

ENVIRONMENTAL IMPACT ASSESSMENT OF LIGHT-FRAME AND TIMBER FRAME STRUCTURES

Brian P. Malone,¹ Rakesh Gupta,² Thomas H. Miller,³ and Maureen E. Puettmann⁴

ABSTRACT

The objective of this study was to analyze the environmental performance of different wood structural assemblies for residential buildings. Two structural systems (a traditional timber frame and a light-frame) were compared together with alternate material options for each system. Environmental impacts were determined using the Athena Impact Estimator for Buildings software. Design alterations for generalization were made to an existing timber frame (TF) structure used as the basis of this analysis, and an equivalent light-frame (LF) structure was designed based on the International Residential Code (IRC). Environmental impacts observed include total energy consumption, fossil fuel consumption, global warming potential (GWP), and wood fiber use. All analyses were considered cradle-to-gate, including the manufacturing and construction life-cycle stages. Results show how GWP is linked to both fossil fuel consumption and wood fiber use, and how ultimate environmental impact is driven by energy source. Environmental impacts of structures are driven by material choice, and levels of carbon stored in structural wood serve to decrease GWP. Of the structural assemblies analyzed, the most traditional TF structure outperformed all other options in almost every measure.

KEYWORDS

global warming potential, wood structures, life cycle analysis, carbon storage

INTRODUCTION

As considerations for the environmental impacts of products become increasingly important to designers and consumers, the ability to determine these effects becomes necessary. Though qualitative reasoning to evaluate sustainability is valid for some decisions, an accurate quantitative analysis of these negative attributes is the only way to arrive at conclusive results and make truly informed decisions. Life-cycle Assessment (LCA) research performed to date relating to the environmental impact of wood in structures has focused primarily on either individual products (Kline 2005, Bergman and Bowe 2010, Lippke et al. 2010, Lippke and Wilson 2010, Puettmann et al. 2010) or comparisons with non-wood structural systems (Salazar and

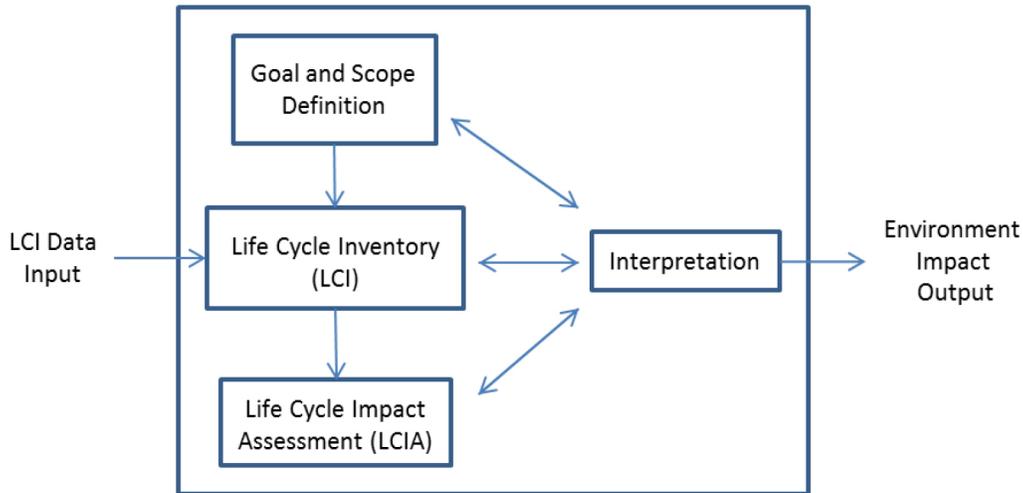
¹Structural Designer, KL&A Structural Engineers and Builders, Carbondale, CO.

²Professor, Dept. of Wood Sci. & Eng., Oregon State Univ., Corvallis, OR-97331; email: rakesh.gupta@oregonstate.edu (corresponding author)

³Associate Professor, School of Civil and Construction Engineering, Oregon State University, Corvallis, OR 97331.

⁴PhD, WoodLife Environmental Consultants, LLC, Corvallis, OR 97330.

FIGURE 1. Steps to perform a life-cycle assessment.



Meil, 2009). LCA is a procedure by which the environmental burdens of products, assemblies of products, or activities can be measured and evaluated (ISO 2006). This study follows LCA methodology as outlined in the ISO 14040 (2006) Standard. LCA is comprised of four phases. These include a goal and scope definition phase, a life-cycle inventory (LCI), a life-cycle impact assessment (LCIA), and an interpretation of results (ISO 2006). Figure 1 illustrates the interaction of these phases, as well as general LCA input and output points.

The Athena Impact Estimator software (AIE) (ASMI 2012b), published by the Athena Sustainable Materials Institute (ASMI) simplifies a complex process by providing a database of common building materials and assemblies. The LCI that comprise AIE are the result of a vast network of contributing researchers and industry professionals that have determined the material and energy input and environmental releases pertaining to individual building materials (NREL 2012). It is important to note that additional proprietary LCI data gathered by ASMI, is also built into this software. The LCI database provided and maintained by the National Renewable Materials Laboratory (NREL) is called the US Life-cycle Inventory Database (USLCI). The primary contributor of inventory data for wood and other bio-based materials to this database is the Consortium for Research on Renewable Industrial Materials (CORRIM) (CORRIM 2013). CORRIM has performed the most up-to-date research in this field, and has released their findings in two phases (2005 and 2010) of collections of published reports on a wide range of wood products focused on different geographical areas of the United States (Lippke and Wilson 2010). Furthermore, LCI are incorporated into AIE and are used to perform LCIA. Using impact categories based on the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) (Bare 2011), AIE determines the relative impact of a product or system based on various environmental impact stressors such as fossil fuel consumption, global warming potential (GWP), or resource use.

Objectives

This environmental impact assessment (EIA) is part of a research effort that compares residential wood framing systems. The overall objective of this research was to compare a traditional timber frame (TF) structure with an equivalent light-frame (LF) structure and determine the

differences in performance of each based on both EIA results and structural performance. For more information on the structural analysis portion of this research, please see Malone (2013). The objective of this EIA was to determine which structural system performs most favorably in a cradle-to-gate analysis using five environmental impact categories: 1) total energy consumption, 2) fossil fuel use, 3) GWP, 4) wood fiber use and 5) wood waste. All upstream processes for resource and wood extraction, fuel and electricity production, and transportation are included while observing the environmental impacts from two life cycle stages; the manufacturing and construction phases. Furthermore, because this study focuses on material choice and framing methods, investigations focus on how the environmental impacts observed within each structural system change with common substitutions are explored, rather than a complete building life cycle assessment. (Note that the term EIA is used to describe this study, because where a true LCA has complete knowledge of all LCI data sources, the use of AIE inhibits some knowledge of this. This is explained further in the following section.)

LCA Limitations and Assumptions

Life-cycle assessment is a complex science that is still developing. As advances are made in the methods and tools for quantifying environmental impact, an increase in the level of accuracy of LCA will continue to emerge. All LCA (or EIA) studies are subject to inherent limitations and assumptions that must be considered for appropriate analysis of results.

AIE is a decision support tool, and is not considered a means of assigning any definitive rating or score (ASMI 2012a), and it is understood that there are more factors involved in the decision-making process than can be included in an EIA study such as this. These factors include, but are not limited to the structural or isolative capability of materials, or their cost.

A significant assumption made by AIE is that a project lies in one of a list of set geographical locations in North America. Since material sourcing, power generation, and transportation vary highly by geographic region, the user must define a project by the most appropriate city available. From here, AIE ties its analysis to local power sources, electricity grids, transportation modes, average distances to manufacturing, and manufacturing technologies available (ASMI 2012a). Additionally, materials for input are also based on what is most common, and not all specific material data are available. Construction assemblies and material inputs available are, however, applicable to more than 95% of the building stock in North America (ASMI 2012a). Furthermore, analysis is based on data collected from a multitude of sources, and the accuracy of LCI and LCIA results is tied closely to how current and accurate these original data are. Due to “assumptions and uncertainties in the basic LCI data,” and the assumptions necessary to develop a tool that is useful to the general public, ASMI “considers any comparative impact measure differences of 15% or less as being equal or insignificant” (ASMI 2012a). For this reason, only generalized statements can be made based on seemingly precise numeric output values.

Global warming potential and carbon stored in wood products

The phenomenon of global warming has been primarily attributed to the abundant presence of gases in the atmosphere which absorb outgoing infrared radiation rather than allow it to escape. Carbon dioxide (CO₂) is considered to be the primary anthropogenic cause of global temperature increase. Over time, increased concentration of these gasses in the atmosphere increases the Earth's temperature. Among other effects, this causes sea levels to rise, weather patterns to alter, and extreme weather events to occur more frequently and with more

intensity (Florides and Christodoulides 2008). GWP is measured in equivalent weight (kg) of CO₂ released. It is important to note that since global warming emissions commonly include gases other than CO₂, all values are normalized to be reported in CO₂-equivalent units.

