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Life Cycle Analysis of a Residential Home in Michigan

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LIFE CYCLE ANALYSIS OF A RESIDENTIAL HOME IN MICHIGAN

By:

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Abstract

A 2,450 ft^2 residential home (referred to as SH or Standard Home) built in Ann Arbor, Michigan was analyzed to determine total life cycle energy consumption of materials fabrication, construction, use and demolition over a 50 year period. Life cycle global warming potential (GWP) and life cycle cost were also determined. The home was then modeled to reduce life cycle energy consumption by employing various energy efficiency strategies and substitution of selected materials having lower embodied energy (referred to as EEH or Energy Efficient Home). The total life cycle energy was found to be 15,455 GJ for SH (equivalent to 2,525 barrels of crude oil[1]) of which 14,482 GJ (93.7%) occurred during the use phase (space and water heating, lighting, plug loads and embodied energy of maintenance and improvement materials). The life cycle energy of EEH was reduced to only 5,653 GJ (equivalent to 927 barrels of crude oil) of which 4,714 GJ (83.4%) occurred during the use phase. The purchase price of SH was $US 240,000 (actual market value) and determined to be $22,801 more for EEH. Four energy price escalation scenarios were run to determine un-discounted life cycle cost using falling, constant, and rising future energy costs. Accordingly, the un-discounted life cycle cost of SH varied between $791,500 and $875,900 and between $796,300 and $824,100 for EEH. Using a 4% discount rate, the present value cost varied between $423,500 and $454,300 for SH and $433,100 and $443,200 for EEH. Life cycle GWP for SH was determined to be 1,013 metric tons of CO_2 equivalent (91.9% during the use phase) and 374 metric tons for EEH (78.6% during the use phase). EEH use of energy efficiency strategies and materials with lower embodied energy reduced pre-use phase energy by 37 GJ (3.9%) while use-phase energy was reduced by 9,768 GJ (67.4%). Total life cycle energy was reduced by a factor of 2.73, and life cycle GWP decreased by a factor of 2.71.

EXECUTIVE SUMMARY

As concern over the environmental impacts of residential house construction grows, many researchers are beginning to use life cycle assessment as a means to quantify natural resources consumption, and emissions of global greenhouse gases. Historically, focus has been on understanding energy use during the operational period of the home (use phase). With this approach, an important factor has been neglected; the embodied energy of construction materials. To understand overall environmental impacts of the building, all life cycle stages should be inventoried (material production, manufacturing, use, retirement). Assessing the environmental impact of a complex system, such as a house, requires an understanding of the environmental impacts of all of its parts. As the production sequence is followed upstream, the tributaries of material and energy input require exponential effort to quantify. The procedures used in this study are standard life cycle assessment methods[2].

The object of study was a 2,450 ft^2 home (referred to throughout this report as the Standard Home, SH) built in Ann Arbor, Michigan. A two car garage and a full unfinished basement are included in the study and add an additional 2,100 ft^2 of space to the above number. The home was selected because it is close to the average size of new homes built in the US[3] and uses standard construction materials and techniques. Using developer-supplied blue prints, the mass of all building materials was determined. Local and regional suppliers contributed substantially to this effort. Many home components and construction materials (e.g., carpet, fuse-boxes, refrigerators, paint) consist of multiple materials. The percentage of different materials in each multi-material product was established. This inventory was then divided into eight home systems: walls, roof/ceilings, floors, doors/windows, foundation, appliances/electrical, sanitary/HVAC, and cabinets.

The study was focused only on life cycle primary energy and global warming potential. Other environmental burdens (e.g., resource consumption, air/water pollution, solid waste), and health related issues (e.g., off-gassing materials, use of carcinogenic substances) were not inventoried. Published data from several research groups[4,5,6,7] that have determined the environmental burdens for the production of selected materials were used. Combining this information with the mass of the various materials, the primary energy and global warming potential of SH was determined.

The life cycle of SH consist of three distinct phases; pre-use, use and end-of-life. The pre-use phase consists of the manufacturing and transportation of all building materials used, and the construction of the house. The use phase encompasses all activities related to the use of the home over an assumed life of 50 years. These activities include all energy consumed within the home, including heating, cooling, lighting and use of appliances. The use phase also consists of the energy to manufacture all materials required to maintain the physical building and for home improvement projects. The end-of-life phase inventories the eventual demolishing of the home, and includes the actual dismantling of it, and transportation of waste to recycling operations or landfills. The recycling, incineration, or other end-of-life management processes have not been included in this study.

To determine use-phase energy and global warming potential, annual energy consumption was determined. Energy-10[8], an energy-use modeling software package for small buildings and residential homes was used to determine SH energy consumption, using energy related parameters (e.g., building envelope heat conductivity, electricity consumption of appliances, ventilation requirements), as well as average temperature, wind speed and humidity data for Detroit, MI. The annual home energy consumption, based on these calculations, was multiplied by 50 (years) to provide one part of the life cycle use-phase energy. To determine the home maintenance and improvement component in terms of use-phase energy, a schedule of activities was generated, listing which activities will take place, at what future time, and the mass of all materials required. This information was converted into primary energy and global warming potential in the same fashion as original construction materials.

