practices and excessive harvest rates, while promoting forest sustainability. However, changes in domestic forest policies and movement toward certification can have differential impacts on the underlying production cost structure of various countries thereby influencing the comparative production and trading capacities and costs. Thus, trading patterns would be expected to respond to these changes and countries are seen to strive to modify rules and practices so as to advantage their forestry production sector in relation to its competitors.

See also: **Mensuration**: Yield Tables, Forecasting, Modeling and Simulation. **Papermaking**: World Paper Industry Overview. **Resource Assessment**: Regional and Global Forest Resource Assessments. **Tree Breeding, Principles**: Economic Returns from Tree Breeding.

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Environmental Benefits of Wood as a Building Material

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Introduction

The management of forests to obtain wood for use in the production of houses and a host of manufactured products is often criticized based on environmental concerns. Such concerns have led some to conclude that periodic harvesting of forests and the use of wood should be minimized, or even halted altogether. However, careful consideration of global environmental concerns in the context of the realities of today's world leads to a much different conclusion: to protect the environment, forests and the wood they produce should be utilized to the maximum extent possible within sustainable limits.

It is essential that forests be managed in a manner that sustains a myriad of forest values over the long term. At the same time, it is vitally important that forests be managed in such a way as to minimize impacts on the global ecosystem, of which forests are one part. Thus, there are a number of things to consider when contemplating the proper role of forests. One of these is the fact that growing populations worldwide consume vast quantities of raw materials, including wood. Another is that wood is the only widely available industrial raw material that is renewable. Yet another, and very important consideration, is that the environmental impacts associated with the manufacture and use of wood products are less, and in many cases substantially less, than those associated with the manufacture and use of products made of non-wood materials.

Assessing Environmental Impacts of Industrial Activity

An effective means of assessing the relative environmental impacts of a product is to examine them over the life cycle of the product from raw materials extraction, through processing and conversion, and ultimate use. Examination of energy use is particularly revealing, since a number of serious environmental problems are related to consumption of energy including acid deposition, oil spills, air pollution (SO_2, NO_x), and increasing concentrations of atmospheric carbon dioxide.

Research involving systematic examination of the environmental impacts of a product over its life is commonly referred to as life cycle assessment or simply LCA. An LCA typically begins with a careful accounting of all the measurable raw material inputs (including energy), product and coproduct outputs, and emissions to air, water, and land; this part of an LCA is called a life cycle inventory, or LCI. The LCI can be set up to deal with raw material extraction and product manufacture only, or the boundaries of an inventory may be defined more broadly to include product use, maintenance, and disposal. A full LCA seeks to assign values to factors that are currently not precisely measurable, such as impacts of an industrial activity on the landscape, flora, fauna, air, or water. Most life cycle assessment studies to date have focused primarily on the life cycle inventory.

Environmental Impacts of Wood Products Manufacturing

Energy Consumed in Manufacturing

One of the first comprehensive life cycle assessments of wood products was completed in the United States in the mid-1970s. Commissioned by the National Academy of Sciences, the study examined the energy required to build wall systems for residential homes. Energy use associated with raw material gathering (harvesting or mining), transport, manufacturing, and building construction was considered. Wood-frame construction was found to require the use of only one-half to one-seventh the energy needed for construction using steel, aluminum, concrete block, or brick (**Table 1**).

Although technologies in all industries, as well as protocols governing the conduct of LCA/LCI studies, have changed significantly since the mid-1970s, a growing number of studies have confirmed the energy advantages of wood. Dramatic differences have been shown in the quantities of energy needed to manufacture primary materials used in construction or in the manufacture of secondary products. Researchers at the University of Tokyo in the early 1990s determined, for example, that the energy needed to manufacture 1 cubic meter of steel, aluminum, and concrete was 191 times, 791 times, and 3.5 times greater, respectively, than that needed to manufacture 1 cubic meter of kiln dried lumber (**Table 2**). Energy calculations were based on production of virgin materials in all cases. When comparisons were made on a mass basis, the manufacturing energy ratios in comparison to wood became 12.5, 155, and 0.7, again for steel, aluminum, and concrete. Although these figures suggest the very large impact that materials choice can have on energy consumption, such numbers are difficult to compare, since equal volumes or masses of materials are almost never used for a given application.

The most meaningful comparisons of materials are made when comparing products that have the same function. For instance, a comparison of energy requirements for producing wood and steel siding products for structures can be very informative as long as care is taken to ensure that the same boundaries are used in defining the scope of analysis. The same is true of analysis of entire buildings. Though more complicated than examination of single products, analysis of complete structures is often favored by LCA researchers since a large segment of industrial wood globally is used in building construction.