Values reported by AIE for GWP reflect only the emissions released directly to the atmosphere during manufacturing and construction. It should be noted that emissions related to the burning of biofuels, however, are considered carbon neutral by AIE, and therefore do not contribute to GWP. Though combustion causes the release of carbon stored in tree material to the atmosphere in the form of CO₂, AIE considers this release equal to the amount of carbon that the tree stored during its lifetime (Finlayson 2013). Carbon stored in materials manufactured, however, is not credited by the software (ASMI 2012a). As a tree grows, CO₂ is sequestered from the atmosphere and carbon is stored in the wood as a large percentage of its composition. For as long as the wood does not decay or burn, approximately half of its weight is comprised of carbon that has been kept from entering the atmosphere, and therefore kept from contributing to global warming. When wood products are employed for the construction of a building, the carbon in these products is stored in the building's structure for at least as long as the building exists, and possibly longer if these wood products are reused or recycled.

RESEARCH METHODS

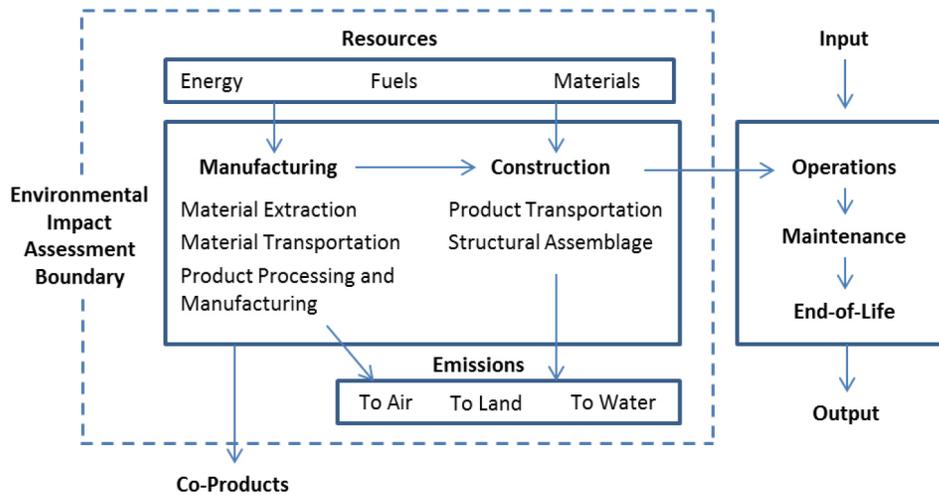
This EIA was performed using the Athena Impact Estimator for Buildings (AIE). System boundaries were defined by the user, and these boundaries were part of the definition of each structure within AIE by providing necessary inputs. It is important to note that AIE automatically generates results for a cradle-to-grave analysis. Though these results include all of the five life-cycle stages observed by AIE (manufacturing, construction, operations, maintenance, and end-of-life), a boundary ("gate") was easily set to include life-cycle stages through construction only by ignoring results from operations, maintenance, and end-of-life. (Note that to include these life-cycle stages, additional information not included here would be required for meaningful results.) Results were analyzed objectively with the assistance of previously published LCI reports on wood products (Kline 2005, Bergman and Bowe 2010, Lippke et al. 2010, Lippke and Wilson 2010, Puettmann et al 2010). The parameters concerning the development, analysis, and interpretation of EIA are explained in the following sections.

System Boundaries

Comparisons for this EIA included the wood structural system for each building, as well as necessary metal fasteners (screws, nails, etc.). To make the system boundaries the same for both structures, insulation was included for two structures because it is an inherent component of structural insulated panels. Since foundations would be considered equal for both structures, these components were not included in the study. TF pins are made of wood, and were considered as already included in the volume of large-dimension lumber.

The analysis performed for each structure was cradle-to-gate, cataloguing all material and energy input, and environmental releases from material extraction and product manufacturing through construction. Material extraction of forest products includes seedling production, forest operations, thinning, and logging. Manufacturing includes all of material extraction, as well as log transportation to the sawmill, and all sawmill operations and material processing necessary for the manufacture of each product (Finlayson 2013). OSB manufacturing, for example, requires wood flaking, drying and screening of flakes, blending with adhesives and pressing of the panel product, finishing, as well as heat generation and emission control

FIGURE 2. Environmental impact assessment boundary for this study.



for these processes (Kline 2005). Product manufacturing phases and LCI results vary for each individual product. Energy and environmental emission considerations for the manufacture of adhesives and metal connectors (nails, screws, etc.) are also attempted, as well as for insulation options for two structures. The construction phase includes transportation of construction materials from the manufacturing site to the construction site, and the on-site energy required to assemble the products and construct the structure (ASMI 2012a). Figure 2 provides a visual rendering of the system boundary for this study.

Research Structures

The structures described herein were inspired by an existing traditional TF building. This building was completed in 2011, and is located in Jay, Vermont. Figure 3 and Figure 4 are images of the exposed framing system and the completed building, respectively.

The Vermont structure served as inspiration for this study. For simplicity and generalization, it was necessary to make changes to this design (for research purposes only). Theoretical

FIGURE 3. Exposed timber frame structure in Jay, Vermont looking north-west.



FIGURE 4. Completed timber frame structure in Jay, Vermont, looking north-east.



alterations to the Vermont structure for this study include omission of the cupola and 2nd floor entry dormer, as well as minor adjustments in framing member locations. Additionally, some window locations were assumed and added to the design. This altered version of the Vermont structure is referred to as the “traditional TF” for this study. All other physical and material attributes detailed in the traditional TF design are reflective of the Vermont structure.

The Vermont structure was constructed of solid-sawn, unseasoned (green) eastern hemlock (*Tsuga canadensis*) timbers by traditional timber framing methods. All joinery is mortise-and-tenon-style fastened primarily with wooden pins, siding is kiln-dried 19-mm (nominal 1-in) –thick pine shiplap, flooring is green solid-sawn 38-mm × 184-mm (nominal 2-in × 8-in) lumber, and roofing is kiln-dried 38-mm × 140-mm (nominal 2-in × 6-in) lumber. The traditional TF structure was designed using the NDS (AF&PA 2005) and follows the guidelines outlined by the Standard for Design of TF Structures (TFEC 2010). See Malone (2013) for a thorough description of the design of this structure. Figure 5 is a Google Sketch-Up rendering of the traditional TF structure (Google 2012).

All structural systems outlined for this study reflect a rectangular 2-story residential building that has a 7.9-m × 12.2-m (26-ft × 40-ft) footprint, is approximately 8-m (26.5-ft)-high at the gable, and has a 9:12-slope gable roof.

An equivalent LF structure (called the “standard LF” in this study) was designed based on the traditional TF structure. Equivalence for this design was defined as maintaining building envelope and shape, and meeting the same operational needs as the traditional TF structure. The design of the standard LF was performed in accordance with the guidelines outlined in the IRC (ICC 2009). Where design requirements could not be met by these guidelines, necessary components of the structural system were engineered according to the NDS (AF&PA 2005). These components include the beams that support the 2nd floor and the columns that centrally support these beams. Additionally, where available shear wall area on the gable end with garage door openings was deemed insufficient by the IRC, a moment-resisting portal frame was engineered (Martin et al. 2008). Figure 6 is a Google Sketch-Up rendering of the standard LF structure (Google 2012).

FIGURE 5. Traditional timber frame structure model.

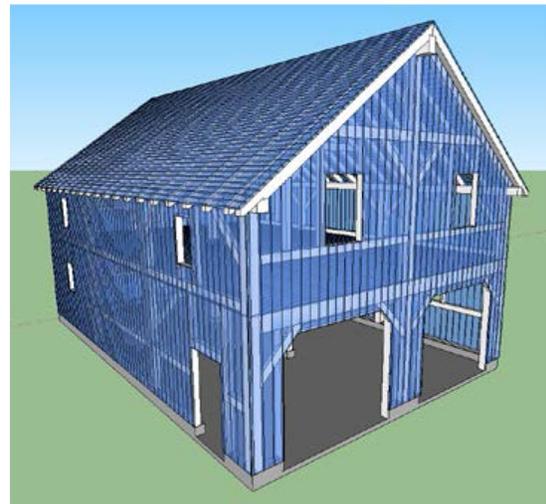


FIGURE 6. Standard light frame structure model.



Material substitutions were made to both the traditional TF and the standard LF structures to determine the environmental impacts of these design options, since material and product choice are likely to have the most significant impact on results. Changes to structural systems included the following:

Timber Frame

- Replaced large-dimension green framing materials with large-dimension kiln-dried framing materials. (“Kiln-dried TF”)
- Installed (kiln-dried) small-dimension light-framing “infill” between timber framing members to serve as connection points for OSB for roof, wall, and floor sheathing. (“TF with light-framing infill”)
- Utilized structural insulated panels (SIPs) for roof and wall sheathing. (“TF with SIPs.”)

SIPs were explored both with and without considering the environmental contribution of expanded polystyrene insulation (foam). Note that SIPs inherently include foam insulation, and though a TF structure with SIPs neglecting this insulation was considered for this study, it is for comparison only.

