypothetically built with the construction methods of the company, but with fewer material inputs, in accordance with the specifications of a typical conventional home in Hokkaido today. This house was assumed to have been constructed by the vertically integrated company so that the efficiencies gained by vertically integrated construction would be equally weighted for both the VIH and the CH. Figure 1 shows photographs of a VIH and of a CH from the Hokkaido region. The environmental impacts in terms of energy consumption and CO_2 emissions for all production stages of home construction, from the production of building materials to on-site construction, were assessed. Energy use and CO_2 emissions during the use phase of the homes were evaluated based on an energy-consumption survey of 12 VIHs and 13 CHs as well as the published values of average household energy consumption in Hokkaido. LCI analysis was used to measure the environmental costs and benefits of increasing material inputs in the con-

(a)

(b)

Figure 1 Photographs of (a) a vertically integrated home (VIH) and (b) a conventional house (photo credit: Yurika Nishioka).

struction phase. Some of the initial environmental impacts of the increased material inputs may be balanced by the improved longevity of homes (i.e., greater resistance to earthquake damage and less frequent replacement of the structure), energy saving during the use phase, and the reutilization of wood waste through production loops within the vertically integrated firm. To explore energy saving during the use phase, the annual energy consumption of a VIH was compared with that of a CH and an average home in Hokkaido (AH).

Characteristics of Vertically Integrated Factory-Built Homes

The winter climate in Hokkaido is severe. The mean daily temperature in Sapporo, the capital of Hokkaido, is –4.4°C (24.1°F) in January, and the mean winter snowfall is 6.0 m (19.7 ft) (National Astronomical Observatory 1995). Homes in Hokkaido are designed for cold climates and have to comply with rigid earthquake construction codes. Despite these standards, conventional wooden homes in Japan are ravaged by excess moisture. Designing homes that are resistant to condensation and penetration of moisture extends longevity.

The following innovations have been incorporated into the design of vertically integrated houses (VIHs) to improve their compatibility with the climate and increase their durability and energy efficiency:

1. Increasing the quantity of materials per unit area of floor space.

2. Incorporation of the post-and-beam construction method, as used in historic Japanese structures. This method uses complex wooden joints, thereby reducing the number of steel connectors such as nails, fasteners, and hinges. These unique complex joints allow wood structural supports to expand and contract with moisture, thus reducing the stress moisture places on these elements.
3. Elevation of the wooden structural components from the standard 0.63 m above grade to 2.38 m above grade, by construction of a ground-floor concrete structure. This design element keeps the wooden components away from ground moisture and snowdrifts. In Hokkaido, snowdrifts along the sides of homes are routinely over 1 m high throughout the winter season. The concrete structure can also serve as a garage and an additional storage area.
4. Use of a five-paned window system. The heat-transfer resistance (R-value) of this five-paned system is 0.52 $m^2h°C/kcal$ (or 2.54 $ft^2h°F/Btu$), while that of the CH is 0.39 $m^2h°C/kcal$ (or 1.90 $ft^2h°F/Btu$).
5. Use of thick insulation in the walls and roof with R-values of 4.1 $m^2h°C/kcal$ (20.0 $ft^2h°F/Btu$) and 5.4 $m^2h°C/kcal$ (26.4 $ft^2h°F/Btu$).

Methods

The life-cycle process inventory was split into three categories: materials, energy, and carbon dioxide (CO_2) emissions. Material matrices were developed for both CH and VIH construction. The following building components were included in the matrices: foundations, framing, steel reinforcement, sidings, window systems, doors, interior finished carpentry (cabinetry, moldings, and railings), roof tops, on-site assembly, and wallcovering. Building components not included in the material matrices were kitchen and bathroom plumbing fixtures, lighting, electrical fixtures, furnace and ductwork, bricks, curtains, paints, sand, gravel, mortar, tiles, paper products, urethane foam and isocyanate foam siding insulation, terrace components, carpets, and plastics. These materials were excluded because our goal was to compare energy and CO_2 intensities resulting from differences in structural design. The excluded components except for sand and gravel account for 4 percent of the total building mass of VIH and 6 percent of CH, but the absolute quantities or quality of those excluded materials were not significantly different. The amount of sand and gravel required for site preparation varies depending on the location and the soil conditions of construction sites.

The vertically integrated company's records on lumber inputs for October 1996 through February 1997 were used to evaluate the resource-use efficiency of logs. During this period, approximately 62 homes were constructed per month with floor areas ranging from 85 to 205 m^2, with an average of 148 m^2.

