Environmental performance improvement in residential construction: The impact of products, biofuels, and processes

Bruce Lippke*
Lucy Edmonds

Abstract

Understanding the environmental burdens from residential construction is increasingly important as consumers become more aware of the impacts of their purchasing decisions. In 2004, The Consortium for Research on Renewable Industrial Materials (CORRIM) evaluated the life-cycle environmental impacts of building materials used in residential construction. This report builds upon those findings by examining the environmental burdens of each component used to construct wall and floor subassemblies in residential homes. Evaluating components and subassemblies illuminates how the environmental burdens from different products, designs, and processes compare. Summary performance measures were developed for fossil fuel energy requirements, global warming potential, air and water pollution, and solid waste. This study clearly shows that the use of wood-based building materials significantly reduces most environmental burdens. The study also demonstrates the benefits of biofuels, recycling, and pre-cutting to reduce solid waste. This study's significance is enhanced by the detailed insights it provides on how architects and product and process engineers can substantially reduce environmental burdens.

Determining the environmental burdens from product manufacturing has become increasingly important in recent years as consumers become more aware of the impacts from their purchasing decisions. The Consortium for Research on Renewable Industrial Materials (CORRIM) addresses this in their landmark study: *Life-Cycle Environmental Performance of Renewable Building Materials in the Context of Residential Building Construction*.[1] The study's summary report[2] shows that the energy difference in producing a steel-framed house in Minneapolis is 17 percent larger than a wood-framed house. This difference may seem small until one realizes that only 6 percent of the materials in the house (by weight) are involved in creating this 17 percent difference; hence we should expect this impact to be amplified in assemblies where the products that can be substituted make up a larger share of the total materials.

This study extends the findings in the CORRIM report by characterizing the environmental burdens of each component used in the wall and floor subassemblies in the construction of a house. The benefit of characterizing the burdens at this level is that it becomes quite obvious which components or designs are contributing the greatest environmental burden and how they might be exchanged or modified by product manufacturers, engineers, and architects to lower the environmental burden of buildings.

Determining embodied energy, global warming potential (GWP), air and water pollution, and solid waste for each component that makes up a wall or floor subassembly in a building is an essential first step in identifying opportunities for improving environmental performance. The environmental burden from products that require less fossil fuel in manufacturing will generally be substantially lower than other products since the energy used in construction maintenance and demolition is comparatively much lower. One must exercise some caution when the downstream uses may have differential im-

The authors are, respectively, Professor, Director of Rural Technology Initiative, and President of CORRIM; and Graduate Research Assistant, College of Forest Resources, Univ. of Washington, Seattle, WA (blippke@u.washington.edu, ledmonds@u.washington.edu).
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[1] Bowyer, J., D. Briggs, B. Lippke, J. Perez-Garcia, and J. Wilson. 2004. Life cycle environmental performance of renewable materials in the context of residential building construction: Phase I research report. Consortium for Research on Renewable Industrial Materials, CORRIM Inc., Seattle, WA. 60 pp +15 chapter modules of approximately 800 pp.

[2] Lippke, B., J. Wilson, J. Bowyer, J. Perez-Garcia, and J. Meil. 2004. CORRIM: Life cycle environmental performance of renewable building materials. Forest Prod. J. 54(6):8-19.

Table 1. — Cold climate – Minneapolis walls. Single-family residential exterior wall, no windows, 8 feet high by 250 feet long (2,000 ft^2) (185.8 m^2), ½-inch plywood sheathing (12.7 mm).[a]

Category	Green-wood wall	Steel wall	KD-wood wall	MN-subs wall
Stud type	Green lumber	Steel	Kiln-dried	Kiln-dried
Stud thickness (in)	2 by 6	1⅝ by 3⅝	2 by 6	2 by 6
Stud spacing	16 in on center (400 mm)			
Stud weight	N/A	Heavy (20 ga)	N/A	N/A
Insulation	Fiberglass batt, Thickness: 137.5 mm (R19)	Fiberglass batt, Thickness: 90 mm (R13) XPS, Thickess: 37.5 mm	Fiberglass batt, Thickness: 137.5 mm (R19)	Wood-based insulation
Wall covering	Regular ½-in. gypsum board			¼-in plywood[a]
Cladding	Vinyl cladding			½-in plywood[a]
Vapor barrier	6-mil polyethylene vapor barrier			