Light-Frame

- Decreased stud size, and therefore wall thickness to that of a 38-mm × 89-mm (nominal 2-in × 4-in) stud. (“LF with 38-mm × 89-mm (nominal 2-in × 4-in) walls.”)
- Sheathed the roof, walls, and floor with plywood instead of OSB. (“LF with OSB.”)

Fiberglass batt insulation was also considered for environmental comparison with the expanded polystyrene in SIPs. (“LF with insulation.”) Design alterations considered but omitted from this study include using green framing material for the LF structure, as well as spacing studs at 610-mm (24-in) o.c. rather than 406-mm (16-in) o.c. Since light-framing with unseasoned material is not a common practice in Vermont, this option was not considered. Though spacing studs at 610-mm (24-in) o.c. is a viable option often considered to increase insulation space, this slight reduction in overall volume of framing material was minimal and was therefore not considered. Table 1 outlines the materials used in each structural system. The structures selected for this study were chosen because they represent common design configurations for each construction method considered.

Life-cycle Inventory and Data Entry

AIE is a software package that was developed to simplify the LCA process and make it more accessible and user-friendly. For this reason, its results are limited to the range of inputs it allows. LCI and LCIA results are based solely on the data entry that it requires, as well as the user-defined material or assembly information for each building to be analyzed. Basic project information for each structure includes a “project location,” “building type,” “building height,” and “gross floor area.” Note that for this cradle-to-gate EIA, “building life expectancy” is negligible because the boundaries of this study include only the manufacturing and construction life-cycle stages. AIE offers only a limited number of building locations, and due to its closest proximity to the actual building site, the “project location” chosen for this study was Montreal, Quebec, Canada. “Building type” was selected as “single-family residential.” “Gross floor area” for each structure was 193 m² (2,080 ft²), and building height was either 7.9-m (26.2-ft) for TF structures or 8.2-m (26.8-ft) for LF structures. Note that in order to maintain interior wall and ceiling heights, building height between TF and LF structures varied slightly due to the nature of the construction techniques.

TABLE 1. Structural system materials description.

Structural System		Materials					
Frame	Option	Wall Framing	Roofing	Flooring	Siding	Insulation	
						Wall	Roof
Light-Frame	Standard	Kiln-Dried 38-mm × 140-mm, 406-mm o.c.	OSB, 12-mm	OSB, 12-mm	OSB, 12-mm	None	None
	2 × 4 Walls	Kiln-Dried 38-mm × 89-mm, 406-mm o.c.	OSB, 12-mm	OSB, 12-mm	OSB, 12-mm	None	None
	Plywood	Kiln-Dried 38-mm × 140-mm, 406-mm o.c.	Plywood 12-mm	Plywood 12-mm	Plywood 12-mm	None	None
	Standard Insulated	Kiln-Dried 38-mm × 140-mm, 406-mm o.c.	OSB, 12-mm	OSB, 12-mm	OSB, 12-mm	140-mm Fiberglass	235-mm Fiberglass
Timber Frame	Traditional	Large- Dimension Solid-Sawn, Green	Kiln-dried, Solid-Sawn 38-mm × 140-mm Lumber	Green, Solid-Sawn 38-mm × 203-mm Lumber	Kiln-Dried, Solid-Sawn Shiplap Lumber, 19-mm	None	None
	Kiln-dried	Large- Dimension Solid-Sawn, Kiln-Dried	Kiln-dried, Solid-Sawn 38-mm × 140-mm Lumber	Kiln-Dried, Solid-Sawn 38-mm × 203-mm Lumber	Kiln-Dried, Solid-Sawn Shiplap Lumber, 19-mm	None	None
	LF Infill	Large- Dimension Solid-Sawn, Green	OSB, 12-mm	OSB, 12-mm	OSB, 12-mm	None	None
	SIPs	Large- Dimension Solid-Sawn, Green	SIPs (2 Layers OSB, 9.5-mm)	OSB, 12-mm	SIPs (2 Layers OSB, 9.5-mm)	140-mm Expanded Polystyrene	235-mm Expanded Polystyrene
	SIPs No Foam	Large- Dimension Solid-Sawn, Green	SIPs (2 Layers OSB, 9.5-mm)	OSB, 12-mm	SIPs (2 Layers OSB, 9.5-mm)	None	None

The primary step in performing an analysis with AIE is to create a “bill of materials.” The bill of materials is the backbone of all results generated by AIE, and therefore these results are based on each material’s volume, surface area, or weight depending on its required functional unit. Functional units are the units by which all building materials are input to AIE by the user or reported by AIE. Functional units vary based on building material and are defined by AIE. Though AIE has the ability to self-calculate a bill of materials based on user-defined construction assemblies (walls, roofs, etc.), this feature was not used for this study. Since AIE

does not recognize TF construction practices, material quantity data were input directly using the “extra basic materials” option. This feature allows for the input of user-calculated material quantities to form the bill of materials, which overrides any necessary material calculation by AIE (ASMI 2012a). A bill of materials defined directly by the user also allows for greater accuracy, because the bill of materials calculated by AIE is considered accurate only within +/- 10% (ASMI 2012a). For consistency, this feature was used for each frame analyzed, including LF models. Since the system boundary ends at the construction gate, all material inputs are reflective of purchased quantities rather than exact quantities in the final building, and therefore include the environmental impact of any materials that would end up as waste.

For the calculation of each bill of materials, a thorough inventory of all materials within each wooden structural system was performed. A three-dimensional model of each structure was created using Google Sketch-up software (Google 2012), providing an interactive visual of all components except small fasteners (nails, screws). Using these models and a working knowledge of standard construction practices, the total quantities of each material were calculated. Material quantities were determined either by volume, surface area, or weight, as dictated by AIE, and were reported in the functional units required by AIE. Material estimates were calculated by hand, and multiple checks were performed to verify accuracy. Due to limitations concerning input categories in AIE, material quantities were entered in their respective most appropriate category. For example, “small dimension lumber” is considered to be 38-mm × 140-mm (nominal size 2-in × 6-in) and smaller, and “large dimension lumber” is considered to be 38-mm × 203-mm (nominal size 2-in × 8-in) and larger (ASMI 2012a). Note also that all OSB and plywood values are entered in the equivalent of 9.5-mm (3/8-in) thickness, and therefore a multiplication factor of 1.25 was applied to calculate the equivalent quantity of 12-mm (15/32-in) -thick sheathing materials. Other materials including insulation were also entered on a per-thickness basis, as required. Fasteners were estimated based on a working knowledge of standard construction practices, and reported by weight. Table 2 outlines the “Bill of Materials” for each structure. Each value in this table is presented in the functional unit required by AIE.

Carbon Storage in Wood Products

The amount of carbon stored in each structural system was calculated based on the weight of wood products in each structure. Material weights were based on specific gravities of species and panel products as reported by the NDS and the Panel Design Specification, respectively (AF&PA 2005, APA 2012). Carbon calculations assumed a carbon composition of 50% by weight, which is approximately typical of most softwood species (Lamloom 2003). This value was then scaled to CO₂-equivalence based on molecular weight for direct comparison with AIE GWP values. To account for the actual carbon stored in the structures, a 10% reduction in wood mass was assumed to account for the wood waste generated at the construction site. Table 3 shows the carbon emitted in kg CO₂ equivalent for each life cycle stage and the long term storage of carbon as kg CO₂ equivalent, in the wood product during use.

RESULTS AND DISCUSSION

Life-cycle impact analysis

Cradle-to-gate environmental impacts analyzed included total energy consumption, fossil fuel consumption, GWP, and wood fiber use and waste.

TABLE 2. Bill of materials.

Material	Units	Light-Frame				Timber Frame				
		Std.	2x4 Walls	Plywood	Std. Insulated	Traditional	Kiln-Dried	LF Infill	SIPs No Foam	SIPs
Large-Dim Softwood Lumber, kiln-dried	m ³	7.861	7.861	7.861	7.861	0	15.55	0	0	0
Small-Dim Softwood Lumber, kiln-dried	m ³	6.396	4.835	6.396	6.396	6.276	6.276	3.511	0.675	0.675
Large-Dim Softwood Lumber, green	m ³	0	0	0	0	15.55	0	12.16	12.16	12.16
Oriented Strand Board	m ²	631.2	631.2	0	631.2	0	0	628.0	918.0	918.0
Softwood Plywood	m ²	0	0	631.2	0	0	0	0	0	0
Pine Wood Shiplap Siding	m ²	0	0	0	0	919	919	0	0	0
Nails	tonnes	0.0701	0.0654	0.0701	0.0701	0.0607	0.0607	0.0622	0.0164	0.0164
Screws Nuts & Bolts	tonnes	0.008	0.008	0.008	0.008	0.0168	0.0168	0.0168	0.0740	0.0740
Hot Rolled Sheet (Steel)	tonnes	0	0	0	0	0.0113	0.0113	0.0113	0.0113	0.0113
Batt Fiberglass	m ²	0	0	0	1,954	0	0	0	0	0
Expanded Polystyrene	m ²	0	0	0	0	0	0	0	0	2,777

Though many additional environmental impacts are reported by AIE, these were determined for analysis based on relevance and ease of comparability. For Results of these analyses are presented in Figures 7 through 12. The values contributing to these graphs were determined by AIE.

