THE ENVIRONMENTAL PERFORMANCE OF RENEWABLE BUILDING MATERIALS IN THE CONTEXT OF RESIDENTIAL CONSTRUCTION

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ABSTRACT

This paper presents the Life-Cycle Assessment (LCA) of alternative building materials from forest resource regeneration or mineral extraction through product manufacturing, the assembly of products in constructing a residential home, occupancy and home repairs, and the eventual disposal or recycle. A unique feature of this study's LCA framework is that temporal distribution of events and associated environmental effects during the seed to demolition life cycle were considered by extending the scope to include forest growth through to demolition of the builidng. Our approach was to first conduct LCIs that quantified the energy, resource use, and emissions associated with a particular product, service, or activity. We followed this activity with the assessment of the house, and investigated the potential environmental

Wood and Fiber Science, 37 Corrim Special Issue, 2005, pp. 3 – 17

consequences of energy and resource consumption and waste emissions. Finally we identified improvement opportunities for future research.

Keywords: Life-cycle inventory, life-cycle assessment, building materials, environmental performance, energy use, carbon emissions.

INTRODUCTION

This paper updates and extends a 1976 National Academy of Science/National Research Council study that evaluated the performance of wood products with respect to energy use and material utilization. In that landmark study, wood products were compared to other materials used in similar end uses to determine whether wood had any advantages over similar usage products from an energy perspective (NRC 1976). Since then a number of environmental questions have raised new issues with respect to the use of renewable building materials. There is increasingly intense public interest and debate regarding environmental impacts and sustainability of building products manufacture and use, and, in particular, the intense concerns about forest management and the flows of products that originate from forests. Do these materials have any advantage over similar usage materials in residential construction from an environmental perspective?

Until this effort was undertaken, there had been no attempt to update or extend the 1976 study, and to include environmental issues not addressed in the original study. Furthermore, an analytical procedure, now known as Life-Cycle Assessment (LCA), which was in rudimentary form when the 1976 study was conducted, has become a standardized protocol from the ISO 14040 family of standards (International Organization for Standardization (ISO) 1997, 1998, 2000a, 2000b). LCA analyzes and accounts for the environmental consequences of a product or service, typically as created in an industrial system. This life-cycle concept refers to all activities from extraction of resources through product manufacture and use and final disposal or recyle, i.e. from "cradle to grave" (Fig. 1).

A research consortium known as the Consortium for Research on Renewable Industrial Materials (CORRIM) was formed to evaluate the life-cycle performance of comparable materials used in the construction, use and demolition of residential houses. CORRIM, a nonprofit research corporation made up of 15 member research institutions, was formed in 1996. CORRIM completed a comprehensive research plan in 1998 to guide all aspects of the research. Working capital for the startup was provided by member research institutions, and funding to complete the research plan was augmented by company contributions and a grant from U.S. Department of Energy. Other funding partners include the U.S. Forest Service. Member research institutions are the Universities of Minnesota, Idaho, Washington, Oregon State, Louisiana State, North Carolina State, Mississippi State, Washington State, Purdue, and Virginia Polytechnic Institute. Other partners are FORINTEK, Western Wood Products Association, APA—the Engineered Wood Association, and US Forest Products Laboratory.

The study followed CORRIM protocol, which is based on ISO LCA standards. It developed an inventory database of environmental performance measures associated with the production, use, maintenance, re-use, and disposal of alternative wood and non-wood materials used in light construction, i.e., from forest resource regeneration or mineral extraction to end use and disposal, thereby covering the full product "cradle-to-grave" life cycle (Bowyer et al. 2004). The database included measures of all resource and energy inputs to production and all outputs (products, co-products, emissions, effluents, and waste). We also developed the framework for, and analyzed the impacts of, key wood materials such as lumber, plywood, oriented strandboard, and other structural wood-derived products, and provided environmental data on all life-cycle stages from planting and growing the renewable raw material, manufac-

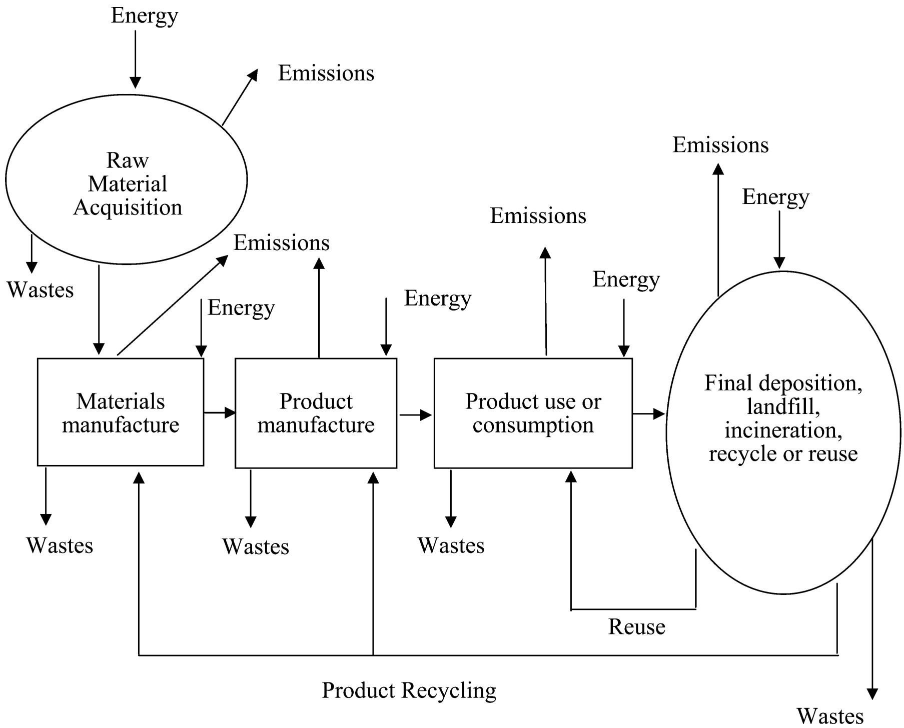

FIG. 1. General flows in a "Cradle-to-Grave" LCA system. Source: Franklin Associates (1990)

