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# Wood versus Concrete and Steel in House Construction

## A Life Cycle Assessment

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ABSTRACT

The environmental friendliness of building materials can be measured in life cycle assessments of the total energy inputs for the product, from cradle to grave. How do the environmental costs of wood compare with concrete and steel in housing construction? First we compare energy values for each material and for house components. Taking the viewpoint of a consumer, we then compare three typical houses in which steel, concrete, or wood is the dominant component. It appears that wood, wood components, and houses built primarily of wood require lesser amounts of energy in their manufacture, assembly, and operation. The robustness of the conclusions is shown by the degree of agreement among researchers and through an assessment of the impact of uncertainties in the analysis.

**Keywords:** embodied energy; wood products

Life cycle assessments attempt to determine the environmental consequences of particular products by measuring the energy consumption and waste generation associated with their manufacture, transport, operation, and eventual disposal. Considering how much energy and raw materials are used and how much waste is generated at each stage of a product's life lets us compare the environmental burdens of different products.

One component of a product's life cycle assessment is "embodied energy"—the amount of energy (direct or indirect) that is required to produce one unit of material. Previous studies of the embodied energy requirements of steel, concrete, and wood as building materials include Buchanan and Honey (1994), Lawson (1995), and the Canadian Wood Council (CWC 2000). Before comparing those studies in an effort to draw some conclusions

***Above:*** **Houses built mainly of wood appear to have the lowest levels of embodied energy.**

about the energy embodied in the materials, we note the financial backing for each study: The Buchanan and Honey study was sponsored by Tasman Forestry Limited, an industry group; the Lawson study was sponsored by the Environmental Protection Authority of Australia, a government group; and the CWC is an industry group. The data reflect circumstances in Australia and Canada but are nevertheless relevant to the United States.

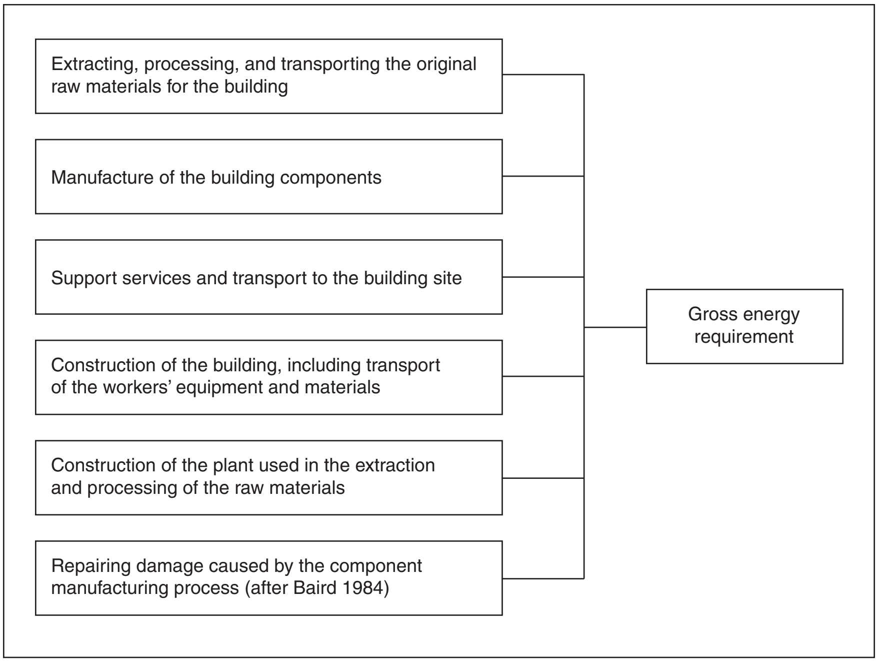


***Figure 1.* Components of the Gross Energy Requirement, from Lawson (1995).**

**Table 1. Energy data available for steel.**

| Source | Product | Energy (MJ/kg) |
|---|---|---|
| Alcorn and Baird (1996) | Steel, recycled, sections | 8.9 |
| | Steel, recycled, wire rod | 12.5 |
| | Steel, virgin, general | 32.0 |
| Buchanan and Honey (1994) | Steel, sections | 59.0 |
| | Steel, rods | 34.9 |
| | Steel, general | 34.9 |
| | Steel, pipes | 56.9 |
| FEMP (2001) | Steel (Greening Federal Facilities [GFF] range) | 25.7–39.0 |
| Lawson (1995) | Steel | 35.0 |
| | Basic oxygen steel, coated sheet | 38.0 |
| | Basic oxygen steel, stud | 38.0 |
| | Electric arc furnace steel, reinforcing rod | 19.0 |
| | Range of values | 8.9–59 |