The primary life cycle energy consumption for SH was 15,455 GJ. This is the energy equivalent of burning 2,525 barrels of crude oil9. Of this, 6.1% (942 GJ) was consumed in the pre-use phase, 93.7% (14,482 GJ) in the use phase, and 0.2% (31 GJ) in the end-of-life phase. With respect to the 14,482 GJ consumed during the use phase, 96% (13,877 GJ) was heating and electrical energy consumption and 4% (604 GJ) was the embodied energy of maintenance and improvement materials. The total life cycle amount of global warming gases, after conversion into an equivalent amount of CO_2, was 1,013 metric tons. This provides an approximate measure of the overall environmental impacts of the home studied.

How can these impacts be reduced? Clearly, focus should be on the use-phase because its impact on the environment overshadows the other phases. To examine the effect of design changes made to reduce these impacts, a second home was modeled. Referred throughout the report as the Energy Efficient Home (EEH), this home mirrors the original in size and layout. All functions provided by SH are provided by EEH. In addition to reducing use-phase impacts, EEH served to test which materials reduce pre-use phase impacts. Strategies that lowered impacts in both phases were adopted as design parameters for EEH.

Based on Energy-10 simulations, and use of the energy and global warming potential databases, EEH evolved into a much more energy efficient structure. The defining feature of EEH is its 12” thick, R-35 walls. The walls are constructed from double 2x4 studs, with a 3.5” spacing between the inner wall and outer wall studs. The wall cavity is filled with cellulose insulation. Because cellulose requires much less energy to manufacture than the fiberglass insulation in SH, the overall wall structure consumed less pre-use phase energy. At the same time the thermal resistance of the wall increased by a factor of three. Combined with a doubling of the insulative value in the ceiling, the EEH thermal envelope was greatly improved. Air infiltration was also greatly reduced. The effective leakage area (ELA) of SH was determined by blower-door test to be 153 in^2. For the EEH, 20 in^2 was deemed to be achievable.

Energy efficient appliances where used in EEH. Based on a review of products available on the market, energy efficient appliances reduced annual electricity consumption by approx. 40%. Energy efficient appliances included the refrigerator, clothes washer and dishwasher. The kitchen range and clothes dryer were selected to operate on natural gas vs. electricity in the SH. Furnace efficiency was increased from 80% to 95%. The peak heating load was reduced from 95,300 to 28,200 Btu/h. A/C efficiency was increased from a SEER (seasonal energy efficiency ratio) value of 10 to 13. The peak cooling load was reduced from 36,600 to 28,160 Btu/h. Compact florescent lights were used throughout EEH.

These improvements in energy efficiency were not obtained without cost. The market value of SH was $240,000. A base price was determined by subtracting the land price and dividing out the developer's profit. SH materials to be replaced were quantified and priced, and subsequently subtracted from the base price of SH. EEH replacements materials were similarly quantified, priced and added. Finally, the Developer's profit was added back, as was the land price. The EEH home purchase cost was $22,801 more than SH.

Life cycle costs were then calculated for both homes. The life cycle cost was determined by adding mortgage payments (based on a 30 year mortgage at 7% annual interest), natural gas and electricity costs (based on utility rates of $0.462/therm and $0.08/kWh respectively) and the cost of home maintenance and improvements (based on material and labor costs that were escalated at 3%/year). Finally, four future energy price escalation scenarios were run to determine sensitivity to changing energy prices. The scenarios included falling, constant, and rising energy rates as well as energy rates presently used in Germany. Un-discounted life cycle costs for SH varied from $791,500 to $875,500. SH mortgage payments made up between 62-69% of the life cycle cost, with energy comprising between 8-17%. Home maintenance and improvements make up the remainder. Un-discounted life cycle costs for EEH varied from $796,300 to $824,100. EEH mortgage payments made up between 73-75% of the life cycle cost with energy making up between 3-6%.

Using a discount rate of 4%, each future annual total cost (mortgage, energy, maintenance) was converted into a present value cost. The summation of all years gives the discounted present value cost of the home. This serves as a useful economic tool in evaluating the two home alternatives. The discounted present value cost varied between $423,500 and $454,300 for SH and $433,100 and $443,200 for EEH. From an investment standpoint, setting aside future uncertainties, both homes are approximately of equal value.