The energy required to build a square meter of floor area was calculated from the material inputs. The energy intensity per m^2 of floor area was analyzed in terms of (1) the production energy with all major building components considered, and (2) the embodied energy of the house with the use phase taken into consideration. The manufacturing processes of vertically integrated housing were divided into seven categories:

1. Logging and hauling
2. Shipping
3. Miscellaneous delivery within the company
4. Primary processing
    - processing of structural lumber, finger-joint glued and laminated lumber ("glulam" and veneers)
    - boiler operations
    - office building operations
5. Boiler heating fuel (renewable)
6. Secondary processing
    - sizing and assembling wall panels, furniture, doors, windows, carpets, and decorative materials.
7. Construction
    - site preparation and transportation of workers
    - transportation of materials
    - diesel-powered construction equipment
    - kerosene for concrete treatment on site

The energy use in each category was obtained from company records covering the period October 1996 through February 1997. Process energy data for building materials manufactured by external companies were obtained from values in the literature (table 1).

The energy and CO_2 budgets for a home having the material inputs of a CH, yet optimizing material resources using a vertically integrated manufacturing process were evaluated. Information on material inputs was obtained from a materials inventory of a CH with a floor area of 112.5 m^2.

The household energy consumption from November 1997 through April 1998 was reported for 15 VIHs and 15 CHs. Due to missing values, the records available on kerosene consumption were, on average, for a period of 5.7 months for the VIHs and a period of 5.2 months for the CHs. The records available on electricity consumption were, on average, for a period of 5.3 months for the VIHs and a period of 4.7 months for the CHs. None of these homes used electricity for cooking stoves. Almost all homes used kerosene for both space heating and water heating. Homes using natural gas or electricity for water heating and/or main space heating were excluded from the analysis because we could not differentiate energy use for space heating alone. A household using a public bath facility was also excluded in order to avoid underestimating the average water-heating energy consumption. Consequently, we used 12 VIHs and 13 CHs to calculate the average household winter heating-energy and electricity consumption.

The annual energy consumption, as well as the space-heating and water-heating energy during the use phase, was estimated from the winter energy survey and the values published by Nagasaka and colleagues (1995) and by the Hokkaido Electric Power Research Corporation (HEPRC 1993). From the data given in Nagasaka and colleagues (1995), we found that the space heating as well as the electricity for the period from November to April corresponded to 90% and 57% of the annual consumption, respectively. Water-heating energy was proportionally adjusted for the number of occupants. Electricity was assumed to have 40% energy efficiency at the generation site. Because Nagasaka and colleagues (1995) do not differentiate heating sources, for an AH we used HEPRC's values for the average annual space-heating and water-heating energy that represented solely kerosene.

The following formulas, therefore, were used to estimate the average annual water-heating and space-heating energy as well as electricity consumption.

Table 1 Embodied energy and CO_2 emissions per unit of building products

Products	*Embodied process energy (MJ/kg product)*	*Process CO_2 emissions (g/kg product)*	*Reference sources*
Lumber	11.9	1,084.1	Company records, EMR 1990
Concrete	0.505	78.7	Ministry of International Trade & Industry 1990a Japan Environment Agency 1992
Glass	16.6	1,061.7	Franklin Associates 1990
Steel, electric furnace	6.7	440	Japan Environment Agency 1992 Ministry of International Trade & Industry 1990b
Steel, blast furnace	16.8	1,467	Japan Environment Agency 1992 Ministry of International Trade & Industry 1990b
Fiberglass	29.1	2,622.3	Franklin Associates 1990
Aluminum	207.7	18,115.5	Franklin Associates 1990
Plywood	8.8	587.0	Forintek Canada Corp 1993
Gypsum	6.7	492.3	American Institute of Architects 1996

- Annual kerosene consumption for water heating (VIH or CH, per m^2) = annual kerosene for water heating (AH, per m^2) × number of occupants in VIH or CH / number of occupants in AH (Eq. 1)
- Annual kerosene consumption for space heating (VIH or CH, per m^2) = [the mean total kerosene consumption from November to April (VIH or CH, per m^2) – (Eq. 1) × .05)]/0.9
- Annual electricity consumption (VIH or CH, per m^2) = Total electricity consumption from November to April/0.57

The estimated values were compared with the values for an AH published by the HEPRC (1993).

CO_2 emissions were calculated based on the energy sources and reported emissions factors (EMR 1990; Japan Environmental Agency 1992; Franklin Associates, Ltd. 1990; Forintek Canada Corp 1993; The American Institute of Architects 1996). Carbon fixed in wood fiber residuals or "hogfuel" (i.e., residual wood waste such as offcuts and saw dust) was discounted from the CO_2 emissions estimated for the production stages in order to account for the environmental burden avoided by using renewable fuels instead of fossil fuels:

Net CO_2 emissions = {CO_2 emissions from production stages (including emissions from hogfuel combustion)} – {Carbon fixed (CO_2 equivalent) in hogfuel}

By subtracting the CO_2 bound in wood, credits were given to the avoided burden arising from the use of renewable resources rather than fossil fuels. When CO_2 released from wood used for processing is excluded, the analysis is consistent with the Technical Research Center of Finland's report on the environmental impact of building materials (Häkkinen 1994).