Substantial differences in the quantity of energy needed for building construction have been shown for a wide range of building types. For example, a 1992 Canadian assessment of alternative materials for use in constructing a large research laboratory building showed all-wood construction on a concrete foundation to require only 35% as much energy as steel construction on a concrete foundation (**Table 3**). A New Zealand study in the same year found wood-frame construction of residential buildings with wood-framed windows and wood fiberboard cladding to require only 42% as much energy as

Table 1 Relative quantity of energy (oil equivalent) needed to manufacture various wall systems using construction practices common to the United States

	GJ of energy needed to manufacture 100 m² of wall (#2 = 1.000)
1. Plywood siding, no sheathing, 2 × 4 wood frame	0.782
2. MDF siding, plywood sheathing, 2 × 4 wood frame	1.000
3. Concrete building block, no insulation	6.725
4. Aluminum siding, plywood, insulation board, 2 × 4 wood frame	1.949
5. MDF siding, plywood sheathing, steel studs	2.009
6. Brick veneer over sheathing	7.039

MDF, medium density fiberboard.

Source: National Research Council (1976) *Renewable Resources for Industrial Materials*. Washington, DC: National Academy of Sciences.

Table 2 Energy consumption and carbon dioxide emissions in the production of various materials

Material	*MJ kg^{-1}*	*MJ m^{-3}*	*Carbon emission during production (kg m^{-3})*	*CO_2 storage*	*Net CO_2 emissions*
Lumber (air dry, SG 0.55)	1.5	750	15 (16)[a]	250	– 235 (– 234)[b]
Lumber (kiln dry, SG 0.55)	2.8	1 390	28 (100)[a]	250	– 222 (– 150)[b]
Plywood (SG 0.55)	12	6 000	120 (156)[a]	248	– 128 (– 92)[b]
Particleboard (SG 0.65)	20	10 000	200 (224)[a]	260	– 60 (– 36)[b]
Steel	35	266 000	5 320	0	5 320
Aluminum	435	1 100 000	22 000	0	22 000
Concrete	2.0	4 800	120	0	120

[a] Values in parentheses indicate total carbon emissions during production assuming fossil fuels used to supply all manufacturing energy. Values outside of parentheses indicate typical carbon emissions from fossil fuels during manufacturing assuming that wood residues generated in manufacturing are used to produce process energy. Although burning of wood liberates carbon, the process is carbon neutral if it is assumed that trees are replanted following harvest.
[b] Negative values result from the fact that wood is 49% carbon by weight and that the quantity of carbon released in generating process energy is less than the carbon stored in the finished wood product. For explanation of values within and outside of parentheses see footnote above.
SG, specific gravity.
Source: Arima T (1991) Tokyo University Prof. Arima points to contribution of wood products to environmental preservation. *Rinkei Shimbun* July 17.

Table 3 Calculated energy consumption and carbon dioxide emissions for alternative wood and steel construction: Forintek Canada Western Laboratory

Location	*Energy consumption (GJ)*		*CO_2 emissions (tonnes)*	
	Wood assembly	*Steel assembly*	*Wood assembly*	*Steel assembly*
Office/Laboratory floor	2 837	9 458	157	581
Office/Laboratory roof	3 653	7 648	197	463
Pilot plant	1 646	5 818	94	352
Total	8 136	22 924	448	1 396

Source: Marcea R and Lau K (1992) Carbon dioxide implications of building materials. *Journal of Forest Engineering* 3(2): 37–43.

Table 4 Embodied energy carbon dioxide emissions analysis of a large office building

Construction	*Total energy use (GJ × 10^3)*	*Above grade energy use (GJ × 10^3)*	*CO_2 emissions (kg × 10^3)*
Wood	3.80	2.15	73
Steel	7.35	5.20	105
Concrete	5.50	3.70	132

Source: Canadian Wood Council (1997) *Comparing the Environmental Effects of Building Systems*, Wood the Renewable Resource Series no. 4. City: Publisher.

brick-clad, steel-framed dwellings built on a concrete slab and fitted with aluminum-framed windows. When office and industrial buildings were considered, those constructed of timber were found to require only 55% as much energy as steel construction and approximately 66–72% as much energy as concrete construction. Another late-1990s Canadian study involving analysis of a large three-story building yielded almost identical results (**Table 4**). A 2002 study in Western Europe found significant differences in energy required to build wood and brick houses, although the differences were lower than in the studies just mentioned. In this case, the total energy needed to produce a wood timber-frame house was 83% of that needed to produce a concrete and brick house of the same design; both houses were built on concrete foundations and both had concrete shingles. Removing these and other common elements from the comparison, and focusing only on the parts of the structures built with different materials showed much larger differences in energy requirements, again favoring wood construction. In another mid-1990s comparison of wood- and steel-frame construction for light-frame commercial structures in Canada, which examined a wide range of factors in addition to energy, low environmental impacts of wood construction relative to steel were again demonstrated (**Table 5**).

