CORRIM: Phase I Final Report

Module J

ENVIRONMENTAL IMPACTS OF A SINGLE FAMILY BUILDING SHELL -

FROM HARVEST TO CONSTRUCTION

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EXECUTIVE SUMMARY

This module presents the LCI and LCA for the single family home designs located in Atlanta and Minneapolis that simulate construction activity in a cold (Minneapolis) and warm (Atlanta) climate. The LCA compares typical shells constructed of either wood framing or an alternative material: concrete in Atlanta and steel in Minneapolis. The analysis summarizes the environmental effects from resource extraction through to the completion of the shell on-site. The in-place structural frame, envelope components and interior wall partitions are compared for alternative materials maintaining similar structural capability and code R-values.

The Athena™ *Environmental Impact Estimator* (EIE) was used to evaluate the impact of product and construction process LCI data. In addition to raw material resource measures, it develops five indices to summarize the large number of output measures. These summary measures include primary (embodied) energy , greenhouse gas potential (both fuel and process related), measures of air and water pollution, and solid waste emissions. Results are provided in terms of building totals by assembly. Additional analyses were concluded on several subassemblies, and the results are also reported here.

There are many common materials between the two designs. The primary structural difference between the Minneapolis wood and steel house designs is the use of materials for floors and walls. Both designs share the same basement, roof and window elements. The wooden structure is constructed using 2x6 wood studs versus 2x4 steel studs in above grade exterior walls. The steel studded walls have a smaller cavity and use R13 insulation plus an extruded polystyrene (EPS) insulation on the exterior versus the R19 valued insulation for the wooden wall. Below grade exterior walls and partition walls use 2x4 dimension wood and steel studs respectively, with the below grade exterior walls furred out to allow for insulation, wires and pipes. Flooring materials are engineered wood I-joist for the wooden structure and steel C-joists for the steel structure. These alternative house designs in Minneapolis lead to bills of materials with some significant differences. The major differences are 5 metric tonnes of galvanized studs are used for steel framing in place of 6 mbfm of small dimension studs, 0.34 msf of panels and a cubic yard of laminated veneer lumber. The steel design employs extruded polystyrene in place of 25% of the fiberglass insulation in the wooden structure. The differences in resource use are six times more metallurgical coal, five times more iron ore and only one half of the wood fiber is used in the steel design than the wood design in Minneapolis. In addition, two times more water and 35% more scrap steel is used in constructing the steel house design than the wooden home. However, wood fiber is only 14.6% of the mass used in the construction of the wood house and raw materials related to steel production make up only 12.6% of the mass used in constructing the steel house.

The majority of the energy associated in home construction is used in the extraction and manufacture of the building materials. In the Minneapolis area this represents around 95% of total energy through to construction. For manufacturing, construction and transportation, the steel design utilizes 17% more MJ than the wood house. This energy profile leads to greater air emissions. The steel design emits 47 metric tonnes of air emissions, 98% of which are in the form of carbon dioxide. In contrast the wood design emits 38 metric tonnes with 98% of it in the form of carbon dioxide. Water pollution differences exist as well. The steel design's total water emissions are some four times greater than that of the wood design. The mix of largest pollutants changes with design. For steel, cyanide is the worst offender, whereas for wood, phenols contributed the largest percentage of the wooden design's water emissions. Total solid wastes, on a mass basis, are very similar for the two material designs.

Overall and relative to the wood design, the steel design embodies 17% more energy (113 GJ), produces 26% more global warming potential (10 metric tonnes), emits 14% more air and 311% more water pollution, but produces 1% less solid wastes (0.1 metric tonnes). Focusing on only the assembly groups affected by the change in material, i.e., walls and floors and roofs, the differences in the two designs are more pronounced. For example, when using the wood results as the baseline, the steel design's floors and roof embody 68% more energy (74 GJ), produce 156% more global warming potential (6 metric tonnes), emit 85% more air and 322% more water pollution, and produce 31% more solid wastes (0.4 metric tonnes). In effect, the steel design is relatively less efficient in the floor where stiffness is required than in the walls, where narrower steel wall studs with an extra 1.5" EPS insulation layer on the outside are contrasted with 2x6 wood wall studs.

Almost all of the substitution in the Minneapolis designs takes place in the structural components (studs) and the insulation. The structural steel wall assembly embodies 43% more energy, produces 147% more GWP, 60% more air and 867% more water pollution with 27% less solid waste than the wood wall. The steel assembly insulation embodies 73% more energy, produces 61% more GWP, 20% more air and a similar impact on water pollution with 14% less solid waste.

The alternative house designs in Atlanta also lead to bills of materials with significant differences. More concrete blocks (1668), mortar (5.35 m^3), rebar rods (1 ton) are used in place of 0.45 mbfm of small dimension studs in the concrete house. On the exterior 1.97 msf of additional structural panels, 140 m^2 of additional vinyl and an additional 470 m^2 of felt paper are used in the wood design in place of latex paint and stucco in the Atlanta concrete design. Only 10% of the mass of raw materials used in the construct of the wooden home is wood fiber in Atlanta. As in the Minneapolis home, the majority of the energy associated in home construction in Atlanta is used in the extraction and manufacturing of the building materials. This represents around 92% of total energy in Atlanta.

The concrete design utilizes 16% more energy than the wood design in Atlanta, leading to greater air emissions. The concrete design emits 15% more substances to air than the wood design. Ninety-five percent of the emissions to air by the concrete design are released during the manufacturing phase of the life cycle. Overall carbon dioxide accounts for 98% of all emissions to air for the concrete design. Differences in water emissions between the two designs are not large. The concrete design resulted in almost 4 metric tonnes more solid waste.

Relative to the wood design, the concrete design embodied 16% more energy (63 GJ), produced 31% more GWP (7 metric tonnes), emitted 23% more air and a similar amount of water pollution, but produced 51% more solid wastes (4 metric tonnes). Focusing only on the wall assembly group as the only place where concrete replaces wood, the concrete design embodies 38% more energy, produces 80% more GWP, emits 49% more air and a similar amount of water pollution, while producing 165% more solid waste.

Almost all of the substitution occurs in the structural components (studs and sheathing vs. concrete block) and cladding (vinyl vs. stucco). The structural part of the concrete wall embodies 262% more energy than the wood design, 657% more GWP, 589% more air pollution with a similar amount of water pollution and 613% more solid waste. Taken collectively the concrete wall structure and cladding embody 88% more energy than the wood design, 152% more GWP, 112% more air pollution, similar water pollution, and 474% more solid waste.

Substitution within wood products leads us to compare different wood products that have substituted for each other in recent years. Oriented-strand board (OSB) has replaced plywood in many applications. Wooden I-joists are rapidly replacing solid sawn lumber in floor applications. We also compare green versus kiln-dried softwood as appropriate for some locations.

The plywood design when compared to the OSB design embodies 13 GJ less energy (3%), and produces 0.8 metric tonnes less GWP (3%). It produces a similar improvement in air pollution and a small improvement in solid waste, but a 50% increase in water pollution. A comparison of the use of solid sawn lumber in the floor joists with the I-joists used in the base design for the Minneapolis wood design leads to a slight increase in embodied energy, GWP and air pollution but a 12% decrease in water pollution. The higher energy intensity of I-joists largely offsets the benefit of a reduced volume of material used in construction, however, I-joists are more efficient in wood utilization using 1.3 metric tonnes less wood fiber, a 10% reduction, requiring fewer acres for timber production. Green wall studs compared to the kiln-dried studs used in the base case Minneapolis wood design embody 25 GJ less energy, (a 4% improvement), a 1 metric ton reduction in GWP (2%), a 3% reduction in air pollution and almost no impact on water pollution or solid waste.

Wood manufacturing industries are unique in the availability of waste materials (biofuel) that can be used for energy substitution. An analysis of the substitution possibilities associated with allocating more low valued wood (all co-products except chips) to the energy stream leads to the conclusion that over the design of the house, biofuel can (i) make wood processing nearly self sufficient in the steel design requiring the purchase of only 3 GJ, and (ii) provide an energy surplus (0.3 GJ) in the wood design. The residuals from lumber and plywood that can be allocated to energy production are in sufficient quantity to produce a substantial surplus. There is little surplus in OSB production, however. For the Atlanta designs, biofuel can produce an 8 GJ surplus in the concrete design, and a 2 GJ surplus in the wood design.

With the current use of biofuels, substitution of steel reduces the energy in wood production by 13.4 GJ, which is partially offset by a 7.3 GJ reduction in biofuel energy. There is an increase of 103.9 GJ needed for the steel substitution and 23.6 GJ for increased insulation. The 125.7 GJ increase in purchased energy for steel and additional insulation dwarfs the 6.1 GJ reduction in purchased energy for wood. The increased biofuel more than offsets the energy required in wood production reducing the purchased energy needs when wood co-products, except for the chips allocated to paper production, are used as biofuel.

Substitution of concrete and steel rebar reduces the energy in wood production by 8.3 GJ. It is partially offset by a 5.4 GJ reduction in biofuel energy with an increase of 40.8 GJ for the concrete and 21.9 GJ for rebar. This 62.7 GJ increase in purchased energy for concrete and rebar is much larger than the 2.9 GJ reduction in purchased energy for wood. When the wood co-products except for the chips allocated to paper production are used as biofuel the increased bio energy produced from the biofuel in the concrete structure exceeds the increase in the wood structure while reducing the purchased energy needs in both designs.

While this study demonstrates the merits of wood residential construction relative to alternative material designs, it should be noted that the study only considers the in-place design and does not consider the full life cycle of the complete building.

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1.0 INTRODUCTION

The objective of this module is to compile a life cycle inventory (LCI) and life cycle assessment (LCA) of wood and alternative material home designs in two regions of the US, consistent with ISO 14040 series LCA standards (ISO 14040 1997, ISO 14041 1998, ISO 14042 1998). CORRIM's main goal for this module is to place this data into authoritative databases such as ATHENA™'s Environmental Impact Estimator (EIE) software so that designers can better characterize the sustainability of using wood based solutions in their residential designs. This module demonstrates the use of the data within the confines of the EIE software.

Specifically, the LCI/LCAs' of the various material house designs are provided for use in the following applications:

- Market Support – The results will be avialable to users of LCI/LCA information, as needed, to help them evaluate material options for new residential dwellings.