[a]MN-subs wall also evaluated with OSB sheathing, OSB wall covering, and OSB cladding.

pacts such as the impacts of a different useful life, maintenance requirement, or disposal. For example, the structural products used in framing buildings are very unlikely to produce different environmental burdens during the use and maintenance life stages.[1] Differences in energy use over a building's life are largely eliminated by designing to the same effective insulation standard. Maintenance issues are minimal for wall and floor subassemblies except for the exposure of siding to weather, and demolition/disposal issues have been shown to be relatively small.[1] When the differences between the environmental burdens of components are large and consistent across the assessment of different risks such as water or air pollution and the creation of solid waste, there is little likelihood of making an incorrect decision by directly comparing the burdens from regeneration or extraction through product processing and initial construction.

The CORRIM life cycle inventory (LCI) data was used as the primary source for life cycle product information on wood products and the ATHENA™ Environmental Impact Estimator (EIE)[3] model was used to extend the analysis from the manufactured product to include the construction of building subassemblies. The EIE model also contains source data for non-wood products, largely steel and concrete that can substitute for wood in some applications. The EIE model allows a designer to model a building or subassembly, generate the bill of materials needed, analyze the long list of inputs and outputs, and to then aggregate environmental impacts into several summary impact measures for a comparative Life Cycle Assessment (LCA) on the tradeoffs associated with using one product or design over another.

Consistent with the CORRIM study, we concentrate on building wall and floor subassemblies to local code with wood or steel in a cold climate like Minneapolis, and with wood or concrete in a warm climate like Atlanta.

Assembly designs

Table 1 itemizes the basic components for four exterior above-grade wall subassembly designs in Minneapolis, each designed to meet the same thermal efficiency code. The four different exterior wall designs are: green-wood wall, KD-wood wall, steel wall, and MN-subs wall. The green-wood wall uses green lumber studs. The KD-wood wall uses kiln-dried lumber studs with biofuels used in drying sourced from woodwastes in the Pacific Northwest, and the steel wall uses steel studs. Components of the wall designs include studs, sheathing, cladding, vapor barrier, insulation, and wall covering. Window and door openings are excluded given our primary focus on the basic structural differences. Other than their studs, the only difference between the green-wood and KD-wood walls and the steel wall is insulation. The green and KD walls use fiberglass batts for insulation but the steel wall uses a combination of fiberglass and an exterior layer of extruded polystyrene (XPS) in addition to sheathing in order to avoid using cross bracing to meet sheer requirements.

The MN-subs[4] wall increases the substitution of wood for non-wood components and biofuel for fossil fuel. The kiln-dried wood studs and plywood sheathing are produced with increased biofuel making the dryer nearly self sufficient on bioenergy; 1/2-inch plywood is used as a substitute for cladding, 1/4-inch plywood is used instead of gypsum for wall covering, and a wood cellulose-based insulation is used instead of fiberglass batts.

The base design uses plywood for sheathing and the impact of substituting oriented strandboard (OSB) is discussed as an alternative. The wall size (8 ft high by 250 ft long) approximates the exterior wall perimeter for a typical Minneapolis house design.

Table 2 itemizes the basic components for two above-grade wall subassembly designs in Atlanta. The KD-wood wall uses kiln-dried wood studs produced with average biofuel usage, plywood sheathing, fiberglass insulation, gypsum wall covering, vinyl cladding, and a polyethylene vapor barrier. The concrete block wall uses a wood frame similar to the KD-wood wall inside the block to house the insulation, but with wider stud spacing. The concrete wall uses concrete blocks, fiberglass insulation, gypsum wall covering, stucco cladding, and a vapor barrier.

Table 3 provides similar information for four different floor designs in Minneapolis. These designs assume consistent structural codes and exclude any insulation that might be needed to equalize thermal properties i.e., appropriate for above-grade floors. The engineered wood product (EWP) floor joist system uses OSB webs and laminated veneer lumber (LVL) flanges. The dimension wood floor uses dimension

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[3] ATHENAInstitute™. 2004. Environmental Impact Estimator, Version 3.0.2. CD-ROM. ATHENA™ Sustainable Materials Inst., Merrickville, ON, Canada.

