ENERGY CONSUMPTION AND GREENHOUSE GAS EMISSIONS RELATED TO THE USE, MAINTENANCE, AND DISPOSAL OF A RESIDENTIAL STRUCTURE

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ABSTRACT

Virtual residential houses in Atlanta, Georgia, and Minneapolis, Minnesota, were analyzed to determine energy consumption and greenhouse gas emission during the building use, maintenance, and demolition phases of their life cycle. An analysis of Census data on housing stocks provided estimates for the useful life of a house. Home Energy Saver, an internet tool for energy analysis sponsored by the Department of Energy and available from the Lawrence Berkeley National Laboratory, was the primary tool used in assessing energy consumption for heating and cooling during the use phase of the buildings. A survey on the life span of house components by the National Association of Home Builders (NAHB) was used to estimate a maintenance/replacement schedule. Emissions during demolition and transport to the landfill were estimated based on the initial bill of materials in the house and distance to the landfill.

The energy consumption over a 75-year life was estimated to be 4,575 GJ for the Atlanta wood frame, 4,725 GJ for the Atlanta concrete block structure, and 7,800 GJ for the Minneapolis wood frame. A steel-framed Home Energy Saver model was not available, but since the steel-framed house was designed to code for equal thermal properties with the wood frame house, we assume no difference. Energy consumption related to structural/exterior maintenance was estimated at 110.5 GJ for the Atlanta location and 73.3 GJ for Minneapolis, only 1–2% as large as used for heating and cooling. The energy needed for demolition and waste removal was even smaller.

Carbon dioxide (CO_2) emissions from the consumed energy were estimated using the regional energy grids in SimaPro at 227,000 kg (501,000 lbs) for the Atlanta wood frame, 235,000 kg (519,000 lbs) for the concrete frame, and 338,000 kg (856,000 lbs) for the Minneapolis wood frame. CO_2 emissions related

Wood and Fiber Science, 37 Corrim Special Issue, 2005, pp. 128–139

to structural (primarily exterior) maintenance were 4143 kg and 3468 kg, respectively, for Atlanta and Minneapolis. The emissions from deconstruction and waste removal were roughly 1/10th that of maintenance.

Reducing energy consumption during building use provides a major opportunity to reduce environmental burdens. When time-valued discounting over the building life is considered, reducing the burdens associated with product use and construction is equally important.

Keywords: Housing life, energy use, maintenance, disposal, LCI, life cycle.

INTRODUCTION

As concern over the environmental impacts of the materials and energy used in residential housing has increased, interest in methods to improve environmental performance has also increased. Accordingly, life-cycle assessment (LCA) has become an important tool to analyze natural resources consumption and the emissions generated in manufacturing processes and subsequent product use. An LCA of residential housing refers to the assessment of the environmental impact through every step of the life of a house — from obtaining raw materials, through production, construction, use, maintenance, and disposal. The primary focus of the CORRIM research has been to develop a database from which to identify and assess alternatives for improving the environmental performance of residential structures. In this article we extend the CORRIM analysis for the product processing and construction stages of processing to include building use, maintenance, and disposal. An analysis of the expected life of residential buildings is developed first and used in a lifelong analysis of the heating and cooling requirements and provides support for the maintenance requirements. Finally, an analysis of the process of demolition, waste disposal, and recycling closes out the life cycle of the use of a building. Like the other CORRIM research modules, the analysis follows the CORRIM research guidelines (CORRIM 2001) which are based on the 14000 series of standards of the International Organization for Standardization (ISO 1997, 1998, 2000a, 2000b). Unlike the CORRIM analysis covering the extraction of materials through construction, which for wood products was based on primary survey data collected for each plant and unit process, this analysis of building use, maintenance, and disposal has been developed from available secondary data and models. As such, neither the level of detail nor the accuracy of estimates is comparable. In addition, the nature of the use, maintenance, and disposal stages of a life cycle will inherently be more uncertain as they represent estimates of processes that in the real world have evolved over long time periods. The analysis of the impact of design on energy uses, for example, requires the collection of data for many different designs, which limits the practicality of examining complex structures. Important insights can, however, be gained by analyzing simple design differences in constructed test sites (Biblis 2005). Prudence and limited budgets dictated that estimates from secondary data would be sufficient to demonstrate the major differences between the processing and construction stages over the life cycle of a house from the use, maintenance, and disposal stages, while providing a place holder for future work. As a consequence of these budget and data limitations in addition to the relatively small burdens associated with the maintenance and final demolition/disposal stages of the life cycle of a house, we deviate from our LCI guidelines by only tracking carbon and energy use as the two most important metrics for analysis across all stages of processing and use.