Results

Material Input

The material inputs for a CH and a VIH are listed in tables 2 and 3. The VIH was more material intensive than the CH per square meter of floor space in all materials except for fiberglass. As compared to the CH, the VIH contained approximately five times more steel (rebar) and four times more concrete. Concrete, reinforcing steel bars, and mesh are the principal components of the foundation, which is one of the design changes aimed at improving the longevity of the structure.

The VIH consumed 64 m^3 (2,261 ft^3) of raw roundwood. The resource-use efficiency of the raw log inputs for the VIH was close to 100%, because all waste was used as hogfuel for the boiler or coproducts in the factory. The resource allocation for raw logs was 58% final lumber products, 39% for hogfuel, and 3% for coproducts.

Energy Input

Production Energy

The system boundaries, material inputs, and energy sources for each manufacturing process are listed in table 4. During logging and hauling, trees were cut, hauled to the roadside, and delivered to the lumber mill in trailers either directly or via seaports. Diesel fuel consumption, estimated from company records, was 8 liters of diesel fuel per m^3 of tree logging and hauling in forests, and 56 ton-km/liter (146 (short) ton-mi/gal) during road transportation.[1] Logging and hauling required 147 MJ (1.40×10^5 Btu) of fuel energy per m^2 of floor area, corresponding to 3.8 percent of the total production energy.

Shipping distances to Hokkaido were estimated to be 7,700 km (4,786 mi) from Vancouver or Seattle, 1,400 km (870 mi.) from Polonaisk, Russia, and 7,443 km (4,626 mi.) from Jakarta. A bulk carrier was hired for shipping, which consumed 0.00735 kg (0.0162 lb.) heavy oil per ton-km and 0.00063 kg (0.0014 lb.) diesel fuel per ton-km. Log shipping required 233 MJ per m^2 of floor area, corresponding to 6.1% of the total production energy.

Electricity was used in the primary manufacturing plant to (1) process structural lumber, finger-joint glued laminated lumber ("glulam") and veneers; (2) to run the boiler and the drying kilns; and (3) to operate the office buildings. If we assume 40% conversion efficiency from primary energy to electricity, the primary processing required 192 MJ per m^2 of floor area, corresponding to 4.9% of the total production energy.

Wood was delivered to areas of the plant by front-end loaders, fork lifts, and cranes, all of

Table 2 Materials used in the conventional home in Hokkaido (kg/m^2)

	Lumber	*Plywood*	*Concrete*	*Steel*	*Glass*	*Fiberglass*	*Aluminum*	*Gypsum*	*Cement*
Framing	97.7 (0.97)	—	—	—	—	—	—	—	—
Rebar/mesh	—	—	—	5.2 (0.60)	—	—	—	—	—
Furniture	0.9 (0.01)	0.3 (0.025)	—	0.4 (0.045)	—	—	—	—	—
Door/windows	2.0 (0.02)	0.9 (0.07)	—	0.2 (0.022)	2.9 (1.0)	—	0.3 (1.0)	—	—
Sidings	—	7.2 (0.55)	—	—	—	7.6 (1.0)	—	—	13.4 (1.0)
Foundation	—	1.3 (0.10)	246.1 (1.0)	0.1 (0.015)	—	—	—	—	—
On-site assembly	—	—	—	0.4 (0.051)	—	—	—	—	—
Roof tops	—	3.4 (0.26)	—	2.3 (0.27)	—	—	—	—	—
Covering	—	—	—	—	—	—	—	26.6 (1.0)	—
TOTAL	100.6	13.1	246.1	8.7	2.9	7.6	0.28	26.6	13.4
TOTAL MASS IN BUILDING	100.6	13.1	246.1	12.4	2.9	7.6	0.50	26.6	13.4

( ) indicates fractions

Table 3 Materials used in the vertically integrated home in Hokkaido (kg/m^2).

	Lumber	*Plywood*	*Concrete*	*Steel*	*Glass*	*Fiberglass*	*Aluminum*	*Gypsum*
Framing (including wall panels)	120.9 (0.92)	3.4 (0.18)	—	0.1 (0.0025)	—	2.4 (0.37)	—	—
Rebar/mesh	—	—	—	25.6 (0.57)	—	—	—	—
Furniture	5.6 (0.04)	4.1 (0.22)	—	0.1 (0.003)	0.5 (0.064)	—	0.002 (0.002)	—
Door/windows	4.4 (0.03)	0.7 (0.036)	—	0.4 (0.01)	1.90 (0.25)	—	0.8 (0.99)	0.1 (0.003)
Sidings	0.7 (0.005)	10.4 (0.56)	—	10.6 (0.23)	5.2 (0.69)	3.9 (0.63)	—	—
Foundation	—	—	1028.6 (1.0)	0.4 (0.009)	—	—	—	—
On-site assembly	—	—	—	1.3 (0.03)	—	—	—	—
Roof tops	—	—	—	6.7 (0.15)	—	—	—	—
Covering	—	—	—	—	—	—	—	41.5 (0.99)
TOTAL	131.6	18.5	1028.6	45.3	7.6	6.3	0.8	41.6
TOTAL MASS IN BUILDING	134.2	20.3	1028.6	48.4	7.8	6.3	1.0	41.6