ture of product, design and construction of buildings, occupation and use, through final demolition or recycle. Finally, the study utilized the LCA framework to evaluate the environmental impacts for alternative building materials. The study provided a consistent database of environmental performance measures and an analytical framework for evaluating life-cycle environmental and economic impacts for alternative building materials in competing or complementary applications. The results will appeal to decision makers so that they can make consistent and systematic comparisons of options for improving environmental performance. This report and its database should be of use to resource managers, product manufacturers, architects and engineers, environmental protection and energy conservation analysts, and global policy and trade specialists.

In the section that follows, we explain the LCA framework and how it was applied in this study. In section 3 we describe the general approach and data sources. Various assumptions were made while implementing the study and are explained in this section. Section 4 describes the LCA of a completed house. We first present general results and then the results of more in-depth analysis of the various components of the house. Finally we discuss the energy and carbon implications from the LCA and present economic measures in section 5. We conclude the study with an outline of improvement opportunities. The complete CORRIM Phase 1 report covering protocol, data collection and analysis, product LCI databases, carbon flow, cost analyses, and the LCA of two model residential homes can be found in Bowyer et al. (2004).

THE LIFE-CYCLE ASSESSMENT FRAMEWORK

The origin of life-cycle assessments (LCA) began in the 1960s and has evolved into the internationally accepted ISO 14040. LCA analyzes complex processes by accounting for all inputs and outputs and their effects on the environment. For this study, "life cycle" refers to all activities from forest resource regeneration or mineral extraction through product manufacturing, the assembly of products in constructing a residential home, occupancy and home repairs, and the eventual disposal or recycle. National standards that are counterparts to ISO 14040 have been adopted in many countries and have been translated into guidelines for specific industries, an example of which is the AF&PA User's Guide for the U.S. Forest Industry (AF&PA 1996). Figure 2 illustrates the major components of an LCA study and emphasizes the iterative nature of the process. An LCA study begins with a problem definition phase including the functional unit, scope, system boundaries, data categories, and review process to be used in the study. This phase is followed by three interrelated phases that may be conducted simultaneously or in a sequence that best suits the problem being studied: a life-cycle inventory (LCI) phase that identifies and quantifies the energy, resource use, and environmental effects of a particular product, service, or activity; an impact assessment phase that investigates the potential environmental consequences of energy and natural resource consumption and waste releases associated with the system being studied; and an improvement assessment phase where opportunities to reduce environmental impacts and resource use are investigated.

In our study, we had two functional units depending on whether we were doing LCIs or LCAs. For LCIs of products we used the industry production measure, i.e., plywood was given on a MSF 3/8-inch basis, and for LCAs we used the residential home. The residential home of fixed design within a specific climatic zone was considered to be occupied for a fixed time; the design incorporated alternative combinations of materials. We viewed the LCA of a residential home as a building system composed of many separate and related LCAs based on the LCIs of each product and process. We created the building system LCA by cumulatively embedding the LCAs of many processes and their associated products, sub-assemblies and assemblies, each containing a specific set of life-cycle stages from raw materials through recycling and waste management. For some products, such as framing materials, certain stages become a part of the process only when the aggregated LCA of the entire building is assembled. Examples are wall studs and other main framing lumber products that are covered by other materials, and remain unchanged during the building life. These items typically have no maintenance stage of their own. Similarly, the recycling and disposal stage may apply to only some of the products when the building is finally demolished (i.e. recycling and disposal of these individual products are not separable from the building as a whole).

There are at least two rather unique features of this study's LCA framework. The scope of many LCA studies considers only the analysis from extraction or raw materials to the production of products, a gate-to-gate analysis where time is of little importance. In this study the scope is extended to include forest growth and the time a house is in service. While some LCAs involving agricultural products or bio-energy have expanded the generic gate-to-gate model by including a crop growing stage prior to raw material acquisition (Andersson and Ohlsson 1999; Mann and Spath 1997), incorporating forest growth is more complex. The relative complexity of forest growth is due to 1) the much longer time frame involved, 2) the use of intermediate harvests (thinning) to yield products, 3) the broader array of joint products arising from a single tree (saw, veneer, and pulp logs) and stand (due to mixed species having different use preferences), and 4) the unique set of forest coproducts (water, recreation, berries, and mushrooms, etc.) and environmental effects (such as water quality, species diversity, wildlife habitat, and carbon sequestration).