AGE OF HOUSE WHEN REMOVED FROM USE

Developing a life-cycle analysis for the use phase of residential housing requires estimates of the age that a house would be removed from use, perhaps demolished and/or recycled, and discarded to the waste stream. Degradation of wood components by exposure to excessive moisture in particular can reduce structural life, but the life of a house can be extended by proper and timely maintenance; therefore, a maintenance schedule is an integral part of a life-cycle analysis. Properly protected, the physical properties of wood are known to maintain their structural integrity for many centuries as evidenced by centuries-old wooden churches and monasteries across Europe.

The life of a house in the United States is more directly related to other social acceptability factors. Recent decadal census data show demolitions/disasters ranging between 200,000 to 300,000 per year, which is less than 0.3% of total stock (Census of Housing). Removals from housing stock for reasons such as conversions, condemnations for roads etc. are not as related to life expectancy issues. We have analyzed the available housing stock data in order to develop a useful life age for our analysis with full recognition that there are many data limitations. In particular, record keeping has changed, survey methodologies have changed, and the incompleteness of reporting has changed. Even so, the estimates provide support for a rather long functional life for housing.

The housing stock in 1920 was reported at about 24 million (Census of Housing 1940). Recent surveys show about 10 million of the current stock were built before 1920 (American Housing Survey 2001). The inference is that almost half of the 1930 stock is still in use 70 years later (Table 1).

A more in-depth comparison of the survey and the history of starts and stock suggests the survey probably underestimates the age of the stock as there are more young stock in the survey than were built in the comparable period. It seems quite logical that remodels might result in understating the age for many houses built long ago. If the survey understates the age significantly, it would suggest that more than half of the 1920 stock could be in use 80 years later. The overstatement of houses under 40 years old was estimated at 19% by comparing the survey's measure of units under age 40 to the actual starts put in place during the comparable time period (Table 2).

TABLE 1. *The age of existing houses compared to early stock put in place.*

Year	Housing stock (millions)	"Year Structure Built" from 2001 housing survey (millions)		% of initial stock remaining in 2000
1940	37.325	Pre 1940	21.885	59%
1930	31.998	Pre 1930	15.292	48%
1920	24.352	Pre 1920	9.827	40%

By comparing two surveys taken a decade apart (2000 and 1990), one can see that there is a somewhat larger decline in the 50 years and older age groups compared to younger groups but very little difference between those 60 to 70 years old and those even older. The removal rate for houses built 80 years ago may be as low as 0.4 percentage per year (Table 3). In effect, housing is removed from use for a variety of reasons, and while one can expect a larger percentage of older houses to have been removed, there is a wide distribution on the age that a residential house leaves the housing stock. There is not a narrow age range within which houses suddenly become un-functional.

Adjusting the most recent survey on "year structure built" for the overestimate of young stock by moving about eleven million units (the approximate number of homes whose ages were underestimated according to Table 2) to the older age groups allows one to make an improved estimate of the percentage of old houses that are still in use. Assuming we lose 1 million units in each decade prior to 1950 (a more rapid loss rate than in the survey), the adjusted data (Table 4) suggest that well over half of the 80-year-old housing is still in use.