Most LCA studies to date have assumed the use of virgin materials (i.e., no recycled content). One mid-1990s study that did consider incorporation of recovered material examined the use of recycled steel in wall studs. In this case, the manufacturing energy differences between wood and steel were found to narrow, but wood retained a significant advantage. As part of the wood vs. steel wall comparison, load-bearing wood and steel-framed walls, in which the steel contained 50% recycled steel content, were examined. In this case the steel-framed wall was found to be

> some four times as energy intensive, and correspondingly…at least that much more environmentally damaging, despite its recycled steel content.

Several interesting studies have examined differences in energy required to manufacture various kinds of building components. A team of Swiss researchers compared window units made of wood, aluminum, and PVC and found the manufacture of the wood-framed window to require only 75% of the energy needed for production of aluminum windows and 95% of that needed for production of PVC windows. It was noted that the wood waste generated in the process is often burned to produce energy, increasing the magnitude of difference in total energy consumption while also replacing fossil fuels in the process. In a 1995 Swedish study of linoleum, vinyl, and wood flooring, very large differences in net manufacturing energy were found for the three material types, with wood favored by a wide margin.

Table 5 Comparative energy consumed in manufacturing wood vs. steel-framed interior wall

	Energy consumption (GJ)	
	Wood-framed wall	*Steel-framed wall*
Extraction	0.7	1.2
Manufacturing	2.1	9.7
Construction	0.6	0.6
Total	3.4	11.5

Source: Meil J (1994) Environmental measures as substitution criteria for wood and nonwood building products. In *Proceedings, The Globalization of Wood: Supply, Processes, Products, and Markets*, pp. 53–60. Madison, WI: Forest Products Society.

An early 1990s study lent some perspective to the significance of the differences in processing energy associated with different kinds of building materials. While commenting on a proposal to reduce markedly timber harvesting activity in the Pacific Northwest region of the United States, Peter Koch noted that one possible outcome could be substitution of nonrenewable structural materials such as steel, aluminum, concrete, and plastics to replace the wood not harvested. He calculated that the impact on energy consumption and carbon dioxide releases, were this to occur, could be as high as 6 billion gallons of oil and 62 million tonnes of carbon dioxide annually – equivalent to operating a fleet of about 11 million automobiles.

Carbon Storage and Emissions

Recent concern about the possibility of global warming has focused attention on liberation of carbon dioxide in materials production and use. Wood is at the center of the global warming debate because of the ability of forests to store or sequester carbon. Dry wood is 49% by weight carbon, meaning that 0.5 kg of carbon is contained within each 1 kg of dry wood. Moreover, for each kilogram of wood produced, 3.7 kg of carbon dioxide is removed from the atmosphere. Thus, substantial carbon storage accompanies the growth of trees.

Findings of recent studies consistently indicate that wood has a large advantage over other materials with respect to carbon emissions resulting from manufacture and use for at least three reasons:

1. Relatively little energy is required to manufacture wood products as compared to non-wood materials. As a result, the quantity of greenhouse gases liberated through combustion of fuels is significantly lower when manufacturing wood products.
2. Wood is 49% carbon by weight, and thus wood used in structural and other long-lived products stores or sequesters carbon over extended time periods.
3. The majority of energy (65–70%) used in producing wood products is obtained from burning of wood residues such as sawdust, bark, and papermill waste liquors. Thus, quantities of fossil fuels used in wood products manufacture are typically vastly lower than those used in the manufacture of

Table 6 Net carbon emissions in producing 1 tonne of different materials

Material	*Net carbon emissions (kg t^{-1})*
Framing lumber	−460
Concrete	45
Concrete block	49
Brick	148
Glass	630
Steel	1 090
Aluminum	2 400
Plastic	2 810

Source: Honey BG and Buchanan AH (1992) *Environmental Impacts of the New Zealand Building Industry*, Research Report no. 92-2. Canterbury, New Zealand: Department of Civil Engineering, University of Canterbury–Christchurch.