Energy Consumption

Total energy consumption is defined as the cumulative energy, from all sources, necessary to complete all tasks within the EIA boundary. Total manufacturing energy consumption is a portion of total energy consumption, and is defined as all energy necessary to produce the materials that comprise the structure. Energy consumption is measured in total megajoules (MJ) of energy consumed for the manufacturing of materials (including material extraction) and construction of each structural system (ASMI 2012a). Reports present several types of

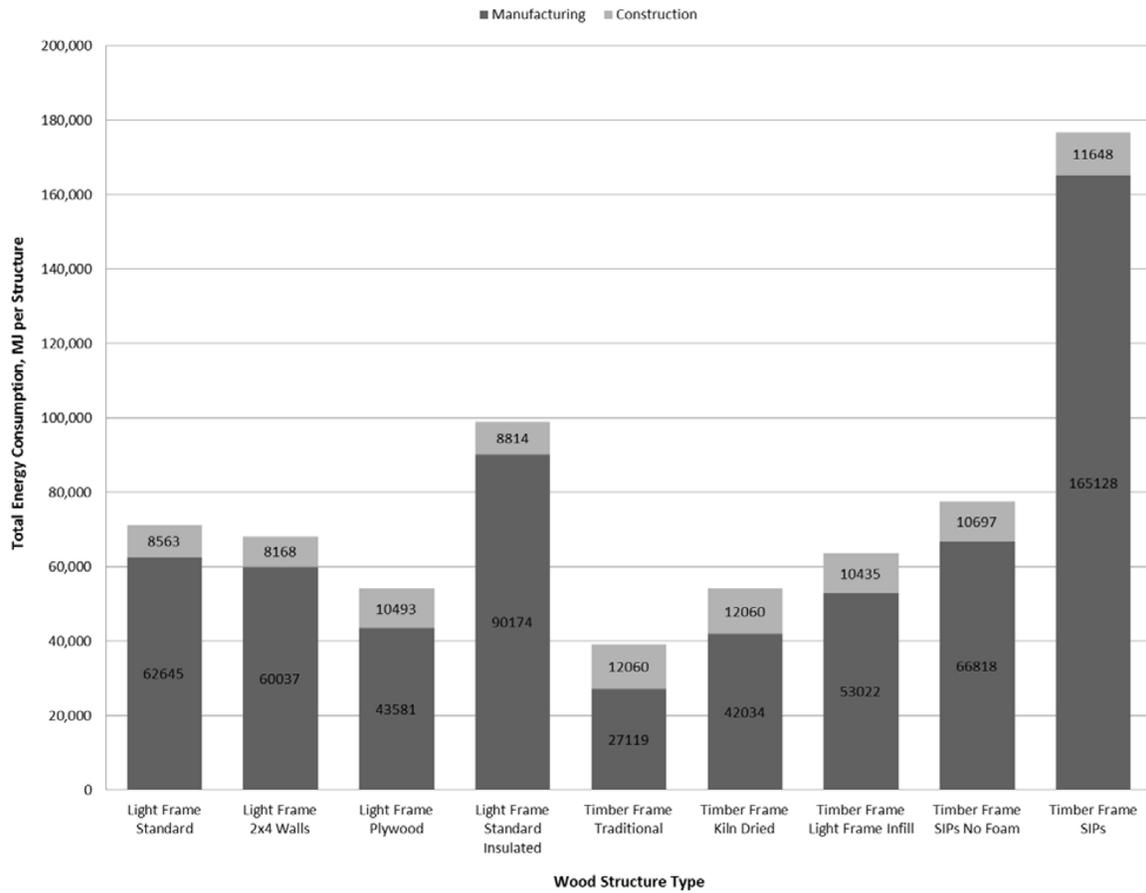
TABLE 3. Global warming potential compared with carbon stored in wood products.

Framing System		Emissions (Kg CO ₂ -Equivalent)			Carbon Stored in Wood Products*
		Manufacturing	Construction	Total Emissions	
Light Frame	Standard	1,402	398	1,800	16,340
	2x4 Walls	1,327	377	1,704	16,807
	Plywood	1,204	352	1,556	14,100
	Standard Insulated	3,198	416	3,614	16,340
Timber Frame	Traditional	1,037	462	1,499	24,245
	Kiln Dried	1,261	462	1,723	24,245
	Light Frame Infill	1,343	436	1,779	21,656
	SIPs (No Foam)	1,755	498	2,253	19,773
	SIPs (with Foam)	6,773	570	7,343	19,772

fuel sources for energy generation. Figure 7 shows the LCIA results for total energy consumption for all LF and TF structures considered in this EIA.

Cradle-to-gate energy consumption for both designs and their alternatives was dominated by the manufacturing life-cycle stage. Manufacturing energy consumption ranged from 69% of total energy consumption for the traditional TF to 93% for the TF with SIPs. The remaining percentage of total energy consumption was consumed during the construction life-cycle stage. Among the structures that do not include insulation, the total energy consumption ranged from 39,200 MJ (3.71×10^7 btu) to 77,500 MJ (7.35×10^7 btu). Once engineered wood products that require additional processing (OSB, kiln-dried solid-sawn framing, etc.) were added to the traditional TF structure, however, total energy consumption values were comparable to those of light-framing options. Energy consumption therefore increased with the use of materials that require kiln drying or additional mechanical processing (chipping, pressing, etc.). For example, the TF structure with kiln-dried timbers and flooring rather than green materials for these purposes required an increase in manufacturing energy requirement of 55%. Since AMSI considers any comparative difference of 15% or less to be equal or insignificant, some structures required comparatively equal amounts of energy (ASMI 2012a). The option to construct the LF walls with 38-mm \times 89-mm (2-in \times 4-in) framing material instead of 38-mm \times 140-mm (2-in \times 6-in) framing material, for example, results in a manufacturing energy consumption decrease of only 4%. This value therefore provides no significant conclusion for comparison. The LF sheathed with plywood, however, consumed 27% less manufacturing energy than the standard LF sheathed with OSB. This reduction can be attributed to the higher level of processing required to manufacture OSB (Kline 2006). When plywood is compared directly to OSB, the energy to manufacture plywood is less than half of the energy required to manufacture OSB (Lippke et al. 2010). Also considered equal or insignificantly different were the kiln-dried TF and the TF with LF infill (of which timbers are green, light-framing infill is kiln-dried, and sheathing is OSB). Both of these structural options required less energy than the TF with SIPs, but more energy than the traditional TF constructed with green timbers and without panel products. With insulation considered, the energy necessary for the manufacture of expanded polystyrene (foam) required more than twice the manufacturing energy of the LF structure with fiberglass batts. Note that these were the only two

FIGURE 7. Total energy consumption from cradle to construction gate for timber frame and light-frame structures and their alternatives.



assemblies that included insulation. Biofuels provided 47% of the energy for manufacturing, followed by diesel fuel (16%), feedstock (15%), natural gas (14%), and hydroelectric power (10%). These values are part of the energy consumption results generated by AIE.

Construction energy varied only slightly among building assemblies, and for many comparisons the difference is less than 15% and therefore considered insignificant. The energy required to construct the standard LF remains comparatively equivalent when stud size is decreased to 38-mm × 89-mm (2-in × 4-in). When plywood is substituted for OSB for siding and roofing, however, construction energy requirements increase by 29%. Here it must be noted that the total energy comparison for these assemblies (standard LF, and LF with plywood) still favors sheathing the LF with plywood. Construction energy requirements for the TF design options were all within 15% difference. Since the TF structures weigh more than the LF structures, they required more energy consumption for construction. The traditional TF structure consumed 40% more energy than the standard LF structure. It should be noted that moisture content (green versus kiln-dried) does not affect the assumed weight of wood products within AIE, which assumes kiln-dried weight, and therefore it is likely that a green TF would require significantly more energy for construction than reported. The calculation for construction energy by AIE is based on the energy necessary to lift the mass of

construction materials to one half the height of the building with a crane (ASMI 2012a). For this reason, the source of construction energy is primarily diesel fuel. Transportation from the manufacturing site to the construction site is included, and also consumes diesel fuel.