Keeping in mind that houses built prior to 1930 lacked many features of the houses built since 1950, in particular less functional plumbing and electricity, it would seem reasonable that more recently designed houses would remain functional for a longer duration than housing built in earlier periods. In addition, farm houses that were removed during the migration to the

TABLE 2. *Starts put in place compared to the age of existing homes.*

"Year Structure Built" from 2001 housing survey (millions)		Housing starts (millions)		Survey ÷ starts
1960–1999	72.051	1960–1999	60.375	1.19

TABLE 3. *2001 vs. 1991 survey of "Year Structure Built".*

Year built	2001 survey (millions)	1991 survey (millions)	% loss 2001 vs. 1991
1990–99	16.086	NA	
1980–89	16.542	17.243	4.1%
1970–79	23.529	23.598	0.2%
1960–69	15.894	16.161	0.17%
1950–59	13.779	13.836	0.4%
1940–49	8.284	8.607	3.8%
1930–39	6.593	6.768	2.6%
1920–29	5.465	5.677	3.7%
pre 1920	9.827	10.314	4.7%

TABLE 4. *Adjusted age of existing houses compared to early stock put in place.*

Housing stock (millions)		Adjusted 2001 survey of "Year Structure Build" (millions)		% of initial stock
1940	37.325	Pre 1940	30.9 (+10)	83%
1930	31.998	Pre 1930	24.3 (+9)	76%
1920	24.352	Pre 1920	16.8 (+7)	69%

cities, and houses that were in the path of the heavy investments in road construction, have added significantly to removals for non-structural reasons. In effect, the housing stock and survey data support a housing life almost certainly in excess of 75 years, and more likely well over 85 years. Acknowledging that there is a substantial uncertainty in any estimate as social changes could result in an increase or decrease in useful life, we have generally used 75 years as a conservative estimate of life expectancy of single family residential housing.

SCOPE OF ANALYSIS FOR ENERGY USE

Virtual houses comparable to those evaluated in the other CORRIM Phase I reports were analyzed: a one-story house (2,153 square feet) in Atlanta, Georgia (GA), representing a warm climate house and a two-story house (2,062 square feet) in Minneapolis, Minnesota (MN), representing a cold climate house. Their useful life was assumed to be 75 years as described above. For the Atlanta location, two construction framing methods were compared: concrete block walls and wood-frame construction. For the Minneapolis location, only a wood-frame house was modeled, pending availability of a model that can handle steel-framed structures.

Home Energy Saver (http://homeenergysaver.lbl.gov/), an internet tool for energy analysis, available from the Lawrence Berkeley National Laboratory (operated by the University of California for the U.S. Department of Energy), was the primary tool used in assessing energy consumption and greenhouse gas emission for these structures. This data set is intended for internal use with the cradle to completed construction LCI/LCA dataset developed by CORRIM, thereby extending the coverage from cradle to grave. The structures used in the Home Energy Saver model are customized to be as close to the CORRIM building designs as possible, but it should be recognized that different energy analysis models are being used for the energy use calculation than for the construction phase, so the data comparison is not exact, but no single model tool was available that could be applied across all phases of construction and building use. The impacts of any differences between models used on results are believed to be insignificant in comparison to geospatial differences related to the location of a house. In that sense, while there is a larger degree of uncertainty with the estimates of energy use than that provided by the cradle to construction gate analysis provided in earlier modules of this report, the comparisons are still useful. One should not expect equivalent accuracy for processes that take place over a short time interval such as a cradle to construction gate analysis and processes that take place over a long period of time or are represented by a cross-section of processes that emulate the impacts of different time intervals.

In keeping with CORRIM objectives to provide relevant comparative information important to improvements in the construction of residential buildings that reduce environmental burdens, we limit our analysis to the heating and cooling aspects of building use that are dependent upon the design of the construction. Energy associated with human uses such as cooking, laundry, water heating, lighting and appliances are noted for a relative comparison but are better analyzed separately as they are more dependent upon other characteristics of use than on the structural design. The effect of construction practices on building efficiency can be important, but there is no methodology to invoke a construction practices auditing process within the energy use model that might consider a 'reduction factor' for various practices in the field.