Given that life cycle energy use and global warming potential can be reduced by a factor of nearly three without compromising the home as a financial investment, it is natural to ponder why it is not happening on the home market. Several possibilities are:

- The home buying market does not consider reduction of environmental burdens as a significant element in evaluating home selection.
- Many home buyers, who on an average, move about every eight years, do not believe the added cost of energy efficiency will be appraised in future transactions. They may be skeptical that reduced energy costs will compensate for higher financing costs.
- There are no "green" regulatory or market incentives to motivate property developers.
- There is an insufficient volume of low energy homes being built to force the home design and construction industries into developing lower cost, higher efficiency homes. If there was a sufficiently high volume, the market might quickly focus on the life cycle energy savings of EEH- type residences.

1.0 INTRODUCTION

1.1 Overview

Annually, 24 % percent of the natural gas, and 35% of the electricity in the US, is consumed by the residential housing sector[10,11]. As a result, 1.3 million metric tons of green-house gases are emitted annually. This is equal to 31% of the green-house gases emitted from electricity and natural gas consumption by all sectors in the US.

The above figures represent energy consumption and emissions data for residential utility services. Of these, natural gas and grid electricity combine for over 90% of all energy used for space and water heating, lighting, ventilation and appliances in 1990. Coal, fuel oil, wood, and liquefied propane gas account for the remainder. In 1994, CO_2 emissions associated with the residential housing sector contributed approximately 19% of total CO_2 emissions released by all US sectors combined[12].

What is conventionally not considered in determining residential energy consumption is the energy required to make building materials and home appliances. This is the energy required to extract the raw materials (mining, oil extraction, timber cutting), refine those resources (smelting, refining, cutting), and manufacture ready-to-use construction materials. This last item, for example includes extrusion, molding, punching and assembly of metal, plastic, and other material into usable shapes, as well as combining different materials into composite forms such as windows, doors, pre-assembled panels, floor coverings, electrical and plumbing fixtures, and the many appliances found in modern homes.

Life cycle analysis (LCA) quantifies the environmental impacts caused by the energy and material flows in all stages of a product's life cycle. Some of the impact categories widely used to compare product systems are global warming potential (GWP), ozone depletion, nutrification, acidification, and ground-level ozone creation potential. In LCA research, the product system being investigated is structured into several stages[13]. Conventionally, these are 1) raw material acquisition, 2) parts fabrication, assembly, and construction, 3) use, and 4) retirement (or end-of-life). Life cycle assessment is commonly referred to as a cradle-to-cradle analysis because it looks at all inputs and outflows in a product system over its entire life history. In a full LCA, all inputs (material, energy, water) and outflows (air and water emissions and solid wastes) are accounted for. In this project, only primary energy and the global warming potential (GWP) will be evaluated. Primary energy is the energy that is embodied in resources as they exist in nature: the chemical energy embodied in fossil fuels or biomass, the potential energy of a water reservoir, the electromagnetic energy of solar radiation, and the energy released in nuclear reactions. For the most part, primary energy is not used directly but is first converted and transformed into electricity and fuels such as gasoline, jet fuel, heating oil, or charcoal. This statement applies to raw material extraction, transportation, manufacturing and home energy consumption as well.

While quantification of resource consumption, water emissions and solid waste resulting from material manufacturing and product use are important, the project scope focused on primary energy and GWP, which are two important indicators of the overall environmental impact of home construction and use. Using a similar approach, life cycle costing is used to determine all costs in monetary terms associated with a product. The life cycle costs in this study are all costs borne by the owner. These include all finance costs associated with:

- buying the house, covering the cost of all materials and all labor
- land purchase
- provision of natural gas and electricity
- home repair and improvements

Understanding energy consumption, GWP, and cost from a life cycle perspective is essential if a systematic and comprehensive reduction of environmental impacts is desired. All three are linked. Changes to the energy intensity of building products will change the GWP. Reductions in home energy consumption will reduce utility costs and GWP. Use of building materials with lower embodied energy may or may not affect use phase energy. Accordingly, an inventory of the product's life cycle, identifying mass and energy flows, helps in understanding the complexity of the various interactions.

1.2 Purpose of Study

The goal for undertaking the project was to determine the relationship between material production/construction (pre-use) phase energy, and use phase energy, as energy efficiency strategies are applied to various home systems. It is commonly believed that to achieve higher energy efficiency, more materials are needed in the initial construction. Thicker walls are needed obtain lower thermal conductance properties (i.e., higher R values). More windows of higher quality optimize solar heat gain. Additional internal thermal mass is required to allow for temporary storage of the increased solar heat for release at night. While these energy efficient strategies lower the building's heating fuel requirements, it is not entirely intuitive whether they actually lower total life cycle energy consumption. For example, is the additional energy required to manufacture the glass for more windows recovered with lowered heating requirements?

Other research questions to be addressed in this study include:

- What is the relationship between material fabrication/construction energy, and use phase energy in a "standard" residential home?
- How does total life cycle energy, cost and GWP of a "standard" residential home vary with changes to various home systems (walls, roof, floor, appliances, etc.)?
- Which home system improvements provide the greatest reductions in life cycle energy and GWP?
- How do varying projections of future energy costs affect the life cycle costs of a home?
- How do home maintenance and improvement projects impact the life cycle energy, cost and GWP of such a building?
- Do the results from this study correlate with other studies performed in this area?