## Energy Use for Life Cycle Assessments

Embodied energy is measured in international units of energy—often millions of Joules per kilogram (MJ/kg) or billions of Joules (GJ).

This article draws from several studies of the energy values embodied in building materials. The studies are not directly comparable, however; they vary considerably in their assumptions about transport distances, functional units, fuels used, energy efficiencies, amounts recycled within and outside processes, composition and purity of material, and time spans, to name a few variables. One example is that steel produced using a hydroelectric power source will have significantly different impacts than steel produced by electricity from conventional fuels.

Each study also draws different boundaries for its analysis. That is, a product's gross energy requirements can be broken down in different ways; *figure 1* illustrates one structure for these "system boundaries." Lawson's (1995) report focused mainly on the process energy requirement (the highlighted box), which relates directly to the manufacture of the building material in question and accounts for 50 to 80 percent of the gross energy requirement. The process energy requirement generally contains an allowance for the energy required to obtain and process the raw materials plus transportation to and from the manufacturing stage.

Buchanan and Honey (1994) defined the boundaries an entirely different way, as levels:

*Level 1.* The direct and transport energy inputs to the process.

*Level 2.* Level 1 plus the energy required to make the material inputs to the process.

*Level 3.* Level 2 plus the energy required to generate the capital for the process.

*Level 4.* Level 3 plus the energy required to make the machines that carry out the process.

Those differences affect the results the researchers obtain and, consequently, our comparisons.

## Comparing Individual Materials

The range of embodied energy values for steel is 8.9 to 59 MJ/kg *(table 1).* These values cover a variety of steel product types generated from the application of different processes. Virgin steel, for example, requires considerably more energy to produce than recycled steel. There is a corresponding difference in energy values between the two main steel processes, basic oxygen steel and electric arc furnace steel, because the latter can accept recycled steel as feedstock.

Energy values for concrete also vary significantly *(table 2, p. 36).* Cement, one of the main components of concrete, is up to 4.5 times more energy intensive

**Table 2. Energy data available for concrete.**

| Source | Product | Energy (MJ/kg) |
|---|---|---|
| Alcorn and Baird (1996) | Cement | 7.8 |
| | Fiberboard cement | 13.1 |
| | Concrete block | 0.9 |
| | Concrete, glass reinforced | 3.4 |
| | Concrete, 30 MPa | 1.4 |
| | Concrete, precast | 2.0 |
| Buchanan and Honey (1994) | Cement | 9.0 |
| | Concrete, *in situ* | 1.6 |
| | Concrete, precast | 2.0 |
| FEMP (2001) | Concrete (Greening Federal Facilities [GFF] range) | 1.2–2.0 |
| Lawson (1995) | Cement render | 2.0 |
| | Cement mortar | 2.0 |
| | Concrete, *in situ* | 2.0 |
| | Concrete, autoclaved, aerated | 9.5 |
| | Concrete raft slab | 8.4 |
| | 150mm aerated concrete | 5.4 |
| | 150mm concrete slab | 8.8 |
| | Concrete, autoaerated | 4.8 |
| | Range of values | 0.86–13.1 |