- Process Improvements and New Technology Evaluation – The module can be used by forest products companies and policy analysts to run scenarios to evaluate process improvements, forest management regimes, new technologies and energy self-sufficiency (see section 5.4 of this module).

- Product Profiles - the module provides a rolled-up detailed product profile, with key indicators of environmental performance from the various phases of production through putting materials in place. These product profiles can be used in education and marketing efforts with environmentally conscious consumers of wood products.

- Product Innovation – each product's LCI/LCA profile can be used to pinpoint opportunities to improve that product, or to highlight its life cycle profile in comparison to other products for certain applications.

The scope of the study is described in detail below. Refer to the "Main Project Report" for information concerning the status of the peer review for this and the other modules.

Modules A-H in this report have presented LCIs for the individual wood products based upon primary mill surveys conducted in 2000 and 2001. In this module we integrate these individual product LCI databases with LCIs for alternative materials in order to complete, first an LCI and, then an LCA of single family home designs inclusive of structure and envelope components as located in Atlanta and Minneapolis. The LCA for residential construction is produced by the Athena™ Sustainable Materials Institute (the Institute). The Institute maintains commercially available software for simulating building construction and generates both LCI data and impact measures for a constructed building using an array of building materials for which comprehensive LCI data are available. The Institute has modified and expanded its Athena™ Environmental Impact Estimator (EIE) software to accept the US wood product production LCI data developed by CORRIM and to simulate construction activity in the two different US end markets of interest - Minneapolis and Atlanta.

The LCA produces an environmental comparison of typical shells for single-family houses in each market location constructed of wood and of alternative materials (steel frame in Minneapolis and concrete block in Atlanta) from resource extraction through to the completion of the shell on-site. The environmental assessment was limited to the in-place structural frame, envelope components and interior wall partitions used in each of the comparable designs. The alternative material comparisons are similar in their structural capability and code R-values. No attempt was made to optimize any of the designs. Instead, the designs represent typical practice in each building location. Nor were any operating energy scenarios explored, so the effective R-value of the designs was not considered. The issues of material or operating energy optimization (e.g., optimum value engineering) are beyond the scope of the Phase I assessment.

The assessment includes a large number of output measures including resource extraction, energy consumption, air and water emissions and generation of solid wastes. Environmental performance results are summarized in terms of five measures to make long lists of outputs more tractable: 1) initial embodied energy (initial embodied energy includes the direct and indirect energy associated with resource extraction, product manufacturing and on-site construction activity stages, including all transportation within and between these three stages, 2) global warming potential (both fuel and process generated, but excluding CO_2 from the combustion of biomass[2]), 3&4) critical volume measures of air and water pollution, and 5) solid waste emissions. While the Institute's software supports a weighted resource use measure, it is not reported here due to its geographical limitation. A new index – for environmental measures associated with sustainable forest resource management appropriate for the Northwest is provided in module O.

[2] Biogenic CO_2 is in a constant state of equilibrium and hence any such emissions are treated as being neutral with respect to the calculation of global warming potential.

2.0 SOFTWARE & METHODOLOGY

2.1 BACKGROUND

Since the early 90s the Athena™ Institute has been developing an environmental life cycle assessment decision support tool known as the Athena™ *Environmental Impact Estimator* (EIE). The objective of the software is to assist the building community in making more informed decisions regarding the selection of design and material options that will minimize a building's life cycle environmental impact. This study was undertaken using version 3.0 of the Institute's software (ATHENA EIE 2004).

Currently, the Athena™ EIE software (v3.0) encompasses steel, wood and concrete structural products and assemblies, as well as a full range of envelope materials (e.g., cladding, insulation, glazing. etc.). It covers a building's life cycle stages from the "cradle" (resource extraction or winning) through to its "end-of-life" (grave). All energy flows are regionally specified and traced back to nature. Specifically the model encompasses the following building life cycle stages:

- **Product manufacturing**: includes resource extraction, resource transportation and manufacturing of specific materials, products or building components;
- **On-site construction**: includes product/component transportation from the point of manufacture to the building site and on-site construction activities and their effects;
- **Maintenance and replacement**: includes life cycle maintenance and replacement activities associated with the structure and envelope components based on building type, location and a user defined life for the building;
- **Building "end-of-life"**: simulates demolition energy and final disposition of the materials incorporated in a building at the end of building's life.

This module only draws on the first two activity stages supported by the EIE model. In the EIE model, the product manufacturing stage not only considers virgin raw materials, but also the recycled content materials in various products. For example, all post-consumer recycled material in the various product LCIs is considered to enter the product manufacturing stage burden free, except for any burdens associated with collecting, sorting, packaging and transportation of the material to its point of use. Pre-consumer recycled material (industrial prompt scrap), however, carries with it the burdens associated with its primary manufacture, collection, sorting packaging and transport when it re-enters the manufacturing activity stage.

Neither the EIE model nor the CORRIM project tracts the heat content of wood; i.e., wood's inherent heat content or feedstock value. This is traditional practice in N. America where wood is rarely burned for heat content outside of the forest product industry itself. Finally, the cut-off criteria for inclusion of material flows for a particular product are the same for CORRIM and EIE software – see the CORRIM Research Guideline Protocol for more on this topic.

The software also includes a calculator to convert operating energy to primary energy and associated emissions, which allows users to compare embodied and operating energy environmental effects over the building's life. The operating energy calculator requires a separate estimate of operating energy as an input to the model.

In terms of results, the software provides a detailed environmental life cycle inventory of the embodied effects associated with the building as well as the set of five summary measures or impact indicators described below. These summary measures include primary (embodied) energy and raw material use, greenhouse gas potential (both fuel and process related), measures of air and water pollution, and, solid waste emissions.

Results are provided in terms of building totals by assembly. Additional analyses were concluded on several subassemblies, and the results are also reported here.

The software and its embedded databases are North American in scope, representing average or typical manufacturing technologies and appropriate modes and distances for transportation. The model is currently divided into eight Canadian geographic regions (represented by Vancouver, Calgary, Winnipeg, Toronto, Ottawa, Quebec City and Halifax) and four USA geographic regions (represented by Minneapolis, Pittsburgh, Atlanta and an USA average location). The software, used in conjunction with product and process LCI databases, can also assist in the evaluation of the environmental effectiveness of alternative manufacturing and forest management process changes.

In this report, neither the model's ability to include life cycle maintenance, replacement, and demolition nor its operating energy calculator capability is used as these impacts are addressed separately in modules K, L and M.

2.2 INTEGRATING CORRIM LCI DATA

The LCI for each product (modules A through H) was entered in the EIE software free of any electricity or gate-to-market transportation related burdens to maintain consistency across US wood products studied as part of CORRIM and the alternative building materials already modeled in the Institute's EIE software. It was also necessary to separate out transportation and material related flows that were combined into a single unit process as developed by the CORRIM team since the EIE software reports material and transportation effects separately for each activity stage in the life cycle (i.e., manufacturing and construction in the case of this protracted analysis). US average and regional electricity grid flows from and to nature were previously incorporated in the EIE software as stand alone databases, which are invoked when each regional product is specified, as were wood product transportation distances and modes as determined in the CORRIM project (see Table below). The EIE software calculates transportation effects on the basis of a tonne-km by mode of transportation. For commercial rail transport it is assumed that there is no empty backhaul. For commercial long haul truck transport, it is determined whether the transportation involves a specialized container/truck bed, which may limit backhaul capabilities, and if the container is deemed to be non-specific then no empty backhaul is assumed. Truck transportation from the local distribution center to the building site is assumed to include an empty backhaul.

Mill processing environmental burdens were allocated to products using the ratio of product/(product + sold co-products) mass excluding bark which is consumed internally as hog-fuel . While the energy=value of the hog-fuel is measured accurately, the mass is less accurate . The energy created from the hog fuel is allocated to products and co-products in the same way.

Each regional LCI product profile was then imported into the Institute's software. In some instances it was also necessary to force the software to use CORRIM data in the EIE software. For instance, in the Minneapolis region it would be quite common for both small dimension lumber and OSB to come from various parts of the US and Canada; however, for the purposes of this study the Minneapolis location was deemed to be served only by the PNW so as to pull on the latest available CORRIM data. In some cases CORRIM produced high, low and mid-point estimates for various unit processes (e.g., forest resource management and harvesting), but the EIE software is only capable of modeling a single value per flow per unit process (please refer to the individual modules for information concerning their LCI data development and data quality). In such cases the model incorporated the mid-point value or a weighted average value for the unit process under consideration. Further, the final component assembly (manufacturing) of roof trusses and wood I-joists rely on previously developed EIE data for Canada. Typically, these secondary manufacturing elements are of considerably less significance than the primary material manufacturing process.

Table 2.1 Product Transportation Distance by Mode for Atlanta and Minneapolis

	Atlanta		Minneapolis	
	Rail (km)	**Road (km)**	**Rail (km)**	**Road (km)**
Softwood Lumber, Green	na	na	2538	60
Softwood Lumber, Kiln-dried	0	120	2538	60
Softwood Plywood	0	300	2538	60
Oriented Strand Board	0	160	0	397
Parallel Strand Lumber	0	300	2455	60
Laminated Veneer Lumber	0	300	3149	60
GluLam Sections	0	300	3397	88

2.3 LCA ENVIRONMENTAL IMPACT INDICES

The LCI for residential construction contains a large number of emissions to the environment which makes evaluation of their effects difficult. For example, the different emissions do not produce similar impacts from a health risk assessment perspective and cannot be added together to produce a useful emissions index. Three different indices are created to summarize the effects into a global warming potential, and air and water pollution indices for easier interpretation. The number of solid waste emissions for the residential construction are substantially less, all measured by mass and easily summarized as a fourth index by their summation.

2.3.1 Global Warming Potential

Carbon dioxide is the common reference standard for global warming or greenhouse gas effects. All other greenhouse gases (e.g. primarily methane CH_4 and nitrous oxide N_2O) are referred to as having a "CO_2 equivalence effect" which is simply a multiple of the greenhouse potential (heat trapping capability) of carbon dioxide. This effect has a time horizon due to the atmospheric reactivity or stability of the various contributing gases over time. The 100-year time horizon figures are used in the ATHENA™ model as the basis for the equivalence. The 100-year horizon Greenhouse CO_2 Equivalence factors appear in the Global Warming Potential Index (GWPI) equation shown below (IPCC 2000).

$$\text{GWPI (kg)} = CO_2\text{ kg} + (CH_4\text{ kg x 23}) + (N_2O\text{ kg x 296})$$

While greenhouse gas emissions are largely a function of energy combustion, some products also emit greenhouse gases during the processing of raw materials. Process emissions often go unaccounted for due to the complexity associated with modeling manufacturing process stages. One example where process CO_2 emissions are significant is in the production of cement (calcination of limestone). All relevant process emissions of greenhouse gases are included in the EIE's resultant global warming potential index since the Institute uses a detailed life cycle modeling approach. In addition, the GWPI measure treats CO_2 emissions from biomass burning as being CO_2 neutral, because the net effect of carbon sequestration and release are neutral. A more comprehensive analysis of carbon storage including forest floor and product contributions over time is provided in module N.