Site-specific assumptions are required by the energy use model. The orientation of both houses on their respective lots faced south. It was assumed that there were no neighboring houses or large trees within 25 feet. It was assumed that both houses were built in 2002. The Minneapolis house followed the 2000 Uniform Building Code (UBC). The Atlanta houses followed the 2000 International Building Code (IBC). Heating for both houses was by a central gas furnace, which was fueled by natural gas. Central furnaces were connected to duct systems that distribute hot air around the house. Use of a central air conditioner was assumed; the system uses indoor coils to drive cool air to the duct system of the house, and has an outdoor unit exhausting system. A single central air conditioner was sized to cool the complete living areas of all houses. Double pane, low-emission (low E) windows were used in the model for both locations, based on personal communication with state energy office officials in Georgia and Minnesota. Minimum code recommendations for insulation for Georgia and Minnesota were used in the DOE model, and were as follows:

Location	R-value per code specification
Roof (ceiling)	R-30 Georgia; R-49 Minnesota
Wall	R-13 Georgia; R-21 Minnesota
Crawl Space or Slab	R-8 Georgia; -R-20 Minnesota
Basement Walls	R-7 Georgia; -R11 Minnesota

Temperature assumptions for heating a cooling were:

Heating—daytime 68°F, nighttime 62°F
Cooling—daytime 78°F, nighttime 80°F

The reported costs of energy for Feb. 2002 were:

	Electricity ($/kWh)	Natural Gas ($/100 cubic foot)
Atlanta, GA	0.076	0.738
Minneapolis, MN	0.074	0.668

ENERGY USE RESULTS

For the unoccupied structures in Atlanta, the annual average energy consumption for the one-story wood-framed house was estimated at 61 GJ; for the concrete block structure, the annual average energy consumption was 63 GJ (Table 5). For the unoccupied wood-frame structure in

TABLE 5. *Unit energy cost, total energy consumption and total energy cost for virtual CORRIM houses (unoccupied).*

	Atlanta unit price $/unit	Mpls unit price $/unit	Wood-frame Atlanta $	Concrete-frame Atlanta $	Wood-frame Mpls $	Annual energy use: Wood-frame house Atlanta	Annual energy use: Concrete-frame house Atlanta	Annual energy use: Wood-frame house Mpls
				Annual Cost				
Heating (blower) electricity (kWh)*	0.076	0.074	19.68	19.76	32.41	259	260	438
Heating gas (Therm)*	0.783	0.668	433.00	448.66	644.62	553	573	965
Cooling electricity* (kWh)	0.076	0.074	38.22	38.15	15.32	503	502	207
Total energy (GJ)						61.042	63.246	104.090
Total annual cost $			490.91	506.57	692.35			
				Life Cost				
Present Value (PV) $ For 75-yr life @ 5%			9,565	9,870	13,490			
House cost $			135,000	135,000	168,000			
Structure cost $			74,000	74,000	92,000			
PV of energy cost % of structure cost			12.9	13.3	14.7			

* 1 Therm = 105.5 MJ (553 Therms = 58344.66 MJ): 1kWh = 3.5394MJ

Minneapolis the estimated annual average energy consumption was 104 GJ. The energy use from occupancy by a family of four (water heating, lighting etc.) adds about 20 GJ for each unit unrelated to these structural differences.

Although the buildings were designed to the same insulation standards at the component level, there are small differences between the wood-frame and concrete-frame completed structure, and the same would be expected for comparisons between wood and steel framing in Minneapolis.

The annual cost has been accumulated over a 75-year life with a 5% inflation adjusted discount rate to demonstrate an equivalent energy use cost over the life of the building. This cost can be more directly compared with the cost of construction for the structure.

GREENHOUSE GAS EMISSIONS FROM HEATING AND COOLING ENERGY USE

Greenhouse gas emissions from the energy used for heating and cooling of the unoccupied structure are based on local fuel sources and calculated using SimaPro©. The breakdown of electricity generation by fuel source was used as an input into the SimaPro model (Table 6). Annual emission outputs are shown in Table 7. Carbon dioxide (CO_2) emissions from the energy use were estimated at 3032 kg (6,685lbs) for the Atlanta house and 5174 kg (11,409 lbs) for the Minneapolis house.

