Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House

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Summary

The life-cycle energy, greenhouse gas emissions, and costs of a contemporary 2,450 sq ft (228 m^3) U.S. residential home (the standard home, or SH) were evaluated to study opportunities for conserving energy throughout pre-use (materials production and construction), use (including maintenance and improvement), and demolition phases. Home construction and maintenance materials and appliances were inventoried totaling 306 metric tons. The use phase accounted for 91% of the total life-cycle energy consumption over a 50-year home life. A functionally equivalent energy-efficient house (EEH) was modeled that incorporated 11 energy efficiency strategies. These strategies led to a dramatic reduction in the EEH total life-cycle energy; 6,400 GJ for the EEH compared to 16,000 GJ for the SH. For energy-efficient homes, embodied energy of materials is important; pre-use energy accounted for 26% of life-cycle energy. The discounted (4%) life-cycle cost, consisting of mortgage, energy, maintenance, and improvement payments varied between \$426,700 and \$454,300 for a SH using four energy price forecast scenarios. In the case of the EEH, energy cost savings were offset by higher mortgage costs, resulting in total life-cycle cost between \$434,100 and \$443,200. Life-cycle greenhouse gas emissions were 1,010 metric tons CO_2 equivalent for an SH and 370 metric tons for an EEH.

Introduction

The design and construction of a new house is one of the most resource-intensive and economically significant decisions made by developers and consumers. In 1998, 1.62 million new homes were built in the United States, of which approximately 1.28 million were single detached dwellings and 0.34 million were multifamily units (NAHB 1999). Household energy consumption accounts for approximately 11% of the total U.S. energy consumption.[1] This translates into an average annual household expenditure of $1,282 for all major energy sources. The residential home construction industry accounts for 43% of all U.S. construction expenditures (Construction Review 1997). During 1992, single home construction accounted for $49.5 billion in total value of business (U.S. Department of Commerce 1995). Of this amount, the industry paid $16.7 billion for materials, components, and supplies and $15.0 billion for construction work subcontracted to others. Costs for selected power, fuels, and lubricants for the industry were $647 million. Gaining a better understanding of the specific material and energy flows and costs associated with an individual residential home requires the application of the tools of industrial ecology.

A comprehensive assessment of the resource intensity of a residential home requires a life-cycle perspective. The life cycle of a house encompasses materials production, construction, operation and maintenance, and demolition. Most research on energy consumption has focused on the use phase of a house. More recently, some attention has been directed toward recognizing the energy associated with the production of construction materials. In 1992, the American Institute of Architects (AIA) began to develop the Environmental Resource Guide for Architects, which featured environmental characterizations of a variety of building materials and components including steel, concrete, wood, glass, brick and mortar, plaster and lath, ceiling systems, and gypsum board systems (AIA 1992). These characterizations provide a qualitative description of the inputs, outputs, and environmental impacts associated with each material's life cycle. Energy requirements for the production of materials also are reported in Btu/lb or MJ/kg, but other quantitative metrics are limited. The National Institute of Standards and Technology has developed a software tool for selecting "environmentally and economically balanced building products." The BEES (Building for Environmental and Economic Sustainability) tool provides a more comprehensive life-cycle inventory analysis for a select group of construction materials (BEES 1998). BEES also provides life-cycle cost data on the initial investment, replacement, operation, maintenance and repair, and disposal of alternatives.

A few life-cycle energy analyses have focused on construction materials in residential dwellings.[2] Cole (1993) studied the embodied energy of alternative wall assemblies including 2 × 6 wall construction, increasing roof insulation, and increasing the amount of south-facing window area. He found that, although the embodied energy (materials production and construction) was increased in each case, the use-phase energy savings was more significant. A comparison of how embodied energy and heating energy vary among generic wall systems (Pierquet et al. 1998) found that straw bale wall systems provide the best combination of higher insulating value and lower embodied energy. Cole (1999) investigated energy and greenhouse gas emissions associated with the construction of alternative structural systems and determined the significance of on-site construction relative to total initial embodied energy associated with materials production and fabrication. He found that construction accounted for 6% to 16% of the total embodied energy for wood assemblies, 2% to 5% for steel assemblies, and 11% to 25% for concrete assemblies. Debnath and colleagues (1995) determined the energy requirements for major building materials of residential buildings in India. Energy intensity varied from 3 to 5 GJ/m^2 of floor area for single, double, and multistory dwellings. The studies by Cole (1999), Debnath and colleagues (1995), and Pierquet and colleagues (1998) indicate how alternative structural materials influence the life-cycle energy profile of a home.

This study addresses the primary life-cycle energy consumption, the corresponding release of greenhouse gases, and related costs for the construction and use of a typical detached home in the United States. Whereas previous life-cycle studies have focused on structural elements of a home, this investigation addresses the entire set of home subsystems and components, including wall systems, flooring, roof and ceiling systems, foundation and basement, doors and windows (fenestration systems), appliances and electrical systems, sanitary systems, and cabinetry. Life-cycle building costs have been analyzed previously (ASTM 1993), but this investigation links life-cycle energy and costs for a specific residential home. In addition, the use of effective design strategies to reduce life-cycle energy and greenhouse gas emissions are explored. Although the use phase currently dominates the life-cycle energy consumption, the importance of materials production and manufacturing/construction are expected to increase as designs become more energy-efficient. This research will demonstrate how eco-efficiency can influence the life-cycle energy profile.

The research consisted of three primary elements. First, four life-cycle metrics, mass, energy, global warming potential (GWP), and cost, were determined for a 2,450 sq ft home built in Ann Arbor, Michigan, referred to as the Standard Home (SH). Second, a portfolio of primary energy-reducing strategies were investigated to improve the SH. The new structure, referred to as the Energy-Efficient Home (EEH), incorporated the same floor plan and architectural style as the SH. Third, the same four life-cycle metrics were calculated for the EEH.

Methods

Life-cycle inventories for the SH and the EEH were calculated, using the mass of construction materials, processing, and manufacturing energy requirements; annual energy consumption; energy for demolition; and transportation energy requirements. The total life-cycle energy and GWP were determined from these model inputs. To ensure that the model reflected the impact of scheduled home improvement projects and maintenance, the frequency of these activities was estimated along with the mass and embodied energy of the materials used. Key features of the life-cycle energy and cost analyses follow. (A more detailed description of the modeling is provided elsewhere (Blanchard and Reppe 1998).) Although this study focuses on life-cycle energy and greenhouse gas emissions, future work should also consider other environmental aspects, including air and water pollutant emissions and solid waste generation, and their related consequences, including acidification, ozone depletion, smog formation, eutrophication, and human and ecological toxicity. Although many burdens and impacts are directly associated with energy consumption, many effects, nevertheless, originate from non-combustion–related processes.

System Definition

The home studied was a single-family, two-story residence with 2,450 ft^2 (228 m^2) of primary living area, an attached two-car garage (484 ft^2), and an unfinished basement (1,675 ft^2), recently built in a new Ann Arbor, Michigan subdivision and referred to as the Standard Home (SH). This home is shown in figure 1. The 2 × 4 frame construction is typical of the majority of homes built in the United States. The basis for this analysis is a 50-year service life.

Three options for defining the EEH were explored. Selecting a home with nearly identical functionality was important. Usable floor space and equivalent room function were stressed. The first option consisted of finding an energy-efficient passive solar home already built in the upper Midwest with a floor arrangement similar to that of the SH. A second alternative would have required the design of a new energy-efficient home incorporating passive solar heating, but ensuring functional equivalence. The third (and selected method) consisted of modeling the thermal characteristics of the SH and making incremental changes to achieve the desired energy-efficiency attributes. The selected method ensured near functional equivalency, an objective that was much more problematic for the first two methods.

Life-Cycle Phases

Figure 2 defines the key process phases of the home life cycle. The boundaries and major activities of each life-cycle stage are described here.

Figure 1 South elevation of the Princeton home designed and built by Guenther Building Co. in Ann Arbor, Michigan. Photo credit: Diane Swanbrow Yahouz, University of Michigan.