2.3.2 Air and water pollution indices

It takes considerable expertise to understand and appreciate the significance of individual emissions to air and water. Both categories encompass a relatively large number of individual substances with varying environmental impacts. Air and water pollution indices are developed to capture ecosystem and/or human health effects of groups of substances emitted at various life cycle stages. In this case the commonly recognized and accepted critical volume method is used to estimate the volume of ambient air or water that would be required to dilute contaminants to acceptable levels, where acceptability is defined by the most stringent standards (i.e., drinking water quality standards).

ATHENA™ EIE calculates and reports the indices based on the worst offender -- that is, the substance requiring the largest volume of air and water to achieve dilution to acceptable levels (ERGSA 1994, ATHENA 1994). The hypothesis is that the same volume of air or water can contain a number of pollutants. The equation for the Air Pollution Equivalence Index (arbitrary scaling) is:

Air Pollution Equivalence Index = MAX of [SO_2/.03(mg/m^3) … SPM/.06(suspended particulate mater, mg/m^3) … CO/6(mg/m^3) … NO_2/.06(mg/m^3) …VOC/6(mg/m^3) … Phenol/2(mg/m^3)]

The equation for the Water Pollution Equivalence (arbitrary scaling) is:

Water Pollution Equivalence Index = MAX of [TDS/5(mg/L) … PAH/.0000001(mg/L) … Non-Ferr/.003(mg/L) … CN/.00005(mg/L) … Phenol/.00001(mg/L) … Nitr-Ammn/.02(mg/L) … Halg.Org/.0002(mg/L) … Chlor/3.5(mg/L) (mg/L) … Alum/.001(mg/L) … Oil.Gr./.01(mg/L) … Sulphate/5(mg/L) … Sulphide/.0005(mg/L) … Iron/.003]

There are concerns about the cumulative or synergistic effects of some substances and other methods for scoring may be considered in the future. The indices are not designed to provide absolute levels for safety standards but are appropriate for comparing conceptual designs to focus on relative differences between design options. While more work will be required to set useful tolerance limits when comparing two or more designs, relative differences greater than 15% are generally considered significant. Given this project’s greater level of effort to accurately model complete and detailed design drawings, it is believed that comparative result differences of 10% or more can be interpreted as significant.

2.4 HOUSE DESIGNS

Single-family structural home designs for Minneapolis and Atlanta were prepared and reviewed with Softplan® CAD files detailing the elevations, floor plans and specified materials (module I). Some material specification refinements were made such as determining the working gauge for steel products, the use of either plywood or OSB sheathing materials where they could be interchanged, and the specific strength of concrete to be used in various applications. For the purposes of wood and alternative material comparison, OSB was selected as the default sheathing material for the analysis.

The house designs were specified to be as close as possible to “as built” in each end market; i.e., no attempt was made to optimize material use in construction. In the Minneapolis market, the primary structural material alternative to wood was determined to be steel, although insulated concrete form is gaining popularity. For Atlanta, the alternative material design to wood was determined to be concrete block.

It is important to note that while the designs in a region were intended to be structurally equivalent, no assurance can be given that the houses would be functionally equivalent over their respective life spans. Functional equivalence could only be attained with the modeling of the complete house designs over a similar lifespan whereby maintenance, operating, and end-of-life effects are included. These functional issues will be considered in future work, hence the reader is cautioned not to draw any conclusions about the durability and long-term performance of any of the house designs. Module L does provide an evaluation of the useful life of houses in the US but not specific to the designs featured in this report.

2.4.1 Minneapolis

Table 2.2 summarizes the similarities and differences in alternative house designs for Minneapolis. Note that the similarities are greater than the differences in material use. The primary structural difference between the Minneapolis wood and steel house designs is the use of materials for floors and walls. Both designs share the same basement, roof and window elements. The basement walls were also furred out over their full height using the partition wall system as specified below for each material design.

The wooden structure is constructed using 2x6 wood studs versus 2x4 steel studs in above grade exterior walls. Insulation for these exterior walls is also different. The steel studded walls have a smaller cavity and use R13 insulation plus an extruded polystyrene (EPS) insulation on the exterior versus the R19 valued insulation for the wooden wall. Below grade exterior walls and partition walls use 2x4 dimension wood and steel studs respectively, with the below grade exterior walls furred out to allow for insulation, wires and pipes. Flooring materials are engineered wood I-joist for the wooden structure and steel C-joists for the steel structure.

Table 2.2. Summary of Alternative House Designs for Minneapolis

Characteristic	Wood Design	Steel Design
Single-family dwelling type	2 story with full basement	
Floor area	2062 sq. ft. (192 sq.m)	
Structure & Envelope Components		
Foundation (footing and slab)	3000psi (20 Mpa) concrete	
Foundation walls	Concrete block	
1st &2nd floors	Engineered wood "I"- joists @ 16" (400mm) o/c & 19/32" (15mm) plywood decking	Steel 18 ga. "C" joist @ 12" (300mm) o/c &19/32" (15mm) plywood decking
Above grade exterior walls	2"x6" wood studs @ 16" (400mm) o/c, #15 organic felt, OSB sheathing, R19 fiberglass batt insulation, 6mil polyethylene vapor barrier, 12mm gypsum board, vinyl siding	1.5"x3.63" Steel 20 ga. "C" studs @ 16" (400mm) o/c, #15 organic felt, OSB sheathing, R13 fiberglass batt insulation, 1.5" EPS insulation, 6mil polyethylene vapor barrier, 12mm gypsum board, vinyl siding
Below grade exterior wall	2"x4" wood studs @ 24" (600mm) o/c, R13 fiberglass batt insulation, poly v.b. 12mm gypsum board	1.5"x3.63" Steel 25 ga. "C" studs @ 24" (600mm) o/c, R13 fiberglass batt insulation, poly v.b. 12mm gypsum board
Partition walls	2"x4" wood studs @ 16" (400mm) o/c, 12mm gypsum board two sides	1.5"x3.63" Steel 25 ga. "C" studs @ 16" (400mm) o/c, 12mm gypsum board two sides
Window system	PVC frame, operable, double glazed Low "E" Argon filled	
Roof	Light Frame Wood Trusses with OSB sheathing, R44 blown cellulose insulation, 6mil poly vapor barrier, 16mm gypsum board with 25 yr durability asphalt shingles over #15 organic felt building paper.	

Note: #15 organic felt used in place of house wrap. House wrap is not included in the ATHENA EIE software database.

2.4.2 Atlanta

Table 2.3 lists the design elements for the Atlanta house. The only major difference between the Atlanta wood and concrete house designs is their respective exterior wall structure; all other structural elements are common between the two designs. The exterior walls use 2x4 studs for the wooden structure and concrete blocks for the concrete design. The exterior concrete block wall has a different cladding finish and was furred out on the inside wall surface with wood studs to provide a cavity for the insulation and a chase for electrical and plumbing services.

Table 2.3. Summary of Alternative House Designs for Atlanta

Characteristic	Wood Design	Concrete Design
Single-family dwelling type	1 story bungalow slab-on-grade	
Floor area	2153 sq. ft. (200 sq.m)	
Structure & Envelope Components		
Foundation (footing and slab)	3000psi (20 Mpa) concrete	
Foundation walls	None	
Main floor	100mm reinforced Slab-on-grade on footings	
Exterior walls	2"x4" wood studs @ 16" (400mm) o/c, #15 organic felt, OSB sheathing, R13 fiberglass batt insulation, 6mil poly vapor barrier, 12mm gypsum board, vinyl siding	Concrete Block furred out with 2x4 wood studs 24"(600mm) o/c, R13 fiberglass batt insulation, 6mil poly vapor barrier, 12mm gypsum board, two-coat stucco finish
Window system	PVC frame, operable, double glazed Low "E" Argon filled	
Partition walls	2"x4" wood studs @ 16" (400mm) o/c, 12mm gypsum board two-sides	
Roof	Light Frame Wood Trusses with OSB sheathing, R30 blown cellulose insulation, 6mil poly vapor barrier, 16mm gypsum board with 25 yr durability asphalt shingles over #15 organic felt building paper.	

Note: #15 organic felt used in place of house wrap. House wrap is not included in the ATHENA EIE software database.

3.0 LIFE CYCLE INVENTORY

3.1 BILL OF MATERIALS FOR HOUSE CONSTRUCTION

The bill of materials produced by the EIE software appears in Table 3.1 for each alternative material design by market location. In general, there are many similar materials used in home construction in the alternative design. The major exceptions for the Minneapolis designs are 5 metric tonnes of galvanized studs are used in the steel design in place of 6 mbfm of small dimension studs, slightly more structural panels and a cubic yard of laminated veneer lumber, along with a third more fiberglass insulation in the wood design in Minneapolis. The steel design employs extruded polystyrene in place of the extra fiberglass insulation in the wooden structure. For the concrete house in Atlanta, concrete blocks (1668), mortar (5.35 m^3), rebar rods (1 ton) are used in place of 0.45 mbfm of small dimension studs. On the exterior 1.97 msf of additional structural panels, 140 m^2 of additional vinyl and an additional 470 m^2 of felt paper are used in place of latex paint and stucco.