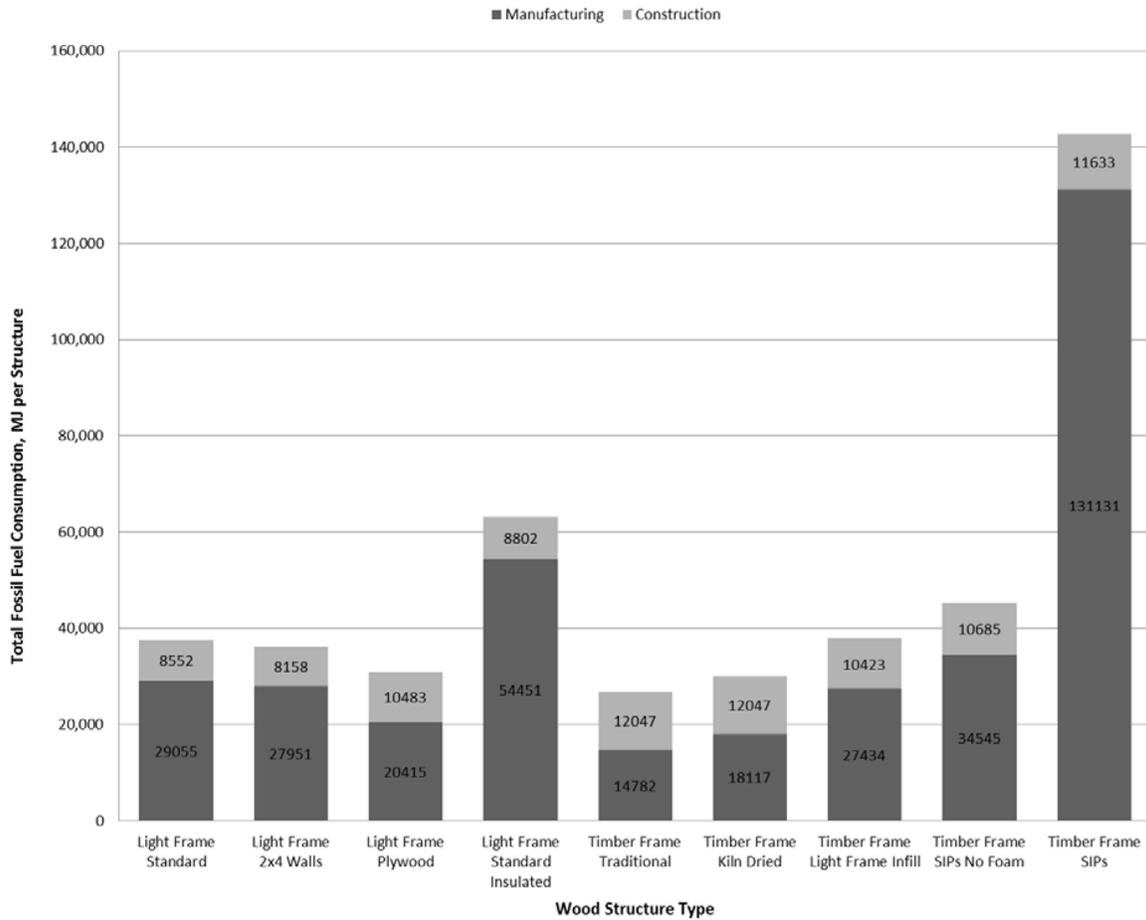
Cradle-to-gate total energy for the traditional TF structure consumed the least amount of energy. The addition of further-processed materials such as OSB or kiln-dried lumber, however, increased the energy requirement, as did the increased weight of the structural assembly. The kiln-dried TF and TF utilizing light-framing infill required 38% and 62% more energy (total) than the traditional TF, respectively. Though the TF options generally required less energy to create than the light-framing options, this was only true for the TF structures that were not constructed with SIPs. Sheathing the TF in SIPs increased the energy consumption requirement of the traditional TF (sheathed in less processed kiln-dried sawn lumber products) to more than double, even without the consideration of expanded polystyrene. The standard LF consumed 40% more energy (total) than the traditional TF, however other TF options, such as the TF with light-framing infill, were similar to light-framing options in total energy consumed. Considering the addition of insulation, the standard LF outperformed the TF with SIPs, consuming only approximately half of its total requirement of energy.

Fossil Fuel Consumption

Fossil fuel consumption represents fuel utilized for energy in resources extraction, manufacturing, and construction, whether used directly (e.g. as diesel fuel) or for the production of electricity. Fossil fuels are also used as feedstock ingredients necessary for some product manufacturing, namely insulation and adhesives in this study. Figure 8 shows the LCIA results for fossil fuel consumption for all LF and TF structures considered in this EIA.

Total fossil fuel consumption was also dominated by the manufacturing life-cycle stage. Due to the use of biofuels, namely hog fuel (wood waste) used on-site by wood product manufacturers for heat generation, fossil fuel consumption levels were considerably lower than total energy consumption values. Over half (58-60%) of the total energy required to manufacture kiln-dried softwoods (and hardwoods) in the Northeast and North Central USA is generated by burning wood biomass (Puettmann et al. 2010). This difference, however, is evident only in the manufacturing life-cycle stage because construction energy is provided primarily by diesel. Manufacturing fossil fuel consumption increases with increased kiln drying, and this is apparent by an increase of 23% of fossil fuels necessary for the manufacture of the kiln-dried TF. It is important to note that though this comparison is valid for current typical Northeastern mills, biofuels contribute a large amount of energy to the drying process and their increased or decreased utilization can cause this percentage to vary considerably. Fossil fuel consumption increase is more prevalent, however, for structures constructed with more processed wood products that require resins and further mechanical processing such as chipping or pressing. The LF structure sheathed with OSB (standard LF) requires 37% more fossil fuels for manufacturing than the LF sheathed with plywood. Manufacturing requires electricity, and fossil fuels are the primary source of off-site electricity in the Northeast (Puettmann et al. 2010). Coal represents 59% of off-site electricity, 11% by burning natural gas, and a small percentage is provided by petroleum. Non-fossil fuel sources of electricity include nuclear (25%) and hydroelectric (3%), and renewable energy accounts for less than 2% (Bergman and Bowe et al. 2010). Off-site electricity for the production of kiln-dried softwood in the Northeast, for example, comprises 85% of total electrical energy required for production (Bergman and Bowe 2010). The difference in fossil fuel consumption between the

FIGURE 8. Total fossil fuel consumption from cradle to construction gate for timber frame and light-frame structures and their alternatives.



manufacture of the standard LF structure with 38-mm × 140-mm (nominal 2-in × 4-in) wall framing and the LF structure with 38-mm × 89-mm (nominal 2-in × 4-in) wall framing is insignificant, results showing a decrease of only 5%, respectively. Since expanded polystyrene is a petroleum product and requires a significant energy contribution, its introduction to the TF sheathed with SIPs increases fossil fuel consumption drastically. Comparatively, fiberglass batts introduced to the LF double the fossil fuel consumption of the standard LF, though still consuming less fossil fuel than the expanded polystyrene.

Fossil fuel use accounts for nearly 100% of the energy consumption required for the construction of each structure. The construction life-cycle stage is dominated by the use of diesel fuel on-site to assemble the structure with a crane, as well the diesel fuel required for material transportation from the manufacturing site to the construction site. Travel distance is assumed by AIE, and is based on average distances from manufacturing sites to construction sites in the region. Since these differences are based on building weight (transportation distances assumed equal by AIE), heavier structures require the consumption of more fossil fuels during construction. Notable observations for the fossil fuel consumption for construction include an increase of 29% when plywood is used rather than OSB for the LF (LF with plywood vs. standard LF, respectively). Additionally, the traditional TF requires significantly

more fossil fuel for its construction than any LF option since it is a heavier structure. Specifically, the traditional TF structure requires 23% more fossil fuels to construct than the standard LF structure. As noted previously, AIE does not account for the increased weight of a green wood product over a kiln-dried wood product, and therefore a difference in fossil fuel consumption between the traditional TF structure and the kiln-dried TF is not notable here. For this same reason, it is likely that the gap between the amount of fossil fuel consumed constructing the traditional TF and the standard LF is even greater. Adding to this likelihood is the fact that though a crane is commonly employed for the erection of a TF structure, this is rarely necessary when constructing an LF (Allen and Thallon 2011).