**Table 3. Energy data available for wood.**

| Source | Product | Energy (MJ/kg) |
|---|---|---|
| Alcorn and Baird (1996) | Timber, kiln-dried, dressed | 2.5 |
| | Timber, glulam | 4.6 |
| | Timber, medium-density fiberboard | 11.9 |
| Buchanan and Honey (1994) | Timber, kiln-dried, treated | 9.4 |
| | Timber, glulam | 9 |
| | Timber, rough | 1.7 |
| | Timber, air-dried, treated | 2.4 |
| | Timber formwork | 0.6 |
| | Hardboard | 41.2 |
| | Softboard | 31.0 |
| FEMP (2001) | Lumber (Greening Federal Facilities [GFF] range) | 4–7 |
| | Particleboard (US Department of Energy range) | 14–20 |
| | Plywood | 18 |
| Lawson (1995) | Timber, softwood stud | 3.5 |
| | Timber, particleboard (softwood) | 8.0 |
| | Timber hardboard (hardwood) | 24.0 |
| | Timber, imported western redcedar frame | 4.5 |
| | Timber hardwood engineered product | 11.0 |
| | Timber floors | 1.9 |
| | Timber frame, timber weatherboards, plasterboard | 1.5 |
| | Timber studs with plasterboard | 1.3 |
| | Range of values | 0.57–41.2 |

to produce than concrete as a whole. The average embodied energy for concrete is around 2 MJ/kg, with the range being 0.86 MJ/kg to 5.4 MJ/kg.

The range of energy values for wood *(table 3)* is the widest of the three building materials, with values as low as 0.57 MJ/kg and as high as 41.2 MJ/kg. After we remove the outliers, however, the range falls between 0.6 MJ/kg and 9 MJ/kg. The largest difference between these values comes from use of native hardwoods versus plantation softwoods. Hardwood lumber on average incorporates around three times as much energy for each kilogram, for various reasons: Hardwood forests are often more energy intensive to manage; they are more difficult to harvest and require different, more energy-intensive machinery; and they must undergo a slow drying process that takes longer and consequently consumes more energy.

Although the tables provide a basis for comparison within and between each type of building material, some caution is required. Comparing the three sets of ranges superficially would suggest that concrete and wood have similar embodied energy values and therefore that concrete could perhaps substitute for wood and also increase the durability and strength of a house. However, because it is rare for materials to be directly substituted for each other, a study of typical components for mainly steel, concrete, and wood houses needs to be performed.

## Comparing House Components

Some components of a house—such as steel nails and aluminum window frames—are the same in nearly all types of construction. We must therefore look at components that are *predominantly* steel or wood or concrete: the floor, the walls, and the roof. Both Honey and Buchanan (1994) and Lawson (1995) addressed the three types of materials considered here and constructed hypothetical steel, concrete, and wood houses from those components.

The values used in the two studies differ, however *(table 4)*. The most notable difference is in the maximum values: 38 MJ/kg for steel in Lawson compared with 59 MJ/kg in Buchanan and Honey. The former calculated all values on an area basis; the latter did the calculation on a mass basis (per wall, floor, or roof). However, the area that each component covers was kept constant throughout Buchanan and Honey, and therefore both steel- and timber-framed walls were assumed to cover the same area. Each energy value in the study can therefore be translated into an area basis *(table 5, p. 38).*

To effectively compare the two studies, each component needs to be assessed individually. The floor values in the table allow only timber and concrete to be compared. The timber values, the lowest in both categories, are significantly different, with the highest values being 293 MJ/$m^2$ in Lawson and 558 MJ/$m^2$ in

**Table 4. Energy values for building materials.**

| Lawson (1995) | | Buchanan and Honey (1994) | |
|---|---|---|---|
| Material | Energy (MJ/kg) | Material | Energy (MJ/kg) |
| **Steel** | | | |
| Mild steel | 34.0 | Steel, general | 34.9 |
| Galvanized mild steel | 38.0 | Steel, rods | 34.9 |
| Range | 34.0–38.0 | Steel, sections | 59.0 |
| | | Steel, pipes | 56.9 |
| | | Range | 34.9–59.0 |
| **Concrete** | | | |
| *In situ* concrete | 1.9 | Concrete, *in situ* | 1.6 |
| Precast steam-cured concrete | 2.0 | Concrete, precast | 2.0 |
| Precast tilt-up concrete | 1.9 | Range | 1.6–2.0 |
| Concrete blocks | 1.5 | | |
| Autoclaved, aerated concrete | 3.6 | | |
| Range | 1.5–3.6 | | |
| **Wood** | | | |
| Kiln-dried sawn softwood | 3.4 | Timber, kiln-dried, treated | 9.4 |
| Kiln-dried sawn hardwood | 2.0 | Timber, glulam | 9 |
| Air-dried sawn hardwood | 0.5 | Timber rough | 1.7 |
| Particleboard | 8.0 | Timber, air-dried, treated | 2.4 |
| Hardboard | 24.2 | Timber formwork | 0.6 |
| Range | 0.5–24.2 | Hardboard | 41.2 |
| | | Softwood | 31.0 |
| | | Range | 0.6–41.2 |