Second, buildings, which account for the largest use of wood in North America and a main focus of this study, are unique in their size, complexity, and longevity. For example, a residential house is constructed, used for a long period of time, and eventually demolished and may even be recycled. The period of use and occupancy involves cycles of maintenance and repair (e.g. re-roofing) and may involve a series of

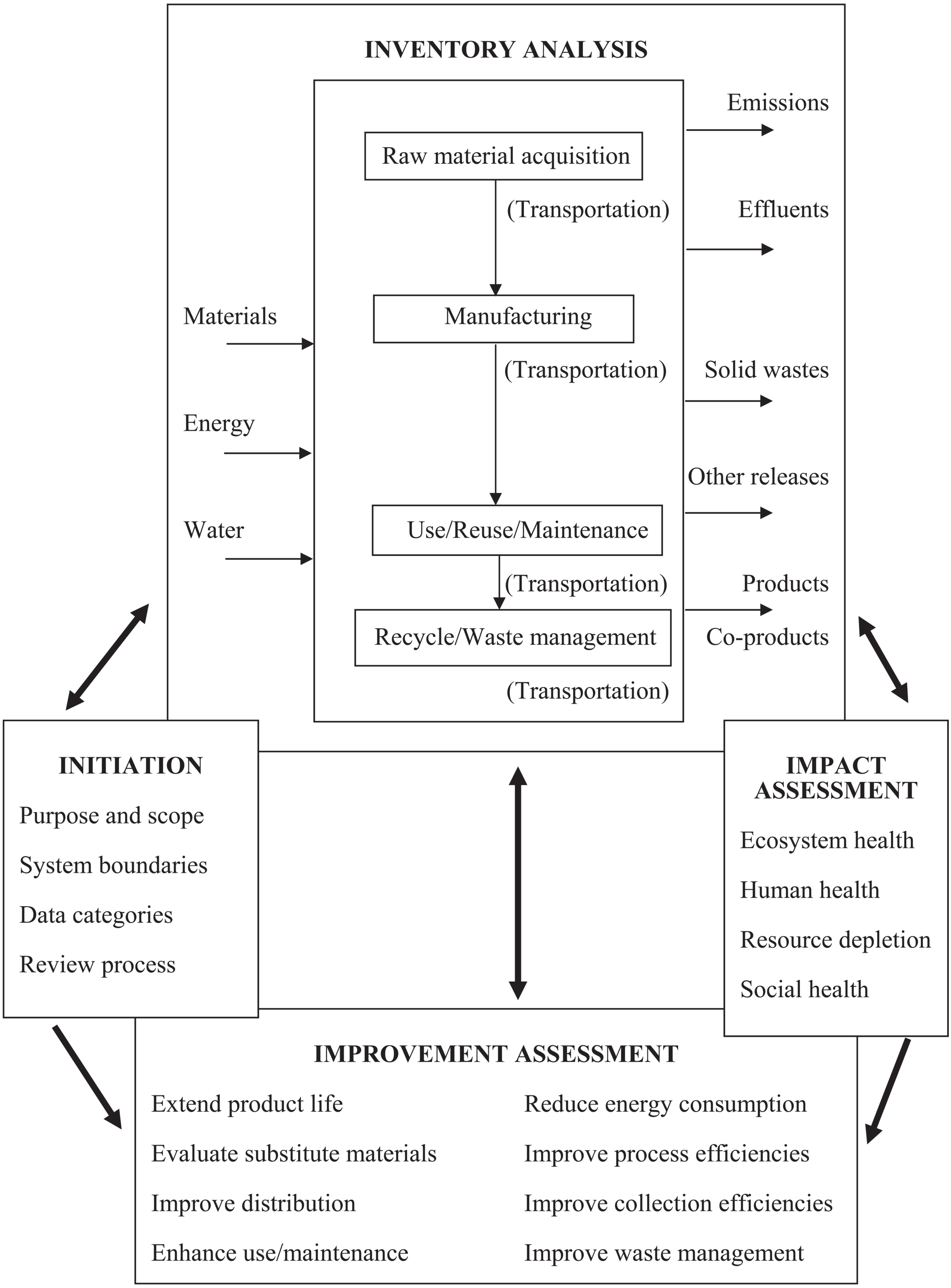

FIG. 2. Main components of an LCA study. Source: ATHENA (1997a)

owners each of whom may remodel the structure to accommodate changes in desired functionality and aesthetics. As a result, the time frame between when a tree seed germinates and when a house is demolished could be on the order of one to several centuries or more. Thus, the temporal distribution of events and associated environmental effects during the seed to demolition life cycle must be considered; merely summing all of the events and effects would produce the naïve and meaningless result that all of the activities and associated impacts occur simultaneously.

Table 1 highlights the major differences between the generic LCA model and this study's framework. The major stages in the generic LCA model originated for investigating consumer products and packaging materials with short lives where a simple temporal summation of effects is reasonable. Table 1 also indicates a rough estimate of time associated with each of the components of the study's framework with comments identifying some of the associated activities and environmental effects.

THE GENERAL APPROACH AND DATA SOURCES

Our approach was to first conduct LCIs that quantified the energy, resource use, and emissions associated with a particular product, service, or activity. We followed this activity with the assessment of the house, and investigated the potential environmental consequences of energy and resource consumption and waste emissions. Finally we identified improvement opportunities for future research.

LCIs were prepared for forest resources, softwood lumber, softwood plywood, oriented strandboard, composite I-joists, glue-laminated beams, laminated veneer lumber, and residential house (Bowyer et al. 2004). LCIs for non-wood products, such as steel and concrete, were taken from already established data sources (Athena Institute 2004).