( ) indicates fractions

Table 4 Materials and energy of process category for the vertically integrated home

Materials	*System boundaries**	*Material inputs*	*Important energy sources*
Wood manufacturing	Raw material extraction, transportation, final product		
Log transportation by truck	Logging activities, forest ~ port, port ~ company	Roundwood	Diesel
Log transportation by bulk carrier	Port ~ port	Roundwood processed lumber	Heavy fuel oil (HFO), diesel
Manufacturing plant 1	Debark, cutting, slicing machineries, drying fan operation, building operations	Roundwood	Electricity
Miscellaneous transportation	Miscellaneous delivery of materials and products within the facility	Processed lumber	Diesel
Manufacturing plant 2	Product processing, product assembly	Processed lumber	Electricity
Boiler	Lumber drying (70%), veneer drying (20%), and heating (10%)	Processed lumber	Wood waste
Ready-mixed concrete	Raw material extraction and transportation, processing of 20Mpa concrete	Gravel, sand, cement	Natural gas, coal, oil, electricity
Glass	Raw material extraction and transportation, final product	Glass sand, limestone, soda ash	Natural gas, electricity
Steel	Raw material extraction, raw material transportation, steel product	Coal, iron ore, limestone, or scrap iron	Natural gas, electricity, coal
Glassfiber	Raw material extraction, raw material transportation, final product	Glass sand, limestone, soda ash, colemanite	Natural gas, electricity
Aluminum	Raw material extraction, raw material transportation, final product	Limestone, bauxite, rock salt, crude oil, coal	Natural gas, electricity
Plywood	Raw material extraction, raw material transportation, final product	Roundwood, resin	natural gas, hogfuel
Gypsum board	Raw material extraction, raw material transportation, final product	Gypsum, wood, waste paper	N/A
Construction	Site preparation, construction equipment, worker/material transportation from the company to the site	Construction materials	Diesel

*All system boundaries do not include the pre-combustion energy of materials resources.

which use diesel fuel. This miscellaneous delivery required 40 MJ per m^2 of floor space, corresponding to 1% of the total production energy.

Ninety percent of the steam generated by the hogfuel was used to dry wood, and 10% was used to heat the primary manufacturing plant and the office buildings. The hogfuel energy used in the boiler was 770 MJ per m^2 of floor area, corresponding to 19.8% of the total production energy.

Electricity was used in the secondary processing plant to size and assemble wall panels, furniture, doors, windows, carpets, and decorative materials. Kerosene was also used to heat the plant and some buildings. The energy consumption of the secondary processing was 182 MJ per m^2 of floor space, corresponding to 4.7% of the total production energy.

The construction stage includes site preparation, diesel-powered construction equipment, material transportation, laborer transportation, and concrete treatment by kerosene heaters. The construction stage consumed 396 MJ per m^2 of floor area, corresponding to 10.1% of the total production energy. The equipment, transportation, and kerosene energy correspond to 48%, 35%, and 17% of the construction energy, respectively.

The energy consumed per square meter of floor space for a VIH and a CH, at each production stage, is listed in table 5. The total production energy for a VIH, including all building components, was 3,899 MJ per m^2 of floor space, which was higher than that of the CH by 59%. Because the total production energy for the VIH included furniture production, the total production energy is reduced to 3,615 MJ per m^2 of floor space by discounting the energy used by furniture production. This is still 48% percent higher than that of the CH. The major difference is in the concrete and reinforcing steel. These components represent 26.2% of the total production energy for the VIH, and only 8.9% of the total production energy of the CH. The renewable energy derived from hogfuel accounted for 21% of the production energy of the VIH. This environmental dividend (i.e., the renewable character of the energy) is not included in the calculations of production energy.

By taking into account the projected life span of homes, a total annualized environmental burden can be estimated. The projected life span of a new conventional wooden home is 50 years, and the resulting annualized production energy to construct a CH is 49.0 MJ per m^2 per year. If a VIH lasts 79.6 years, its annualized production energy will equal that of a CH.

Household Energy Consumption

The process energy, the household energy, and the total cumulative energy after 50 years for a VIH, a CH, and an AH are presented in table 6. On average, the annual household-heating energy consumption per m^2 for a VIH, a CH, and an AH totaled 725 MJ, 874 MJ, and 851 MJ, respectively. The household energy consumption of a VIH and a CH correspond to 19 percent and 36 percent of the total production energy, respectively. The cumulative household energy consumption of a VIH surpasses its production energy in 5.4 years, while that of a CH surpasses its production energy in 2.8 years. In a span of 50 years, the cumulative household energy consumption of a VIH is over nine times the initial production energy. Also, the total energy required during the manufacturing and use of a CH will reach parity with that of a VIH in nine to ten years after construction (figure 2). Our result is comparable to the general trend as reported by Blanchard and Reppe (1998), whose values are equivalent to 4.13 GJ/m^2 of process energy and 1.219 GJ/m^2 per year of use-phase energy consumption for a standard home in Ann Arbor, Michigan. Our process energy value is also comparable to 3 GJ/m^2 for wooden single-family houses as reported by Suzuki and colleagues (1995).