Buchanan and Honey. The values for concrete floors hover around 650 MJ/m$^2$ in Lawson but rise to 937 MJ/m$^2$ in Buchanan and Honey. Including a comparison of the estimated mass for each type of floor explains the difference: The particleboard floor with timber framing studied by Buchanan and Honey was more than 3,000 kg heavier than Lawson's elevated timber floor.

Similar problems attend a comparison of the values for the walls. Two apparently similar walls—the timber frame, clay brick veneer, plasterboard-lined wall in Lawson and the timber frame, brick veneer cladding wall in Buchanan and Honey—have masses of approximately 52,000 kg and 21,000 kg, respectively. Accordingly, the range of energy values in Lawson is higher than in Buchanan and Honey.

Masses also differ for the steel-framed walls, but the energy calculations are less divergent. Consistent for walls in both studies, however, is the increase in energy values from timber to steel and the increase in energy values from timber-framed timber walls to timber-framed concrete walls. There is less difference between steel and concrete values.

Three types of roofs appear to be directly comparable between the two studies—the timber frame with concrete tiles, the timber frame with steel sheet or corrugated iron roof, and the steel frame with steel sheet roof or corrugated iron roof. The values are generally similar, but in both studies, the timber values are clearly lower than both the concrete–steel ones *(table 5).*

The different approaches to defining system boundaries partly explain the differences between the values. Nevertheless, the two studies come to the same conclusion: Wood and wood components are generally less energy intensive than the other materials.

## Comparing Houses

It is, of course, impossible to build a house entirely of one material. To assess the energy requirements of a predominantly steel, concrete, or wood house, therefore, all components of the house need to be considered: those containing the building material in question, components that are necessary for construction but consisting of other materials, and finally common components for all building types. For simplicity, we use one study, Buchanan and Honey (1994), who assessed typical houses and their components according to the energy values just reviewed.

*Table 6* (p. 38) shows how each type of house has been defined, highlighting the differences between its main components. *Table 7* (p. 39) indicates what fraction each type of building material contributes to the overall mass and energy of the structure. Although the concrete house contains the most mass (64.2 tonnes compared with 61.5 tonnes for steel and 27.6 tonnes for wood), the steel house requires the most energy (553 GJ compared with 396 GJ for concrete and 232 GJ for wood).

Both the steel and the wood houses have a higher percentage of their building materials as steel and wood, respectively, but the fraction of the mass that is concrete in both houses is still larger than the amount of steel and wood.

The analysis of the housing components can be extended further by focusing on each house individually. Take the typical steel house. The mass fraction of steel in this house is only 6 percent, but this 6 percent consumes up to 31 percent of the total energy. For the