The LCIs for the resource and products were done as gate-to-gate inventories. The transportation mileage and mode for the resource to the mill were provided in each product module. The transportation mileage and mode of product to

TABLE 1. *Comparison of the generic LCA model and the CORRIM research framework*

Generic LCA Model	CORRIM	Comment
	Forest Growth Time frame: 25-100+ years	Nursery, planting, thinning, fertilizing, during the growth cycle. Effects on carbon sequestration/global warming, diversity, habitat, streamside conditions, etc.
Raw Material Acquisition	Harvesting Time frame: <1 year	Logging during commercial thinning or final harvest. Effects on soil compaction and productivity, diversity, habitat, siltation, etc.
Manufacturing	Manufacturing Processes Time frame: <1 year	Individual products (lumber, plywood, LVL, OSB, etc.). Assemblies of products (trusses, glulam beams, I-joists, etc.). Effects on air and water emissions, solid waste.
	Construction of Structures Time frame: <1 year	On-site or factory built components (floor, wall, roof) and finished structure. Effects on solid waste.
Use/Reuse/Maintenance	Service Life and Use Time frame: 40–100 + years House life: 75 + years	Maintenance cycles (painting, reroofing, siding, etc.) and remodeling. Effects on energy use and associated emissions/waste, energy and emissions associated with repair/remodel products.
Recycle/Waste Management	Recycling and Disposal Time frame: <1 year	Teardown, segregation of materials, recycle, combust for energy, landfill. Effects on energy use and substitution, air and water emissions, solid waste/carbon sequestration.

construction site were provided with the residential construction module. A summary LCI for each product from resource to the output side (referred to as cradle-to-gate) of the manufacturing process is provided as a separate article. The protocol used to conduct the LCIs was as follows:

- External reviews of the proposed research protocol and the final Phase I reports for compliance with CORRIM protocol (CORRIM 2001) were conducted.
- A detailed description of each product process and technology was provided (Bowyer et al. 2004).
- A process flow diagram by each product unit process was provided along with a description of the boundary system. Two boundary systems were studied, one for site emissions and the other to consider all emissions including the production and delivery of fuels, electricity and resources as well as the site emissions.
- A survey was taken of product manufacturers to collect primary process data, a minimum of 5% of total annual production for the region was surveyed; for most cases this represented four mills and anywhere from 10% to 40% of total production. Delivery of resources to mill in terms of mode and mileage was also requested. The mills were targeted for representativeness and technology type.
- The surveys covered two U.S. regions: the Pacific Northwest and the Southeast
- All inputs of resources, electricity, and fuels were listed on a production unit basis, as well as all outputs of product, co-products, and emissions to air, water, and land.
- Type and amount of fuel were recorded to keep track of fossil and biomass fuels and their related emissions during combustion.
- Data were checked for accuracy by reviewing for outliers and missing entries, comparing to other mills, and comparing between regions, and conducting mass balances and energy analyses.
- Data were weight-averaged based on the annual production of each mill to determine the average process data for a product and region.

Producing forest resources from a forest ecosystem involves activities associated with establishment and growth of trees and other vegetation, the removal of wood biomass used as input into product manufacturing processes, and associated impacts on non-wood forest co-products including water, habitat, diversity, and aesthetics. The impacts from these processes change through time due to basic tree and plant physiology and competitive stand dynamics, past and prospective technologies, evolving silvicultural practices, and changing population demands for forest outputs. Hence, time is a critical element since the period from establishment to removal can vary from a few years for short rotation, intensive culture fiber/energy plantations to a century or more for selectively managed forests. Life-cycle inputs and outputs include both quantitative measures of productivity, costs, and environmental effects and qualitative measures that describe difficult-to-measure aspects of the forest environment. Growth and yield models representing conditions in the Pacific Northwest and Southeast growing regions and recent studies of harvesting activities were used to produce LCI data for forest regeneration, growth, and log production.

Forest products followed a more traditional LCI approach. Survey data from a representative sample of mills were collected on all mill inputs and outputs. For this study we treated each major step of each manufacturing process as a separate unit ("unit process") for process modeling. For example, a saw mill was viewed as consisting of the following processing centers (or unit processes): maintaining a log yard, debarking and bucking of logs, primary breakdown of logs into trimmed-green lumber, boiler operation, kiln-drying, planer milling, and grading and packaging. This level of detail allowed for recognition of various product grades and co-products from each center that may be sold to other industries without further processing. It also recognized alternative pathways of primary material through the mill (green lumber to grading and packaging versus green lumber to kiln-drying). The unit process level data allowed us to resolve potential issues with respect to co-product allocation and differences among various technological configurations for a unit process. We sampled individual facilities and unit processes to measure the variation in the industry and provide us with the range and median values associated with unit processes. The research gathered data through questionnaires sent to selected individual manufacturers. Table 2 lists wood products and assemblies for which data were collected from manufacturers.

The most challenging aspect of our data collection was to maintain consistency across many products made from different processes and wood species. Product characteristics vary substantially, as do the measurement practices used by different producers. We conducted analyses of mass balance and energy calculations for each processing stage in order to provide a validity check on the data quality. Different measurement conventions and imprecise measurement of characteristics such as moisture content made additional data collection necessary. In selected cases, such as the unit process for boilers (the conversion of biomass to energy), and softwood green lumber, additional data were collected to improve the sample size and resolve mass balance discrepancies.

Construction of buildings involves consumption of non-wood materials such as concrete for foundations and steel for nails and fasteners, etc. Life-cycle data for these materials and products were taken from previous life-cycle studies compiled and conducted by the Athena Sustainable Materials Institute (ATHENA 1993a, 1993b, 1993c, 1997a, 1977b).

The LCI of a building involves a fundamental shift from individual products to the combination of these into building assemblies (wall, floor, and roof systems) using spans, loads, and other variables that comply with building codes for the construction site. The activities associated with construction include those involved in producing building materials, as well as new life-cycle steps and impacts tied to construction activity in which materials and energy are consumed, and solid wastes and emissions are produced. Some effects are simply the aggregate of the various materials used in the construction assemblies while others are unique to the construction activities and are not attributable to an individual component product. To integrate various combinations of products into functionally equivalent assemblies and completed structures, two typical house designs were developed consistent with residential building codes in Minneapolis, MN, and Atlanta, GA, to represent cold and warm climate conditions, respectively.