[4] "Subs" refers to the fact that the design substitutes in additional wood products.

lumber and the steel floor uses light gauge “C” shaped joists. Decorative finishing is not included and, except for the concrete slab, plywood decking is included.

Procedures

To isolate the impacts associated with each component in the designs described in **Tables 1**, **2**, and **3**, each subassembly (e.g., exterior wall or floor) was constructed one component at a time in the EIE model. This permitted comparisons of the environmental burdens associated with different studs, sheathings, cladding, wall covering, and a basis for developing designs with lower burdens.

Results

The different designs for the Minneapolis exterior wall are compared in terms of net resource use, fossil fuel energy, GWP, air and water pollution, and solid waste. Next, the two Atlanta exterior wall designs are compared, and lastly the four Minneapolis floor designs are compared. For brevity, the Atlanta wall and the floor comparisons are limited to resource use, fossil fuel energy, and GWP, the most important differences.

Burdens from Minneapolis above-grade exterior wall designs

Figure 1 shows the resources used in the steel wall and the KD-wood wall. It takes approximately 1000 kg of iron ore in the steel studs to replace approximately 2500 kg of wood fiber in the KD-wood wall’s studs (the remaining 1500 kg of wood fiber is common to both walls as plywood sheathing). Since the total mass for the KD-wood wall design is about 8000 kg, the difference in resource use between the two designs only involves about 1/3 of the components in the wall by mass, leaving 2/3 as common to both wall assemblies.

Table 2. — Warm climate – Atlanta walls. Single-family residential exterior wall, no windows, 8 feet high by 250 feet long (2,000 ft^2) (185.8 m^2).

Category	KD-wood wall	Concrete wall with furred out wood frame
Stud type	Kiln-dried	
Stud thickness (in)	2 by 4	
Stud spacing	16 in o.c. (400 mm)	24 in o.c. (600 mm)
Rebar	N/A	15 m (# 5)
Sheathing	½-in plywood (12.7 mm)	N/A
Insulation	Figerglass batt insulation, Thickness: 87.5 mm (R13)	
Wall covering	Regular ½-in gypsum board	
Cladding	Vinyl cladding	Stucco cladding
Vapor barrier	6-mil polyethylene vapor barrier	

In spite of the smaller mass of resources required by steel when compared with kiln-dried studs (**Fig. 1**), **Figure 2** demonstrates that the steel studs and associated insulation require 82 percent more fossil energy than the KD-lumber wall’s studs and insulation (shown above the dotted horizontal line delineating the common and uncommon components in the walls). The steel studs alone require more energy than the KD lumber studs even though they are nominally 2 inches narrower than the 2 by 6 wood studs. The insulation associated with the steel wall design requires 76 percent more energy than the insulation required for the KD-wood wall assembly.

The significance of wood drying is demonstrated in **Figure 2** by comparing the “lumber” components of the MN-green and MN-KD wall designs. The fossil energy allocated to the lumber component of the KD wall is 121 percent larger than the fossil energy allocated to the lumber component of the green wall. Although the use of green lumber is limited to certain species, opportunities exist for increasing the efficiency of the drying process. Using biofuels to generate the energy for wood drying reduces and potentially eliminates the use of fossil fuel in drying. Sufficient volumes of low-cost residuals are available to approach 100 percent energy self-sufficiency in the Pacific Northwest (does not include those low-cost residuals used for making paper), as is the common practice in the Southeast.

Figure 2 demonstrates that the energy associated with the basic framing materials (e.g., studs and sheathing) makes up only a small fraction of the fossil fuel energy in the MN exterior wall. This suggests the possibility of achieving a greater reduction in environmental burdens by substituting fewer energy intensive materials for the non-frame components. The MN-subs design (left-most bar in **Fig. 3**) demonstrates this possibility. In addition to the fact that MN-sub’s KD lumber studs and plywood are produced using increased levels of biofuels, the design also includes the following substitutions: 1)

Table 3. — Floors with no insulation, Minneapolis. Single-family residential, no finished floor or carpet on decking, area: 768 ft^2 (71.35 m^2).