Table 7 displays the characteristics of the VIH, the CH, and the AH. Figure 3 displays the annual household energy consumption in the VIH, the CH, and the AH. The VIH housed 21% more residents on average, and the average floor area was larger than that of the CH by 18%, yet the energy consumption per house was 5% lower than that of the CH. On a per m^2 basis, the difference was –17%. This trend is opposite to the trends previously reported in the literature. Both Nagasaka and colleagues (1995) and the HEPRC (1993) show that the total household energy consumption increases with the number of occupants, income, and the floor area. Also, Nagasaka and colleagues (1995) re-

Table 5 Energy inputs by process per m² of a vertically integrated home

	Vertically integrated home		*Conventional home*			
	Energy (MJ)	*%*	*Energy (MJ)*	*%*	*Fuel type*	*Vehicle type*
Lumber	1565	40.1	1196	48.8		
(Log T. by truck)	(147)	(3.8)	—	—	DO	Trailer
(Log T. by bulk carrier)	(233)	(6.0)	—	—	HFO, DO	Bulk carrier
(Manufacturing plant 1)	(192)	(4.9)	—	—	El. from coal	
(Miscellaneous T)	(40)	(1.0)	—	—	DO	Shovel, loader, lifter
(Manufacturing plant 2)	(182)	(4.7)	—	—	El. from coal	—
(Boiler)[a]	(770)	(19.8)	—	—	Hogfuel	—
Construction[b]	396	10.2	335	13.7	DO, Kerosene	Truck
Concrete*	519	13.3	124	5.1	DO, HFO, Gas, NG, El.	Truck, pipeline, rail barge, ocean transport
Glass*	126	3.2	48	2.0	DO, HFO, Gas, NG, El.	Truck, pipeline, rail barge, ocean transport
Steel, electric furnace [c]	172	4.4	35	1.4		
Steel, blast furnace	330	8.5	59	2.4	DO, HFO, Gas, NG, El.	Truck, pipeline, rail barge, ocean transport
Glassfiber*	183	4.7	221	9.0	DO, HFO, Gas, NG, El.	Truck, pipeline, rail barge, ocean transport
Aluminum*	167	4.3	58	2.4	DO, HFO, Gas, NG, El.	Truck, pipeline, rail barge, ocean transport
Plywood* [d]	162	4.2	115	4.7	El., DO, Gas, NG, Hogfuel	—
Gypsum board	279	7.2	179	7.3	N/A	—
Cement [e]	—	—	79	3.2	DO, HFO, Gas, NG, El.	Truck, pipeline, rail barge, ocean transport
TOTAL	3899		2448			

NOTE: The environmental impact of electricity was evaluated at primary energy assuming 40% conversion efficiency from primary energy to electricity.

[a] Including all energy used during wood processing such as steam generation for building, heating, and plywood drying.

[b] Including diesel-powered equipment, materials and worker transportation, and kerosene for concrete treatment. An average transportation distance of 60 km was assumed for the material transportation.

[c] Assuming rebars are made from scrap iron in the electric-arc furnace.

[d] Does not include feedstock energy for resin.

[e] Assuming 50% weight of cement board is cement.

* Converted from fuel source and amount used during extraction, transportation and final processing. This does not include pre-combustion energy or transportation of the materials to site.

Abbreviations: HFO = heavy fuel oil, DO = diesel oil, Gas = gasoline, NG = natural gas, El = electricity

Table 6 Process, household, and cumulative energy for the vertically integrated home and conventional home (MJ/m^2/year)

	VIH	*CH*	*AH*†
Process energy	3899	2449	2449*
Household energy	725	874	851
Total cumulative energy after 50 years	40,146	46,170	45,018

†*Reference* Hokkaido Electric Power Research Corporation (HEPRC). Investigation of Residential Energy Consumption in Hokkaido. 1990.

* The process energy of AH is assumed to be the same as CH.

Table 7 Characteristics of homes used for comparison of household energy consumption

	Average floor area (m^2)	*Age of structure*	*Structural characteristic*	*Average # occupants*	*Effective study period (MM/YY)*	*Sample size*	*Window system*
VIH	161.3±10.0	<2 years	Wood	4.3± 1.8	11/97 ~ 04/98	12	2× double pane (wood frame) + 1 storm window (aluminum frame)
CH	136.2±24.8	<2 years	Wood	3.6±1.2	11/97 ~ 04/98	13	1× double pane (vinyl frame)
AH†	127.7	14 ~ 18 years (50th percentile)	Wood, concrete, etc.	3.3	07/89 ~ 06/90	628	1× double pane (vinyl frame)

†*Reference* Hokkaido Electric Power Research Corporation (HEPRC). Investigation of Domestic Energy Consumption and Occupants' Characteristics in Hokkaido. 1990.

port that homes using kerosene for water heating tend to have high energy consumption regardless of floor areas. Our study validates the general trends showing that increased material inputs that improve the energy efficiency of the final product will be recouped within a short period of time, and will significantly reduce the environmental energy burden of the home over its lifetime.