1.3 Similar Studies

- Mali, N., "Embodied Energy-Just What is it and Why do We Care", Environmental Building News Volume 2 Number 3, pp. 8-9. Cites work performed by Professor Ray Cole of the University of British Columbia's School of Architecture who performed an LCA of conventional and energy efficient versions of a 3,750 ft^2 ranch house.

- Pierquet, P., Bowyer, J., Huelman, P., "Thermal Performance and Embodied Energy of Cold Climate Wall Systems", Forest Products Journal, Vol. 48, No. 6 pp. 53-60. Review of 12 different wall systems comparing the embodied energy of the wall materials and the energy savings (compared to a base case 2x4 wall) over time.

- Willars, P., Wånggren, B., "kv. Apoteket. Detaljanalys av yttre miljöpåverkan orsakad av byggmaterialsens innehåll och resursförbrukningen i byggprocessen", Skanska Bygg AB Division Boståder Stockholm. Life cycle analysis of a 50 unit apartment building in Sweden with a total of 4,030 m^2 of usable floor area.

- Cole, R., Kernan, P., "Life-Cycle Energy Use in Office Buildings:" Building and Environment, Vol. 31, No. 4, pp. 307-317. Review of life cycle energy of a 50,000 ft^2 three-story generic office building for alternative wood, steel and concrete structural systems.

2.0 METHODS

2.1 Overview

2.1.1 Selection of Standard Home (SH)

FIGURE 2-1 The Princeton Home, South Elevation

It was decided to select a home that had been built in the Ann Arbor, Michigan area. This allowed for detailed measurement of the building and examination of area-specific construction methods. After meeting with several local developers who provided blue prints of various home models, the Princeton home (see Figures 2-1 and 2-4) designed and built by the Guenther Building Co., was selected. Throughout this report it is referred to as the Standard Home (SH).

2.1.2 Definition of the Energy Efficient Home (EEH)

This report analyzes the life cycle energy consumption, GWP, and cost of the SH. To understand how the environmental impacts of SH could be reduced, it was redesigned to become a fundamentally more energy efficient home, based on the floor plan of SH. Throughout this report it is referred to as the Energy Efficient Home (EEH). The design changes were reviewed by two architects[14] to ensure technical feasibility.

2.1.3 Functional Units

To provide a base line for objective comparison between SH and EEH, both homes had to be similar. The means for ensuring equivalency between two systems is the definition of functional units that each home must meet. If each home meets certain underlying requirements, or provides the same services in terms of quality and quantity, then they are functionally equivalent.

The functional units adopted and held constant for the SH/EEH comparison were:

- Internal/usable floor area: 2,450 ft^2 (see Figures 2-2 and 2-3 for 1st and 2nd floor plans respectively). The thicker EEH walls increased the outside diameter of the building. All EEH and SH internal dimensions are the same.
- Internal useable building volume: 26,960 ft^3
- Occupancy: 4 people
- Life span of home: 50 years

- Architectural style (see Figures 2-1 and 2-2)
- Basement and garage area: 1,675 ft^2 and 484 ft^2 respectively
- Thermal comfort comparable in both homes: heating set-point: 70°F, set-back: 65°F; cooling set point: 75°F, set-up: 79°F; heating and cooling set-back/set-up set for between 11 p.m. and 7 a.m.
- Indoor air quality comparable in both homes (i.e., humidity, air pollution)
- Domestic services supplied by common appliances and entertainment products including refrigerator/freezer, range, range hood, microwave, toaster, dishwasher, sump pump, cloths washer, cloths dryer, computer, TV, radio, and heated aquarium. The SH has an electric garbage disposal replaced in EEH with a composting box
- Municipal supply of potable water
- In-home generation of hot water with a natural gas boiler
- In-home heat generation with natural gas furnace; cooling with central air-conditioning unit
- Grid-supplied 110 volt electricity
- Daylighting comparable in both homes
- Internal and external lighting intensity comparable (as provided by installed lamps)

Areas where functional equivalency may not hold true include:

- Increased comfort in EEH resulting from fewer drafts and less radiative heat losses
- Personal aesthetic preferences related to wall thickness (EEH walls are 12” thick)