Category	EWP floor	Dimension wood floor	Steel floor	Concrete slab floor
Floor type	Wood I-joist and wood decking	Wood joists and wood decking	Light gauge “C” shaped steel joists and wood decking	Concrete slab on grade
Live load	2.4 kPa			
Decking type	Plywood			
Decking thickness (mm)	15			100
Web type	OSB			
Web thickness (mm)	9.5			
Flange type	LVL			
Flnage size (mm by mm)	38 by 38			
Joist type			38 by 245 mm	
Joist spacing (mm)			300	
Steel gauge			18	
Concrete (MPa)				20

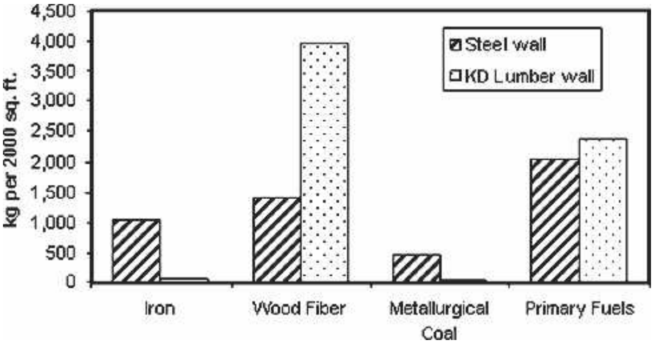

Figure 1. — Resources used in a steel frame wall vs. a KD-wood frame wall – cold climate.

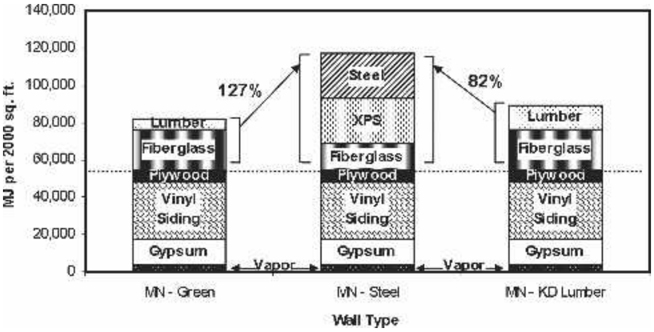

Figure 2. — Fossil fuel energy per wall component – cold climate.

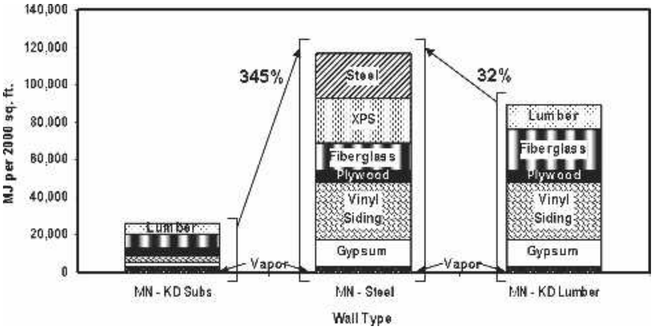

Figure 3. — Fossil fuel energy per wall component – cold climate. Plywood and wood-based product substitutions to reduce energy for MN-subs design.

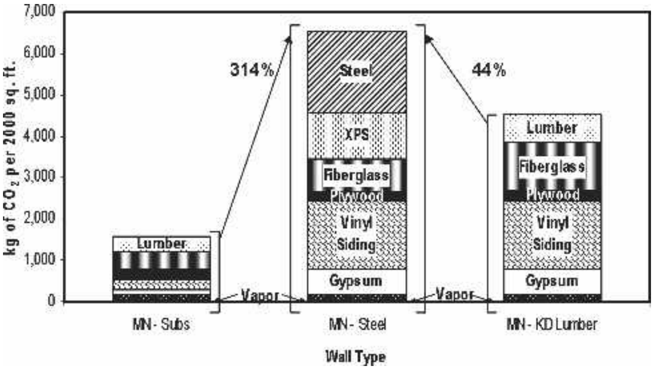

Figure 4. — Global warming potential (GWP) per wall component – cold climate. Plywood and wood-based product substitutions to reduce GWP for MN-subs design.

vinyl siding is replaced by 1/2-inch plywood siding; 2) fiberglass insulation is replaced by recycled paper; and 3) the gypsum wall covering is replaced by plywood paneling. Note that, in application, the 1/2-inch plywood exterior siding would require a durable finish. Collectively, design changes of this type that use less fossil-intensive products and rely more on the use of biofuel have the potential of substantially reducing the energy used in constructing a wall. **Figure 3** shows that the typical steel wall design uses 345 percent more fossil fuel than our speculative design.