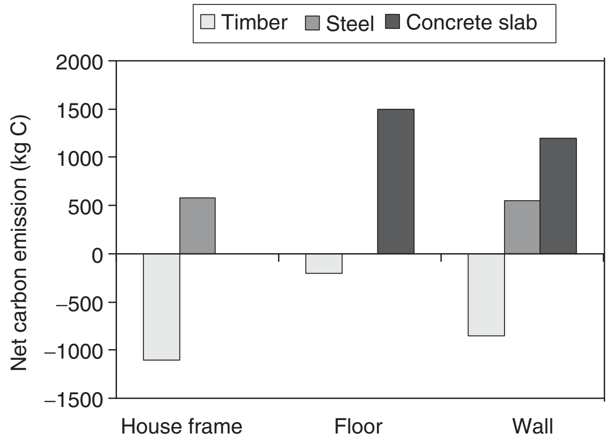

Figure 1 Carbon dioxide emissions of various components in a typical house. (Reproduced with permission from Honey BG and Buchanan AH (1992) *Environmental Impacts of the New Zealand Building Industry*, Research Report no. 92-2. Christchurch, New Zealand: Department of Civil Engineering, University of Canterbury.)

non-wood products; this translates to avoided carbon emissions from fossil fuels.

Many LCA/LCI studies have shown substantial differences in carbon liberation when comparing wood products manufacture and use with non-wood products. For example, the New Zealand study that examined manufacturing processes, including raw material extraction and transportation, not only revealed large differences in net carbon dioxide emissions from material to material, but a carbon emission figure for lumber that is actually negative (**Table 6**). Others (see **Table 2**) have reported similar findings. The negative values for wood are due to its carbon content.

When carbon dioxide emissions associated with constructing wood and other kinds of structures are examined, large differences favoring wood again become evident. Data presented in **Tables 3** and **4** and **Figure 1** are typical of findings from recent studies. One study, a portion of which is highlighted in **Figure 1**, involved analyses of alternative designs of structures ranging from single family homes, to an industrial building, to a large office structure. Included among the findings of the authors is the observation that

> The choice of building material has a huge effect on the carbon emissions to the atmosphere. Timber used for framing, floor, and wall components of a house compare much more favorably than other common materials.

Recognizing that the potential for global warming is related to compounds in addition to carbon dioxide, such as methane, LCA researchers have very recently begun expressing total greenhouse gas emissions in terms of a global warming potential (GWP) value. A life cycle assessment of houses built in Minneapolis and Atlanta in the United States (**Tables 7** and **8**) showed the GWP of steel-framed and concrete block structures to be 49% and 65% greater, respectively, than otherwise identical wood-framed structures. In both comparisons houses had common foundations (concrete) and roof systems (wood). Much larger differences, again favoring wood, resulted when common elements were removed from the comparisons.

The study of windows referred to earlier showed the GWP of aluminum and PVC-framed windows to be 10–20% greater than those framed in wood. Similarly, the potential for acid rain, eutrophication, and photochemical ozone was found to be 114–136%, 45–55%, and 42–65% greater when manufacturing aluminum and PVC windows than when manufacturing wood windows.

It should be noted that although it is often assumed that trees grown to offset carbon dioxide emissions need then to be preserved in order to keep the carbon dioxide from returning to the atmosphere, recent research shows that carbon storage can be significantly enhanced by periodic harvest of trees and their use in long-lived products. Several researchers recently determined the carbon storage implications of short- and long-term wood products use, low energy consumption and carbon liberation associated with wood products manufacture, and avoided fossil fuel use, and concluded that carbon accumulation in forests is more rapid when a portion of the wood is harvested and used in long-lived products (**Figure 2**). They noted that the greater the manufacturing efficiency and useful product life, the stronger the case for wood becomes.

In short, concerns regarding global warming potential point to greater use of wood as a part of the solution.

Table 7 Environmental performance indices for residential structure in Minneapolis, USA

	Wood			*Steel*			*Increase resulting from use of steel*
	Wall	*Floor*	*Total*	*Wall*	*Floor*	*Total*	
Energy	97	12	186	148	83	308	+66%
Global warming potential	20 790	1 970	39 810	28 930	13 332	59 290	+49%
Air emissions	1 497	242	2 778	2 246	1 414	4 711	+70%
Water emissions	31	10	185	492	544	1 179	+537%
Solid waste	7 600	1 130	12 110	6 320	1 323	11 020	−9%

Source: Consortium for Research on Renewable Industrial Materials (2002) *Life Cycle Environmental Performance of Renewable Building Materials in the Context of Residential Building Construction: Phase I Interim Research Report on the Research Plan to Develop Environmental-Performance Measures for Renewable Building Materials with Alternatives for Improved Performance*. Seattle, WA: CORRIM, Inc., University of Washington.