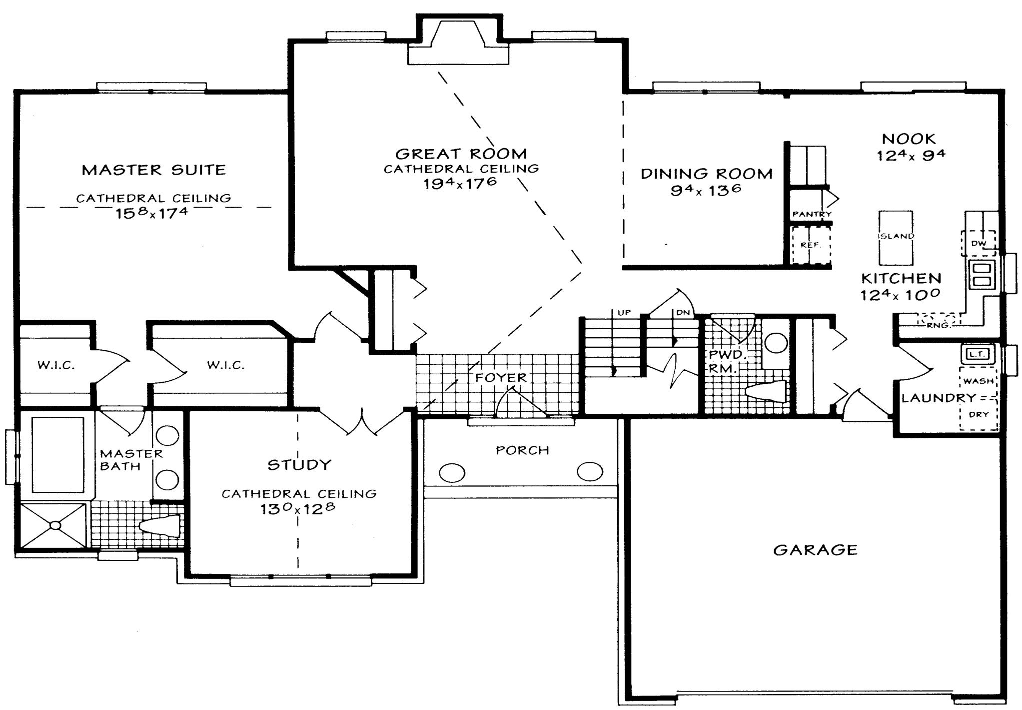


FIGURE 2-2 The Princeton Home, Floor Plan, 1st Floor

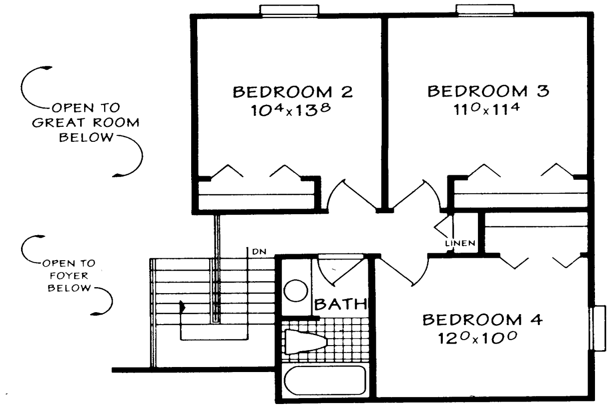


FIGURE 2-3 The Princeton Home, Floor Plan, 2nd Floor

The design of EEH, while maintaining functional equivalency to SH, did hamper optimization of passive solar heating and cooling strategies. Such strategies include integration of south-facing windows with natural house ventilation[15,16], design of solar induced air flow through the building, clerestories for increased daylighting, and use of additional thermal storage to balance diurnal temperature swings[17]. Nevertheless, SH architectural style and shape were retained in order to stay within perceived market preferences.

2.1.4 Guidelines on EEH Design

SH life-cycle energy and GWP results were used as guidelines in reducing the overall energy consumption of EEH. The majority of SH primary energy consumption and GWP is generated during the use-phase of the house (i.e., heating, cooling, electricity consumption for appliances). Effort was therefore focused on measures that would reduce the use phase energy consumption (e.g., lowering the thermal conductance properties of the building envelope, reducing energy consumption of appliances, etc.). In addition, building materials were selected that would reduce the embodied or “pre-use phase” energy by either choosing materials with lower embodied energy, or materials that had a significantly lower rate of replacement.

2.2 Description of Princeton Standard Home (SH)

FIGURE 2-4 The Princeton Home, North Elevation

The Princeton SH is a two-story home with 2,450 ft^2 of livable space and an internal volume of 26,960 ft^3. This is close to the national average of 2,120 ft^2 for new homes built in the U.S.[18]. It has an unfinished basement and a two car garage. The first floor has a living room with a vaulted cathedral ceiling, an attached dining room, and a master bedroom with an attached bathroom (shower/bathtub, toilet, two sinks, and two large closets). There is also a kitchen, a laundry room, and a lavatory (sink/toilet). The second floor is comprised of three smaller bedrooms and a bathroom (shower/bathtub/sink/toilet).