The ATHENA™ Environmental Impact Estimator (EIE) model was employed with the data collected and LCIs constructed for the various wood products (Athena Institute 2004). The EIE model provided LCI measures based on the bill of materials developed for the two house designs. The EIE also contained LCIs for non-wood materials used in construction such as steel, concrete, glass, insulation, and roofing materials. Alternative architectural designs for the Minneapolis and Atlanta climatic regions, using different combinations of framing materials, resulted in a unique bill of materials for each design and location for analysis by the EIE model.

We also assigned burdens on building materials so that a sensitivity analysis for forest management alternatives on forest ecology can be performed since the product life cycle includes the time from planting and growing the renew-

TABLE 2. *Wood products for which unit process data were collected.*

Wood Product	Production Region
Softwood lumber, kiln-dried	U.S. Southeast, U.S. Pacific Northwest
Softwood lumber, green	U.S. Pacific Northwest
Softwood plywood	U.S. Southeast, U.S. Pacific Northwest
Oriented strandboard	U.S. Southeast
Glue-laminated beams	U.S. Southeast, U.S. Pacific Northwest
Laminated veneer lumber	U.S. Southeast, U.S. Pacific Northwest
Wood "I" joists and beams	U.S. Southeast, U.S. Pacific Northwest

able raw material to final demolition of the house. In the United States, a little over half of the wood produced in the forest is used directly in construction. The environmental burdens from the production processes used to produce building materials were allocated according to the mass of product and co-product in the production processes and to the mass of materials used in building construction. Other burdens were allocated to co-products such as the chips used to make paper. Similarly, the burden accumulated from transportation, processing energy, and construction energy was allocated to the building according to the mass of materials used in building construction. The environmental impacts from energy uses are derived from regional or national grids of purchased electrical energy and for fossil and bio-fuels. Thus the environmental burdens derived from energy consumption are allocated according to the specific type of energy consumed (11 types) and its place of origin (raw material and manufacturing producing regions and construction regions). Burdens for the capital equipment and buildings to produce energy or products were not included since their contribution was small based on their long life.

Many emissions were reported for each stage of production (extraction, manufacturing, transportation) with the most important being carried forward to the building construction stage. Manufacturing during the construction stage identified sixteen and twenty-three different air and water emissions, respectively. Six categories of solid waste were tracked for all production stages. Vital stand structure measures of the forestland environment were also tracked to describe their effects on water, habitat, carbon, and biodiversity, several of which required landscape-wide measures to be useful. These complex arrays of environmental outputs for the construction of a residential building were reduced to environmental performance indices to simplify the communication of findings. However, the science behind the best weighting schemes to represent aggregate environmental risk indices for water, air, solid waste, global warming potential, and forest health is still evolving and beyond the scope of this paper.

The ATHENA™ Institute derived indices for water and air emissions, solid waste, and global warming potential to reduce the complexity associated with the large number of individual emissions (Bowyer et al. 2004). Indices were used to measure the impacts from the use, maintenance, and disposal of a building. Indices for the forest biodiversity and the carbon stored in the forest were developed separately since these effects occur over a long period of time in contrast to the narrow time frame associated with impacts from extraction to construction.

An accurate depiction of the recycling and waste management stage would require forecasting technologies and markets for recycling and waste management far into the future since a building may not be demolished for many years after construction, and recycling activities and waste management focus on the individual materials for which recycling and waste management opportunities differ greatly. One must also consider the energy and emissions that are involved in demolition/deconstruction, separation and transport of the materials, and in recycling and waste management processes. As these conditions are unknown to us presently, the study assumed that current practices are applicable. This assumption may not be severely limiting since research suggests that demolition, recycling, and disposal differences between alternative designs are small (ATHENA 1997a). Therefore, we assume that the comparisons between design alternatives will be reasonably accurate in the absence of good data for this stage. However, when absolute effects of individual designs are required, better data for this stage may be necessary, a topic for future research.

Other articles in this publication describe the LCI data for each of the wood products used in construction including the forest regeneration to harvest activities and also the building use, maintenance, and disposal stages of activity for the house, which provided the common service unit for making comparisons. In the concluding section of this article, we provide summary information for the residential houses first from forest regeneration to construction and then for all stages of processing, from cradle to grave. Given the complexities raised by the renewable nature of wood resource, the long time interval involved and the other amenities forests provide, supplementary articles provide a time-dynamic perspective on carbon linked to forest management and an assessment of changing forest structure.

ENVIRONMENTAL PERFORMANCE INDEX COMPARISONS FOR RESIDENTIAL BUILDING CONSTRUCTION ALTERNATIVES

The analysis indicated that many similar materials are used in the construction of residential wood and non-wood structures for a cold climate (Minneapolis) and a warm climate (Atlanta). In other words, a wood-framed house had many non-wood materials used in its construction. The primary difference in materials between the Minneapolis wood and steel house was the substitution of 6,000 kg of steel for wood studs and joists in the walls and floors. Both designs shared the same basement and roof elements with the total weight of all structural materials approaching 100,000 kg. The substitution of 6% of the materials by weight (steel for wood) resulted in a substantial percentage increase in all of the environmental performance indices except solid waste, which was essentially unchanged.

For the Atlanta structure, the major difference between the wood and concrete design was the substitution of 8,000 kg of concrete (2,000 kg of limestone plus rebar and aggregate material) for 2,000 kg of wood in the exterior wall structure as both designs used similar concrete floors and wood roofs. The substitution of 8% of the materials by weight resulted in a substantial percentage increase in all of the environmental performance indices except water, which was essentially unchanged.