Pre-Use Phase (Materials Production and Construction)

Pre-use phase activities include raw materials extraction and processing, construction materials fabrication, transportation, and home construction. Major processes are elaborated here:

- Raw materials extraction includes processes such as mining, growing/harvesting, and drilling processes that yield iron ores, bauxite timber, and petroleum. Primary materials are then converted into engineered materials such as steel, aluminum, lumber, polystyrene, and nylon through steelmaking, refining/smelting, milling, and refining/polymerization processes.
- These materials are then fabricated and assembled into building components (e.g., roof trusses, windows, and exterior siding), furnishings (e.g., nylon carpeting), and appliances.
- Construction of the home at the building site also includes site earthwork.
- Transportation of materials from raw materials extraction to part fabrication, and then to the construction site is inventoried as well.

Use Phase

Use-phase activities were threefold: the supply of natural gas for home heating, the supply of electricity for air-conditioning and all appliances, and all activities related to home improvement and maintenance. The last activity includes the production and installation of maintenance and improvement components, such as shingles and carpeting. For consistency, the energy intensities (manufacturing) and GWP of all maintenance and improvement materials were the same as those for identical materials used in construction (pre-use phase).

End-of-Life Phase

This final phase consists of all activities related to the eventual demolition of the home and includes the energy to demolish the building, except for the concrete foundation, which was assumed to remain in place. It also includes transportation energy to deliver all materials to landfills or recycling facilities. This study did not account for potential energy expenditures or credits from future reuse or recycling of disposed end-of-life materials.

Omissions

Processes and systems not modeled in this study include:

- site location as it pertains to impacts on local ecosystems, personal transportation issues (e.g., commuting energy consumption can be very significant), and urban planning issues (e.g., roads and sewer infrastructure)
- energy and materials issues related to external house infrastructure (e.g., driveway concrete, landscaping, and irrigation systems)
- furniture (except built-in kitchen and bathroom cabinets) and curtains
- utility hookups including water and gas mains, and electrical power connections (e.g., excavation of mains, pipes, wiring, and meters) up to the point where they enter the building
- household supplies including food, clothing, entertainment equipment, and cleaning materials
- municipal services including the production and disposal/treatment of potable water and collection and disposal of municipal solid waste (consequently, methane emissions during biodegradation processes were not inventoried)
- worker transportation to manufacturing and construction sites
- changes over time in the mix of power plant fuels that can affect energy efficiency and greenhouse gas emissions
- changes over time in home electricity consumption, possibly resulting from newer generations of energy-efficient appliances or greater use of home office equipment

EEH Strategies

Numerous primary strategies for lowering life-cycle energy consumption were investigated. These strategies mainly focused on methods to reduce utility-supplied energy. The reduction of the embodied energy of construction materials and increased product durability were also addressed. Table 1 below shows the major strategies investigated.

Life-Cycle Mass Assessment

The life-cycle mass assessment evaluated the total mass of building materials required to construct and maintain the SH and EEH over the estimated 50-year service life. The SH mass was assessed from construction drawings, field measurements, and supplier's data. Many home construction materials and appliances (e.g., windows, carpet, and kitchen appliances) consist of a combination of multiple primary materials. Where possible, the mass of each component material was determined by direct measurement or by multiplying measured dimensions (volume) by material density. Home improvement and maintenance materials were also determined.

The greatest difficulty in determining the mass composition of individual components occurred with electrical appliances. Suppliers do not normally provide such information, and without the use of destructive testing, accurate determination was not possible. Consequently, a study of a kitchen range (Jungbluth 1997) was used as a surrogate to establish the material composition for all other appliances. A more recent paper (Deumling 1999) provides composition data on refrigerators. Deumling's work could lead to refinements on total composition and mass of appliances. Using composition data for steel, plastics, copper, etc., the material composition of all other electric appliances was estimated using shipping weights provided by local distributors. Although this method introduces error, it was rather negligible when compared with the overall mass of the house system. Appliance mass accounts for less than 1.5% of the total life-cycle mass of the home. Over 90% of the total mass of each appliance studied was steel. Thus, the error in estimating the mass of nonsteel materials for all other appliances is expected to be less than 0.15% of the life-cycle mass of the home. The same procedures were used to determine overall life-cycle EEH mass and material composition.

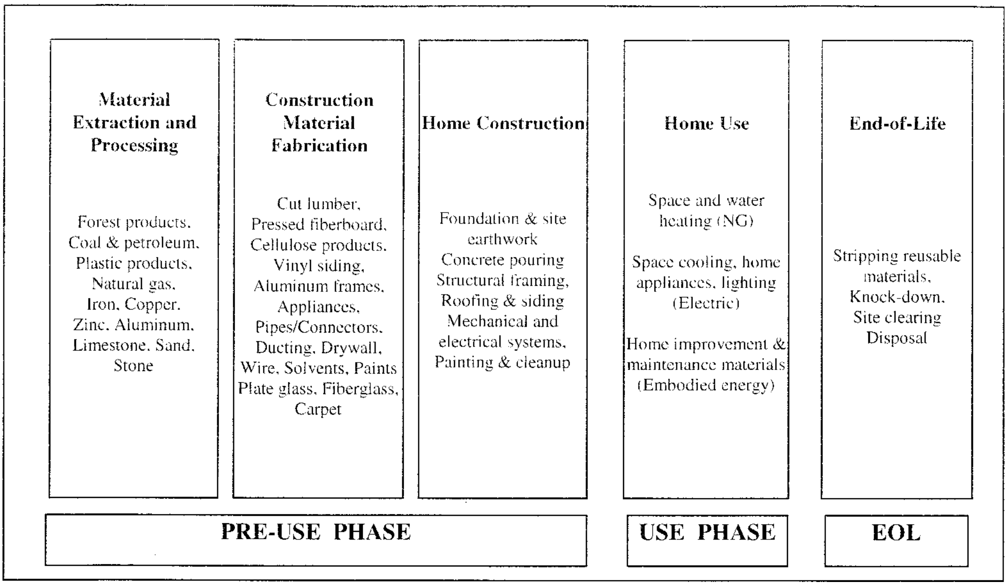

Figure 2 Life-cycle stages of the residential home system.

In order to adequately account for the additional energy and materials requirements caused by manufacturing and construction losses, efficiency factors were employed. For the manufacturing of building products and appliances, a 95% efficiency factor (by mass) was assumed for all materials, unless an efficiency factor was otherwise specified directly in the inventory database [e.g., secondary aluminum (88%), ceramic tiles (98%), mortar for ceramic tiles (88%) , and vinyl (99.6%), from the DEAM Database (Ecobalance 1998)]. This 95% efficiency factor reflects waste generated during the various manufacturing processes such as steel stamping, plastics molding, machining of metal parts, or gypsum board manufacturing. An additional efficiency factor of 95% was used to account for construction losses, which are losses of materials on site due to cutting and fitting (i.e., roof underlayment, copper wire, and concrete).

Life-Cycle Energy Assessment

Pre-Use Phase Energy

The life-cycle energy analysis was conducted in accordance with U.S. EPA (1993), SETAC (1993), and ISO 14041 methodology (ISO 1998). Energy is measured as the primary energy associated with the consumption of energy sources such as coal, natural gas, fuel oil, and gasoline. The primary energy is calculated from the energy content of these resources, expressed as a higher heating value (HHV). For example, the HHV of natural gas is 52 MJ/kg (Ecobalance 1998). In addition to the energy content (or combustion energy), the energy for extraction and processing of these resources is also inventoried. In the case of natural gas this value is 1.6 MJ/kg (Ecobalance 1998). Consequently, the total fuel-cycle energy for consumption of natural gas is 53.6 MJ/kg. Energy sources are used as material feedstocks in addition to their primary use as process and transportation fuels. For example, the total primary energy for materials production of HDPE is 81 MJ/kg; this consists of feedstock energy of 64 MJ/kg and process fuels of 17 MJ/kg.