The floor area of the unfinished basement is 1,675 ft^2 which contains the furnace, the water heater, the main fuse-box, and a sump pump. Figure 2-5 provides a cross section of the basement foundation. It has plain concrete walls, a concrete floor and no ceiling drywall. The garage is not insulated. The basement and garage construction materials are included in the SH-materials inventory. It was assumed that the owner would fit out the basement within the first year after purchase, adding drywall to the foundation walls and ceiling, and vinyl tile to the floor. Because this activity takes place soon after construction, the primary energy and GWP were included in the pre-use phase inventories.

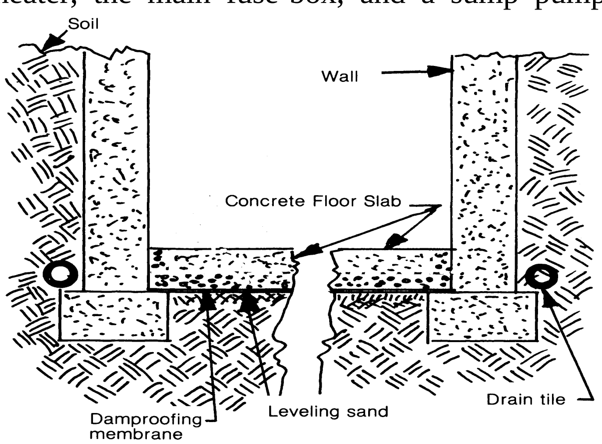


FIGURE 2-5 The Basement and Foundation of the SH [19]

The SH has a 2x4 wall construction with 3.5” fiberglass insulation, and 8” of sprayed fiberglass insulation in the ceiling (see Figure 2-6). The house is wired to meet electrical code, and provides the typical amounts of light-switches and outlets. Non-insulated hot and cold water copper piping run throughout the house. The living room has a natural gas fireplace. The kitchen has a sink, electric garbage disposal, stove and stove hood, dishwasher, refrigerator/freezer, and several cabinets. The laundry room features only a plastic sink. Other major energy consuming appliances included in the study, and which must be purchased by the home buyer include a clothes washing machine and a clothes dryer. Except for kitchen and bathroom cabinets, no furniture was included in the study.

The first floor is fully carpeted, except for vinyl tile in the bathrooms, kitchen and garage entrance/hallway, and ceramic tiles in the foyer. The second floor is also fully carpeted with the exception of vinyl tile in the bathroom. Incandescent lighting is used in all rooms except for the closets.

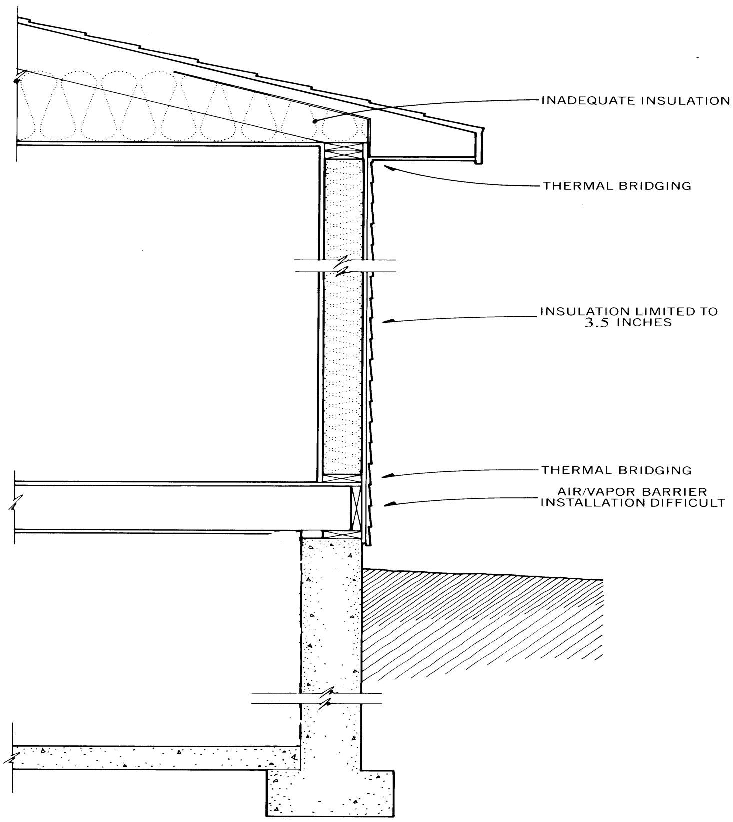


FIGURE 2-6 SH 2x4 Wall Design [20]

The home was divided into several systems to allow for easier tracking of materials, energy, green-house gases, and cost. System interaction could then be observed when EEH design changes were made. Table 2-1 below summarizes the eight home systems.