Table 3 presents the environmental indexes associated with the different production stages. With two exceptions, all of the construction index measures indicated significantly lower environmental risk for the wood framing design in Atlanta and Minneapolis compared to non-wood framing alternatives. The exceptions are that the steel design in Minneapolis produced less solid waste than the wood design although the difference was insignificant and there was no significant difference in the water pollution index for the Atlanta designs.

ENVIRONMENTAL PERFORMANCE INDEX COMPARISONS FOR SUBASSEMBLIES

It is instructive to compare subassemblies given the many common components in the residential construction. Tables 4 and 5 present the environmental indexes for the above-grade wall, and floor and roof assemblies, respectively. Across designs, the comparisons for the wall and floor sections generally showed larger percentage differences than for the buildings as a whole

TABLE 3. *Environmental performance indices for residential construction.*

MINNEAPOLIS DESIGN	Wood	Steel	Difference	Other design vs. wood (% Change)
Embodied Energy (GJ)	651	764	113	17%
Global Warming Potential (CO_2 kg)	37,047	46,826	9,779	26%
Air Emission Index (index scale)	8,566	9,729	1,163	14%
Water Emission Index (index scale)	17	70	53	312%
Solid Waste (total kg)	13,766	13,641	–125	–0.9%
ATLANTA DESIGN	**Wood**	**Concrete**	**Difference**	**Other design vs. wood (% Change)**
Embodied Energy (GJ)	398	461	63	16%
Global Warming Potential (CO_2 kg)	21,367	28,004	6,637	31%
Air Emission Index (index scale)	4,893	6,007	1,114	23%
Water Emission Index (index scale)	7	7	0	0%
Solid Waste (total kg)	7,442	11,269	3,827	51%

TABLE 4. *Environmental performance indices for above-grade wall designs.*

MINNEAPOLIS DESIGN	Wood	Steel	Difference	Other design vs. wood (% Change)
Embodied Energy (GJ)	250	296	46	18%
Global Warming Potential (CO_2 kg)	13,009	17,262	4,253	33%
Air Emission Index (index scale)	3,820	4,222	402	11%
Water Emission Index (index scale)	3	29	26	867%
Solid Waste (total kg)	3,496	3,181	–315	–9%
ATLANTA DESIGN	**Wood**	**Concrete**	**Difference**	**Other design vs. wood (% Change)**
Embodied Energy (GJ)	168	231	63	38%
Global Warming Potential (CO_2 kg)	8,345	14,982	6,637	80%
Air Emission Index (index scale)	2,313	3,373	1,060	46%
Water Emission Index (index scale)	2	2	0	0%
Solid Waste (total kg)	2,325	6,152	3,827	164%

TABLE 5. *Environmental performance indices for floor and roof assemblies.*

MINNEAPOLIS DESIGN	Wood	Steel	Difference	Other design vs. wood (% Change)
Embodied Energy (GJ)	109	182	73	67%
Global Warming Potential (CO_2 kg)	3,763	9,650	5,914	157%
Air Emission Index (index scale)	981	1,813	832	85%
Water Emission Index (index scale)	17	70	53	312%
Solid Waste (total kg)	13,766	13,641	–125	–0.9%

since the materials being substituted made up a larger share of the subassemblies.

The Minneapolis wood wall subassembly used less energy, and produced less global warming potential (GWP) than the steel wall subassembly that incorporated an outside layer of insulation to provide equivalent thermal properties. The steel disadvantage was substantially greater in the floor where stiffness became more important. The Atlanta wall concrete subassembly comparison was substantially worse given the wood used with the concrete to house the insulation and its gypsum covering.

In effect a substantial environmental performance difference for nearly substitutable products did not seem so great for a completed structure with many common components but was much more significant for subassemblies. The large percentage of common components in all designs suggested that the materials are more often complements than substitutes. The noted differences between the wood and steel wall versus the wood and steel floor also suggested that the design itself, based on the intrinsic properties of the materials, can have a substantial impact.

IMPACTS OF WITHIN WOOD SUBSTITUTION

The study also analyzed within wood substitution. The substitution of plywood for oriented strandboard (OSB), simulating the practice of a few years back, generally resulted in 3% lower environmental burdens for the completed house except for water. This result may simply reflect the lesser energy needed to dry PNW species for plywood compared to the SE species of OSB, and a more complete response by OSB mills to changing compliance standards regarding water emissions. The substitution of solid-sawn wood joists for engineered I-joists showed very little difference between the environmental performance indices as the increased use of resins and energy was offset by the greater material efficiency of the I-joists. The use of green Douglas-fir lumber for studs, which was still prevalent in the West, reduced energy by 4% and GWP by

2%. Other low grade co-products could be used as biofuel, lowering the energy requirement for manufacturing and especially for drying. Sensitivity analysis revealed that using all co-product material, except chips for paper production as biofuel, generally resulted in surplus energy for the production of wood, which can offset some of the energy purchased for steel, concrete, insulation, and other materials.

These substitutions also raised issues on material use. OSB is produced from wood of several species, generally considered of lower value. In that sense OSB reduced the pressure on forest acres that have been producing higher quality wood and are in greater demand. This results in a substantial productivity increase in terms of total production per acre of forestland. In addition, the I-joists used OSB and required less wood per house. I-joists used only 62 – 65% of the wood required by solid-sawn lumber joists. Since I-joists were only used in the floor in designs studied, returning to the use of solid-sawn joists would increase the use of wood fiber by 10% (1.3 metric tons) for the total house and this wood would generally be higher-valued species i.e. in greater demand. These material-use efficiency gains were significant when wood use was traced to the producing land base.