When compared to an AH, the CH's kerosene energy consumption is lower, but its electricity consumption per m^2 is higher by 59%. This difference may be due to (1) overestimation of annual electricity consumption in the CH by our methods of extrapolation, (2) use of electric devices not reported in the survey, (3) design differences, and/or (4) occupants' characteristics.

Material inputs that increase the durability of homes should be carefully evaluated because longevity depends on several factors not directly related to the construction of the home, such as maintenance by occupants, occupant's preferences based on satisfaction level, changing fashions, and architectural styles.

CO_2 Emissions and Carbon Fixation

Carbon dioxide (CO_2) emissions during the production stages of the VIH were 361 kg/m^2. The total CO_2 emissions estimated from the materials inputs for the CH during the production stages were 217 kg/m^2. A value of 250 kg/m^2 has been reported in the literature (Suzuki et al. 1995). The difference in the production CO_2 intensity for the VIH and the CH is due to the increased material inputs of the VIH. More than 85% of the variance is from increased wood, concrete, and steel inputs in the VIH (figure 4).

Because a tree takes in 1.47 kg of CO_2 to make 1 kg of wood (Canadian Wood Council 1995), carbon fixed in hogfuel used for construction of a VIH is equivalent to 68 kg/m^2 of CO_2

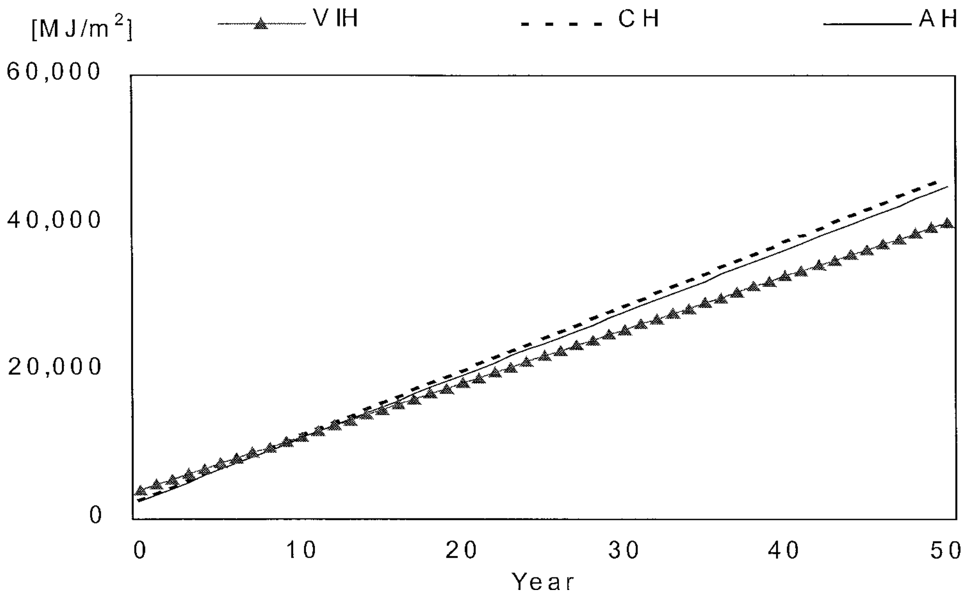
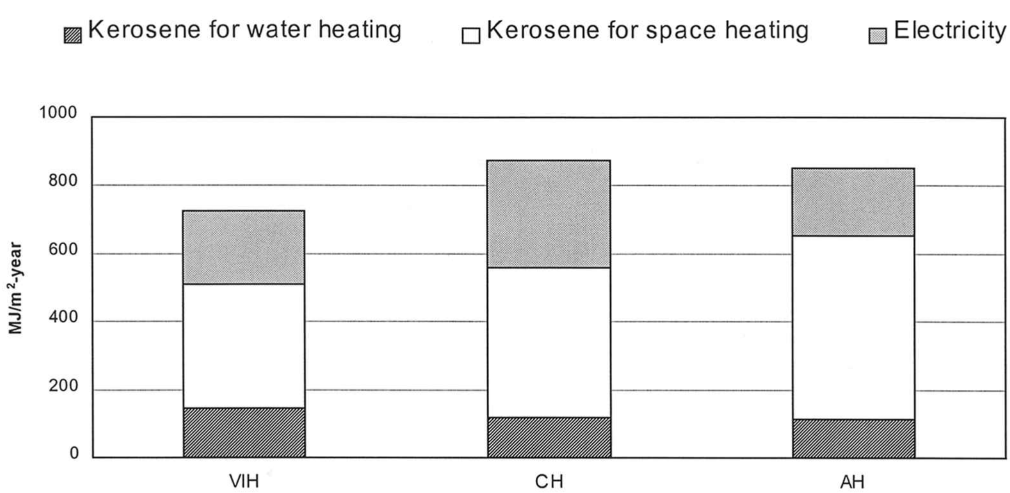


Figure 2 Cumulative energy consumption over a 50-year use period.