Table 3.1. Bill of Materials for Minneapolis and Atlanta Alternative House Designs

	Minneapolis		Atlanta	
	Steel	**Wood**	**Concrete**	**Wood**
Concrete 20 MPa (flyash av): m^3	21.89	21.89	31.80	31.80
Concrete Blocks: blocks	2,327.42	2,327.42	1,667.77	
Mortar: m^3	7.40	7.40	5.35	
Nails: tonnes	0.15	0.20	0.12	0.13
Welded Wire Mesh / Ladder Wire: tonnes	0.13	0.13	0.18	0.18
Screws Nuts & Bolts: tonnes	0.13			
Wide Flange Sections: tonnes	0.43	0.43		
Rebar, Rod, Light Sections: tonnes	1.01	1.01	1.23	0.18
Hollow Structural Steel: tonnes	0.10	0.10		
Galvanized Sheet: tonnes	0.14	0.27	0.24	0.24
Galvanized Studs: tonnes	5.13			
Small Dimension Softwood Lumber, kiln-dried: Mbfm	1.75	7.99	6.00	6.45
Softwood Plywood: msf ($^3/_8$inch basis)	2.82	3.45		
Oriented Strand Board: msf ($^3/_8$inch basis)	5.60	5.32	3.12	5.09
Laminated Veneer Lumber: yd^3		1.00		
Large Dimension Softwood Lumber, kiln-dried: mbfm	0.35	0.35		
Batt. Fiberglass: m^2 (25mm)	1,144.31	1,518.70	468.46	468.46
Extruded Polystyrene: m^2 (25mm)	308.36			
Blown Cellulose: m^2 (25mm)	1,761.30	1,761.30	2,099.96	2,099.96
6 mil Polyethylene: m^2	610.05	610.05	582.71	582.71
1/2" Regular Gypsum Board: m^2	669.47	669.48	378.84	378.84
5/8" Regular Gypsum Board: m^2	137.21	137.21	240.09	240.09
Joint Compound: tonnes	0.81	0.81	0.62	0.62
Paper Tape: tonnes	0.01	0.01	0.01	0.01
Water Based Latex Paint: l			15.51	
Stucco over porous surface: m^2			144.16	
Aluminum: tonnes	0.16	0.16	0.08	0.10
Vinyl: m^2	703.02	720.77	327.17	467.39
Organic Felt shingles 25yr: m^2	130.98	130.98	229.18	229.18
#15 Organic Felt: m^2	1,259.85	1,259.84	248.82	718.64
EPDM membrane: kg	55.97	55.97	37.71	37.71
Low E Silver Argon Filled Glazing: m^2	46.77	46.77	31.25	31.25

3.2 RESOURCE EXTRACTION

Table 3.2 lists the extracted resources derived by tracing the products in the bill of materials back to the resources required for their manufacture. This table allows one to compare the alternative house designs and isolate differences in resource use. For example six times more metallurgical coal, five times more iron ore and only one half of the wood fiber is used in the steel design than the wood design in Minneapolis. In addition, two times more water and 35% more scrap steel is used in constructing the steel house design than the wooden home. However, wood fiber is only 14.6% of the mass used in the construction of the wood house and raw materials related to steel production make up 12.6% of the mass used in constructing the steel house. In a similar vein, only 10% of the mass of raw materials used in the construct of the wooden home is wood fiber in Atlanta.

Table 3.2. Raw Resources Consumed for Minneapolis and Atlanta Alternative House Designs

	Minneapolis		Atlanta	
Raw Material	**Steel**	**Wood**	**Concrete**	**Wood**
Limestone (kg)	10,333	9,775	11,590	9,518
Clay & Shale (kg)	2,496	2,496	2,916	2,269
Iron Ore (kg)	6,614	1,019	667	507
Sand (kg)	1,256	1,403	776	748
Ash (kg)	48	48	59	45
Other (kg)	4,571	4,666	3,956	4,505
Gypsum (kg)	1,712	1,712	5,721	5,621
Semi-Cementitous Material (kg)	728	728	1,057	1,057
Coarse Aggregate (kg)	24,687	24,687	35,997	35,871
Fine Aggregate (kg)	24,437	24,437	32,848	26,427
Water (l)	520,484	168,814	98,241	102,301
Obsolete Scrap Steel (kg)	1,361	971	874	291
Coal (kg)	3,567	2,876	2,346	2,113
Wood Fiber (kg)	6,595	12,993	8,191	9,811
Phenol Form. Resins (kg)	126	144	65	103
Uranium (kg)	<1	<1	<1	<1
Natural Gas (m^3)	11,848	9,488	8,613	8,016
Crude Oil (l)	3,623	3,004	2,4263	2,605
Metallurgical Coal (kg)	2,864	407	254	189
Prompt Scrap Steel (kg)	764	602	545	178
Primary Fuels (kg)	14,200	14,318	10,741	8,641

3.3 ENERGY CONSUMPTION

Energy consumption is analyzed for each stage of processing: extraction, product manufacturing, and construction. Athena's *Environmental Impact Estimator* software combines resource extraction and manufacturing energy and reports them together under the manufacturing heading. Energy consumed in transportation is an important subcategory included within both manufacturing and construction life cycle stages. Manufacturing transportation includes all raw material transportation from the point of resource extraction or the source recycling facility to the point of manufacturing. Construction transportation includes all transportation from the manufacturing plant to the building site. Embodied energy is reported in mega-joules (MJ). Embodied energy includes all energy, direct and indirect, used to transform and transport raw materials into products and buildings, including inherent energy contained in raw or feedstock materials that are also used as common energy sources. For example, natural gas used as a raw material in the production of various plastic (polymer) resins is part of the embodied energy of plywood. In addition, the model captures the indirect energy use associated with processing, transporting, converting and delivering fuel and energy.

Table 3.3 lists the energy consumed by source for each alternative house design and stage of processing. The primary energy necessary to generate and deliver the pruchased electricity is included in the table by fuel type. The refined petroleum fuels have not been reported as traced back to crude oil; however, this is indeed the case in terms of upstream material and energy use and emissions to air, water and land. We have chosen to report these fuels in the form they are used to provide those less familiar with LCI data a more readily understood set of energy carriers. Table 3.2 contains the crude oil values. The wood energy associated with OSB production is reported in the feedstock fuels to avoid double counting of air emissions (see OSB module for more on this issue). A thorough analysis of wood energy is provided in Section 5.4. Total primary fuels reported in Table 3.3 exclude hydropower. The heating value of wood used in construction is not included in the calculation of embodied energy except when the wood is consumed as a biofuel to produce energy.

Table 3.3 indicates that the majority of the energy associated in home construction is used in the extraction and manufacturing of the building materials. In the Minneapolis area this represents around 95% of total energy through to construction and 92% of total energy in Atlanta. The steel design utilizes 17% more MJ than the wood house in Minneapolis, whereas the concrete design utilizes 16% more MJ than the wood design in Atlanta.

Table 3.3. Energy Consumption by Process Stage for Minneapolis and Atlanta Alternative House Designs

	Minneapolis		Atlanta	
	Steel	**Wood**	**Concrete**	**Wood**
Manufacturing				
Hydro (MJ)[a]	10,214	13,192	4,571	4,985
LPG (MJ)	237	277	102	151
Diesel (MJ)	11,896	16,590	5,840	6,066
Gasoline (MJ)	278	392	236	275
Natural Gas (MJ)	161,151	162,964	94,027	86,429
Wood (MJ)	5,241	15,431	12,870	13,844
Coal (MJ)	196,123	173,840	138,259	106,303
Heavy Fuel Oil (MJ)	70,387	62,152	46,576	23,896
Nuclear (MJ)	51,248	43,677	36,335	29,752
Feedstock Fuels (MJ)	218,430	125,597	84,168	96,651
Total (Primary Fuels) (MJ)	714,991	600,920	418,413	363,367
Manufacturing Transportation				
Diesel (MJ)	7,070	7,973	6,424	6,280
Natural Gas (MJ)	12	14	10	11
Coal (MJ)	1	1		
Total (Primary Fuels) (MJ)	7,083	7,988	6,434	6,291
Construction				
Hydro (MJ) [a]	52	56	158	158
LPG (MJ)	0	0	0	0
Diesel (MJ)	9,083	9,340	9,494	6,004
Gasoline (MJ)	0	0	0	0
Natural Gas (MJ)	158	168	52	52
Wood (MJ)	0	0	0	0
Coal (MJ)	5,497	5,843	6,591	6,591
Heavy Fuel Oil (MJ)	59	63	72	72
Nuclear (MJ)	1,829	1,944	2,521	2,521
Feedstock Fuels (MJ)	0	0	0	0
Total (Primary Fuels) (MJ)	16,626	17,358	18,730	15,240
Construction Transportation				
Diesel (MJ)	20,066	19,544	12,558	10,036
Natural Gas (MJ)	29	31	21	17
Coal (MJ)	1	1	-	1
Total (Primary Fuels) (MJ)	20,096	19,576	12,579	10,054
Total				
Hydro (MJ) [a]	10,266	13,248	4,729	5,143
LPG (MJ)	237	277	102	151
Diesel (MJ)	48,115	53,447	34,316	28,386
Gasoline (MJ)	278	392	236	275
Natural Gas (MJ)	161,350	163,177	94,110	86,509
Wood (MJ)	5,241	15,431	12,870	13,844
Coal (MJ)	201,622	179,685	144,850	112,895
Heavy Fuel Oil (MJ)	70,446	62,215	46,648	23,968
Nuclear (MJ)	53,077	45,621	38,856	32,273
Feedstock Fuels (MJ)	218,430	125,597	84,168	96,651
Total (Primary Fuels) (MJ)	758,796	645,842	456,156	394,952

[a] Hydro energy is not included in the total since no environmental impacts are estimated for hydro-power.