**Table 5. Energy values of housing components.**

| Lawson (1995) | | | | Buchanan and Honey (1994) | | | |
|---|---|---|---|---|---|---|---|
| | Energy ($MJ/m^2$) | Mass ($kg/m^2$) | Mass (kg) | | Energy (GJ) | Energy ($MJ/m^2$) | Mass (kg) |
| **Walls** | | | | | | | |
| Timber frame, timber weatherboard, plasterboard-lined wall | 188 | 30.3 | 8,250 | Timber framing, weatherboard cladding | 27 | 99.3 | 5,220 |
| Timber frame, reconstituted timber weatherboard, plasterboard-lined wall | 377 | 28.7 | 7,820 | Timber framing, concrete block cladding | 65 | 239.0 | 21,650 |
| Timber frame, aluminum weather-board, plasterboard lined wall | 403 | 20.8 | 5,660 | Timber framing, brick veneer cladding | 135 | 496.3 | 20,650 |
| Timber frame, clay brick veneer, plasterboard-lined wall | 561 | 191.3 | 52,030 | Steel framing, weatherboard cladding | 84 | 308.8 | 4,120 |
| Steel frame, clay brick veneer, plasterboard-lined wall | 604 | 183.6 | 49,940 | Steel framing, concrete block cladding | 86 | 316.2 | 21,330 |
| Double clay brick, plasterboard-lined wall | 906 | 341.5 | 92,880 | Steel framing, brick veneer cladding | 192 | 705.9 | 19,880 |
| Single-skin block, plasterboard-lined wall | 472 | 132.1 | 35,940 | | | ($272 m^2$) | |
| Cement-stabilized, rammed-earth wall | 376 | 570.0 | 155,040 | | | | |
| **Floor** | | | | | | | |
| Elevated timber floor (lowest level) | 293 | 103.4 | 9,830 | Particleboard floor (timber framing) | 53 | 557.9 | 12,170 |
| Elevated timber floor (highest level) | 147 | 27.8 | 2,640 | Steel framing particleboard floor | 75 | 789.5 | 11,010 |
| 110mm slab concrete on ground | 645 | 294.6 | 27,980 | Concrete floor | 89 | 936.8 | 52,530 |
| 110mm elevated concrete slab (permanent framework) | 665 | 270.2 | 25,670 | | | ($95 m^2$) | |
| 200mm precast concrete T-beam, infill flooring | 644 | 55.9 | 5,310 | | | | |
| **Roof** | | | | | | | |
| Timber frame, timber shingle roof, plasterboard ceiling | 151 | 35.6 | 3,310 | Timber framing, corrugated iron roof | 59 | 460.9 | 2,810 |
| Timber frame, concrete tile roof, plasterboard ceiling | 251 | 27.3 | 2,540 | Timber framing, concrete tile roof | 17 | 132.8 | 7,230 |
| Timber frame, terracotta tile roof, plasterboard ceiling | 271 | 74.6 | 6,940 | Steel framing, corrugated iron roof | 83 | 648.4 | 1,920 |
| Timber frame, steel sheet roof, plasterboard ceiling | 330 | 25.7 | 2,390 | Steel framing, concrete tile roof | 29 | 226.6 | 6,580 |
| Steel frame, steel sheet roof, plaster-board ceiling | 483 | 15.4 | 1,430 | | | ($93 m^2$) | |

**Table 6. Typical components of predominantly steel, concrete, and wood houses.**

| House | Frame | Floor | Wall | Roof | Window frames |
|---|---|---|---|---|---|
| Steel | Steel | Concrete | Brick veneer wall cladding | Corrugated iron roof | Aluminum |
| Concrete | Timber | Concrete | Concrete block wall cladding | Corrugated iron roof | Aluminum |
| Wood | Timber | Timber | Weatherboard wall | Concrete tile roof | Timber |

*SOURCE: Buchanan and Honey (1994).*

other houses, the building material of interest requires the largest percentage of energy of the three materials, with concrete consuming 26.6 percent of the energy for the concrete house, and wood, 19.5 percent of the wood house's energy. Each material's contribution to the overall embodied energy of each house is given in *figure 2*.

The component labeled "other" in *figure 2* consists of all components other than steel, concrete, and wood, including paper, plaster products, glass, clay products, plastics, paints, aluminum, copper and alloys, and insulation, along with energy expended at the construction site. The "other" category varies among the three houses because, for example, the concrete and steel houses have aluminum window frames (versus wood frames in the wood house), and the steel

**Table 7. Mass and energy fractions of predominantly steel, concrete, and wood houses.**

| House | Total mass (kg) | % of mass | | | Total energy (GJ) | % of energy | | |
|---|---|---|---|---|---|---|---|---|
| | | Steel | Concrete | Wood | | Steel | Concrete | Wood |
| Steel | 62,000 | 6.0 | 58.5 | 2.5 | 553 | 31.4 | 12.2 | 0.63 |
| Concrete | 64,000 | 3.8 | 84.1 | 5.4 | 396 | 22.5 | 26.6 | 2.19 |
| Wood | 28,000 | 2.6 | 57.9 | 24.9 | 232 | 11.0 | 13.7 | 19.5 |

*Source: Buchanan and Honey (1994).*

house uses large amount of clay products for the brick veneer wall cladding.