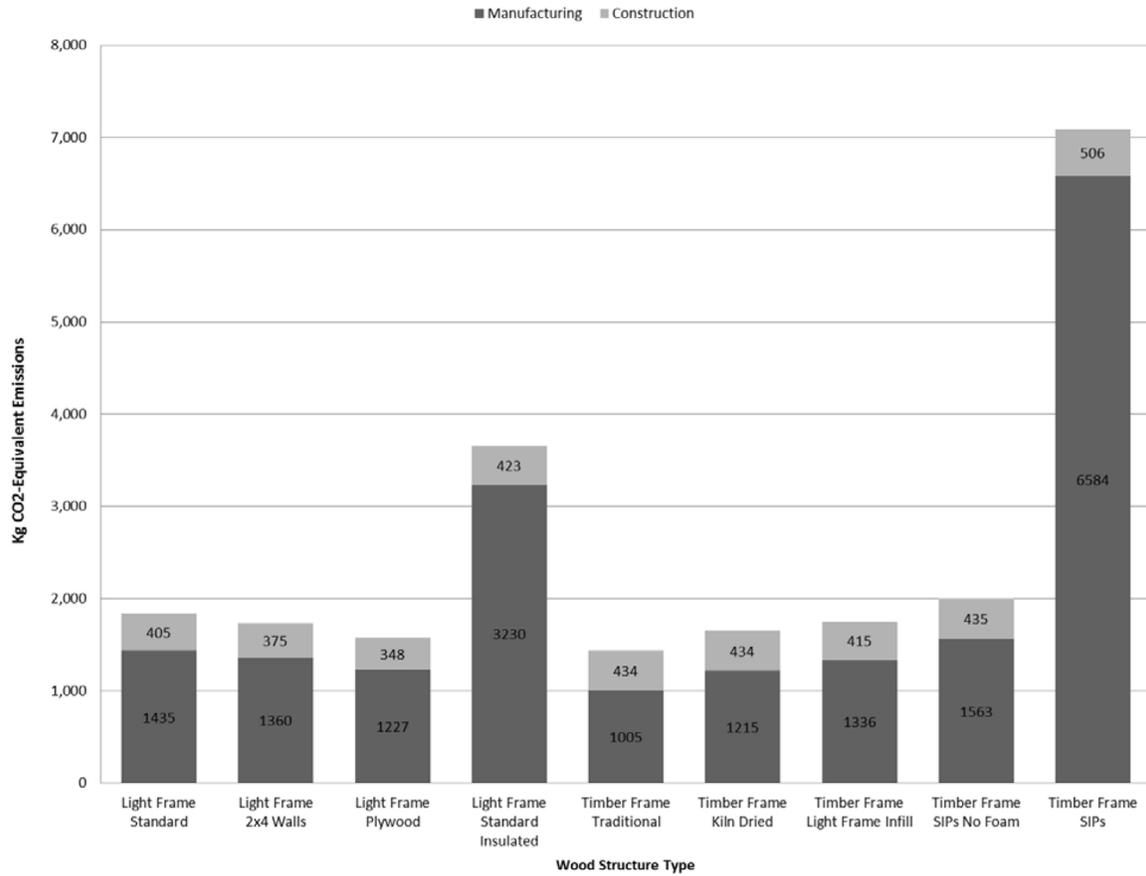
Fossil fuel sources account for slightly over half of the total energy required for the manufacturing and construction life-cycle stages for most structures analyzed. Considering fossil fuel consumption as an important factor when evaluating the environmental impact of a wood structure, the traditional TF structure constructed of green timbers and less-processed sheathing materials performs most favorably. Comparing this structure to the kiln-dried TF option shows that kiln drying (alone) increases fossil fuel consumption by an insignificant amount. This is due to the large percentage of biofuels used to generate energy during manufacturing (Puettmann et al. 2010). Constructing the TF with light-framing infill, however, increases fossil fuel consumption by 41% over the traditional TF, yet this assembly still out-performs the standard LF structure. Constructing the standard LF requires an increase in fossil fuel consumption of 40 % over the traditional TF. Replacing the OSB of the standard LF with plywood, however, provides a decrease of 18% in fossil fuel consumption, and brings the LF to a fossil fuel consumption level equivalent to both the traditional and the kiln-dried TF options. The wooden structural system that requires the highest consumption of fossil fuels is the TF sheathed with SIPs, and when the expanded polystyrene foam is considered this requirement increases drastically. The TF sheathed with SIPs (no insulation considered) requires double the fossil fuel consumption than the traditional TF. Considering insulation, the TF with SIPs requires more than twice the fossil fuel consumption of the LF insulated with fiberglass batts.

Global Warming Potential and Carbon Stored in Wood

Table 3 shows the carbon emitted in kg CO₂ equivalent for each life cycle stage and the long term storage of carbon as kg CO₂ equivalent, in the wood product during use. GWP is widely recognized as an important indicator of overall environmental impact. This value represents the total emissions of gasses that are known to contribute to global temperature increase. Since increased atmospheric concentration of CO₂ is considered to be the primary anthropogenic cause of global temperature increase, GWP is reported in kilograms (kg) of equivalent CO₂ emissions. Though CO₂ is considered the primary contributor to global warming (largely from the combustion of fossil fuels), other gaseous emissions including water vapor and methane also contribute to this phenomenon. These compounds are collectively referred to as greenhouse gasses, and since each contributor has a different effect on the atmosphere, GWP is normalized to values equivalent to CO₂ for reporting purposes (Florides 2008).

Figure 9 depicts the total emission of greenhouse gasses from manufacturing and construction for each structure, represented as equivalent emissions of CO₂. These emissions are caused primarily by the burning of fossil fuels for logging, transportation, sawmill and construction site operations, and manufacturing processes. Emissions from biofuels are considered carbon neutral and therefore are not represented in either graph. Values for the carbon stored in wood products that comprise each structure are also not represented by this graph.

FIGURE 9. Global warming potential (GWP) from cradle to construction gate for timber frame and light-frame structures and their alternatives.



GWP emissions for each structure analyzed are affected most by the manufacturing life-cycle stage. Not considering insulation options, manufacturing emissions range from 1,000 kg (2,210 lb) CO₂-equivalent released for the manufacture of the products that comprise the traditional TF structure, to 1,560 kg (3,440 lb) CO₂-equivalent for the manufacture of the products in the TF with SIPs. Among TF options, this value increased with added material processing. Utilizing kiln-dried material for framing and flooring materials increased GWP by 21% over the traditional TF structure. Likewise, manufacturing GWP for the TF with light-framing infill and OSB siding was 33% greater than the traditional TF. Steadily increasing with increased use of OSB, the TF with SIPs generated 56% more GWP than the traditional TF. Comparing LF options to TF options, it is not evident which framing system outperforms as a whole. Though the standard LF structure caused 43% more GWP than the traditional TF structure, other LF options performed more favorably than some TF options. Of notable interest is the LF sheathed in plywood, which has nearly the exact same GWP affect as the kiln-dried TF. Among light-framing options, the frame sheathed in plywood produced the lowest GWP. (Though the GWP of the LF sheathed with plywood is only 15% less than the GWP of the standard LF, and therefore considered to be of equal or insignificant difference by Athena, it is still considered to have the lowest effect among LF options). This value was still, however, 22% greater than the lowest GWP value from the traditional TF. Considering

insulation, the addition of expanded polystyrene to the TF with SIPs quadrupled its GWP. This structural option also produced two times the GWP of the standard LF sheathed with fiberglass batt insulation.

GWP generated during the construction phase represented approximately 1/3 of the total GWP for most structural assemblies, and is attributed to the burning of fossil fuels (diesel) for transportation and construction site operations. These calculations are based on transportation distances (which are assumed equal for all structures) and weight of materials. For this reason, the LF sheathed in plywood performed most favorably at 350 kg (770 lb) CO₂-equivalent, and the traditional (or kiln-dried) TF options produced the highest GWP at 430 kg (960 lb) CO₂-equivalent. Many construction GWP comparisons are considered to be of equal or insignificant difference (ASMI 2012a).

Figure 10 shows GWP emissions and carbon stored. Emission values are those generated by AIE and account for the total release of greenhouse gasses to the atmosphere from manufacturing and construction. Values for carbon stored represent a calculated sum of carbon in the wood products that comprise each structure. Wood fiber is comprised of approximately 50% carbon by weight, and was stored throughout the tree's life by photosynthesis. Since these structures store carbon indefinitely as long as their wood products do not break down (burn, decay), and the life of a structure is on the order of decades or more, it is appropriate to present these stored values alongside the values for carbon emitted to the atmosphere. Note that the values for carbon stored in each structure have been converted to CO₂-equivalent to facilitate comparison.

The amount of carbon stored in each structure is inherently tied to the total weight of the wood products utilized. For this reason, a structure that utilizes a higher total weight of wood products stores more carbon. The traditional TF structure stores 36% more carbon than the standard LF structure, which indicates that the sum of the weight of its wood products is 36% greater. Though TF structures have been accused of being wasteful of wood fiber, the increased "permanent" storage of carbon in these materials is favorable in this regard (Allen and Thallon 2011). Among most TF options there is very little difference in the amount of carbon stored, however carbon stores for the TF with SIPs are 10% lower than the traditional TF. LF options also show a similar level of carbon stores to one another. Of notable difference from the standard LF is the LF sheathed in plywood, which stores 11% less carbon. Calculations for the inclusion of insulation are not applicable because neither of the types of insulation considered are derived from wood fiber. Note that since these values were hand-calculated based on the actual volumes of wood products in each structure (not generated by AIE), their comparative results are not subject to the same assumption that a value of 15% difference or less is of equal or insignificant difference.

Values for the quantity of carbon stored (represented by negative values, as CO₂ kept out of the atmosphere) were considerably greater than the total GWP emissions produced by the manufacturing and construction life-cycle stages, as reported by AIE. Since the emissions and stores of bioenergy materials are not included (and are considered to be carbon neutral), these values are not reported as a total sum of carbon stores and emissions. Results show that for the construction of any of the structural assemblies considered (even including insulation), the final product is carbon-negative. Values for carbon storage range from 9 times greater than carbon emitted for the LF sheathed in plywood, to 15 times greater for the traditional TF. Overall, TF structures have a lower cumulative impact on GWP when carbon stores are considered. The higher the total weight of wood products drives carbon stores up, and the lower

the amount of manufacturing energy (particularly manufacturing energy generated by the combustion of fossil fuels), the lower the carbon emissions. The amount of wood fiber utilized has the greatest impact on this overall result.