3.4 AIR EMISSIONS

The air emissions produced by each stage of processing are provided in Table 3.4. As stated in Section 2.3.2, three of the elements reported in this table are used to calculate the greenhouse warming potential. Other elements in the table are evaluated in the air emissions index to identify the most polluting element since the worst health risk offender is not revealed by the mass of any given emission

Table 3.4. Emissions to Air by Process Stage for Minneapolis and Atlanta Alternative House Designs

	Minneapolis		Atlanta	
	Steel	**Wood**	**Concrete**	**Wood**
Manufacturing				
Carbon dioxide (kg)	44,246	34,454	25,781	19,451
CO_2 biomass (kg)	526	1,547	1,291	1,388
Carbon monoxide (g)	164,038	76,808	47,052	47,247
Sulfur oxides (g)	284,913	249,670	172,975	141,492
Nitrogen oxides (g)	126,696	119,842	79,207	66,191
Nitrous oxides (g)	220	203	179	163
Particulates (g)	108,848	107,302	74,316	62,958
Volatile organic comp. (g)	12,865	13,813	8,210	11,470
Methane (g)	53,534	51,646	32,474	31,093
Phenols (g)	374	505	176	217
Acid gases excl. HCl & HFl (g)	37	35	21	34
Non methane hydrocarbons (g)	88,400	61,201	33,926	36,247
Metals (g)	280	651	540	565
Hydrogen chloride (g)	72	69	39	40
Hydrogen fluoride (g)	186	191	96	114
Other (g)	1,035	1,326	479	475
Manufacturing Transportation				
Carbon dioxide (kg)	13	14	11	11
CO_2 biomass (kg)	0	0	0	0
Carbon monoxide (g)	66	75	61	60
Sulfur oxides (g)	30	34	27	27
Nitrogen oxides (g)	134	151	122	120
Nitrous oxides (g)	0	0	0	0
Particulates (g)	37	42	34	33
Volatile organic comp. (g)	0	0	0	0
Methane (g)	2	2	1	2
Phenols (g)	0	0	0	0
Acid gases excl. HCl & HFl (g)	0	0	0	0
Non methane hydrocarbons (g)	77	87	71	69
Metals (g)	0	0	0	0
Hydrogen chloride (g)	0	0	0	0
Hydrogen fluoride (g)	0	0	0	0
Other (g)	0	0	0	0
Construction				
Carbon dioxide (kg)	1,188	1,243	1,336	1,090
CO_2 biomass (kg)	0	0	0	0
Carbon monoxide (g)	5,868	6,153	6,205	3,612
Sulfur oxides (g)	4,783	5,135	5,453	5,200
Nitrogen oxides (g)	8,562	9,038	9,494	6,472
Nitrous oxides (g)	7	8	9	9
Particulates (g)	629	669	759	759
Volatile organic compounds (g)	1,038	1,064	1,082	627
Methane (g)	951	1,041	1,150	1,125
Phenols (g)	0	0	0	0
Acid gases excl. HCl & HFl (g)	0	0	0	0
Non methane hydrocarbons (g)	71	76	49	49

	Minneapolis		Atlanta	
	Steel	**Wood**	**Concrete**	**Wood**
Metals (g)	1	1	1	1
Hydrogen chloride (g)	1	1	1	1
Hydrogen fluoride (g)	0	0	0	0
Other (g)	2	2	2	2
Construction Transportation				
Carbon dioxide (kg)	30	32	22	18
CO_2 biomass (kg)	0	0	0	0
Carbon monoxide (g)	159	170	120	96
Sulfur oxides (g)	72	77	54	44
Nitrogen oxides (g)	319	342	242	194
Nitrous oxides (g)	0	0	0	0
Particulates (g)	89	95	67	54
Volatile organic compounds (g)	0	0	0	0
Methane (g)	5	5	3	3
Phenols (g)	0	0	0	0
Acid gases excl. HCl & HFl (g)	0	0	0	0
Non methane hydrocarbons (g)	183	197	139	111
Metals (g)	0	0	0	0
Hydrogen chloride (g)	0	0	0	0
Hydrogen fluoride (g)	0	0	0	0
Other (g)	0	0	0	0
Total				
Carbon dioxide (kg)	45,477	35,743	27,150	20,570
CO_2 biomass (kg)	526	1,547	1,291	1,388
Carbon monoxide (g)	170,131	83,206	53,438	51,015
Sulfur oxides (g)	289,798	254,916	178,509	146,763
Nitrogen oxides (g)	135,711	129,373	89,065	72,977
Nitrous oxides (g)	227	211	188	172
Particulates (g)	109,603	108,108	75,176	63,804
Volatile organic compounds (g)	13,903	14,877	9,292	12,097
Methane (g)	54,492	52,694	33,628	32,223
Phenols (g)	374	505	176	217
Acid gases excl. HCl & HFl (g)	37	35	21	34
Non methane hydrocarbons (g)	88,731	61,561	34,185	36,476
Metals (g)	281	652	541	566
Hydrogen chloride (g)	73	70	40	41
Hydrogen fluoride (g)	186	191	96	114
Other (g)	1,037	1,328	481	477

3.5 WATER EMISSIONS

The emissions to water produced from each house design and for each stage of processing are provided in Table 3.5. Care must be exercised in reading the table, as the worst offender is not necessarily the same emission across alternative designs. For this reason we use the water pollution index described in Section 2.3.2 to calculate the worst offender.

Table 3.5. Emissions to Water by Process Stage for Minneapolis and Atlanta Alternative House Designs

	Minneapolis		Atlanta	
	Steel	**Wood**	**Concrete**	**Wood**
Manufacturing				
Biological Oxygen Demand (mg)	588,363	569,003	344,315	371,297
Suspended Solids (mg)	225,372,908	54,474,388	38,845,407	26,603,073
Dissolved Solids (mg)	156,861,270	162,184,373	93,399,481	89,982,586
Polynuclear Aromatic Hydrocarbons (µg)	27	33	12	13
Chemical Oxygen Demand (mg)	16,117,074	6,549,772	3,740,577	3,654,328
Non-Ferrous Metals (mg)	127,616	99,532	93,354	82,600
Cyanide (mg)	3,528,698	477,861	300,787	225,949
Phenols (µg)	138,580,597	126,655,749	37,600,396	58,397,281
Phosphates (mg)	341,618	369,972	309,549	316,736
Ammonia & Ammonium (mg)	202,359	215,016	120,289	119,154
Non-Halogenated Organics (µg)	636,673,484	582,286,737	365,296,560	327,734,331
Chlorides (mg)	168,380,335	144,521,744	76,313,319	82,327,335
Aluminum & Alumina (mg)	18,381	18,373	15,318	14,150
Oil & Grease (mg)	102,691,734	17,069,597	10,632,824	8,436,556
Sulphates (mg)	32,192,359	32,524,263	24,086,792	23,300,461
Sulphides (mg)	10,401,240	1,429,242	906,389	672,303
Nitrates & Nitrites (mg)	3,915,174	588,446	391,473	299,133
Dissolved Organic Compounds (mg)	2,073,869	2,104,190	1,034,039	1,374,308
Phosphorus (mg)	340,516	269,530	245,867	77,852
Iron (mg)	2,125,235	973,283	709,679	585,894
Other Metals (mg)	9,166,855	9,181,566	4,984,734	4,830,252
Acids (mg)	188,466	152,157	129,135	87,910
Other (mg)	74,123,043	79,909,759	41,427,996	43,938,373
Manufacturing Transportation				
Biological Oxygen Demand (mg)	63	72	58	57
Suspended Solids (mg)	386	435	353	345
Dissolved Solids (mg)	16,965	19,136	15,529	15,182
Chemical Oxygen Demand (mg)	425	480	389	380
Phenols (µg)	283	319	259	253
Phosphates (mg)	2	2	1	2
Ammonia & Ammonium (mg)	7	8	5	6
Non-Halogenated Organics (µg)	41,529	46,843	38,015	37,163
Chlorides (mg)	625	705	572	559
Oil & Grease (mg)	396	446	361	354
Sulphates (mg)	503	567	460	450
Iron (mg)	9	10	8	8
Other Metals (mg)	94	106	85	84
Acids (mg)	3	4	2	3
Other (mg)	14	16	12	12
Construction				
Biological Oxygen Demand (mg)	84	89	76	76
Suspended Solids (mg)	292,269	310,666	350,104	350,104
Dissolved Solids (mg)	49,939	53,083	52,812	52,812
Chemical Oxygen Demand (mg)	840	893	834	834

	Minneapolis		Atlanta	
	Steel	**Wood**	**Concrete**	**Wood**
Non-Ferrous Metals (mg)	7,436	7,904	10,253	10,253
Cyanide (mg)	1	1	1	1
Phenols (µg)	209	222	139	139
Phosphates (mg)	2,139	2,274	2,539	2,539
Ammonia & Ammonium (mg)	271	288	370	370
Non-Halogenated Organics (µg)	3,447,735	3,664,764	4,075,624	4,075,624
Chlorides (mg)	4,300	4,571	5,020	5,020
Oil & Grease (mg)	952	1,012	979	979
Sulphates (mg)	2,289	2,433	2,555	2,555
Nitrates & Nitrites (mg)	66	71	92	92
Iron (mg)	25,972	27,607	31,739	31,739
Other Metals (mg)	15,718	16,708	18,787	18,787
Acids (mg)	4,297	4,568	5,100	5,100
Other (mg)	1,286	1,367	1,448	1,448
Construction Transportation				
Biological Oxygen Demand (mg)	151	162	114	92
Suspended Solids (mg)	915	983	696	556
Dissolved Solids (mg)	40,256	43,208	30,608	24,459
Chemical Oxygen Demand (mg)	1,009	1,083	766	613
Phenols (µg)	671	721	510	408
Phosphates (mg)	4	4	2	2
Ammonia & Ammonium (mg)	16	17	12	10
Non-Halogenated Organics (µg)	98,542	105,768	74,926	59,874
Chlorides (mg)	1,483	1,592	1,127	901
Aluminum & Alumina (mg)	0	0	0	0
Oil & Grease (mg)	939	1,008	713	570
Sulphates (mg)	1,194	1,281	907	725
Iron (mg)	22	24	16	13
Other Metals (mg)	223	239	169	135
Acids (mg)	8	9	5	5
Other (mg)	33	35	25	20
Total				
Biological Oxygen Demand (mg)	588,661	569,326	344,563	371,522
Suspended Solids (mg)	225,666,478	54,786,472	39,196,560	26,954,078
Dissolved Solids (mg)	156,968,430	162,299,800	93,498,430	90,075,039
Polynuclear Aromatic Hydrocarbons (µg)	27	33	12	13
Chemical Oxygen Demand (mg)	16,119,348	6,552,228	3,742,566	3,656,155
Non-Ferrous Metals (mg)	135,052	107,436	103,607	92,853
Cyanide (mg)	3,528,699	477,862	300,788	225,950
Phenols (µg)	138,581,760	126,657,011	37,601,304	58,398,081
Phosphates (mg)	343,763	372,252	312,091	319,279
Ammonia & Ammonium (mg)	202,653	215,329	120,676	119,540
Non-Halogenated Organics (µg)	640,261,290	586,104,112	369,485,125	331,906,992
Halogenated Organics (µg)	0	0	0	0
Chlorides (mg)	168,386,743	144,528,612	76,320,038	82,333,815
Aluminum & Alumina (mg)	18,381	18,373	15,318	14,150
Oil & Grease (mg)	102,694,021	17,072,063	10,634,877	8,438,459
Sulphates (mg)	32,196,345	32,528,544	24,090,714	23,304,191
Sulphides (mg)	10,401,240	1,429,242	906,389	672,303
Nitrates & Nitrites (mg)	3,915,240	588,517	391,564	299,225

	Minneapolis		Atlanta	
	Steel	**Wood**	**Concrete**	**Wood**
Dissolved Organic Compounds (mg)	2,073,869	2,104,190	1,034,039	1,374,308
Phosphorus (mg)	340,516	269,530	245,867	77,852
Iron (mg)	2,151,238	1,000,924	741,442	617,654
Other Metals (mg)	9,182,890	9,198,619	5,003,775	4,849,258
Acids (mg)	192,774	156,738	134,242	93,018
Other (mg)	74,124,376	79,911,177	41,429,481	43,939,853

3.6 SOLID WASTE

Solid waste produced is reported in Table 3.6 on a mass basis in kilograms. No attempt has been made to further categorize emissions to land as either hazardous or non-hazardous. Few, if any, of the materials specified in these projects emit meaningful quantities of hazardous solid waste, however. It should be noted that because solid wastes are reported on a mass basis, results tend to favor low-density materials relative to a volume criteria (e.g. wood relative to steel and concrete construction waste). Reporting solid waste on a volume basis could markedly alter comparisons.