TABLE 2-1 Description of Systems

System	Description of System
Walls (interior and exterior)	Building structure consisting of lumber construction, fasteners and braces, insulation, drywall, exterior sheathing and siding, brick facing, vapor barriers, trim, adhesives and paint.
Floors	Floor joist lumber, deck lumber, carpet, ceramic and vinyl tiles, mortar, fasteners, and adhesives.
Roof/ceiling	Wood trusses, fasteners, insulation, roof deck lumber, roof weathering materials, soffit and facia materials, gutters and down-spouts.
Foundation/basement	Gravel substrate, concrete foundation slab and walls, drainage system
Doors/windows	Wood hollow core doors, main entry (insulated) door, garage door. All casement and double hung windows including glazing and frames. Patio sliding door considered to be a window.
Appliances/electrical	Furnace, air conditioning unit, water heater, range, range hood, refrigerator/freezer, clothes washing machine, clothes dryer, fireplace, electric garbage disposal, dehumidifier, dishwasher, sump pump, copper wire cabling, switches, plug outlets, lamp fixtures, bulbs, and circuit breakers.
Sanitary/piping	Bath tubs, jet pump (for master bath), sinks, pedestals, faucets, toilets and accessories, bathroom tiles. Hot and cold water piping, natural gas piping and PVC drainage and vent piping. Air ducts, registers, grills, air intakes, and exhaust flues.
Cabinets	Kitchen and bathroom cabinets and countertops

2.3 System Boundaries of Life Cycle Analysis

2.3.1 Processes Included

Primary energy consumption and GWP gas emissions were accounted for in the following processes:

a) raw material extraction, and production of engineered materials (e.g., steel plates, wood studs, copper slabs)
b) manufacturing of building components (e.g., windows, siding, carpet), and appliances
c) transportation of materials from raw material extraction to part fabrication, and from there to the construction site
d) construction of the home at the building site, including site earthwork
e) energy consumed during the use-phase of the home (utility-provided energy)
f) embodied energy of maintenance and improvement materials (as in a, b, and c)
g) demolition of the home after its useful life
h) transportation of demolished materials to recycling centers or landfills (except the concrete foundation and basement floor, which was assumed to remain in the ground)

In order to adequately account for the additional energy and material requirements caused by manufacturing and construction losses, efficiency factors for these two life cycle steps were employed. For the manufacturing of building products and appliances, a 95% efficiency factor (by mass) was assumed for all materials, except for secondary aluminum (88%)[21], ceramic tiles (98%)[22], mortar for ceramic tiles (88%)[23], and vinyl (99.6%)[24]. 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 5% 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, concrete). For the following house components, the on-site losses were included in total building quantities; the exact percentage of the losses however, could not be identified:

- SH framing lumber and OSB
- drywall
- SH and EEH roof truss lumber

All efficiencies during the material production phase are accounted for in the data sets used for this life cycle step (i.e., raw material production before parts manufacturing).

2.3.2 Processes and Factors Not Included

In an effort to focus on those architectural systems that directly influence energy use and GWP of a residential home, some components that are part of a home and some external factors were not addressed. The following is a list of those issues not included in this study:

- site location as it pertains to impacts on local ecosystems, personal transportation issues, and urban planning issues (including roads and sewer infrastructure)
- energy and material issues related to the house surrounding (e.g., drive-way concrete, landscaping, irrigation)
- furniture (except kitchen and bathroom cabinets), curtains
- utility hook-ups including water and gas mains and electrical power hookups (e.g. excavation, pipes, wiring, and meters)
- TV/phone/data connections (including excavation, internal and external cabling, security and fire warning systems)
- behavioral patterns of habitants including food consumption, clothing, furniture, entertainment equipment, pet supplies, cleaning materials, or other items not requiring energy for operation
- potentials of renewable energy use (on-site electricity generation with photovoltaics and wind turbines or, solar hot water)
- indoor air quality issues (off-gassing from paints and flooring, and cleaning materials)
- energy consumption related to treating/supplying water and waste treatment
- energy consumption related to pick-up and disposal of municipal solid waste
- other environmental impacts occurring in all life-cycle phases, including non-global-warming related air emissions (point source and non-point source), water consumption

and water effluents, solid waste generation, and overall resource depletion from material and energy production use

- methods and equipment used in the construction and demolition process
- embodied energy of the industrial facilities producing raw materials and fabricated products
- house shape as it influences the surface/volume ratio
- environmental and social issues related to the origin of construction materials (effects on local economy and resource use)
- future technological break-throughs that significantly reduce the energy consumption and cost of home appliances

It is important to note that, because wood is a renewable resource, its feedstock energy (combustion fuel energy) was not accounted for according to EPA LCI guidelines[25]. However, for materials made from non-renewable resources (e.g., plastics), feedstock energy has been included in the energy inventory.

The environmental burdens associated with the ultimate treatment of the demolished building materials, such as landfilling, recycling, and reuse were not evaluated. Attempting to determine the nature and efficiency of the recycling industry in 50 years would be conjectural. Moreover, attempting to determine which industrial products might be recovered and recycled at that time was deemed beyond the scope of this study. Such information, if available, would have allowed for assignment of material production burden credits to EEH, based on lowered future material production energy requirements.