Note: Forty percent conversion efficiency is assumed for electricity.

Figure 3 Household annual energy consumption in Hokkaido.

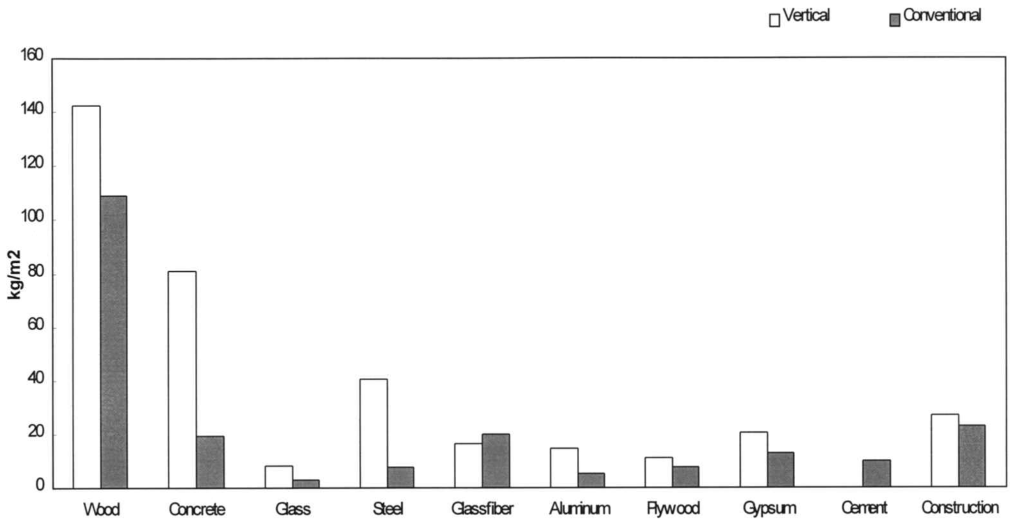


Figure 4 Process CO_2 emissions. Vertically integrated homes vs. conventional homes.

uptake during the tree's growth. After considering carbon fixation, therefore, the net CO_2 emissions resulting from the manufacturing process are 293 kg/m^2. Such net CO_2 emissions resulting from a conventional design are 151 kg/m^2.

Figure 5 displays the process net CO_2 compared to the annual use-phase CO_2. CO_2 emitted annually from the homes was estimated to be 55 kg/m^2 and 68 kg/m^2 for a VIH and a CH, respectively, each of which is equivalent to 19% and 48% of the net process CO_2 emissions. The use phase will surpass the net CO_2 emissions in 5.4 years for a VIH and in 2.1 years for a CH. This again suggests that reduction of CO_2 emissions during the use stage may be more environmentally significant than any reductions in the process stage.

Limitations

In this analysis, CO_2 was considered to be the only contributor to the greenhouse effect and, therefore, the environmental impacts were not completely considered. For example, NO_x emissions per MJ of energy are five times higher in the transportation compartment than in the heating compartment. In addition to the effects of the production stages, the environmental impacts of the demolition stage, including solid waste disposal, energy consumption, and air emissions, should be considered.

Life-cycle inventory analysis offers guidance to housing manufacturers on the extent to which various processes have an impact on the environment and energy use. For companies committed to reducing the environmental burdens of their products, this data is very relevant. Detailed LCI analysis requires fuller understanding and disclosures of assumptions, conversion factors, and subsystem boundaries. Forintek Canada Corporation (1993) reports a hogfuel generation rate of 0.282 kg/kg of oven-dried (o.d.) finished lumber. They assume a 25% coproduct generation rate for the raw log. Our calculations show only a 3% coproduct generation rate, resulting in a higher hogfuel-to-product ratio of 0.68 kg/kg of oven-dried product. Consistent and accurate values must be made available to increase the accuracy and sensitivity of the LCI analysis.