Table 3.6. Solid Wastes by Process Stage for Minneapolis and Atlanta Alternative House Designs

	Minneapolis		Atlanta	
	Steel	**Wood**	**Concrete**	**Wood**
Manufacturing				
Bark/wood waste (kg)	5	16	3	4
Concrete solid waste (kg)	1,591	1,601	1,859	1,837
Blast furnace slag (kg)	1,100	258	199	100
Blast furnace dust (kg)	243	178	157	60
Other solid waste (kg)	4,824	4,552	3,647	3,316
Total (kg)	**7,763**	**6,605**	**5,865**	**5,317**
Construction				
Bark/wood waste (kg)	536	1,820	1,044	1,044
Concrete solid waste (kg)	5,245	5,245	4,249	974
Blast furnace slag (kg)	0	0	0	0
Blast furnace dust (kg)	0	0	0	0
Steel waste (kg)	8	2	2	1
Other solid waste (kg)	90	95	108	108
Total (kg)	**5,879**	**7,162**	**5,403**	**2,127**
Total				
Bark/wood waste (kg)	541	1,836	1,047	1,048
Concrete solid waste (kg)	6,836	6,846	6,108	2,811
Blast furnace slag (kg)	1,100	258	199	100
Blast furnace dust (kg)	243	178	157	60
Steel waste (kg)	8	2	2	1
Other solid waste (kg)	4,914	4,647	3,755	3,424
Total (kg)	**13,642**	**13,767**	**11,268**	**7,444**

This waste stream is dominated by non-wood materials. Construction and manufacturing waste represent roughly 8-15% of the weight of the house, however the largest portion is conrete which is generally used as a land fill and is not considered a hazardous waste. The final waste from the dmolition of the house after its effective life is much larger than the waste stream associated with construction based on current recycling rates.

4.0 LCI RESULTS DISCUSSION

4.1 MINNEAPOLIS LCI RESULTS

The primary materials difference between constructing a steel- versus wood-frame shell in Minneapolis is that 5.13 tonnes of galvanized "C"-studs and joists are used in place of 6.2 mbfm of small dimension softwood lumber, 630 ft^2 of plywood and one cubic yard of LVL. The envelope material differences are relatively minor with the exception of wall insulation materials – the wood design uses fiberglass batt exclusively, while the steel design uses a combination of fiberglass batt and rigid polystyrene to achieve an R-20 rating with a thermal break to reduce the conduction of heat through the steel studs.

The substitution of roughly 6 metric tonnes of one material for another makes up a very small share of the approximately 100 metric ton total, because so much of the construction is common to both designs. However, this substitution still leads to markedly different primary energy profiles for the two alternative house designs. Relative to the wood design, the steel design uses 113 giga-joules (GJ) more primary fuels than wood (+17%, see table 5.1 Section 5.1.1). There is little difference in energy use for construction with almost all of the difference coming from the greater manufacturing energy intensiveness of steel. For both material designs, construction energy is only a minor contributor (< 6%) of the total energy embodied in the two building shells and roughly half of this small share is used for transportation to and from the site. However, construction transportation is two-to-three times greater than that of manufacturing transportation.

The marked differences in energy profiles lead to differences in air emissions. In total the steel design emits 46,867 kg of emissions to air, 98% of which is in the form of carbon dioxide (all sources). In contrast the wood shell is responsible for emitting a total of 37,998 kg of pollutants to air, some nine metric tonnes less than the steel design. Again the single largest air emission for the wood design is carbon dioxide, which accounts for 98% of all emission to air. Relative to the wood design the steel design emits generally higher air pollutant levels.

For both designs, emissions to water occurred primarily during the manufacturing life cycle stage. The steel design's total water emissions are some four times greater than that of the wood design. The mix of largest pollutants changes with design. For steel, cyanide is the worst offender, whereas for wood, phenols contributed a large percentage of the wooden design's water emissions.

Total solid wastes, on a mass basis, are very similar for the two material designs. The wood design's waste production is approximately a 50/50 split between the manufacturing and construction stages. The split between manufacturing and construction is about 70/30 for the steel design.

4.2 ATLANTA LCI RESULTS

The difference between constructing a concrete and a wood frame shell in Atlanta is that 1668 concrete blocks, 5.4 m^3 of mortar and 1.05 tonnes of rebar are used in the production of exterior wall. The block wall is then furred out with 2x4 at 24" on center with a single top and bottom plate to accept the cavity insulation and to provide a chase for electrical and plumbing services. The wood wall on the other hand, is also built using 2x4s, but at 16" on center with a single sill plate and a double top plate, which relative to the concrete design only adds another 0.5 mbfm of lumber usage for the wood design. In essence, the concrete design results in a much thicker wall of both wood and concrete but without the outside wood sheathing. The cladding finish is a relatively thin layer of stucco on the concrete block while the wood wall employs vinyl siding. Other than these wall differences, the two designs share all other components.

As in the case of Minneapolis, these material differences lead to markedly different energy profiles in manufacturing and only small differences in construction. Relative to the wood design, the concrete design uses 61 GJ, 16% more primary fuels (see Table 5.3 Section 5.2.1). Of this, 6 GJ results from the increased energy required for concrete construction and related transportation.

The concrete design emits 15% more substances to air than the wood design. Ninety-five percent of the emissions to air by the concrete design are released during the manufacturing phase of the life cycle. Overall carbon dioxide accounts for 98% of all emissions to air for the concrete design. In descending order, the next three largest pollutants emitted to air by the concrete design are sulfur and nitrogen oxides followed by particulates. A similar proportional mass domination by CO_2 emissions was prevalent for the wood design (98% with biogenic CO_2 included) and it also emulated the concrete design in terms of the next three most prevalent air pollutants, but the amounts are all smaller.

For both designs the manufacturing stage of the life cycle is responsible for 99% of the total emissions to water. The differences between the two designs are not large.

The concrete design resulted in almost 4 metric tonnes more solid waste, (+51%) with almost all of that difference in the construction stage.

5.0 SUMMARY OF LCA RESULTS

We report the LCA results for alternative house designs on a total house design as well as the above grade walls component. Reporting results on the total assembly and component basis provides a contrast between the different materials within the alternative designs. The total assembly basis includes all the common elements in the comparison. The components basis singles out the role different materials play as they substitute each other within the component. It should be noted that some table sums may not add up to those previously stated in the inventory section due to the inclusion of demolition effects in the impact results. These differences have been determined to be minor (less than 2%) and do not change the conclusions drawn from the measures.

5.1 MINNEAPOLIS RESULTS – TOTAL HOUSE DESIGN

Table 5.1 below summarizes the results of the environmental assessment of the wood and steel designs (structure, envelope and interior partitions) for the Minneapolis 2-story home by assembly type. The two designs share a number of the same structural assemblies (e.g., foundation footings and basement block wall, support beams/jack-posts and roof) and therefore, the difference in their environmental impact can be traced to their respective wall and floor assemblies. The wall assembly includes the below grade concrete wall and above grade exterior wood sheathing and vinyl siding which is common to both designs. Within this assembly only the above grade wall materials--wood vs. steel studs-- contributes to the differences. The floor and roof assembly includes the concrete basement floor, and first and second floor wooden subflooring, as well as the roof assemblies as common elements. Only the wood I-joists vs. steel joists in the floor contribute to the differences.

Overall and relative to the wood design, the steel design embodies 17% more energy (113 GJ), produces 26% more global warming potential (10 metric tonnes), emits 14% more air and 311% more water pollution, but produces 1% less solid wastes (0.1 metric tonnes). Focusing on only the assembly groups affected by the change in material; i.e., walls and floors and roofs, the differences in the two designs are more pronounced. For example, when using the wood results as the baseline, the steel design's floors and roof embody 68% more energy (74 GJ), produce 156% more global warming potential (6 metric tonnes), emit 85% more air and 322% more water pollution, and produce 31% more solid wastes (0.4 metric tonnes). In effect, the steel design is relatively less efficient in the floor where stiffness is required than in the walls, where narrower steel wall studs with an extra 1" EPS insulation layer on the outside are contrasted with 2x6 wood wall studs.

Table 5.1. Environmental Results Summary for the Minneapolis Designs

Design by Assembly Group	Embodied Energy MJ	Global Warming Potential Equiv. CO_2 kg	Air Pollution Index Critical Vol. Measure	Water Pollution Index Critical Vol. Measure	Solid Wastes kg
Wood Design					
Foundations	68,487	6,041	1,001	1	2,548
Walls	457,130	26,468	6,472	4	9,701
Floors& Roof	108,552	3,763	981	9	1,383
Extra Basic Mat.	16,424	775	112	3	134
Total	**650,593**	**37,047**	**8,566**	**17**	**13,766**
Steel Design					
Foundations	68,487	6,041	1,001	1	2,548
Walls	496,437	30,360	6,803	28	9,145
Floors & Roof	182,207	9,650	1,813	38	1,814
Extra Basic Mat.	16,424	775	112	3	134
Total	**763,555**	**46,826**	**9,729**	**70**	**13,641**

Notes: The Extra Basic Materials grouping includes the supporting steel jack-posts and beams for the structure.