HOUSE MAINTENANCE

House maintenance is generally considered to include those activities that will keep, restore, or improve all parts of a house, its services and surroundings, to a common acceptable standard (Mills 1980). Maintenance starts at the design stage of any housing project and continues periodically over the life of a building. Replacement of a material is often as a result of functional reasons at the end of a product's life, aesthetic reasons, or due to the replacement of another associated element in an assembly.

TABLE 6. *Breakdown of electricity generation by fuel source for Atlanta and Minneapolis.*

	Atlanta %	Minneapolis (%)
Petroleum	4.9	11.5
Natural gas	6.8	5.1
Hydroelectric	14.9	1.5
Nuclear	17.3	18.4
Coal	56.2	63.5

Source: DOE http://www.eia.doe.gov/cneaf/electricity/st_profiles/

TABLE 7. *Annual emission output data as generated by SimaPro for heating and cooling unoccupied house structures in Atlanta and Minneapolis.*

Unit: kg (lb)	Concrete-frame house Atlanta	Wood-frame house Atlanta	Wood-frame house Minneapolis
Particulates (PM10)	0.27 (0.59)	0.26 (0.57)	0.43 (0.94)
NOx	8.4 (18.5)	8.1 (17.9)	13.7 (30.3)
Non-methane VOC	0.24 (0.54)	0.23 (0.52)	0.41 (0.90)
SOx	2.85 (6.29)	2.79 (6.15)	4.17 (9.20)
CO	1.54 (3.40)	1.49 (3.28)	2.58 (5.68)
CO_2	3136 (6914)	3032 (6685)	5174 (11409)
Methane	0.09 (0.20)	0.09 (0.20)	0.15 (0.34)
Formaldehyde	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Phenol	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Solid	6.44 (14.21)	6.44 (14.21)	6.10 (13.46)

House maintenance has gained more attention in recent decades, and the cost associated with house maintenance has increased. A study by the U.S. Department of Commerce (1997) indicated that about 6.8 million dwelling units out of about 61 million in the U.S. (11%) had total or partial roof replacements costing at least $500 in the previous year. Similarly, nearly 2 millions homes (3%) had at least $500 of siding replaced or added in that time. In 1996, residential improvements and repairs expenditures were $114.3 billion (U.S. Department of Commerce 1997). Of the more than $114 billion in expenditures, 68% (77.7 billion) were spent on house improvements and 32% (36.6 billion) were spent on house repairs. From a house service and functionality perspective, house repairs are considered necessary; home improvements are considered optional as they are more directly related to increased amenities than for preventing replacement. While the annual repair expenditure may seem large, it represents less than 0.3% of the replacement value of the housing stock and less than 20% over a 75-year life.

There is a significant amount of embodied energy involved in the processes for replacing worn materials and maintenance of new materials (Adalberth 1997b). Analyzing the energy, greenhouse gas emission and costs associated with maintenance, while small compared to the constructed house, is a necessary component in a cradle-to-grave analysis of the performance of a house.

The National Association of Home Builders (NAHB 1996) conducted a comprehensive survey on the life-span of house components. Most house components can last the lifetime of the structure, such as framing components and hardwood flooring. Maintenance of the structure itself is largely related to roof maintenance (shingles) and siding including exterior paint. Vinyl siding is estimated to have a service life of 50 years. Many non-structural components have a less than total building life span. Carpeting has a life expectancy of only 11 years. The life of a major appliance is about 15 years (washer, dryer, refrigerator, dishwasher). Kitchen and vanity countertops are expected to last 20 years. Interior doors will last 30 years. Some exterior doors that are protected with an overhang are expected to last 80 years, while exterior doors that are unprotected and exposed average a life of 25 to 30 years.

Using the life-spans of components available in the NAHB survey, we estimated the total mass used in each component by multiplying the number of times the component was replaced by the unit mass of each material used and summed across the materials. The NAHB survey was from a broader sample than our virtual houses but appears to be representative of general maintenance although somewhat higher than estimates developed from Department of Commerce data. At worst we assume our derived estimates are conservatively high while recognizing that these data are not sufficient to make comparisons between the different framing designs analyzed in the other CORRIM reports. Since the maintenance of the structure and its relationship to construction are the focus of this report, we show a subtotal for those components related to the maintenance of just the structure by eliminating the non-structural materials (mainly carpets, interior paint, and appliances).