Table 8 Environmental performance indices for residential structure in Atlanta, USA

	Wood		*Concrete*		*Increase resulting from use of concrete*
	Wall	*Total*	*Wall*	*Total*	
Energy	22	115	69	162	+41%
Global warming potential	1 400	20 020	14 510	33 130	+65%
Air emissions	116	1 035	954	1 862	+80%
Water emissions	10	86	23	99	+15%
Solid waste	562	4 270	4 260	7 970	+86%

Source: Consortium for Research on Renewable Industrial Materials (2002) *Life Cycle Environmental Performance of Renewable Building Materials in the Context of Residential Building Construction: Phase I Interim Research Report on the Research Plan to Develop Environmental-Performance Measures for Renewable Building Materials with Alternatives for Improved Performance*. Seattle, WA: CORRIM, Inc., University of Washington.

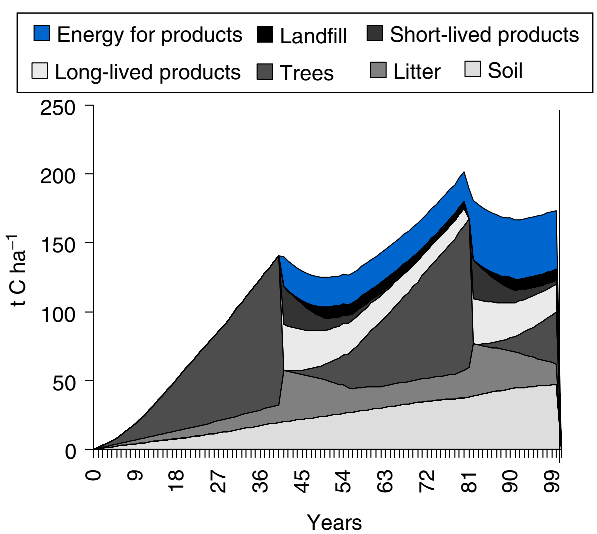

Figure 2 Cumulative changes in carbon stocks with afforestation and subsequent harvest after 40-year rotation. (Reproduced with permission from Marland G and Schlamandinger B (1999) The Kyoto Protocol could make a difference for the optimal forest-based CO_2 mitigation strategy: some results from GORCAM. *Environmental Science and Policy* 2: 111–124.)

Table 9 Comparative emissions in manufacturing wood- vs. steel-framed interior wall

Emission/effluent	*Wood wall*	*Steel wall*
CO_2 (kg)	305	965
CO (g)	2 450	11 800
SO_x (g)	400	3 700
NO_x (g)	1 150	1 800
Particulates (g)	100	335
Volatile organic compounds (g)	390	1 800
Methane (g)	4	45
Suspended solids (g)	12 180	495 640
Nonferrous metals (mg)	62	2 532
Cyanide (mg)	99	4 051
Phenols (mg)	17 715	725 994
Ammonia (mg)	1 310	53 665
Halogenated organics (mg)	507	20 758
Oil and grease (mg)	1 421	58 222
Sulfides (mg)	13	507

Source: Meil JK (1994) Environmental measures as substitution criteria for wood and nonwood building products. In *Proceedings, The Globalization of Wood: Supply, Processes, Products, and Markets*, pp. 53–60. Madison, WI: Forest Products Society.

Manufacturing Effluents

Life cycle analysis involving wood was elevated to a new level in a 1994 study that examined not only energy and related emissions associated with wood- and steel-framed construction, but manufacturing effluents as well (**Table 9**). Differences can only be described as spectacular, with emission levels for steel-framed construction ranging from 1.6 times to 41 times higher than for wood-framed construction. More recent studies support these findings.

Energy Efficiency of Wood vs. Non-Wood Structures

All of the studies of building construction cited herein were based on analysis of structures built according to local building codes and practices. Recent research in the United States showed that because of thermal bridging issues, the differences as shown in **Tables 1**, **3–5**, and **7–9** become even greater when exterior walls are constructed so as to achieve equal thermal insulation or *R* values. Moreover, because of differences in thermal bridging performance of wood, steel, and concrete walls at corners and around doors and windows, even when basic insulation properties of wall sections are equal, both steel-framed and concrete walls require more heating energy over the life of a structure than do wood-framed walls. Thus, energy implications of materials selection in building construction extend well beyond the construction process.

Summary

There is no question that periodic harvesting of forests to obtain wood raw materials results in environmental impacts. What is sometimes forgotten, however, is that the gathering and processing of all raw materials impacts the environment. When the harvesting and processing of wood is examined in this context, the inescapable conclusion is that the global environment would benefit from the maximum use of wood possible within sustainable limits.

See also: **Solid Wood Processing**: Recycling. **Wood Formation and Properties**: Formation and Structure of Wood. **Wood Use and Trade**: History and Overview of Wood Use.

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