The accounting convention for feedstock energy associated with wood products is controversial. The U.S. EPA suggested that, because wood is not currently a major fuel energy source, the energy content of wood products would be neglected (U.S. EPA 1993). The energy content of the wood, which is renewable, is 17.7 MJ/kg (Scientific Certification Systems 1995). The process energy, including kiln drying, is 10.7 MJ/kg; this consists of 5.8 MJ/kg of renewable en-

Table 1 Energy-efficient strategies examined for EEH

No.	*Energy-efficient strategy*	*Physical description*	
	EMPLOYED IN EEH	*SH (as built)*	*EEH*
1	Increased wall insulation	Typical 2 × 4 wall construction, fiberglass insulation (R-15) [1]	Double 2 × 4 Saskatchewan wall, cellulose insulation (R-35)
2	Increased ceiling insulation	Fiberglass (R-23)	Blown-in cellulose (R-49)
3	Reduced building air infiltration	Typical seal (ELA = 153 in^2) [2]	Tight seal (ELA = 20 in^2)
4	Wood basement	Bare concrete basement walls (R-12)	Wood basement walls, cellulose insulation (R-39)
5	High-performance windows	Double glazing	Double glazing, LowE coatings with argon fill
6	Energy-efficient appliances	Dishwasher, oven, clothes dryer (electric)	Dishwasher, oven, clothes dryer run on NG. Energy reductions between 27% and 74%
		All other appliances	Energy-efficient models for refrigerator/freezer, A/C unit
7	All energy-efficient fluorescent lighting	100% incandescent lamps	100% fluorescent lamps
8	Building integrated shading	South eaves extend 0–2 feet	South eaves extend 3–4 feet
9	Waste hot water heat recovery	Not used	Copper waste water heat exchanger coil; decreases NG use by 40%
10	Air-to-air heat exchanger	Not used	Decreases NG space heating consumption by 75%
11	Roof shingles made of recycled materials	Standard asphalt shingle	Composite recycled plastic and wood
	NOT EMPLOYED IN EEH (but investigated)		
13	Replacing external vinyl siding [3]	Vinyl siding	Wood siding
14	Added thermal mass [4]	OSB flooring	4" concrete layer on first floor
15	Additional windows [5]	Glazing area 337 ft^2	Glazing area 490 ft^2
16	Use alternative floor covering	Carpet	Cork or hard wood flooring
17	Use of landscaping for cooling [6]	No trees	Trees for shading

[1] The R value is a measure of resistance to heat flow, with units hr-ft^2-°F/Btu.

[2] ELA stands for Effective Leakage Area.

[3] Wood siding was not employed because the increased maintenance (painting) neutralized the original lower pre–use energy of wood.

[4] Thermal mass was rejected because the increased weight (floor) required costly structural support that had a very low payback.

[5] Additional glazing area had a poor payback due to the nature of Michigan's annual solar gain.

[6] Landscaping was not part of the original scope and therefore was not included as a strategy.

ergy (burned tree limbs) and 4.9 MJ/kg of nonrenewable energy. In this analysis both renewable and nonrenewable energy components were inventoried. Consequently, the total energy for wood, including the feedstock energy (17.7 MJ/kg), is 28.5 MJ/kg.

Table 2 provides a list of all materials inventoried in SH and EEH and gives both the primary energy and global warming potential per unit of mass. The same matrix was used in determining EEH pre-use phase primary energy.

Use-Phase Energy

Natural gas SH annual energy consumption for heating was modeled using "Energy-10," an energy-modeling software program by the Passive Solar Industries Council (PSIC 1998). Program inputs include building dimensions and layout, thermal performance of the building envelope, HVAC characteristics, number/type/orientation of windows, building location/latitude, and electrical usage (to calculate internal heat gains).

National Renewable Energy Lab (NREL) weather data for Detroit was used to simulate annual temperature, insolation, and wind characteristics for Ann Arbor, Michigan. Internal heat gains from waste heat released from electrical appliances, lighting, hot water, and human occupancy (adults radiate approximately 100 Watt/person) were estimated. These heat gains reduce the amount of natural gas heating required in a home. Other factors that determine annual natural gas heating requirements include thermostat temperature settings, effective air leakage of the building envelope, and internal thermal mass. Using these parameters, Energy-10 calculates the total heating requirements (combustion energy) for one year.

Energy-10 estimated the annual SH natural gas consumption for heating to be 2,518 MJ (not including precombustion energy). To validate the accuracy of the program output, this value was compared with the average annual space heating requirement for U.S. midwest homes (average size 1,880 ft^2), which is 2,035 MJ (DOE 1995). Adjusting this value for SH floor area gives an annual heating value of 2,643 MJ, which is only 5% higher than the value determined by Energy-10.

Electricity Table 3 provides a list of electrical appliances used in the SH and selected for use in the EEH. These electricity consumption values are converted to total primary energy for electricity generation using an electricity production efficiency of 0.32 for the U.S. grid. This analysis assumes a constant production efficiency for both the SH and the EEH over the 50-year service life. Increases in the electricity production efficiency over time would reduce the magnitude of the difference in total primary energy between the SH and the EEH. Electricity conservation with the EEH could make renewable technologies, such as photovoltaics, more feasible. The implications of grid fuel-mix changes caused by marginal reductions in electricity demand as more EEHs are built were not investigated.

Electrical energy consumption was determined independently from Energy-10. The finalized electricity consumption data for the SH and the EEH were input into Energy-10 to allow for the accounting of the electrical waste heat loads.

Home improvements and maintenance A schedule was developed to determine the contributions of maintenance and home improvements to life-cycle energy consumption and GWP. The schedule accounts for those regular and unplanned maintenance activities needed to keep the home in good repair (e.g., repair of broken windows, changing of light bulbs), as well as major home improvements (e.g., replacement of siding, carpet, and roofing). Table 4 provides an overview of home maintenance and improvement assumptions, based on a home life of 50 years. Replacement rate data were collected from interviews with contractors, suppliers, and distributors.

Life-Cycle GWP Assessment

Determining life-cycle global warming potential was similar to the assessment of life-cycle energy. Greenhouse gas emissions associated with materials production and fabrication stages were determined by multiplying the emission factors in kg of CO_2 equivalents per kg of construction materials by the life-cycle mass inputs of each material (table 3). Greenhouse gas emissions associated with transportation fuels were also inventoried. Use-phase greenhouse gas

Table 2 Primary energy and GWP (20 year time horizon) coefficients[1]

Material	*Fabrication process*	*Primary energy (MJ/kg)* [2]	*GWP (kg CO_2 equiv./kg)*
acrylonitrile butadiene styrene (ABS)	[3]	112.2	3.5
aluminum, primary	[3]	207.8	10.0
argon	[3]	7.0	0.5
asphalt	[3]	51.0	0.4
asphalt shingle	shingle manufacturing	14.6	0.3
brass	[3]	99.9	[4]
cellulose	shredding, treating	3.2	0.2
ceramic [5]	mixing, firing	20.5	1.4
concrete	mixing	1.6	0.2
copper	extrusion	48.7	6.1
facing brick	firing	4.5	0.3
felt underlayment #15	general manufacturing	41.2	0.4
fiberglass	extrusion	24.5	1.5
formaldehyde resin	[3]	72.1	1.3
glass	forming	18.4	1.3
gravel	crushing	0.9	0.1
gypsum	[3]	3.8	[4]
HCFC 22	[3]	33.7	1.3
high-density polyethylene (HDPE)	extrusion	87.5	3.0
latex [5]	[3]	70.8	0.8
mineral spirits	[3]	5.5	0.4
mortar	mixing	1.9	0.1
oriented-strand board	[3]	3.2	0.7
polyamide resin (PA)	[3]	137.6	4.5
paper	[3]	16.2	1.2
particleboard	[3]	3.9	0.2
polyethylene (PE)	extrusion	87.1	3.0
plastic-wood composite [6]	shredding, molding	5.1	0.2
plywood	cutting, pressing	8.3	0.1
polymethylmethacrylate (PMMA)	[3]	207.3	14.7
polyisocyanurate	[3]	70.6	[4]
polypropylene (PP)	[3]	83.8	2.6
polystyrene (PS)	[3]	100.3	2.1
polyvinyl chloride (PVC)	[3]	77.4	2.9
rubber [7]	[3]	150.4	3.0
styrene butadiene rubber (SBR) [7]	[3]	70.8	0.8
silver	[3]	128.2	[4]
stainless steel	[3]	16.3	1.2
steel, cold rolled	[3]	28.8	2.1
steel	extruding, galvanizing	37.3	3.2
vinyl	extrusion	11.8	0.5
water-based paint	[3]	77.6	[4]
wood	milling	28.5	0.8

[1] Production energy includes pre-use phase resource extraction and production, fabrication/assembly, and transportation.

[2] All parameters based on Ecobalance data unless otherwise noted.

[3] Fabrication primary energy not included.

[4] Data not available.

[5] For materials where specific primary energy and GWP data were not available, similar materials with complete datasets were substituted (for ceramic bathroom sinks, "ceramic tile" data were used; for latex in carpet and paint, "SBR" was used).