The mass of each material is multiplied by its respective embodied energy values and carbon emission numbers to arrive at the embodied energy needed for maintenance and the corresponding emissions. The total life-cycle energy consumption related to structural (primarily roofing and some other exterior) maintenance over a 75-year life expectancy was 110.5 GJ for the Atlanta location and 73.3 GJ for Minneapolis (Tables 8 and 9). The embodied energy in carpeting is the largest energy consumer but is non-structural and is excluded. The cost of maintaining the structure was estimated at 25% of the construction cost for Atlanta and 27% for Minneapolis, somewhat higher than the 20% we estimated from Department of Commerce data. The greenhouse gas emissions related to structural/exterior maintenance were 4,144 kg and

TABLE 8. *Energy use, greenhouse gas emission and cost of maintenance for a house in Atlanta, Georgia over a 75-year life.*

Name	Energy (GJ)	CO_2 (kg)	Cost ($)	Transportation energy (GJ)
Paint	39	2,014	3,310	0.27
Shingle	80	2,129	3,413	1.23
Wood	9	890	5,268	0.19
Carpet	116	3,783	6,995	0.14
Glass	4	189	459	0.03
Steel	50	5,003	14,170	0.27
Total	298	14,009	33,616	2.12
Per sq ft	0.138	6.51	15.61	0.00098
Subtotal structure	111	4,144	10,336	Included in structure subtotal

TABLE 9. *Energy use, greenhouse gas emission, and cost of maintenance for a house in Minneapolis, Minnesota over a 75-year life.*

Name	Energy (GJ)	CO_2 (kg)	Cost ($)	Transportation energy (GJ)
Paint	53	2,719	4,494	0.36
Vinyl	2	99	2,540	0.03
Shingle	33	872	1,459	0.50
Wood	11	1,066	5,731	0.23
Carpet	260	8.514	15,772	0.33
Glass	6	283	574	0.04
Steel	50	5,003	14,325	1.49
Total	415	18,556	44,896	2.98
Per sq ft	0.201	9.00	21.77	0.00048
Subtotal structure	73	3,468	11,977	Included in structure subtotal

3,468 kg, respectively for Atlanta and Minneapolis.

DECONSTRUCTION, DEMOLITION, TRANSPORTATION OF WASTE OR RECYCLING

The last stage of house life inventories includes the deconstruction, demolition, and transportation of waste to the landfills or to a recycling center. We did not consider the landfill itself, i.e. either the infrastructure or the long-term emissions from the waste in storage. Deconstruction is the process of selective dismantling or removal of materials from a building before large-scale demolition (National Association of Home Builders (NAHB) 1996). It is a common practice to remove valuable materials from the dwelling for recycling before complete demolition.

Deconstruction and demolition debris consists of the waste generated during deconstruction and demolition projects. This bulky and heavy debris usually covers a wide range of materials including wood (framing lumber, plywood, laminates, and OSB), concrete, metal (iron, stainless steel, copper), brick, plastics (vinyl siding, floor tiles, pipes), gypsum (drywall, sheetrock), roofing shingles and builders felt, and glass (doors, windows, and lights) (NAHB 1996).

The U.S. Environmental Protection Agency (EPA) estimated that 136 million tons of construction and demolition debris were generated in 1996 in the U.S. (Franklin Associates 1998). Most waste came from building demolition and renovation. The study reports that almost the same amount of wastes came equally from both residential and commercial building demolition. Among the construction debris materials, 43% was attributed to residential dwellings and 57% was attributed to nonresidential buildings. Forty-eight percent of the debris generated came from building demolitions, 44% from building renovation, and only 8% came from new construction activities.