OSB sheathing substitutes for plywood in many uses and has taken over many markets from plywood because it is cheaper and sourced by species that are underutilized relative to softwoods. These species extend the supply to many other regions than can otherwise produce quality plywood, an important resource supply benefit. However, OSB generally uses more than twice as much energy as plywood, largely in drying and the embodied energy in purchased resins. In a direct comparison between the KD-wood-framed walls, the OSB-sheathed KD-wood wall uses about 18 percent more fossil energy than the comparable plywood-sheathed KD-wood wall (detail not shown for brevity). The lumber stud and insulation advantage held by the KD wall over the steel design is essentially unchanged if we use OSB as a substitute for plywood in both designs. Similarly, using OSB does not significantly alter the advantage our speculative design holds over the steel or conventional wood design.

GWP, the index of greenhouse gas emissions based on the carbon equivalent contributions of methane, nitrous oxides, and carbon dioxide represents another important environmental performance measure. **Figure 4** compares the GWP for the same wall designs displayed in **Figure 3**, showing consistently larger differences in GWP between designs than for fossil energy.

Figure 5 compares water emissions for the same wall designs: MN-subs, MN-steel, and MN-KD lumber. Toxicity comparisons are generally based on the most offending substance rather than adding small contributions from many substances. For the steel wall, the most toxic emission is cyanide and phenols are the most toxic emission from the wood designs. The conventional steel wall design produces 181 percent more water pollution than the conventional KD lumber design. When we substitute plywood for non-wood components in MN-subs, the phenol impacts are additive since they are all the same toxin; therefore, the steel wall contributes only 13 percent more toxins to water than MN-subs, a much smaller advantage than noted for GWP or fossil energy. The phenols added by lumber are inconsequential. Also, the cyanide added by non-framing components of the steel wall design is inconsequential compared to the cyanide added by the steel studs.

Figure 6 compares the air pollution emissions for the same three wall designs: MN-subs, MN-steel, and MN-KD lumber. For every component, the most offending pollutant is sulphur oxide with the more fossil-intensive components contributing the most. Note that **Figure 6** looks similar to **Figure 4** (GWP) and **Figure 3** (fossil fuel energy). This is due to fossil fuel energy's large contribution to both greenhouse gases and air pollution.

Figure 7 compares solid waste for the same three wall designs: MN-subs, MN-steel, and MN-KD lumber. Measured in

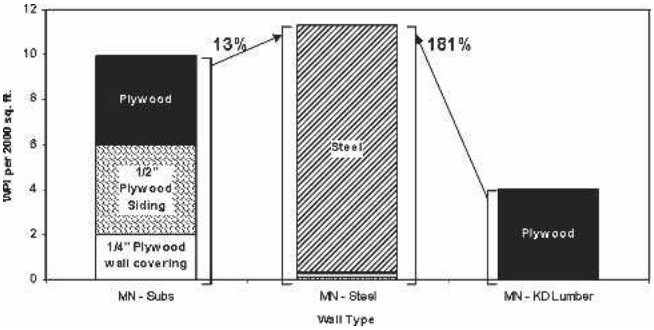

Figure 5. — Water pollution index (WPI) per wall component – cold climate. Plywood and wood-based product substitutions for MN-subs design.

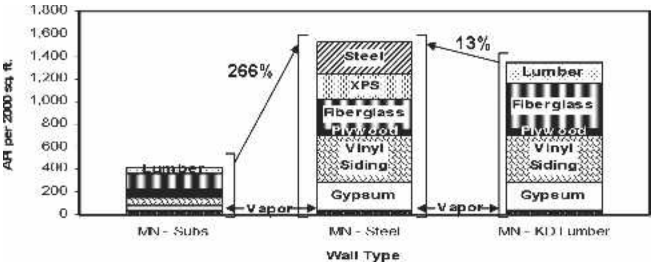

Figure 6. — Air pollution index (API) per wall component – cold climate. Plywood and wood-based product substitutions for MN-subs design.