[6] According to the manufacturer, this consists of 50% postindustrial vinyl, 50% recycled postindustrial wood (Eco-shake).

[7] Other values for SBR and rubber were found: rubber 67.7 MJ/kg (Sullivan et al. 1995); SBR 145.1 MJ/kg (Boustead et al. 1979).

Table 3 SH and EEH electrical and gas appliances

		SH			*EEH*		
NO.	*APPLIANCE*	*kWh/yr*	*Energy source*	*Description*	*kWh/yr*	*Energy source*	*Description*
1	Refrigerator	762	elec.	*Whirlpool ET22PK 21.7 ft³*	555	elec.	*Whirlpool ET21D 20.7 ft³*
2	Garbage disposal	10	elec.	*Hushmaster 1/3 hp*	0	elec.	*None (composting)*
3	Sump pump	40	elec.	*Wayne 1/2 hp*	40	elec.	*Wayne 1/2 hp*
4	Furnace fan	404	elec.	*EIA 1995*	54	elec.	*Calculated* (1)
5	Water heater	7,854	n. gas	*Smith 32,000 Btu/hr*	4,712	n. gas	*Calculated* (2)
6	Range	458	elec.	*Whirlpool*	458	n. gas	*Whirlpool*
7	Range hood	10	elec.	*Whirlpool*	10	elec.	*Whirlpool*
8	A/C central unit	1,580	elec.	*Trane XE 1000 HE*	734	elec.	*Energy-10 model*
9	Dishwasher	700	elec.	*Whirlpool GDS-500*	377	elec.	*Asko 1385*
10	Clothes washer	924	elec.	*ACEEE 1998, p. 206 (3)*	241	elec.	*Asko 12505*
11	Clothes dryer	875	elec.	*EIA 1995*	875	n. gas	(4)
12	Indoor/outdoor lighting	940	elec.	*All incandescent*	254	elec.	*All fluorescent*
13	TV	250	elec.	*ACEEE 1998, p. 239*	250	elec.	*ACEEE 1998, p. 239*
14	Microwave oven	191	elec.	*EIA 1995*	191	elec.	*EIA 1995*
15	Dehumidifier	370	elec.	*EIA 1995*	0	elec.	(5)
16	Computer	77	elec.	*EIA 1995*	77	elec.	*EIA 1995*
17	All other plug loads	960	elec.	*EIA 1995*	960	elec.	*EIA 1995*
18	Heat exchanger fan	0	elec.	*none*	80	elec.	*ACEEE 1998, p. 239*

(1) Reflects an 88% reduction from SH, based on reduced furnace air flow rate due to reduced furnace size.

(2) Reflects a 40% demand reduction due to the use of waste water heat recovery.

(3) See Wilson and Morril (1998).

(4) Reflects the assumption of an unchanged heat demand for drying, and simply substituting electricity for natural gas.

(5) Reflects the assumption that no dehumidifier would be used.

emissions were calculated using emission factors for natural gas use (full fuel cycle) and for averages of the U.S. electrical grid.

The Life-Cycle Cost Assessment

The undiscounted life-cycle cost of the SH was determined by accumulating home finance payments (down and mortgage payments), annual utility payments, and scheduled maintenance and improvement costs for a period of 50 years. This represents all costs borne by the homeowner, excluding items outside the study scope (e.g., furniture, landscaping, home insurance, and property taxes). A mortgage down payment of 15% of the home purchase value was assumed. Monthly mortgage payments were determined using an annual interest rate of 7% over a mortgage period of 30 years, payable on the first of the month. No refinancing was assumed, and these costs did not vary during the mortgage period. This life-cycle cost analysis did not account for externality costs (e.g., damage costs from air pollutant emissions, such as sulfur dioxide, associated with electricity generation).

The market value of EEH was calculated as follows:

1. the market value of the SH ($240,000) was divided by the developer's profit, assumed to be 20%, and then the cost of the property, $55,000, was subtracted. This gives the construction cost of the SH;
2. materials and labor unit rates and contractor overheads for Michigan were determined (Kiley et al. 1996), and cost data

Table 4 Schedule of home improvement activities

Activity	*Years occurring after construction*
1st and 2nd floor internal repainting	10, 20, 30, 40
Exterior repainting	10, 20, 30, 40
PVC siding replacement	25 (1)
New roofing (asphalt shingles) for SH	20, 40 (2)
Inside walls and door repair	25
New refrigerator	15, 30, 45
New garbage disposal	15, 30, 45
New sump pump	15, 30, 45
New water heater	15, 30, 45
New range	15, 30, 45
New range hood	25
New A/C central unit	20, 40
New dishwasher	20, 40
New clothes washer	15, 30, 45
New clothes drier	15, 30, 45
Kitchen and bathroom cabinet replacement	25
Changing of all incandescent light bulbs for SH	Every 3 years
Changing of all compact fluorescent light bulbs for EEH	Every 5 years
Replacement of all vinyl floor tiles in house	20, 40
Replacement carpet	Every 8 years (3)
Replacement of all windows (includes breakage)	25

(1) Per phone conversation with Steve Cook, Astro Building Products, Ann Arbor, Michigan, 22 June, 1998.

(2) DEAM database, Ecobilan.

(3) Per phone conversation with Rob Glancy, Interface Inc., 22 June, 1998.

Note: All other values estimated by the authors.

were adjusted (if more than one year old) using a 3% annual escalation rate;

3. SH systems to be replaced by more energy-efficient systems were determined, and the material quantities and installed cost were estimated and subtracted from the construction cost of the SH determined in step 1;
4. the material quantities and installed cost of the new EEH systems were determined and added to the cost in step 3;
5. the cost of the property, and then the developer's profit, from step 1, were added back. EEH annual mortgage costs were then determined using the same financial parameters for SH.

Yearly home maintenance and improvement costs for the SH and the EEH were based on the replacement timetable given in table 4.

The year-one annual energy cost for the SH was determined by first calculating annual natural gas usage (from Energy-10) and electricity usage, based on annual consumption data for home appliances (table 2), and then multiplying by Ann Arbor utility rates of $0.462/therm and $0.08/kWh (Reppe 1998a). Year-one annual energy cost for the EEH was determined by using the same approach.

Utility rates vary over time, depending on numerous economic and political factors, and are difficult to forecast. To estimate future natural gas and electricity rates for the next 50 years, four energy rate scenarios were used. The scenarios are summarized in table 5.

Results

Life-Cycle Mass

The total life-cycle mass of all construction and maintenance/improvement materials of the SH, consumed during a service life of 50 years, was 306 tonnes. The total mass of materials required to construct the house was 293 tonnes, and 13.4

Table 5 Energy escalation scenarios

Scenario	*Description of scenario*	*Source*
1 (constant)	Natural gas rates remain constant for 50 years. Electricity rates remain constant for 50 years.	Base case
2 (declining)	Natural gas rates decline 1.1%/yr from 1998 until 2010, and rise thereafter by 0.03%/yr until 2020. Prices do not change from 2021 to 2048. Electricity rates decline 1%/yr from 1998 until 2010, and decline an additional 0.58%/yr until 2020. They do not change from 2021 to 2048.	EIA/DOE (1997)
3 (rising)	Natural gas and electricity rates escalate 4.2%/yr from 1998 until 2010. This gives an increase of 63% by 2010. Annual escalation between 2011 and 2048 is 1%.	Wefa Inc.[1]
4 (German)	The cost of energy to home owners in Germany was assumed. Natural gas costs $0.721/therm in 1998 and increases annually 1% until 2048. Electricity costs $0.127/kWh in 1998 and increases annually 1% until 2048.	Reppe (1998b)

[1] See U. S. DOE/EIA (1997, 78).

Note: Escalation rates are real (excludes inflation).

tonnes were required for maintenance and improvement materials. Table 6 provides a summary of the 30 materials with the greatest mass in both the SH and the EEH, and shows their percentage relative to total life-cycle mass. The greatest mass is contributed by concrete and gravel. Both of these materials are associated with the building foundation. As expected for a wood-framed home, lumber has the next greatest mass intensity, followed by gypsum for drywalls, and oriented strand board (OSB) for wall sheathing and floors.