Wood fiber Use and Waste

Wood fiber use refers to the total raw wood material necessary to create the wood products used for the construction of each structural system, as well as the material burned for the production of heat and electricity as biofuel utilized in the manufacturing process (ASMI 2012a). Wood fiber use and waste are reported in kilograms of material on an oven-dry basis. AIE does not attribute any wood fiber use to the construction life-cycle stage, since all wood fiber is initially used in manufacturing, and therefore all results indicate wood fiber use during manufacturing only (ASMI 2012a). Note that the results reflect each structural assembly’s bill of materials, and include the manufacture of all materials purchased, some of which become on-site material waste (cut-offs, sawdust, etc.). Wood fiber waste includes the portion of wood fiber use from manufacturing that is not ultimately part of the final wood product (lost as sawdust, wood-chips, etc.). Construction site waste or wood fiber burned for biofuel are not included here as wood fiber waste. Figure 10 and Figure 11 show the LCIA results for wood fiber use and wood fiber waste, respectively, for all LF and TF structures considered in this EIA.

FIGURE 10. Wood fiber use from manufacturing from cradle to construction gate for timber frame and light frame structures and their alternatives.

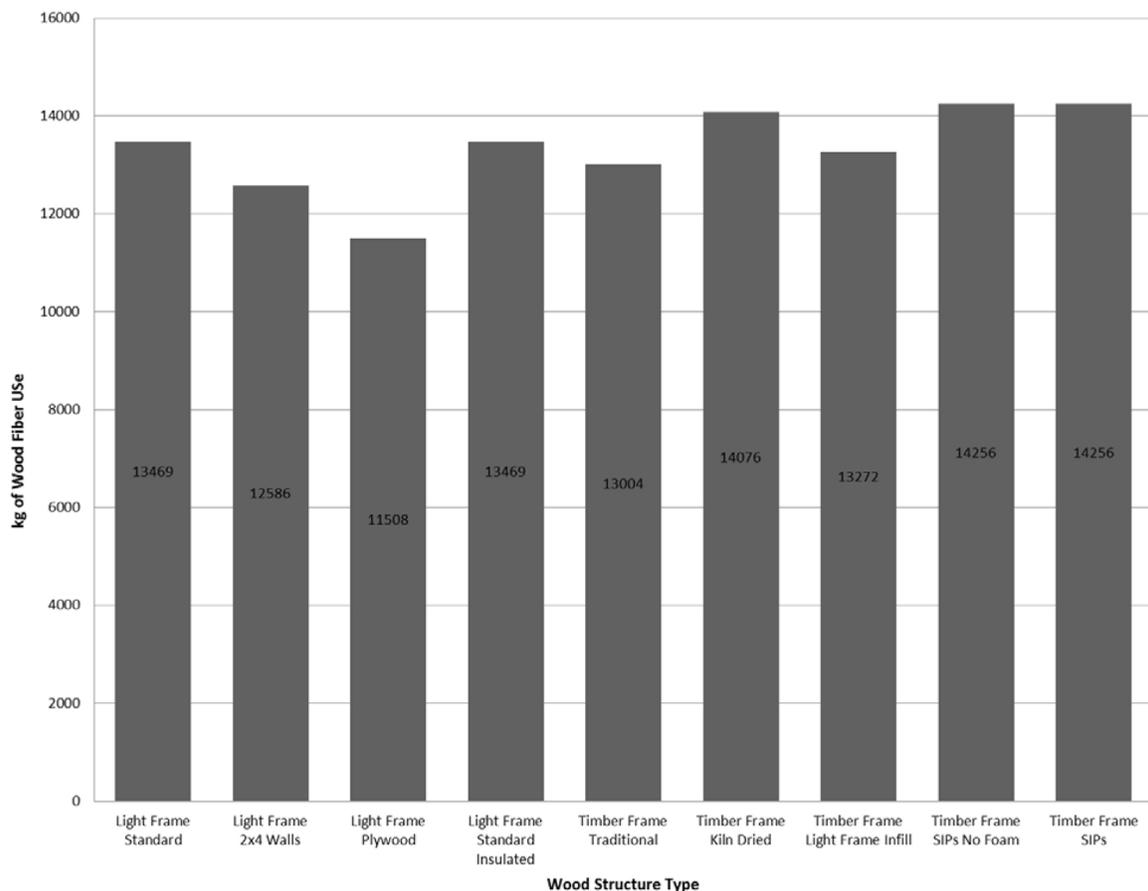
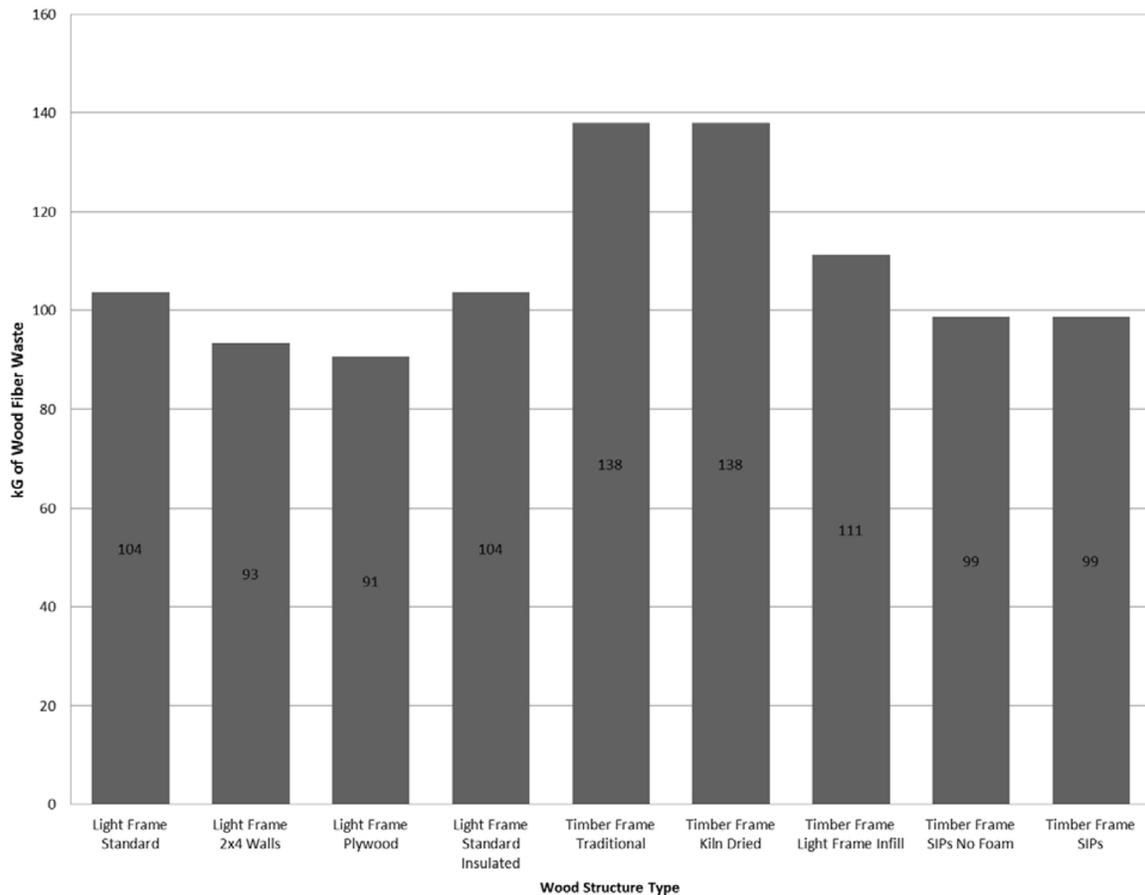


FIGURE 11. Wood fiber waste from manufacturing from cradle to construction gate for timber frame and light-frame structures and their alternatives.



Results for wood fiber use are reported in kilograms of wood fiber. Values range from 11,500 kg (25,300 lb) for the LF sheathed with plywood to 14,300 (31,400 lb) for the TF with SIPs. Wood fiber utilization among TF options differ within a range considered equal or insignificant difference. Similarly, LF structures were comparable, and many LF structures were comparable with TF options. Of notable difference among light-framing options is the LF sheathed in plywood, which requires 17% less wood fiber than the standard LF (sheathed with OSB). The difference between the standard LF structure and the traditional TF structure is insignificant. It should be noted, however, that the apparent increase in wood fiber use from the traditional TF to the kiln-dried TF indicates wood fiber burned for heat and energy required for the kiln drying process. This comparison, however, is technically insignificant, showing an increase of only 8% (attributed to biofuel material). Wood fiber use for the traditional TF and the TF constructed with light-framing infill are equivalent. Overall, wood fiber use appears to be higher among structural systems comprised of less-processed materials.