The availability of recycling facilities to receive and process deconstruction and demolition debris has grown rapidly in the past few years (Leiter 1997). According to a survey by Leiter, the recycle rate of deconstruction and demolition debris is approaching 20 to 30% (i.e., 70–80% of deconstruction and demolition debris is landfilled). Franklin Associates note that this rate has been increasing annually (Franklin Associates 1998). It seems reasonable that this rate will continue to increase with technological advances and environmental pressures. Recycling the debris impacts required landfill availability and ultimately reduces greenhouse gas emission when compared to producing similar new materials from virgin materials. Materials are salvaged mostly from the growing practice of deconstruction—the selective disassembly of buildings to reuse and recycle materials, parts, or components. Many building components can be recycled. The materials most frequently recovered and recycled are concrete, asphalt, metals, and wood. Asphalt, concrete, and rubble are often recycled into new asphalt and concrete products (Franklin Associates 1998). Wood can be recycled into engineered-wood products that incorporate fiber or particle elements, as well as for mulch (Franklin Associates 1998). Metals, including steel, copper, and brass, are also valuable commodities to recycle. NAHB researchers measured the diversion rate of buildings due to recycling efforts. Diversion rate is simply the diversion of materials from final disposal in a landfill as opposed to recycling. The diversion rate for buildings can reach as high as 76% by weight and 70% by volume (Franklin Associates 1998).

A 2,000 square foot, two-story house was disassembled by the NAHB in a demonstration project. In this residential demolition project, on a weight basis, 42% of the debris is wood, 22% of the debris is concrete, 2% of the debris is metal, and miscellaneous materials make up 32% by weight (Franklin Associates 1998). NAHB reported that the total debris generated when a single-family house is demolished is about 111 pounds per square foot (Franklin Associates 1998).

DEMOLITION ENERGY AND EMISSIONS IMPLICATIONS

Current demolition practice requires energy usage in the deconstruction process and in transporting debris to a landfill. The two-story house located in Minneapolis contained 2,062 ft^2 of livable space with an unconditioned basement. The one-story house in Atlanta contained 2,153 ft^2 of living space. The energy and greenhouse gas emission were calculated for the demolition of the wood house in each location and for steel-frame alternative in Minneapolis and a concrete-frame alternative in Atlanta. The transportation distance for this study was arbitrarily selected as 20 miles for both house locations. The demolition materials were transported from the site via a diesel-powered dump truck. The energy for transportation is about 1.2 kWh/ton mile (Adalberth 1997a). The recycling rate was assumed to be 30% for the total of all materials (Franklin Associates 1998), and the corresponding burden of transportation for these materials is allocated to the user of these materials and not to the demolition process. According to the Franklin Associates data, 1 MJ of energy generated via the truck requires 0.0235 gallons of diesel fuel. At the same time, the truck generates about 0.0758 kg of CO_2 emissions.

It is assumed that there is no material gain or loss resulting from house maintenance and use. The raw materials used to build each house were considered the same as the material remaining to be deconstructed and demolished or construction waste that would be landfilled. The weight of the Minneapolis house raw materials was 86,000 kg with wood frame and 89,000 kg with steel frame, and the weight of the Atlanta house was 97,000 kg with wood frame and 106,000 kg with concrete frame. The energy required to move the debris to landfill is 5.7 GJ for the Minneapolis wood frame, 5.9 GJ for the steel frame, 6.5 GJ for the Atlanta wood frame, and 7.0 for the concrete frame (Table 10). Moving all of the raw materials used in the house is likely to double-count materials lost in processing and understate the small amount of materials used in maintenance; however, these estimates ranging from 2.8–3.2 GJ per 1000 sq. ft. are in general agreement with the 0.703 kwh/ft^2 (2.5 GJ/sq. Ft.) that is suggested by the U.S. Advisory Council on Historic Preservation (National Trust for Historic Preservation 1981). Emissions during demolition and transport to the landfill were estimated to be 435 kg of CO_2 for the Minneapolis wood-frame house, 448 kg for the steel-frame and 491 kg for the Atlanta wood-frame house and 533 for the concrete-frame (Table 11).