Changes made to the EEH altered the distribution and quantities of many materials. The use of a 2 × 8 wood frame/plywood basement greatly reduced the amount of concrete in the EEH, but increased the amount of gravel, which was necessary to provide adequate drainage. The amount of wood used in the EEH also increased as a result of the double 2 × 4 (Saskatchewan) wall system. The EEH substituted cellulose insulation for fiberglass insulation. OSB usage increased in the EEH, replacing the partial polyisocyanurate exterior wall sheathing used in the SH. The design changes resulted in a life-cycle mass of 325 tonnes for the EEH. Of this, the EEH pre-use mass was 318 tonnes, and maintenance and home improvement mass was 7.5 tonnes. Maintenance and improvement mass was reduced by 5.9 tonnes compared with the SH. This reduction in life-cycle mass of replacement materials is due largely to the substitution of composite wood-plastic roof shingles (Re-New Wood, 1999) that have a 50-year warranty for the asphalt shingles (replaced every 20 years) used in the SH.

Life-Cycle Energy

Total life-cycle energy consumption of the SH was determined to be 16,000 GJ (equivalent to 2,614 barrels of crude oil). In contrast, the total life-cycle energy of the EEH was 6,400 GJ (equivalent to 1,046 barrels of oil). A 60% reduction in life-cycle energy was achieved with the EEH model. The total life-cycle energy per square meter of living area on an annual basis is 390 $kWh/m^2 \cdot y$ for SH and 156 $kWh/m^2 \cdot y$ for EEH. Figure 3 provides life-cycle energy profiles of each home. The use phase accounts for 91% and 74% of the total life-cycle energy for the SH and the EEH, respectively. The demolition energy is relatively insignificant compared to other life-cycle phases.

Figure 4 shows the 15 most energy-intensive materials in the SH and the EEH. In both houses, wood consumes the most energy, fol-

Table 6 30 most abundant life-cycle materials in SH and EEH

		Mass of SH materials		*Mass of EEH materials*	
No.	*Material*	*(kg)*	*(% of total)*	*(kg)*	*(% of total)*
1	gravel	62,811	20.53%	155,683	47.81%
2	concrete	181,042	59.18%	102,832	31.58%
3	lumber	15,324	5.01%	22,347	6.86%
4	gypsum	13,368	4.37%	13,694	4.21%
5	OSB board	6,733	2.20%	7,868	2.42%
6	asphalt shingles	8,426	2.75%	0	0.00%
7	cellulose	0	0.00%	3,934	1.21%
8	steel	3,901	1.28%	3,797	1.17%
9	PA	2,207	0.72%	2,207	0.68%
10	plywood	0	0.00%	1,807	0.55%
11	particleboard	1,753	0.57%	1,753	0.54%
12	PVC	1,705	0.56%	1,705	0.52%
13	vinyl	1,510	0.49%	1,593	0.49%
14	latex	1,212	0.40%	1,212	0.37%
15	glass	1,012	0.33%	1,063	0.33%
16	ceramic	835	0.27%	832	0.26%
17	water-based paint	745	0.24%	746	0.23%
18	facing brick	475	0.16%	475	0.15%
19	fiberglass	744	0.24%	14	0.00%
20	plastic-wood shingles	0	0.00%	474	0.15%
21	felt #15	411	0.13%	0	0.00%
22	mortar	436	0.14%	436	0.13%
23	PP	379	0.12%	379	0.12%
24	copper	257	0.08%	253	0.08%
25	HDPE	84	0.03%	90	0.03%
26	paper	89	0.03%	90	0.03%
27	SBR	84	0.03%	84	0.03%
28	PMMA	50	0.02%	50	0.02%
29	polyisocyanurate	64	0.02%	0	0.00%
30	PS	49	0.02%	45	0.01%
31	all others	215	0.07%	146	0.04%
	TOTAL	305,920		325,610	

lowed by polyamide (PA), the main component in carpet. The life-cycle energy results were dependent on the convention used to measure primary energy. The methodology developed by U.S. EPA for life-cycle inventory analysis indicated that the embodied energy in wood would not be counted as primary energy (U.S. EPA 1993) because energy associated with the photosynthesis of wood is renewable. Using this convention the life-cycle pre-use energy is lowered significantly from 1,435 GJ to 942 GJ for the SH, and from 1,630 GJ to 905 GJ for the EEH (convention adopted by Blanchard and Reppe 1998).

The large energy contribution by PA is due to the high embodied energy of PA, the large amount of carpet used (in all rooms except the bathrooms, kitchen, and basement), and the high replacement rate of carpet (every eight years). Although concrete and gravel made up the largest mass of the SH and the EEH, their life-cycle energy contributions were much less significant. This results from relatively low material production/fabrication energy intensities for concrete and gravel of 1.6 MJ/kg and 0.9 MJ/kg, respectively.

Alternative flooring materials with lower embodied energy were explored. Cork tiling and

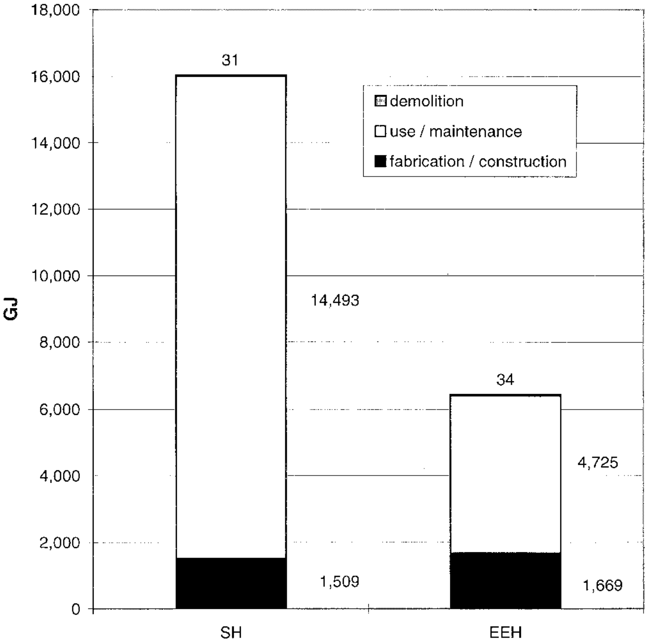

Figure 3 Life-cycle energy consumption for SH and EEH.

parquet wood flooring have a lower embodied energy per unit area. These alternatives were disqualified, however, due to their higher costs. The initial installation cost of a cork floor covering, replacing all carpet and tiles on the first and second floors, would be 2.4 times higher than that for carpet. Over the full life cycle of the house, which includes installation and maintenance, however, cork would be approximately 10% less expensive (discounting at 4%). With proper care (sanding and application of two layers of lacquer every 10 years) cork does not need to be replaced over the 50-year life of the home (National Cork 1998). Other alternative flooring materials were not investigated.

Figure 5 provides a breakdown of the use-phase energy for the SH and the EEH. A significant reduction in natural gas consumption is evident. Natural gas and electricity consumption by major home systems and components are analyzed in the following sections.

Annual Natural Gas Consumption

Figure 6 shows the annual natural gas primary energy consumption (precombustion and combustion energy) for both the SH and the EEH. The dramatic decrease in natural gas use is due to the greatly improved thermal envelope of the EEH, a much more efficient HVAC system, which led to a decrease of 91.8% for space heating, and a hot water heat-recovery unit, which reduced water heating by 40%. EEH also employed a natural gas stove and dryer. As a result of the various EEH strategies employed, annual natural gas use is only 21% of that in the SH. This was done with off-the-shelf technology.

Annual Electricity Consumption

Annual primary energy used to generate electricity for the SH and the EEH are also depicted in figure 6. EEH electricity use for cooling is approximately a third of that for the SH. This is due to an improved thermal envelope, a more efficient HVAC system, and an air-conditioning unit with a higher seasonal energy efficiency ratio (SEER) of 13, compared to a SEER of 10 for the SH. The SH used an electric stove and dryer. EEH electricity use for all other appliances is almost half that for the SH, due to more efficient lighting (all compact fluorescent lights) and appliances. EEH annual electricity use was reduced 58%.