5.1.1 Minneapolis Steel and Wood Above-Grade Wall Comparison

Since the wall assembly uses a substantial amount of concrete below grade common to both designs, a more direct comparison of the components of the above grade wall would allow us to understand differences observed in Table 5.1 more clearly. By focusing only on the wall section for the Minneapolis home designs it is obvious that almost all of the substitution takes place in two subcomponents, the structure (studs and sheathing) and insulation. Cladding, windows and other parts are common to both walls (Table 5.2).

The structural steel wall assembly embodies 43% more energy, produces 147% more GWP, 60% more air and 867% more water pollution with 27% less solid waste than the wood wall. The steel assembly insulation embodies 73% more energy, produces 61% more GWP, 20% more air and a similar impact on water pollution with 14% less solid waste.

Collectively the above-grade wall design embodies 18% more energy compared to 9% for the total wall assembly, which includes the common below-grade wall. It also produces 33% more GWP compared to 15% for the total wall; 11 % more air pollution vs. 5% for the total wall; 867% more water pollution vs. 600% for the total wall; and 9% less solid waste vs. 6% for the total wall.

Table 5.2. Environmental Results Summary for the Minneapolis Steel and Wood Above-Grade Wall Designs

Design by Structural Components	Embodied Energy MJ	Global Warming Potential Equiv. CO_2 kg	Air Pollution Index Critical Vol. Measure	Water Pollution Index Critical Vol. Measure	Solid Wastes kg
Steel wall design					
Structural	101,080	6,114	954	29	781
Cladding	78,069	4,864	1,170	0	256
Insulation	42,938	2,016	525	0	90
Windows	15,581	1,850	471	0	225
Other	58,614	2,418	1,102	0	1,829
Total	**296,282**	**17,262**	**4,222**	**29**	**3,181**
Wood wall design					
Structural	70,463	2,478	599	3	1,063
Cladding	80,123	4,992	1,201	0	263
Insulation	24,874	1,250	439	0	105
Windows	15,582	1,850	471	0	225
Other	59,203	2,439	1,110	0	1,840
Total	**250,245**	**13,009**	**3,820**	**3**	**3,496**

5.2 ATLANTA RESULTS – TOTAL HOUSE DESIGN

Table 5.3 below summarizes the results of the environmental assessment of the wood and concrete designs for the Atlanta house by specified assembly components. Again, the two designs share a number of the same structural assemblies (e.g., foundation footings, slab-on-grade, and roof) and therefore, the difference in their environmental impact can be traced to their respective exterior wall assembly.

Relative to the wood design, the concrete design embodied 16% more energy (63 GJ), produced 31% more GWP (7 metric tonnes), emitted 23% more air and a similar amount of water pollution, but produced 51% more solid wastes (4 metric tonnes).

Focusing only on the wall assembly group as the only place where concrete replaces wood, the concrete design embodies 38% more energy, produces 80% more GWP, emits 49% more air and a similar amount of water pollution, but produces 165% more solid waste.

Table 5.3. Environmental Results Summary for the Atlanta Designs

Design by Assembly Group	Embodied Energy MJ	Global Warming Potential Equiv.CO_2 kg	Air Pollution Index Critical Vol. Measure	Water Pollution Index Critical Vol. Measure	Solid Wastes kg
Wood Design					
Foundations	88,920	8,324	1,385	1	3,610
Walls	167,937	8,345	2,260	2	2,325
Floors & Roof	141,022	4,698	1,248	4	1,507
Total	**397,879**	**21,367**	**4,893**	**6**	**7,442**
Concrete Design					
Foundations	88,920	8,324	1,385	1	3,610
Walls	231,138	14,982	3,373	2	6,152
Floors & Roof	141,022	4,698	1,249	4	1,507
Total	**461,080**	**28,004**	**6,007**	**7**	**11,269**

Notes: Slab footings reported under the Foundations heading. Slab-on-grade reported under the Floors heading.

5.2.1 Atlanta Concrete and Wood Above-Grade Wall Comparison

A direct comparison of the concrete and wood design for the above-grade wall (Table 5.4) shows almost all of the substitution in the structure (studs and sheathing vs. concrete block) and cladding (vinyl vs. stucco). The relatively thin stucco layer uses less energy than vinyl cladding. The structural part of the concrete wall embodies 262% more energy than the wood design, 657% more GWP, 589% more air pollution with a similar amount of water pollution and 613% more solid waste. A portion of these impacts are offset by the cladding so that taken collectively the concrete wall structure and cladding embody 88% more energy than the wood design, 152% more GWP, 112% more air pollution, similar water pollution, and 474% more solid waste.

Table 5.4. Environmental Results Summary for the Atlanta Concrete and Wood Above-Grade Wall Designs

Design by Structural Components	Embodied Energy MJ	Global Warming Potential Equiv. CO_2 kg	Air Pollution Index Critical Vol. Measure	Water Pollution Index Critical Vol. Measure	Solid Wastes kg
Concrete wall design					
Structural	131,335	9,175	1,661	2	4,590
Cladding	38,309	2,359	568	0	124
Insulation	10,289	515	179	0	46
Windows	10,746	1,280	334	0	156
Other	40,459	1,653	631	0	1,236
Total	**231,138**	**14,982**	**3,373**	**2**	**6,152**
Wood wall design					
Structural	36,313	1,212	241	2	644
Cladding	54,082	3,369	811	0	177
Insulation	10,289	515	179	0	46
Windows	10,746	1,280	334	0	156
Other	56,507	1,969	748	0	1,302
Total	**167,937**	**8,345**	**2,313**	**2**	**2,325**

5.3 WOOD TO WOOD COMPARISONS

5.3.1 OSB *vs*. Plywood

Over time there has been greater substitution within wood products than between wood and steel or concrete (Fleishman, et. al. 1999). Oriented-strand board (OSB) has replaced plywood in many applications as a consequence of lower cost while also relying on species of wood with lower demand. A comparison of the base Atlanta house design using OSB with an alternative design using plywood instead of OSB is instructive since OSB uses resins and energy in different ways than plywood.

The plywood design when compared to the OSB design (Table 5.5) embodies 13 GJ less energy (3%), and produces 0.8 metric tonnes less GWP (3%). It produces a similar improvement in air pollution and a small improvement in solid waste, but a 50% increase in water pollution. The OSB disadvantage on these LCA measures is not large in comparison to its lower cost and its use of raw material species that are in less demand than the softwood species used in making plywood.

Table 5.5. Environmental Results Summary for Atlanta Wood Design using Plywood and OSB sheathing

Design by Structural Components	Embodied Energy MJ	Global Warming Potential Equiv.CO_2 kg	Air Pollution Index Critical Vol. Measure	Water Pollution Index Critical Vol. Measure	Solid Wastes kg
Wood Design - Plywood					
Foundations	88,920	8,324	1,385	1	3,610
Walls	162,829	8,053	2,205	3	2,308
Floors & Roof	132,942	4,237	1,161	5	1,479
Total	**384,691**	**20,614**	**4,752**	**9**	**7,397**
Wood Design - OSB					
Foundations	88,920	8,324	1,385	1	3,610
Walls	167,937	8,345	2,260	2	2,325
Floors & Roof	141,022	4,698	1,248	4	1,507
Total	**397,879**	**21,367**	**4,893**	**6**	**7,442**

Notes: Slab footings reported under the Foundations heading. Slab-on-grade reported under the Floors heading.

5.3.2 Engineered Wood I-joist Floor *vs.* Solid Sawn Wood

There has also been substantial within wood substitution between engineered products and solid sawn lumber as well. Wooden I-joists are rapidly replacing solid sawn lumber in floor applications as they use less wood raw material and are lighter and easier to install. A comparison of the use of solid sawn lumber in the floor joists with the I-joists used in the base design for the Minneapolis wood design (Table 5.6) leads to a slight increase in embodied energy, GWP and air pollution but a 12% decrease in water pollution.

In effect, the more energy used during the manufacturing of I-joists tends to offset the energy reduction that would be associated with the lower volume of wood in the I-joists. The amount of wood used in I-joists is however only about 62% to 65% of the wood used for solid wood floor joists. This results in 1.3 metric tonnes less wood fiber (10%) in the Minneapolis wood frame house. In addition, the I-joist can be made largely from species with lower demand. This material use efficiency produces more product from a finite forest acreage.

Table 5.6. Environmental Results Summary for the Minneapolis Wood Design using Solid-Sawn Wood Joists and Engineered Wood I-joists

Design by Structural Components	Embodied Energy MJ	Global Warming Potential Equiv.CO_2 kg	Air Pollution Index Critical Vol. Measure	Water Pollution Index Critical Vol. Measure	Solid Wastes kg
Wood Design – Solid Sawn Wood Joists					
Foundations	68,487	6,041	1,001	1	2,548
Walls	457,130	26,468	6,472	4	9,701
Floors& Roof	115,661	3,948	1,066	7	1,525
Extra Basic Mat.	16,424	775	112	3	134
Total	**657,702**	**37,232**	**8,651**	**15**	**13,908**
Wood Design – Engineered Wood I-joists					
Foundations	68,487	6,041	1,001	1	2,548
Walls	457,130	26,468	6,472	4	9,701
Floors & Roof	108,552	3,763	981	9	1,383
Extra Basic Mat.	16,424	775	112	3	134
Total	**650,593**	**37,047**	**8,566**	**17**	**13,764**

Notes: The Extra Basic Materials grouping includes the supporting steel jack-posts and beams for the structure.

5.3.3 Green (air-dried) vs. Kiln-Dried Softwood Lumber

While the base case used kiln-dried lumber, the drying process is the most energy intensive unit process in the processing of dry, planed lumber. For Northwest Douglas fir, there has been a long history of using green (undried) lumber. Since hemlock and southern pine have a history of warping during natural drying, they are generally kiln-dried before use in construction.

Green wall studs compared to the kiln-dried studs used in the base case Minneapolis wood design (Table 5.7) embody 25 GJ less energy, (a 4% improvement), a 1 metric ton reduction in GWP (2%), a 3% reduction in air pollution and almost no impact on water pollution or solid waste.