ISSUES BASED ON ENERGY USE, MAINTENANCE AND DEMOLITION COMPARISONS

As should be expected, the differences in energy use between the two Atlanta houses are small since the buildings were designed to comparable insulation standards even though different framing methods were used; hence the differences in energy use are not considered sig-

Table 10. *Raw materials transported to landfill.*

Raw material (kg)	Minneapolis house		Atlanta house	
	Steel-frame	Wood-frame	Concrete-frame	Wood-frame
Limestone	10,333	9,775	11,590	9,518
Clay & shale	2,496	2,496	2,916	2,269
Iron ore	6,614	1,019	667	507
Sand	1,256	1,403	776	748
Ash	48	48	59	45
Other	4,571	4,666	3,956	4,505
Gypsum	1,712	1,712	5,721	5,621
Semi-cementitous material	728	728	1,057	1,057
Course aggregate	24,687	24,687	35,997	35,871
Fine aggregate	24,437	24,437	32,848	26,427
Obsolete scrap steel	1,361	971	874	291
Wood fiber	6,595	12,993	8,191	9,811
Phenol form. resins	126	144	65	103
Metallurgical coal	2,864	407	254	189
Prompt scrap steel	764	602	545	178
Total material	88,592	86,088	105,516	97,140

Notes: Excludes water, natural gas, oil coal, but not metallurgical coal.

Table 11. *Energy used and CO_2 emissions from demolition.*

		Minneapolis house		Atlanta house	
		Steel-frame	Wood-frame	Concrete-frame	Wood-frame
Total material (kg)		88,592	86,088	105,516	97,140
Recycled materials (kg)*		26,578	25,826	31,655	29,142
Materials to landfill (kg)*		62,014	60,262	73,861	67,998
Energy for transportation	GJ	5.91	5.74	7.04	6.48
Diesel fuel (gal)		138.2	134.3	164.6	151.6
\$/gal					
Minneapolis	\$1.28				
Atlanta	\$1.26				
Diesel fuel cost (\$)		177	172	207	191
CO_2 k Kg/GJ	76				
CO_2 emissions kg		448	435	533	491

* Assuming 30% recycled

nificant. The difference between the Minneapolis wood-framed house and the Atlanta wood-framed house is more significant but largely reflects the climate difference, a regional difference, and is related to the different designs.

The objective of lowering energy use is given much attention because of the cumulative nature of perpetual use. While the use over one year is small relative to the energy used to create the house, over a 75-year life the reverse is true. The energy use for each home adds 200 – 400 thousand kilograms (metric tons) of CO_2 emissions over the life of a house providing a substantial opportunity for reducing emissions. However, increasing petroleum and gas prices in early 2005 suggests that all associated energy costs for the cradle-to-grave analysis may trend upward unless the efficiency of all processes can be improved in coming decades.

There are many programs being developed to reduce energy use. ENERGY STAR (www.energystar.gov) is a government-backed program helping businesses and individuals protect the environment through superior energy efficiency. With an emphasis on tight ducts, insulation, high performance windows, and energy-efficient heating and cooling systems, substantial reductions in energy use are possible relative to the typical building designs analyzed here. DOE/EPA has as an objective zero energy use. Systems that capture solar energy when used in conjunction with energy-efficient building designs have demonstrated that potential.

While the cost of the energy used in our typical houses is about 10 times the energy used in the structure, maintenance, and demolition, the present value of annual energy bills over the life of these virtual houses represents only 13–15% of the cost of the structure. As a consequence, there is resistance to spending large sums for better energy efficiency in order to lower the environmental burden. In effect, the low cost of energy is a major factor contributing to its use.

The energy in maintenance is about 1/10th the energy in the structure for the Minneapolis house and about 1/4th the energy in the Atlanta house. Furthermore these costs, like the cost of energy used in heating and cooling, are spread over the life of the house and represent a very small share of the cost of the structure.

The energy required for deconstruction and demolition is a very small share of total energy. While anticipated increases in recycling will lower these burdens even further in the future, the real value in recycling is the much lower burden associated with the recycled products in their new use. The recycled use of lumber appears more frequently in products that are not destined for structural use. CORRIM did not evaluate the use of recycled wood materials as product inputs for home construction except for the residuals that were being purchased by otherwise virgin mills, but this perhaps should be a topic for future research. The secondary data used by CORRIM for non-wood products were similarly dependent on the amount of recycled materials used in the production process for each specific material.

ACKNOWLEDGMENTS

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

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