Wood fiber waste, also represented in kilograms of wood fiber, ranges from 0.7 to 1.1% of total wood fiber use. Lower percentages of wood fiber waste are prevalent in results from both the LF structure with walls framed with 38-mm × 89-mm (2-in × 4-in) material, as well as with the TF with SIPs. The highest percentage of wood fiber waste of wood fiber use is from the traditional TF. Specific values for wood fiber waste range from 91 kg (200 lb) for the LF

sheathed with plywood to 140 kg (300 lb) for the traditional TF. Though wood fiber waste does not vary significantly among most structural options analyzed, of interest is a comparison between the standard LF structure (sheathed with OSB) and the same structure sheathed in plywood (LF with plywood). The LF structure with plywood wastes 14% less wood fiber than the LF structure with OSB. This implies (non-conclusively since this comparison shows less than a 15% difference) a more efficient use of wood fiber when manufacturing plywood as compared to manufacturing OSB. Additionally, systems requiring larger cross-section solid-sawn materials appear to waste more wood fiber than some light-framing options.

For specific results discussed but not reported here, or for further LCIA results, please see Malone (2013).

CONCLUSIONS

It is widely recognized that the energy demands and environmental emissions associated with the construction industry are of considerable proportion. For this reason it is important for designers to make informed decisions with the environment in mind. LCA is a tool to aid this decision process which analyzes all environmental inputs and outputs associated with the life-cycle of some product, assembly of products, or process. An LCI is created that catalogues these inputs and outputs, and an LCIA is performed to produce results based on specific environmental burdens of concern, and these results are interpreted based on calculated evidence of environmental impact. This study was considered an environmental impact assessment that utilizes LCA methodology, differentiated from a true LCA with respect to the fact that some data are not traceable through use of AIE.

Two wood structural systems were designed, a light frame (LF) and a timber frame (TF), and several material substitutions were considered for each. A cradle-to-gate environmental impact assessment was performed on each structural assembly based on LCA methodology with the aid of AIE for Buildings software. These structures were analyzed based on total energy consumption, fossil fuel consumption, GWP, and wood fiber use and waste. Quantities for structural assembly materials were catalogued (bill of materials), and AIE provided LCI and LCIA results. Results and conclusions were determined based on these results, as well as reports filed by CORRIM.

LCIA results for fossil fuel consumption represent some portion of total energy use. (Note that some percentage of fossil fuel use is attributed to feedstock). Additionally, GWP is closely tied to fossil fuel consumption since the combustion of fossil fuels is the primary contributor of greenhouse gas emissions. GWP can then be compared directly with the quantifiable amount of carbon stored in wood products, and therefore wood fiber use directly affects cumulative GWP. Considering these interactions and LCIA results, the traditional TF structure (constructed of green framing material and less-processed sheathing materials) performed most favorably with respect to environmental impact. It requires the lowest amount of total energy input for manufacturing and construction, as well as the lowest level of fossil fuel consumption. Additionally, the traditional TF had the least net impact on GWP, a result of less-processed materials and high carbon storage.

The environmental impact of other structural systems analyzed varied with respect to choice of materials. These materials varied in this regard based on manufacturing requirements and weight. The use of products requiring a significant amount of mechanical processing (chipping, pressing, etc.), such as OSB, contributed to increased energy consumption, as

well as fossil fuel consumption, and therefore GWP. This is true for the use of plywood as well, though increases were not as dramatic. For this reason, analysis of the environmental impact of the TF with SIPs (which requires two layers of OSB) resulted in the highest environmental impact. Considering insulation, impacts increased dramatically, and were still more environmentally damaging than the LF insulated with fiberglass batts. The necessity to provide energy for heat in the drying process was also a contributor to negative environmental impacts. Quantities of wood fiber used do not correspond directly with other environmental impacts. It can therefore be concluded that environmental impact is driven primarily by product manufacturing requirements, and the amount of wood in a structure is no implication of negative environmental impact as compared here. Ultimately, it is the source from which energy is generated that has the greatest impact on environmental impact. Further development and utilization of non-fossil fuel-based energy sources will have the greatest effect on mitigating these environmental burdens.

FUTURE RESEARCH

The necessity to make decisions based on an accurate assessment of different wood structural systems and materials is clear. Decisions made possible based on this research, however, are limited. Since only the manufacturing and construction phases lie within the scope of this study, the environmental effects over the life of these structures have not been considered. A future study should overcome a pure material-based assessment and take a holistic approach to consider the overall considerations of architectural design sustainability and energy use over the life of a structure. It is widely recognized that heating and cooling are the primary contributing operations to a building's overall negative environmental impact, so the operational life-cycle stage must also be examined. This will require extending this research beyond that of only the structural system to include a complete building envelope. For this reason, future research is necessary to capture a complete picture of each structure's effects for decision-making purposes. Additionally, it would be particularly useful to perform such a study with actual data measured from existing structures, to complement the work here using typical construction types.

ACKNOWLEDGMENTS

It is recognized that previous LCA-related research performed by all CORRIM contributors to quantify the environmental effects of wood products is what made this study a reality. Technical assistance by Grant Finlayson of the Athena Institute was also an important contribution. Guidance with LCA methodology in the early stages of this research provided by Arijit Sinha is greatly appreciated. Finally, funding and support from the Wood Science and Engineering Department and School of Civil and Construction Engineering Oregon State University made this research possible.

REFERENCES

- AF&PA (2005). *National Design Specification for Wood Construction (NDS)*. ANSI/AF&PA NDS-2005. Washington, DC.
- Allen, E., and Thallon, R. (2011). *Fundamentals of Residential Construction*. 3rd ed. Hoboken: John Wiley & Sons, 2011.

- APA – The Engineered Wood Association (2012). *Panel Design Specification*. The Engineered Wood Association, Tacoma, WA.
- Athena Sustainable Materials Institute (ASMI) (2012a). Athena Impact Estimator for Buildings V 4.2 Software and Database Overview. Toronto, Ontario.
- Athena Sustainable Materials Institute (ASMI) (2012b). Athena Impact Estimator for Buildings. Version 4.2 Build 01 Hotfix. Athena, 2012.
- Bare, J. (2012). “TRACI 2.0: The tool for the reduction and assessment of chemical and other environmental impacts 2.0.” *Clean Technologies and Environmental Policy*, 13(5), 687-696.
- Bergman, R.D., and Bowe, S.A. (2010). “Environmental Impact of Manufacturing Softwood Lumber in North-eastern and North Central United States.” *Wood and Fiber Science*, 42, 76-78.
- Blue Ridge Timberwrights (BRT). 2010. “A History of Timber Framing.” 15, April 2013. <http://brtw.com/historyoftimberframing.php>
- Consortium for Research on Renewable Industrial Materials (CORRIM). 2013. “Life-cycle Inventory & Life-cycle Assessment.” 15, April 2013. http://www.corrim.org/research/lci_lca.asp
- Finlayson, G. “Re: Query from contact us page.” Inquiries to Grant Finlayson of Athena. Jan. 24, 2013. E-mail.
- Florides, G.A., and Christodoulides, P. (2008). “Global warming and carbon dioxide through sciences.” *Environment International*, 35, 390-401.
- Google Sketch-Up Pro. Version 8.0.15158. Google, Mountain View, CA, 2012.
- ICC – International Code Council (2009). International Residential Code for One- and Two-Family Dwellings – 2009. Country Club Hills, IL.
- ICC – International Code Council (2011). International Building Code - 2012. Country Club Hills, IL.
- ISO 14040 (2006): Environmental management – Life-cycle assessment – Principles and framework, International Organization for Standardization (ISO), Genève.
- Kline, D. Earl. (2005). “Gate-To-Gate Life-Cycle Inventory of Oriented Strandboard Production.” *Wood and Fiber Science*, 37, 74-84.
- Lamlom, S.H., and Savidge, R.A. (2003). “A Reassessment of Carbon Content in Wood: Variation Within and Between 41 North American Species.” *Biomass & Bioenergy*, 25, 381-388.
- Lippke, B., and Wilson, J.B. (2010). “Introduction to Special Issue: Extending the Findings on the Environmental Performance of Wood Building Materials.” *Wood and Fiber Science*, 42, 1-4.
- Lippke, B., Wilson, J., Meil, J., Taylor, A. (2010). “Characterizing the Importance of Carbon Stored in Wood Products.” *Wood and Fiber Science*, 42, 5-14.
- Malone, B.P. (2013). “LF Versus Traditional TF: A Study in Comparing the Differences.” M.S Thesis, Oregon State University, Corvallis, OR.
- Martin, Z., Skaggs, T.D., Keith, E.L., Yeh, B. (2008). “Principles of Mechanics Model for Wood Structural Panel Portal Frames.” *Proceedings of the 2008 Structures Congress - Structures 2008: Crossing Borders*, 314.
- National Renewable Energy Laboratory (NREL). 2012. “U.S. Life-cycle Database.” <http://www.nrel.gov/lci/> (April 15, 2013).
- Puettmann, M., Bergman, R., Hubbard, S., Johnson, L., Lippke, L., Oneil, E., Wagner, F.G. (2010). “Cradle-to-Gate Life-Cycle Inventory of US Wood Products Production: CORRIM Phase I and Phase II Products.” *Wood and Fiber Science*, 42, 15-28.
- Salazar, J., Meil, J. 2009. “Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence.” *Journal of Cleaner Production*, 17, 1563-1571.
- TFEC (2010). *Standard for Design of TF Structures and Commentary*. TF Engineering Council. Becket, MA.