Embodied Energy by Building System

Construction and maintenance/improvement materials were grouped into eight building subsystems so that the embodied energy could be

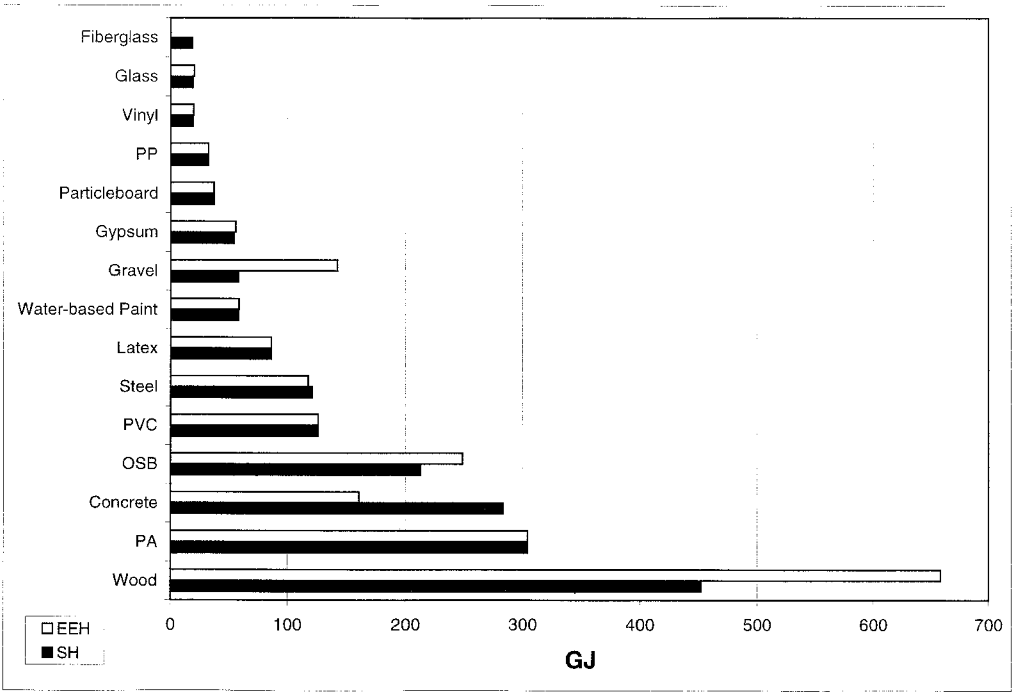

Figure 4 Materials production and fabrication energy of the top 15 materials for SH and EEH (includes maintenance materials and transportation energy for the total life cycle).

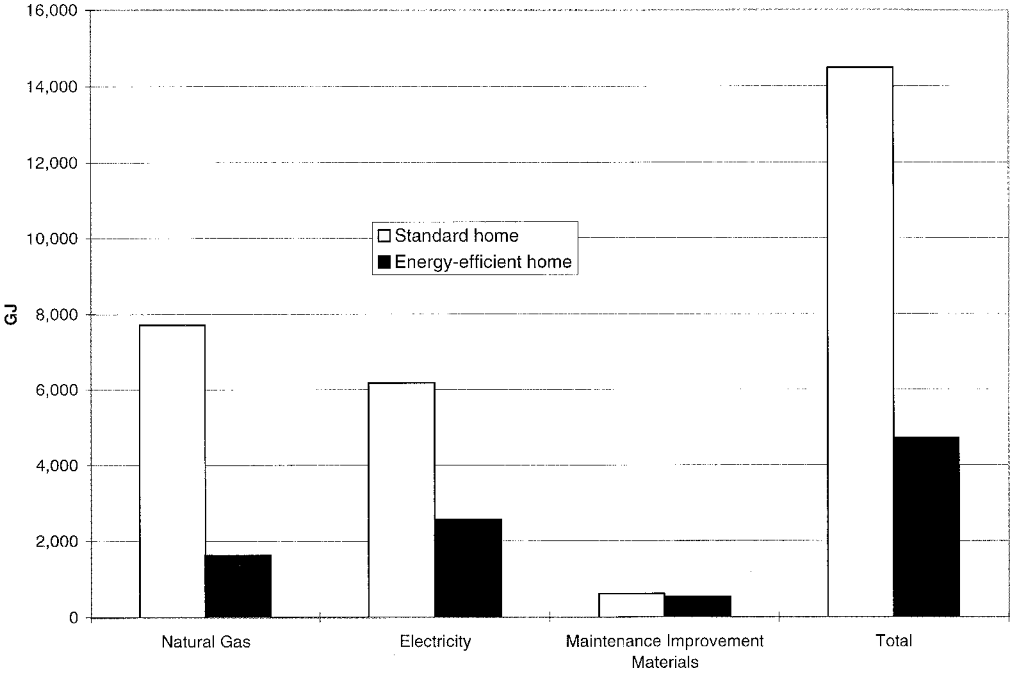

Figure 5 Use-phase energy consumption for SH and EEH over a 50-year life (total fuel-cycle energy for natural gas and electricity).

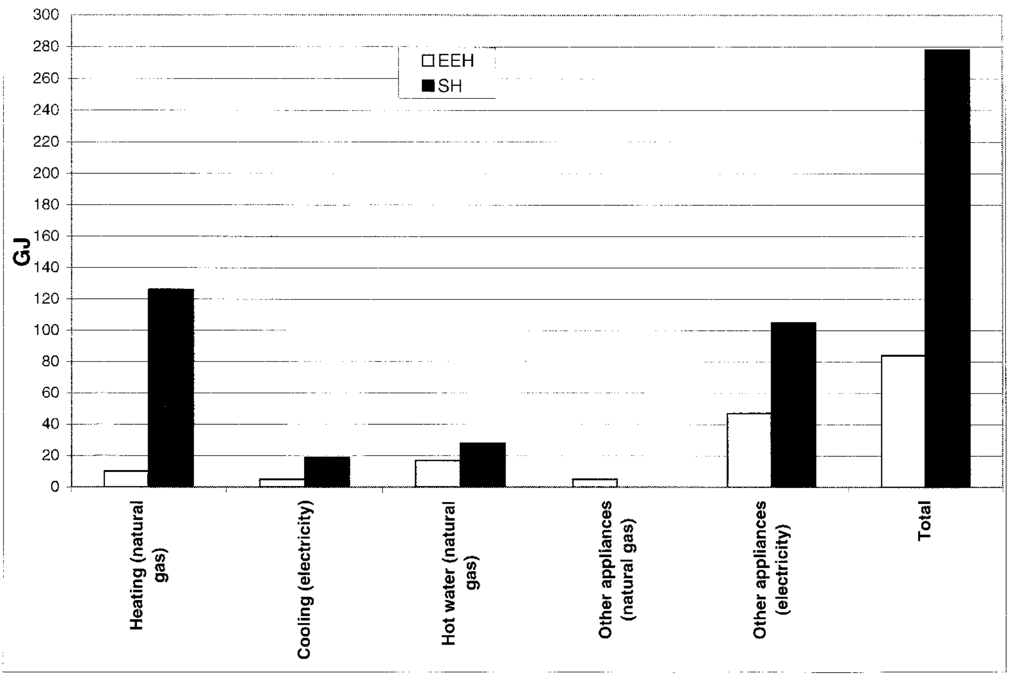

Figure 6 Annual natural gas energy use and the energy consumption in electricity generation for SH and EEH (total fuel cycle precombustion and combustion energy).

computed for each building subsystem. Figure 7 illustrates this distribution. In both houses, carpeting and foundation/basement are the two highest energy consumers, with walls being the third highest. Asphalt shingles in the SH roof, which were replaced three times over the 50-year service life, were the fourth largest. Materials production and construction phases accounted for 9% of the total life-cycle energy, which is dominated by the use phase. The pre-use phase contribution increases to 26% for the EEH, due mainly to the large savings in use-phase energy consumption. The total pre-use energy increased slightly for the EEH relative to the SH, primarily as a result of the substitution of wood for the concrete used in the basement, and additional wood used in the double 2 × 4 walls. A significant fraction of the material production energy for wood, however, is renewable.

Energy Crossover Analysis

A crossover analysis was conducted to determine how long it takes for the additional embodied energy invested in EEH to be recovered.[3] This was determined by dividing the difference in pre-use energy between the SH and the EEH (195 GJ) by the difference in the annual use-phase energy for the SH and the EEH (194 GJ/yr). This calculation showed that the EEH would recover the additional "up-front" energy in slightly more than one year.