The increases in environmental burdens contributed by wood drying or replacing plywood by OSB were only a small fraction of the increases resulting from replacing wood framing by steel or concrete.

ENERGY USE FROM CRADLE TO GRAVE

Table 6 summarizes the energy used for each life-cycle stage. Only the maintenance energy for one framing design is shown since the roof, by far the largest maintenance requirement, was common for all framing designs studied. The energy used in heating and cooling dominated the energy used in all other stages of the life cycle. Again we show only the energy used for one design since the houses were assumed to be equally effective with respects to thermal efficiency. The present value cost was a relatively small share of the total investment from an economic standpoint since the energy used in heating and cooling was spread over the 75-year life cycle of a house, even though heating and cooling dominate energy use.

The table illustrates an interesting insight into energy efficiency. While the energy use for heating and cooling was roughly ten times the energy used in construction, maintenance, and demolition, this cost was less than 1/7th the cost of the structure. Reducing heating and cooling energy use to zero, a goal of the Department of Energy, may be difficult but one could spend an additional $13,490 on the Minneapolis house or $9,565 on the Atlanta house to reach that objective at an interest cost of 5% (adjusted for inflation) since the use of wood materials was substantially more efficient than fossil-intensive substitutes like steel and concrete. Reducing the energy through alternative construction materi-

TABLE 6. *Energy used in representative building life-cycle stages.*

	MINNEAPOLIS HOUSE		ATLANTA HOUSE	
	Wood Frame	Steel Frame	Wood Frame	Concrete Frame
Energy in the structure (GJ)	646	759	395	456
Energy from maintenance (GJ)	73	73	110	110
Energy for demolition (GJ)	7	7	7	9
Energy subtotal	727	840	512	575
Energy use for heating and cooling (GJ) (75 yrs)	7800	7800	4575	4575
House cost	$168,000	$168,000	$135,000	$135,000
Construction cost	$92,000	$92,000	$74,000	$74,000
Cost per year to heat and cool	$692	$692	$491	$491
Present value cost to heat and cool (75 years @ 5%)	$13,490	$13,490	$9565	$9565
Percent of construction cost	14.7	14.7	12.9	12.9

als was sensitive to the design of the building and the processing efficiency of materials.

While the total embodied energy in the steel-frame house was 759 GJ compared to 646 GJ for the wood-frame house, the contribution of wood products to this number was very small. When we looked only at the steel, wood, and insulation that were being substituted, the energy for these products, minus the bio-energy which was internally generated and renewable, was: 164 GJ for the steel frame (22% of the total) and 43 GJ for the wood frame (7% of the total). The explanation for this much-reduced energy consumption is that common products to both house designs, such as concrete, glass, gypsum, and asphalt roofing, have a higher energy intensity than the substitutes—wood, steel, and insulation. While the total energy in the steel house is only 17% greater than the wood house, for the products being substituted, the steel frame uses 281% more non-bio-energy than the wood-framed house. The substitution of steel and insulation for wood increases the fossil fuel energy in steel and insulation by 127 GJ with only a 7 GJ decrease in the energy to produce the remaining wood. While the steel frame used much more energy than the wood frame, the energy used by products other than steel and wood that were common to both designs was substantially greater.

Similar comparisons for the concrete house showed 461 GJ embodied energy compared to 398 GJ for the wood-frame house. The energy embodied in the concrete and rebar, which substituted for wood, minus the fossil fuel energy, was: 84 GJ for the concrete frame (18% of the total) and 24 GJ for the wood frame (6% of the total). While the total energy in the concrete frame was only 16% greater than the wood house, for the products being substituted the concrete frame used 250% more fossil energy than the wood frame. The substitution of concrete block, mortar and rebar requires 63 GJ more energy while the wood energy use decreases by only 3 GJ. Similar to the steel comparison, the concrete frame uses much more energy than the wood frame, but the energy in products common to both designs including the concrete floor and foundation is substantially greater.

CARBON EMISSIONS FROM CRADLE TO GRAVE

The carbon emissions associated with energy use represent one of the more important environmental burdens. We note that the carbon in the forest provides an offset to emissions. Table 7 reports the carbon emissions (and avoided emissions) associated with the life cycle of a house.

Emissions from product manufacturing, construction, and demolition are added to the emissions from maintenance, heating and cooling. These emissions were offset to a large degree by the avoided emissions from the carbon stored in

TABLE 7. *Carbon dioxide emissions (tones) in representative building life-cycle stages.*

	MINNEAPOLIS HOUSE		ATLANTA HOUSE	
	Wood Frame	Steel Frame	Wood Frame	Concrete Frame
Emissions from:				
Fossil fuels in mfg. construction and demolition	37.1	46.8	21.4	28.0
Biofuel	3.6	2.6	3.4	2.7
Maintenance	3.4	3.4	4.1	4.1
Heating and cooling	390	390	232	232
Subtotal of emissions	434	443	261	267
Forest sequestration	(467)	(246)	(103)	(85)
Wood product storage	(22.4)	(11.8)	(17.1)	(14.1)
Subtotal of sinks and stores	(489)	(258)	(121)	(100)
Net emissions	(55)	185	140	167

forests and products. The emissions from biofuels were subtracted to avoid double counting.