Table 5.7. Environmental Results Summary for the Minneapolis Wood Design using Green (air-dried) and Kiln-Dried Wall Studs

Design by Structural Components	Embodied Energy MJ	Global Warming Potential Equiv.CO_2 kg	Air Pollution Index Critical Vol. Measure	Water Pollution Index Critical Vol. Measure	Solid Wastes kg
Wood Design – Kiln-dried Wall Studs					
Foundations	68,487	6,041	1,001	1	2,548
Walls	457,130	26,468	6,472	4	9,701
Floors& Roof	108,552	3,763	981	9	1,383
Extra Basic Mat.	16,424	775	112	3	134
Total	**650,593**	**37,047**	**8,566**	**17**	**13,766**
Wood Design – Green Wall Studs					
Foundations	68,487	6,041	1,001	1	2,548
Walls	431,636	25,778	6,188	4	9,621
Floors & Roof	108,552	3,763	981	9	1,383
Extra Basic Mat.	16,424	775	112	3	134
Total	**625,099**	**36,357**	**8,282**	**17**	**13,686**

Notes: The Extra Basic Materials grouping includes the supporting steel jack-posts and beams for the structure.

5.4 ENERGY SUBSTITUTION SENSITIVITIES

Wood manufacturing industries are unique in the availability of waste materials that can be used for energy substitution. Lumber processing results in a certain percentage of wood waste materials (bark, saw dust, edges, and trim) created during the manufacturing process. Some of the material is sold as by-products such as beauty bark and chips, while others are burned for biofuel. Similarly OSB, plywood and LVL also produce wood wastes.

In this section we analyze the substitution possibilities associated with allocating wood wastes to the energy stream. The allocation is based on the LCI data produced in modules A through H. From these data we calculate the weight per unit product of material input and allocate this material to product and co-products streams. We identify those co-product streams that can be used as biofuel and calculate the potential energy substitution available. These calculations allow us to derive the wood energy available with alternative house designs, and differ from wood energy reported in Table 3.3 since Table 3.3 includes some wood energy as feedstock fuels. The calculations also show the potential energy savings when all the available biofuel is used to reduce the need for purchased energy.

5.4.1 Minneapolis

Table 5.8 reports the biofuel energy associated with the Minneapolis house design. Biofuel values are determined by the amount of wood products used in the design and the allocation of wood fiber according to the product LCI in each respective module. The table reports the weight in pounds and energy in MJ under this current allocation of wood waste products into biofuel for the steel and wood house designs. Total biofuel are higher than those reported in Table 3.3. A large part of the difference is due to the allocation of OSB biofuel to feedstock in Table 3.3 versus their allocation to biofuel in Table 5.8.

Table 5.8. Minneapolis Biofuels With Product Allocation

Product	Steel		Wood	
	Ovendry (lbs)	Biofuel (MJ)	Ovendry (lbs)	Biofuel (MJ)
Lumber	366	2,329	1,454	9,249
Plywood	317	2,016	388	2,466
OSB	2,159	13,738	2,052	13,051
LVL	0	0	93	592
Total	**2,842**	**18,083**	**3,986**	**25,357**

Having determined the biofuel content of energy consumed in the house designs, we next determine the additional biofuel allocation potential by including all co-products as potential fuel sources excluding theallocation of chips for paper production. Table 5.9 presents the results. Further comparing the energy consumed by product processing and the biofuel produced leads to the conclusion that over the design of the house, biofuel can make wood processing nearly self sufficient in the steel design requiring the purchase of only 3 GJ and providing an energy surplus (0.3 GJ) in the wood design. While the total energy burden increases with the reallocation of some co-products to biofuel, the purchased energy reduction is much larger. The residuals from lumber and plywood that can be allocated to energy production are in sufficient quantity to produce a substantial surplus of produced energy over consumed energy. OSB, however, produces very few co-products requiring purchased energy.

Table 5.9. Minneapolis Biofuels Energy Savings in MJ

Product	Steel: Allocated Energy Used with Extra Biofuel	Steel: Energy Surplus/Deficit	Wood: Allocated Energy Used with Extra Biofuel	Wood: Energy Surplus/Deficit
Lumber	5,198	+846	20,695	+3,356
Plywood	3,592	+240	4,394	+294
OSB	22,568	-4,079	21,440	-3,875
LVL	0	0	306	+481
Total	**31,358**	**-2,993**	**46,784**	**+258**
Bio-energy produced	28,365		47,042	
Energy purchased	2,993		-258	

5.4.2 Atlanta

Table 5.10 reports the biofuel energy associated with the Atlanta house design. As in the case of Minneapolis, total biofuels are higher than those reported in Table 3.3.

Table 5.10. Atlanta Biofuels with Product Allocation

Product	Concrete		Wood	
	Ovendry (lbs)	Biofuel (MJ)	Ovendry (lbs)	Biofuel (MJ)
Lumber	1,776	11,297	1,909	12,144
Plywood	0	0	0	0
OSB	1,120	7,123	1,827	11,621
LVL	0	0	0	0
Total	**2,895**	**18,420**	**3,736**	**23,765**

Table 5.11 presents the extra allocation biofuel potential associated with allocating wood co-products to the biofuel stream. The concrete design has a larger potential to offset purchased energy since concrete walls are furred out with 2x4 wood studs. Comparing the energy consumed by product processing and the biofuel produced leads to the conclusion that over the design of the house, biofuel can reduce purchased energy by 9.6 GJ producing an 8 GJ surplus in the concrete design, and reduce purchased energy by 12.4 GJ producing a 2 GJ surplus in the wood design.

Table 5.11. Atlanta Biofuels Energy Savings in MJ

	Concrete		Wood	
Product	Allocated Energy Used with Extra Biofuel	Energy Surplus/Deficit	Allocated Energy Used with Extra Biofuel	Energy Surplus/Deficit
Lumber	15,444	+11,063	15,652	+6,650
Plywood	0	0	0	0
OSB	12,574	-2,848	20,513	-4,646
LVL	0	0	0	0
Total	**28,018**	**+8,216**	**36,165**	**+2,004**
Bio-energy produced	36,234		38,169	
Energy purchased	-8,216		-2,004	

5.4.3 Purchased energy comparisons

The primary material substitutions that result in differences in purchased energy are the substitution of several types of steel and increased insulation for wood in the Minneapolis designs or concrete block, mortar and rebar for wood in Atlanta. Energy to produce the wood products is partially offset by the energy produced from wood residuals. As shown in Table 5.12, for the Minneapolis designs, the substitution of steel reduces the energy in wood production by 13.4 GJ partially offset by a 7.3 GJ reduction in biofuel energy with an increase of 103.9 GJ for the steel substitution and 23.6 GJ for increased insulation. In this and the following tables, the energy used in steel, concrete and insulation were derived from more aggregate non-wood product categories than carried in the Athena EIE model. That is, the energy use for the different kinds of steel, insulation and and concrete were reduced to a single use coefficient for each category, an effective average for each cluster of non-wood products. Using this somewhat aggregated submodel allows us to focus on the major categories where substitution takes place. For energy use and carbon emissions, the tables produce the same result as the EIE model but might not if the mix of non-wood materials associated with each coefficient deviates substantially from the cases evaluated with the EIE model. For the Minneapolis house designs, the 127.5 GJ increase in purchased energy for steel and additional insulation dwarfs the 6.1 GJ reduction in purchased energy for wood.

With an increased allocation of co-products to biofuel the energy required in wood production for the wood frame house is slightly less than the bio-energy contributing net energy to offset some of the purchased energy needs for steel and insulation. There is also a substantial reduction in the purchased energy for wood in the steel frame house but not enough to contribute net energy.

For the Atlanta designs the substitution of concrete and steel rebar reduces the energy in wood production by 8.3 GJ partially offset by a 5.4 GJ reduction in biofuel energy with an increase of 40.8 GJ for the concrete and 21.9 GJ for rebar. The 62.7 GJ increase in purchased energy for concrete and rebar is much larger than the 2.9 GJ reduction in purchased energy for wood.

When the wood co-products except for the chips allocated to paper production are used as biofuel the increased bio energy produced from the biofuel in the concrete structure exceeds the increase in the wood structure while reducing the purchased energy needs in both designs.

Table 5.12. Purchased energy comparisons

	Energy in MJ					
	Energy for Wood Products Used in Steel or Concrete and Wood Frame	**Energy Currently Sourced from Biofuel to Produce Wood Products**	**Energy for Steel Products in Steel or Concrete and Wood Frame**	**Energy for Concrete in Steel or Concrete and Wood Frame**	**Energy for Insulation Used in Steel or Concrete and Wood Frame Houses**	**Total Purchased Energy**
Minneapolis Designs						
Steel frame	28,616	-18,082	116,473	0	36,887	163,894
Wood frame	42,033	-25,357	12,614	0	13,276	42,566
Steel - Wood	-13,417	7,275	103,859	0	23,611	121,328
With Increased Allocation of Co-products to Biofuel						
Steel frame	31,358	-28,365	116,473	0	36,887	156,353
Wood frame	46,784	-47,042	12,614	0	13,276	25,633
Steel - Wood	-15,426	18,677	103,859	0	23,611	130,720
Atlanta Designs						
Concrete frame	24,710	-18,420	37,212	40,797	4,099	88,398
Wood frame	33,017	-23,765	15,348	0	4,099	28,699
Concrete - Wood	-8,307	5,345	21,864	40,797	0	59,699
With Increased Allocation of Co-products to Biofuel						
Concrete frame	28,018	-36,234	37,212	40,797	4,099	73,892
Wood frame	36,165	-38,169	15,348	0	4,099	17,443
Concrete - Wood	-8,147	1,935	21,864	40,797	0	56,450

5.5 CONCLUDING REMARKS

This module provides a comprehensive overview of the CORRIM life cycle inventory data as integrated into the EIE software and demonstrates the merits of wood building materials relative to alternative products by way of a set of cradle-to-gate potential impact measures. It also compares and contrasts various wood products relative to each other. It should be pointed out that the data quality of the CORRIM data set has not been fully reviewed and some changes will inevitably be made to improve it over time. For instance, the *a priori* decision to use mass allocation may benefit some wood products (e.g., lumber) but may have a minimal effect on other products that produce little, if any, co-products (e.g. OSB). Only with time and a full investigation into the affect of various allocation methods will the robustness of the LCI data come to light (see phase II work plan for more on this aspect). Also, omission of maintenance and end-of-life stages may be skewing the results in favor of wood, but limited testing of this hypothesis suggests this is not the case. When using the results of this module it is incumbent on the user to provide a reasonable description of the boundary of the analysis.

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