## Analysis of Uncertainties

To more thoroughly analyze the comparison of the housing components and improve the robustness of the conclusions, we must assess the sensitivity of the results to variability in the inputs. There are at least two important types of sensitivities: the fraction of material used in each house and the uncertainty or variation in the energy requirements of each component.

*Fraction of material.* In the wood house, if concrete tiles were substituted for the corrugated iron roof, the energy contained in the roof would increase from 17 GJ to 83 GJ, which in turn alters the total amount of energy contained in the building. In the steel or concrete house, even changing the window frames from aluminum to wood reduces the energy content by 34.5 GJ; it would also alter the percentages of "other" and "wood" materials.

*Uncertain values.* We need to assess the significance of the difference between the energies for each type of house, given the large range of values obtained for each building material. The value of the overall energy for each house comprises three components—that for the wood, that for the steel, and that for the concrete. Each of these component values has an uncertainty. We can combine them to obtain the uncertainty in the overall energy for this house by taking the square root of the sum of squares of the uncertainties in each component.

The uncertainty in each component may be calculated from the range of values quoted earlier *(tables 1–4)*. Take the steel house: The mass of steel is 3,689 kg, and a representative range of energy values is 32–59 MJ/kg$^{-1}$. Hence the uncertainty in energy values in the steel component for this house is at least 3,689*(59 – 32) = 99,603 MJ. Similarly, the uncertainty in the concrete component for the steel house is at least 36,000*(5.4 –0.86) = 163,440 MJ, and the uncertainty in the wood component for the steel house is at least 1,530*(9 – 0.6) = 12,852 MJ. The overall uncertainty for the steel house is $\div(99{,}603^2 + 163{,}440^2 + 12{,}852^2)$ = 192 GJ. A similar procedure for the concrete house gives an overall uncertainty of 255 GJ; for the wood house, the overall uncertainty is 95 GJ.

**Table 8. Energy values from housing construction studies.**

| House | Buchanan and Honey (1994) | | CWC (2000) | |
|---|---|---|---|---|
| | Total energy range (GJ) | Energy per square meter | Total energy (GJ) | Energy per square meter |
| Steel | 457–649 | 4.9–6.9 | 389 | 1.8 |
| Concrete | 265–521 | 2.8–5.5 | 562 | 2.6 |
| Wood | 185–280 | 2.0–3.0 | 255 | 1.2 |

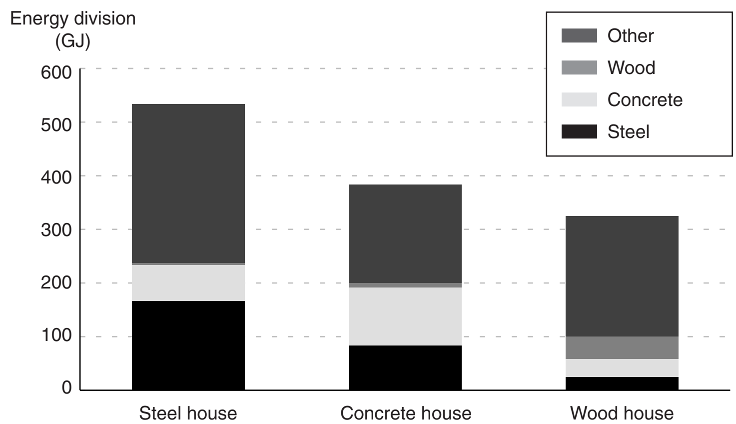


***Figure 2.*** **A breakdown of the embodied energy in the components for each type of house.** ***Source:*** **Buchanan and Honey (1994).**

*Figure 3* (p. 40) shows the extent to which the three energy ranges obtained from the overall uncertainty analysis overlap, demonstrating that, in all three cases, the concrete component contributes most to the error. Even though concrete extends across the smallest range (0.86–5.4 MJ/kg, compared with 0.6–9 MJ/kg for wood and 32–59 MJ/kg for steel), the significant mass of each concrete component contributes to the large uncertainty in its energy value. Ultimately, concrete becomes the largest contributor to the overall energy value. And because the concrete house contains the largest percentage of concrete, in both energy and mass, it has a significantly larger relative uncertainty.