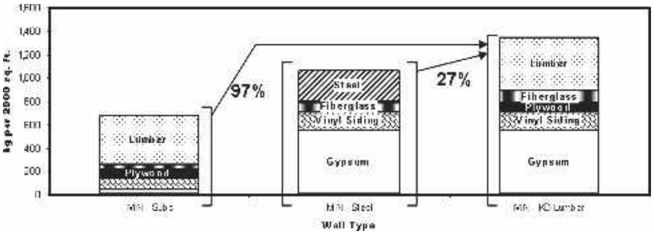

Figure 7. — Solid waste per wall component – cold climate. Plywood and wood-based product substitutions for MN-subs design.

kilograms, the wall framed with KD lumber produces 27 percent more solid waste than the steel-framed wall. This is partially due to the fact that steel is pre-ordered cut to length while wood studs are generally cut to length on the site, which produces greater waste at the construction site. Designs that utilize pre-cutting and pre-assembly reduce waste. **Figure 7** shows that the use of gypsum as a wall covering produces more waste than plywood as a result of its greater density and less useful recovery of trimmings. Substituting plywood for gypsum (e.g., the 1/4-in plywood shown here in the MN-subs design) substantially reduces the waste.

Burdens from Atlanta above-grade wall designs

The prevalent alternative to wood in warmer climates such as Atlanta is concrete. The major differences between the two Atlanta exterior wall designs are due to the use of concrete and stucco siding in the concrete block design vs. the use of plywood sheathing and vinyl siding in the KD lumber wall design. For brevity, we restrict our LCA to fossil energy and GWP, the two summary measures most impacted by the use of concrete.

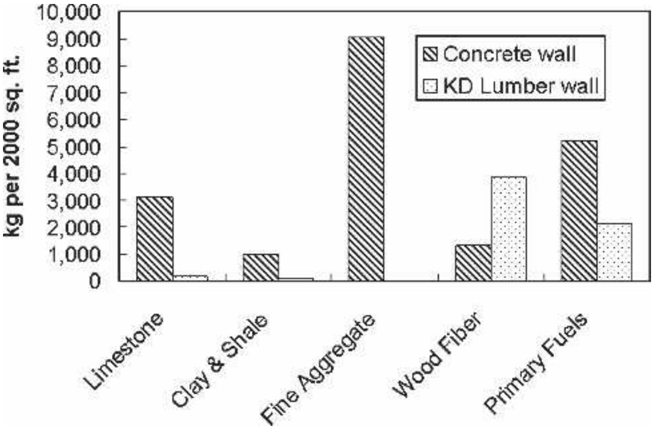

Figure 8. — Resources used in a concrete block wall vs. a KD-wood frame wall – warm climate.

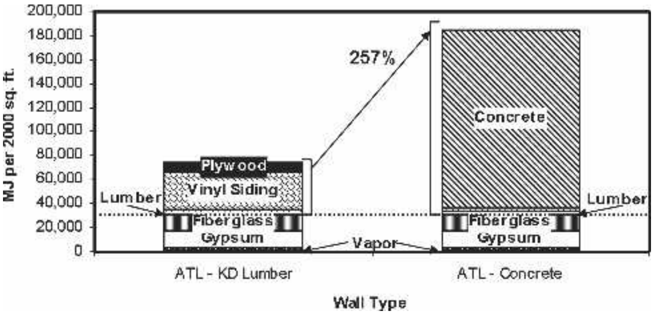

Figure 9. — Fossil fuel energy per wall component – warm climate.

Figure 8 shows the resources used in the concrete wall and the KD-lumber wall. The concrete wall requires almost 3000 kg of limestone and over 9000 kg of fine aggregate, plus an additional 1319 kg of wood fiber for a furred out wood frame used to house insulation. By comparison, the KD-lumber alternative requires slightly less than 4000 kg of wood fiber.

The concrete design's concrete block, stucco cladding, and lumber use 257 percent more fossil energy than the KD-lumber design's plywood sheathing, vinyl cladding, and lumber (**Fig. 9**).

The calcification process in the production of concrete contributes to greenhouse gases, resulting in a 427 percent increase in GWP for the concrete design's concrete block, stucco, and lumber frame relative to the KD-lumber design's plywood, vinyl, and lumber (**Fig. 10**).