While the total sources of emissions were dominated by the impact of energy used in heating and cooling, the forest and wood product sinks for carbon tend to be larger for the Minneapolis wood-frame house. The net carbon dioxide avoided is 55 metric tons for the Minneapolis wood frame house, compared to a net source of emissions of 185 metric tons for the steel frame, 140 for the Atlanta wood frame, and 167 for the concrete frame. That is, only the Minneapolis wood frame showed more carbon dioxide stored than emissions. The shorter rotation in the Southeast sequestered less carbon dioxide in the forest.

Integration over all of the activities performed on today's stocks of forest lands and housing, coupled with today's processing, construction, and demolition and disposal methods, provided a realistic "bottom line" inventory on the current status of resource and energy consumption and releases to the environment. However, efforts to identify cost-effective improvements may need to take into consideration the time value of money, which differs across several of these life-cycle stages.

ENVIRONMENTAL IMPROVEMENT OPPORTUNITIES

The report identifies many areas where environmental improvement opportunities would appear to be attractive and benefit from further work. These opportunities include:

- Redesign of the house to use less fossil-intensive products such as steel and concrete.
- Redesign of the house to reduce energy use (both active and passive).
- Adoption of building codes that result in reduced use of wood, steel, and concrete.
- Greater use of low-valued wood fiber for biofuel to substitute for fossil fuels.
- Greater use of engineered products producing higher-valued products from less desirable species.
- Improved efficiencies for processes such as the boiler or dryer (including air drying) to reduce energy use.
- Environmental pollution control improvements to reduce fuel and electricity use while reducing emissions.
- More intensive forest management.
- Increase recycling of demolition wastes.
- Increased product durability (given the already long expected life of a house, from 75 – 100 years, this applies primarily to moisture/weather exposed areas).

ACKNOWLEDGMENTS

This research project would not have been possible without the financial and technical assistance provided by the USDA Forest Service, Forest Products Laboratory (JV1111169 – 156), DOE's support for developing the research plan (DE-FC07-961D13437), CORRIM's University membership, and the contributions of many companies. Any opinions findings, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the contributing entities.

REFERENCES

American Forest and Paper Association (AF&PA). 1996. Life cycle inventory analysis user's guide: Enhanced methods and applications for the products of the forest industry. AF&PA, Washington, DC.

Andersson, K., and T. Ohlsson. 1999. Life cycle assessment of bread produced on different scales. Intl J. LCA. 4(1):25 – 40.

ATHENA™. 1993a. Raw material balances, energy profiles and environmental unit factor estimates: Cement and structural concrete products. Prepared by: Canada Center for Mineral and Energy Technology, and Radian Canada, Inc. Athena Sustainable Materials Institute, Ottawa, Canada.

_______. 1993b. Raw material balances, energy profiles and environmental unit factor estimates: Structural steel products. Prepared by: Stelco Technical Services, Ltd. Athena Sustainable Materials Institute, Ottawa, Canada.

_______. 1993c. Raw material balances, energy profiles and environmental unit factor estimates: Structural wood products. Prepared by: FORINTEK Canada Corp. Athena Sustainable Materials Institute, Ottawa, Canada.

_______. 1997a. The summary reports: Phase II and phase III and research guidelines. Prepared by: FORINTEK

Canada and Wayne B Trusty & Associates. Athena Sustainable Materials Institute, Ottawa, Canada.

_______. 1997b. Working with ATHENA™: Comparative manual and model case study assessments. Prepared by: The Environmental Research Group, School of Architecture, University of British Columbia. Athena Sustainable Materials Institute, Ottawa, Canada.

_______. 2004. Environmental impact estimator (EIE - software v3.0.1). Athena Sustainable Materials Institute, Ottawa, Canada.

Bowyer, J., D. Briggs, B. Lippke, J. Perez-Garcia, and J. Wilson. 2004. Life cycle environmental performance of renewable building materials in the context of residential construction. Consortium for Research on Renewable Industrial Materials (CORRIM, Inc). Phase I final report. University of Washington, Seattle, WA. 600+ pages.

CORRIM. 1998. Environmental performance research priorities: Wood products. Final report on the research plan to develop environmental performance measures for renewable building materials with alternatives for improved performance. Consortium for Research on Renewable Industrial Materials (CORRIM, Inc.) DOE Agreement No. DE-FC07–96ID13427, Subcontract 417346. on file at the University of Washington, Seattle, WA.

_______. 2001. Research guidelines for life cycle inventories. Consortium for Research on Renewable Industrial Materials (CORRIM, Inc.) on file at the University of Washington, Seattle, WA.

Franklin Associates, Ltd. 1990. Resource and environmental profile analysis of polyethylene and unbleached paper grocery sacks: Final report. Franklin Associates Ltd, Prairie Village, KS.

International Organization for Standardization (ISO). 1997. Environmental management-life cycle assessment-principles and framework, ISO 14040: First edition 1997–06–15. Geneva, Switzerland.

______. 1998. Environmental management-life cycle assessment-goal and scope definition and inventory analysis. ISO 14041: First edition 1998–10–01. International Organization for Standardization, Geneva, Switzerland.

______. 2000a. Environmental management-life cycle assessment-life cycle impact assessment. ISO 14042: First edition 2000–03–01. International Organization for Standardization, Geneva, Switzerland.

______. 2000b. Environmental management-life cycle assessment-life cycle interpretation. ISO 14043: First edition 2000–03–01. International Organization for Standardization, Geneva, Switzerland.

Mann, M. K. and P. L. Spath. 1997. Life cycle assessment of a biomass gasification combined-cycle power system. NREL/TP-430–23076. National Renewable Energy Laboratory, Golden, CO.

National Research Council. 1976. Renewable resources for industrial materials. National Academy of Sciences, Washington, DC. 267 pp.