Although *figure 3* demonstrates that the wood house has the smallest overall uncertainty, the 15 GJ overlap between the energy ranges for the wood and concrete houses means that there is some uncertainty in the conclusion that the wood house has the lowest amount of embodied energy. The overlap be-

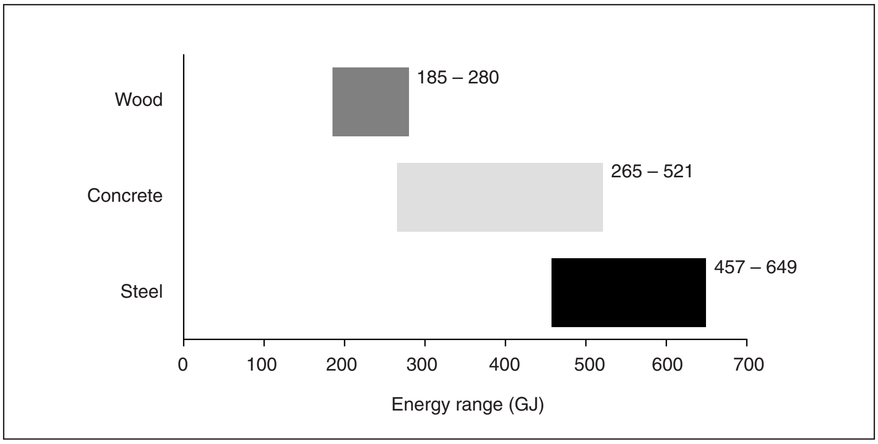


***Figure 3.* Overlap of embodied energy ranges for each type of house. *Source:* Buchanan and Honey (1994).**

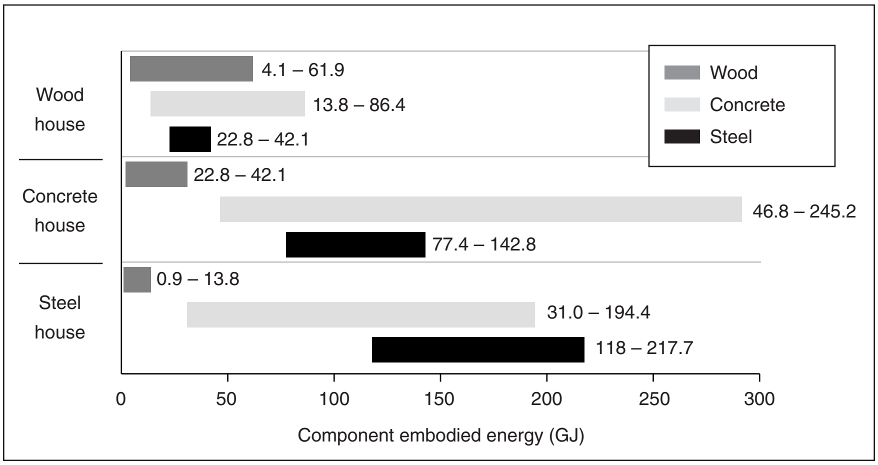


***Figure 4.* Breakdown of the contribution of each component (steel, concrete, and wood) to the overall uncertainty in embodied energies for each house. *Source:* Buchanan and Honey (1994).**

tween the range for the concrete house and the steel house is significantly larger. *Figure 4* demonstrates the extent to which each of the three materials contributes to the overall uncertainty, and resulting range, for each house. It reinforces the observation that concrete is the major component contributing to the overall uncertainty not only in the concrete house but also, to a lesser extent, in the steel and wood houses.