Burdens from alternative floor materials

Different materials demonstrate different advantages in different uses. Floors require greater stiffness than walls, which becomes a disadvantage to steel floor designs that require the use of higher gauge steel. **Figure 11** displays the fossil fuel consumption associated with four different floor designs, all based on Minneapolis. No surface material (carpet, hardwood, or terrazzo) is included, which could alter the comparisons somewhat. The wood I-joist floor design consists of an OSB web and LVL flange with plywood decking. The concrete slab floor design uses approximately 150 percent more fossil fuel energy and the steel floor design uses almost 400 percent more fossil fuel energy than either of the two wood floor designs.

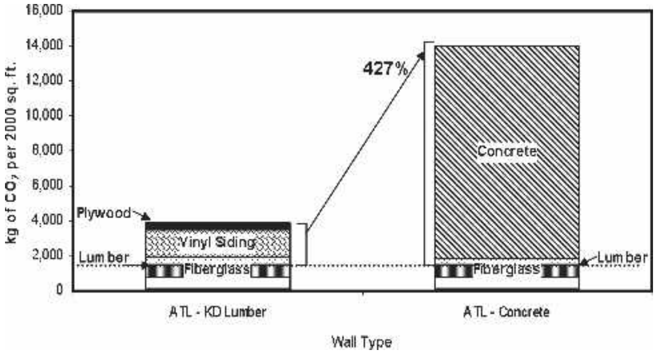

Figure 10. — Global warming potential (GWP) per wall component – warm climate.

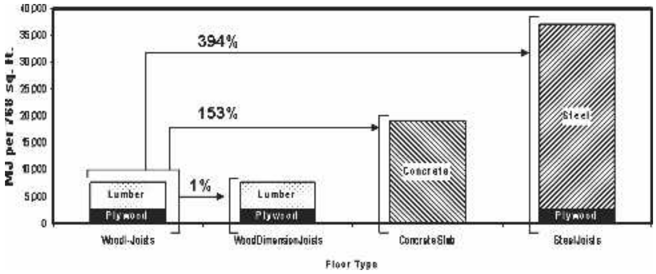

Figure 11. — Fossil fuel energy per floor component.

Differences between the two wood floor designs and the concrete and steel floor designs are larger in terms of GWP (**Fig. 12**) compared to the fossil fuel consumption shown in **Figure 11**. GWP for the concrete floor design is over 400 percent larger than GWP for both of the wood floor designs. GWP for the steel floor design is over 700 percent larger than that for both of the wood floor designs (**Fig. 12**).

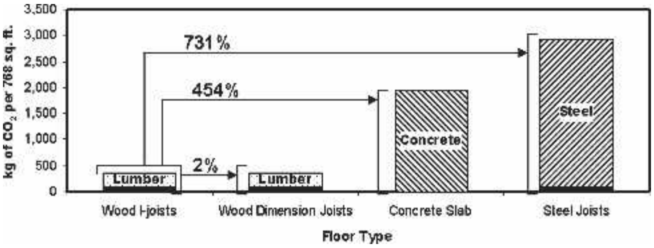

Figure 12. — Global warming potential (GWP) per floor component.

Replacing wood dimension joists with engineered wood I-joists (EWP) does not significantly reduce fossil energy or GWP but does improve resource efficiency as the dimension lumber joists use 105 percent more fiber mass than the I-joist that benefits not just from having a smaller cross-sectional profile but also from stiffness and the reduced waste that results from cut-to-length procurement.

Conclusions

This sampling of materials and designs is not exhaustive but suggests many design, product, and process changes that can improve environmental performance. The most obvious include using a renewable wood resource instead of a fossil-intensive resource, using biofuels to reduce the fossil fuel use in manufacturing wood products, using resource-efficient engineered materials such as I-joists, and cut-to-length or preassembled units or systems to reduce waste and perhaps using recycled materials that do not require fossil energy in their remanufacture. An important caveat in this analysis is the variation in impacts regionally, such as the availability of energy sources, which differ in each region. While many of the impacts demonstrated can be expected to be important in any region, there will be regional differences as well as product, design, and construction method differences.