Under certain circumstances, it may be acceptable to generalize based on industry-wide practices, even if values were obtained from other countries. But when conducting a microanalysis of various components in a complex process, reliance on foreign data will produce faulty estimates. If Canadian data for concrete and steel were used in our Hokkaido, Japan example, the total production energy of a VIH would increase by 30% to 5 GJ/m^2. Table 8 compares published records from the Canada Center for Mineral &

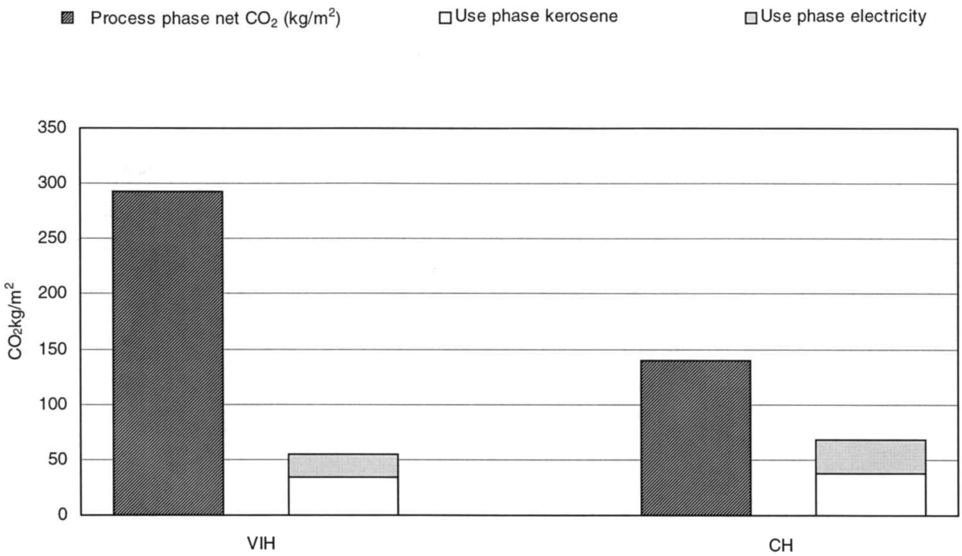


Figure 5 Process vs. annual use phase CO_2 emissions.

Energy Technology and Radian Canada Inc. (1993) and Building Research Establishment (1994). There is a 9% variation by region in the value of the embodied energy of concrete and a 43% variation in the value of the embodied energy of steel. By using these figures, a Canadian construction company may reduce the embodied energy of its concrete structures by 10% solely by selecting from suppliers whose raw material extraction, processing, and transportation minimize the embodied energy of the final product. In Japan, using recycled steel processed in an electric steel arc furnace instead of virgin steel processed in a blast furnace can reduce the process energy requirement by 10.1 MJ/kg crude steel input.

Conclusions

In this article, energy and CO_2 intensities during the manufacturing and use phases of vertically integrated factory-built homes (VIHs) constructed with increased material inputs were evaluated. These intensities were compared to those of a counterpart conventional home (CH) hypothetically built with the vertically integrated construction methods, but with fewer material inputs in accordance with the specifications for a conventional home in Hokkaido today. The esti-

Table 8 Embodied energy of building materials: range of published figures

Material and sources	*Low value (MJ/kg)*	*High value (MJ/kg)*	*Value obtained or used in our study (MJ/kg)*
Finished lumber			
Canadian Center for Mineral & Energy Technology and Radian Canada, Inc. 1993	0.4	9.3	11.89 (Company records)
Concrete (regional average)			
Canadian Center for Mineral & Energy Technology and Radian Canada, Inc. 1993	0.62 (Toronto)	0.73 (Montreal)	0.505 (Ministry of International Trade & Industries, 1990a)
Steel (steel sections)			
Building Research Establishment 1994	24	59	6.7 ~ 16.8 (Ministry of International Trade & Industries, 1990b)

mated environmental impacts of the VIH were approximately 3.9 GJ production energy per m^2 and 361 kg process CO_2 per m^2, values that were higher than those of the CH due to the increased material inputs for concrete, steel, and lumber. The process CO_2 emissions for the VIH can be discounted for carbon fixation during tree growth, resulting in net CO_2 emissions of 293 kg/m^2. This fact emphasizes the significant opportunity to reduce CO_2 accumulation by using wood as a renewable combustion energy source. Because CO_2 emissions can be used as an indicator of sustainability, the results of our study can, in turn, guide the design, material selection, manufacturing, and construction processes.

Both the cumulative household energy consumption and the resulting CO_2 emissions will exceed the net initial process energy in less than six years for a VIH and in less than three years for a CH. This suggests that cumulative household energy is the most significant component in the life cycle of a house. Improvements in energy-use efficiency for homes will produce the largest environmental dividend.

Our article shows that increased material inputs can contribute to significant energy conservation during the use phase. If fewer building materials were used, the process energy of the VIH could be easily reduced. The sustainability of such homes, however, may also be reduced, resulting in less energy-efficient homes that are not as resistant to severe climates and natural catastrophes.

To evaluate the environmental impacts of a house, the annualized production energy and CO_2 intensities of a house should be evaluated, along with other home performance variables such as longevity and energy efficiency. In our example, building a VIH is preferable from an energy perspective because the crossover point occurs in about ten years, while the average life span of the house is substantially longer than that.

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Note

1. All instances of ton refer to metric ton unless noted otherwise, i.e., 1 metric ton = 1,000 kg = 1 Mg = 1.1 short ton = 0.98 long ton.

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