The importance of concrete in the overall uncertainty analysis can be attributed to the significant density of the material and to the mass of concrete required to perform a function similar to that of wood or steel. For example, Ashby (1992) showed that most types of wood and steel generally have a higher strength-to-density ratio than cement and concrete, particularly when the extremely limited tensile strength of concrete is taken into consideration.

Energy usage during the lifetime of the house is another uncertainty that needs to be considered. Although the difference between concrete and wood thermal insulation is small (in most comparative reports they are considered equal), steel has significantly poorer insulating properties. The R-value of steel is about 5 points lower than that of concrete and wood (CWC 2000). Insulation is usually installed in walls and roofs to control energy losses, however, so the difference in R-values is mitigated in the life cycle assessment.

## Other Studies

The Canadian Wood Council (2000) study was not included in the analysis of housing materials and components because it made no clear division of components on a mass or area basis, but we can nonetheless make some comparisons. The CWC houses had larger floor areas (216 square meters compared with 94 square meters in Buchanan and Honey) and included three levels. The CWC wood house was framed with lumber and wood I-joists, the steel house had a structure of light frame steel, and the concrete house was built from insulated concrete forms with a floor system that combined open-web steel joists with concrete slab. All three CWC houses used wood trusses for the roof framing, as this was considered to more appropriately represent house construction.

*Table 8* shows that, although the total embodied energy value for the wood house in the CWC study lies within the Buchanan and Honey ranges, the range for the concrete house is higher and the range for the steel house is lower than that in Buchanan and Honey. The CWC study suggests that a concrete house requires more energy than a comparable steel house—the reverse of what was indicated by Buchanan and Honey. The main source of this difference appears to be the use of timber framing in Buchanan and Honey to support the concrete house's exterior walls, whereas the CWC house assumes insulated concrete forms. This difference accounts for 246 GJ of the CWC calculations, which is almost half the total. The CWC calculations showed a different ratio of energy in the wood house to that in the steel house (1:1.5) than Buchanan and Honey (1:2.4), mainly because a wood trussed roof was used in all three CWC houses. By comparison, the Buchanan and Honey steel house has a corrugated iron roof, which contains 83 GJ of energy (15 percent of the total), and the wood house's timber-framed, concrete-tiled roof accounts for 17 GJ (7 percent of the total).

Furthermore, the energy values per unit area in each house are significantly lower for the CWC study. The differences in the ratios of energy per unit area can be mainly attributed to two features. The first is the purpose of the CWC study: "to compare the environmental effects of the wood, sheet metal, and concrete structure and envelope"; therefore, "elements considered common to all three designs…were not included in the comparison." The common elements were included in Buchanan and Honey's comparison and involve a substantial proportion of the total energy calculated. If these components are removed, the energy values would be similar and more comparable to those in the CWC study.

Second, the multistory house in the CWC study alters the proportion of contributions to the energy values: A three-story house with 216 square meters of floor area requires a roof of only 72 square meters, whereas Buchanan and Honey's one-story house of 94 square meters needs a roof of approximately the same area.

Despite the different housing designs in the studies, however, it appears that wood, mainly wood components, and mainly wood houses have the lowest embodied energy levels. This comparison also demonstrates some of the complexity involved in analysis of these materials, particularly in the definition of a typical steel, wood, or concrete house, which may vary with location, climate, and other factors.

## Conclusions

A comparison of the embodied energy values of the building materials in isolation has suggested that wood and concrete have lower embodied energy values than steel but quite different ranges (0.6–41.2 MJ/kg for wood, 0.9–13.1 MJ/kg for concrete). Steel has a significantly higher energy value and range of values (8.9–59 MJ/kg). The wood components also had the lowest embodied energy values when these isolated component values were applied to the wall, floor, and roof assemblies. A comparison of predominantly wood, concrete, and steel houses indicates that a wood house contains 232 GJ of embodied energy, a concrete house contains 396 GJ, and a steel house, 553 GJ. An overall uncertainty calculation for each house has given the following ranges: 185–280 GJ for wood, 265–520 GJ for concrete, and 455–650 GJ for steel. Overall, wood, mainly wood components, and mainly wood houses appear to have the lowest embodied energy levels of the materials reviewed here.

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