Life-Cycle Global Warming Potential

As would be expected, the ratio of life-cycle GWP between both houses closely correlates with life-cycle energy. The SH GWP was determined to be 1,010 tons of CO_2 equivalents. The EEH GWP was reduced by 63%, to 370 tonnes. Figure 8 provides a comparison of life-cycle GWP for the 15 most significant materials in both the SH and the EEH. Concrete, timber, gravel, and steel are the four largest contributors. GWP for concrete in the EEH is nearly half of that in the SH, due to the use of a wood basement in the EEH. The need for drainage gravel explains why GWP for the EEH gravel is more than twice that of the SH gravel.

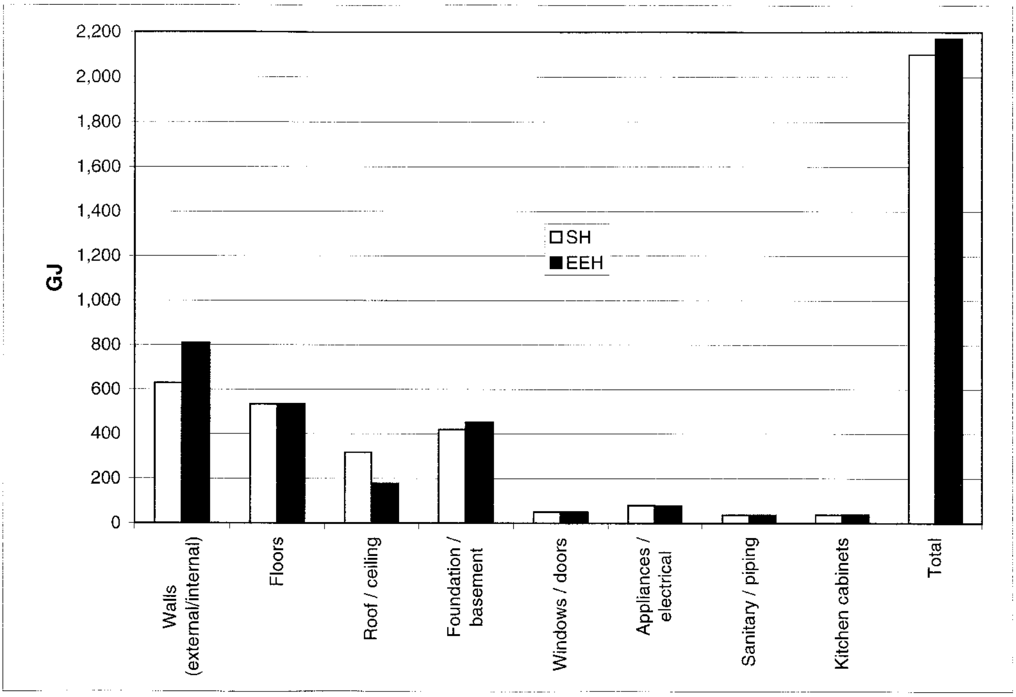

Figure 7 Life-cycle energy contribution by system (does not include heating and cooling energy).

Life-Cycle Cost

The four future energy cost scenarios were used to determine both the discounted present value cost and the undiscounted cumulative life-cycle cost for the SH and the EEH. The purchase price of the SH was $240,000. Figure 9 shows the individual costs of each system after developer markup was added. The construction cost differential between the SH and the EEH of $19,000 and developer markups increased the purchase price of the EEH to $262,800. Life-cycle costs in this study consist of accumulated mortgage, natural gas, electricity, and maintenance/ improvement costs over the assumed 50-year life of the home. The accumulated undiscounted costs for energy scenario 1 are presented in table 7. Although totaling undiscounted costs is not a rigorous calculation, it does show the relative amounts a homeowner could expect to pay for the four cost categories.

To determine if this additional amount spent on energy-efficient enhancements would be economically justifiable, the present value of both the SH and the EEH was calculated. Using a discount rate of 4%, the present value of each future annual total cost was determined. This determines an amount that, if set aside in 1998 at 4% compounded interest, would be sufficient to meet all future costs payments. The time value of money makes investments made in the future worth less today at a given discount rate. Table 8 summarizes the discounted present value of the SH and the EEH for the four utility escalation scenarios. For comparison, the same calculation was performed using a 10% discount rate (table 9).

Tables 8 and 9 indicate that with the higher initial EEH cost of $22,800, energy-efficient enhancements do not pay for themselves (from a present-value perspective) at falling or constant energy prices (scenarios 1 and 2) over a 50-year period. At escalating energy prices (scenario 3), the EEH is marginally better at a 4% discount rate, and worse at a 10% discount rate. If the United States adopted German energy prices (e.g., by internalizing external costs), which continue to escalate, the EEH would be a marginally better investment in both cases.

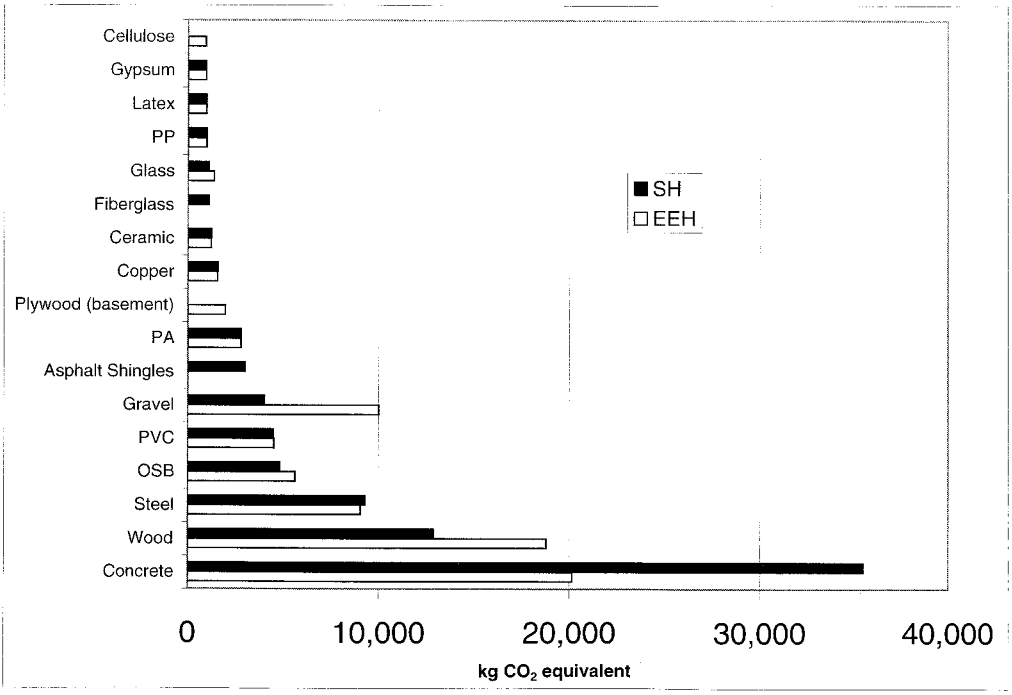

Figure 8 Greenhouse gas emissions from material production and fabrication processes related to 20 most significant materials for SH and EEH (includes maintenance materials and transportation energy for the total life cycle).

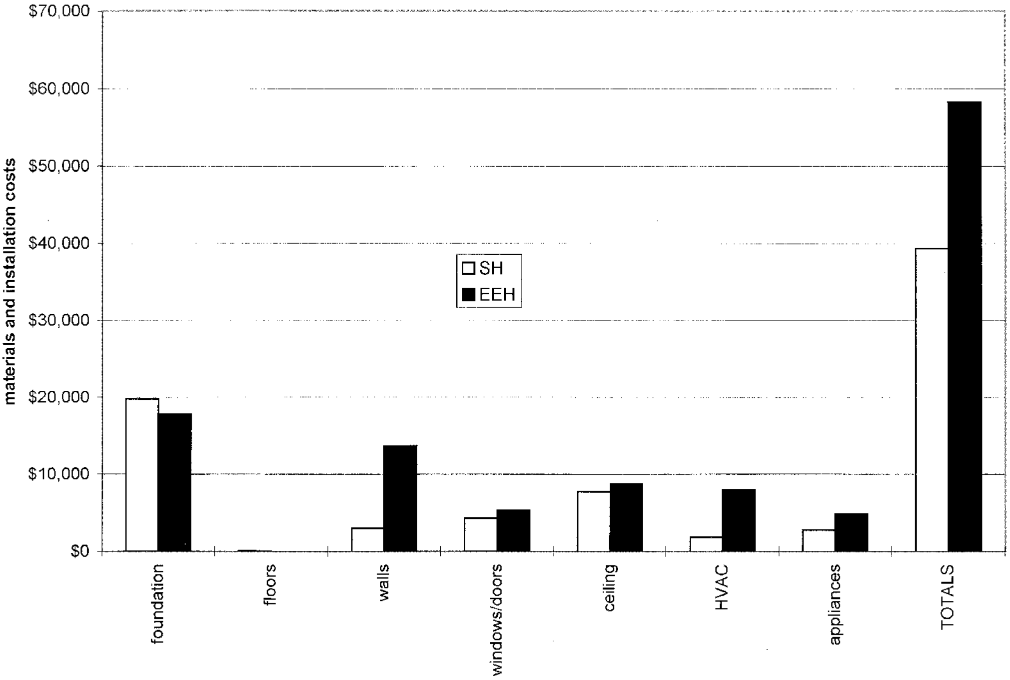

Figure 9 Materials and installation cost differentials for system improvements.

Table 7 Life-cycle cost elements for utility escalation scenario 1

	SH		EEH	
Life-cycle cost element	*Amount ($)*	*Percent (%)*	*Amount ($)*	*Percent (%)*
Mortgage costs	546,314	68.3	598,216	74.8
Natural gas costs	32,699	4.1	7,029	0.9
Electricity costs	40,521	5.1	17,014	2.1
Maintenance costs	180,828	22.6	177,049	22.2
Totals	800,361	100.0	799,307	100.0

Table 8 Present-value LC cost for various utility escalation scenarios (4% discount rate)

Scenario	*SH present value*	*EEH present value*	*Present-value difference between SH and EEH*
1	$426,697	$434,122	($7,425)
2	$423,544	$433,063	($9,519)
3	$445,842	$440,408	$5,434
4	$454,343	$443,200	$11,143

Table 9 Present-value LC cost for various utility escalation scenarios (10% discount rate)

Scenario	*SH present value*	*EEH present value*	*Present-value difference between SH and EEH*
1	$231,561	$237,458	($5,898)
2	$230,506	$237,114	($6,608)
3	$237,272	$239,309	($2,037)
4	$242,316	$240,943	$1,373

Conclusions

These life-cycle energy and cost analyses demonstrate the opportunities for achieving a dramatic reduction in energy consumption by the residential home sector with only incremental energy-efficiency measures. A significant reduction in life-cycle energy, 60%, was achieved by the EEH over the SH. Energy efficiency makes sense to home owners. Lowered monthly utility payments are unquestionably desired goals. Given that the technology for building more energy-efficient homes is available, indeed widespread in many parts of the country, why then is the market for energy-efficient housing still small? Life-cycle cost analysis provides a useful perspective on this question. The 9.5% increase in EEH cost results in a payback period of roughly 50 years, based on escalating future energy costs. The payback period is much longer based on the prospect of constant or falling future energy costs.

People living in owner-occupied housing units in the United States move, on average, every eight years (U.S. Census Bureau 1998). It is logical to conclude that the payback period for energy-efficient enhancements should then be eight years or less. Real estate developers commonly work on a five-year project return cycle. Many even have a three-year window. Given that the energy component of a home's life-cycle cost is secondary to the mortgage, energy efficiency enhancements are overlooked, except when the payback period is much shorter. Current research on building-integrated photovoltaics indicates similar energy and cost performance (Lewis et al. 1999).

The EEH indicated significant life-cycle energy savings relative to the SH, but this did not translate into life-cycle cost advantages. The design of the EEH used in this study focused primarily on techniques to reduce life-cycle energy and GWP as much as possible using equipment and materials readily obtainable in the U.S. market, without altering the fundamental floor layout or building look. If the overall objective had been to minimize both life-cycle cost and life-cycle energy, then a different set of improvement strategies would have been selected. Another drawback of the EEH design was maintaining rigid functionality with the SH. Several major energy-reducing strategies could not be employed because of the shape, layout, and orientation of the SH. Passive solar space heating can be implemented on a wide range of scales. The simplest approach consists of increased glazing on the south-facing wall. For this particular application and climate, however, the addition of more windows did not enhance energy performance (Blanchard and Reppe 1998). At the other end of the spectrum are homes that employ south-facing greenhouse rooms that generate a natural heat convection loop throughout the house, storing daytime solar heat with adequately designed thermal mass. Although these designs are different from those of the conventional two-story U.S. home, quality of life remains essentially unchanged. In fact, the thermal radiative aspects of passive solar homes make them superior in terms of perceived comfort. Houses that consume considerably less use-phase energy will require fundamental design modifications.

The life-cycle energy profiles for both the SH and the EEH indicated that most of the energy consumption is in the use phase, 91% for the SH and 74% for the EEH. The pattern is also characteristic of other product systems such as automobiles where about 90% of the energy consumption occurs in the use phase (Keoleian et al. 1998). Again, the energy consumption in the use phase is large, whereas the economic incentives to conserve energy are relatively weak. In the case of automobiles, relatively low gasoline costs compared to fixed vehicle ownership costs (depreciation and insurance) provide little incentive for encouraging fuel-efficient vehicles.

Special government energy policies can also be implemented to encourage energy efficiency. For example, carbon trading or tax scenarios would provide a financial driver for more energy-efficient technologies. The U.S. Department of Energy estimated marginal compliance costs under certain provisions of the Kyoto Protocol. A regulatory provision based on an emissions cap for CO_2 with a transferable permit system was assumed. In this case, compliance costs for CO_2 are estimated to be 94.4 to 165.3 dollars (in 1998) per ton of carbon. Adjusting the effective energy prices would shorten the payback period of the EEH and lead to a much more rapid implementation of eco-efficient construction technologies. A variety of other strategies can be used to promote eco-efficiency and sustainability, such as more-effective building code standards and appliance standards, better design tools and guidelines, consumer education, and voluntary partnerships for developing new technologies. A recent workshop organized by the Center for Sustainable Systems (CSS) on sustainable buildings compiled a comprehensive list of these implementation strategies that target designers, builders, inspectors, consumers, lenders, insurers, materials suppliers, educators, and other key stakeholders (CSS 2000).

Although pre-use phase energy consumption accounts for only 9% to 26% of the homes' total life-cycle energy, considerable improvement is possible. Substantial use of construction materials with a high content of recycled materials, or organic matter with low embodied energy, could lower pre-use phase energy. As the trend toward energy efficiency in the use phase continues, the embodied energy in materials will become more important. The life-cycle energy analysis indicated unexpected results and improvement opportunities regarding individual building and home improvement components. The impacts of carpeting and roofing are very significant due to their large material production energies and frequency of replacement over the 50-year estimated service life of the house. The substitution of a long-life shingle system for the conventional asphalt system led to a 98% saving of life-cycle energy.

Trends in the average home size in the United States are not pointing toward a sustainable housing future. Between 1975 and 1998 the average area of a new single-family home constructed increased from 1,645 to 2,190 square feet, whereas the average number of occupants per household decreased from 2.94 to 2.61 over the same period (Wilson 1999; NAHB 1999; U.S. Census Bureau 1999). This investigation clearly shows the potential for reducing life-cycle energy consumption, but the effectiveness of the eco-efficient strategies outlined herein would be offset by continued increases in home size. Life-cycle assessment has been shown again to be a useful tool in guiding improvement in residential home design. Changes in consumption patterns, however, through appropriate local and federal policies on land, energy, and materials consumption are also required to achieve significant environmental progress in the residential home sector.

Notes

1. The U.S. household energy consumption in the 1993 was 10.0 quadrillion Btu (5.27 quadrillion Btu natural gas, 3.28 quadrillion Btu electricity, 1.07 quadrillion Btu fuel oil, and 0.38 quadrillion Btu liquid propane gas (LPG)), which accounted for 10.0 quadrillion Btu/87.3 quadrillion Btu = 11% of the total U.S. energy consumption (U.S. DOE/EIA 1995, 10; U.S. DOE/EIA 2000, 9).
2. At the time this article was going to press, the authors became aware of a recent doctoral dissertation by Karin Adalberth (2000) and an article (Nishioka et al. 2000) investigating life-cycle energy use in new residential buildings in Sweden and Japan respectively.
3. *Editor's note:* For a discussion of the mathematics of crossover analysis, see Field, Kirchain, and Clark, "Life Cycle Assessment and Temporal Distributions of Emissions: Limitations of Product-Centered Emission Analyses," this issue.

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