2.4 Life Cycle Materials Data Base

Energy and GWP data sets were supplied by the DEAM™ software database[26], which has information for a wide range of materials. DEAM™ data sets were available for 94.5 % of the materials in the building, by mass. Data sets (accounting for 5.2 % of the building mass) were taken from a study published by the Western Wood Products Association[27]. AIA's Environmental Resource Guide[28] and the Swiss publication Ökoinventare für Verpackungen[29] provided the remaining data sets (accounting for 0.3 % of the building mass). For the majority of materials, complete material production and manufacturing data sets could be located, with gaps only occurring in the manufacturing process of some materials. However, complete data were available for the primary energy consumption of the building's materials, which includes raw material extraction and manufacturing of prefabricated materials, (e.g., cold-rolled steel). Data sets were available (approximately 90% of the building by mass) for manufactured components and assembled items (e.g., windows, roof shingles).This does not introduce significant error since component fabrication burdens are generally far lower than material production burdens. A typical example is the production of high-density-polyethylene (HDPE) pipes. While it takes about 78.5 MJ (fuel and feedstock) to produce HDPE polymer, only 9 MJ are estimated to be required for the manufacturing of the pipe[30].

GWP data sets from this report are a composite measure of many different gases that have varying levels of global warming potential. It is standard convention to convert non-CO_2 gases into equivalent CO_2. Many gases have a much higher global warming potential, pound for pound, than CO_2. Table 2-2 below provides global warming potentials for different gases used in this study, and by many practitioners in the Life-Cycle-Assessment community worldwide.

TABLE 2-2 Global Warming Potentials (20 year time horizon)[31]

Global Warming Gas	GWP Factor CO2 = 1
Carbon Dioxide (CO_2):	1
Methane (CH_4):	56
Nitrous Oxide (N_2O):	280
Halon 1301 (CF_3Br):	5,600
CFC 11 ($CFCl_3$):	4,500

Global Warming Gas	GWP Factor CO2 = 1
CFC 12 (CF_2Cl_2):	7,100
CFC 13 (CF_3Cl):	11,000
CFC 14 (CF_4):	3,500
CFC 114 (C_2F_4Cl):	6,100
HCFC 22 (CHF_2Cl):	4,200

Table 2-3 provides energy consumption/GPW data for all major materials used in this study. Primary energy includes both resource extraction/processing energy and component fabrication energy except where marked (data not available). The major processes associated with component manufacturing are given for those materials where that have manufacturing primary energy data.

TABLE 2-3 Primary Energy and Global Warming Potential of Materials

Material	Fabrication Process	Primary Energy (MJ/kg) (Material Production and Fabrication)	GWP kg CO_2 equiv./kg
acrylonitrile butadiene styrene (ABS)	***	112.2	3.5
aluminum, primary	***	207.8	10.0
argon	***	7.0	0.5
asphalt	***	51.0	0.4
asphalt shingle	shingle mnfg	14.6	0.3
brass	***	99.9	+
cellulose	shredding, treating	3.2	0.2
ceramic **	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 mfg	41.2	0.4
fiber glass	extrusion	24.5	1.5
glass	forming	18.4	1.3
gravel	crushing	0.9	0.1
gypsum	***	3.8	+
HCFC 22	***	33.7	1.3
high density polyethylene (HDPE)	extrusion	87.5	3.0
latex **	***	70.8	0.8
mineral spirits	***	5.5	0.4
mortar	mixing	1.9	0.1
oriented-strand board	***	3.2	0.7
polyamide resin (PA)	***	137.6	4.5
paper	***	16.2	1.2
particleboard	***	3.9	0.2
polyethylene (PE)	extrusion	87.1	3.0
plastic-wood composite *	shredding, molding	5.1	0.2

plywood	cutting, pressing	8.3	0.1
formaldehyde resin	***	72.1	1.3

TABLE 2-3 Primary Energy and Global Warming Potential of Materials (Con't)

Material	Fabrication Process	Primary Energy (MJ/kg) (Material Production and Fabrication)	GWP kg CO2 equiv./kg
polymethylmethacrylate (PMMA)	***	207.3	14.7
polyisocyanurate	***	70.6	+
polypropylene (PP)	***	83.8	2.6
polystyrene (PS)	***	100.3	2.1
polyvinyl chloride (PVC)	***	77.4	2.9
rubber ++	***	150.4	3.0
styrene butadiene rubber (SBR) ++	***	70.8	0.8
silver	***	128.2	+
stainless steel	***	16.3	1.2
steel cold rolled	***	28.8	2.1
steel	extruding, galvanizing	37.3	3.2
vinyl	extrusion	11.8	0.5
water-based paint	***	77.6	+
wood	milling	5.8	0.8

* *according to manufacturer[32] 50% post-industrial vinyl, 50% recycled post-industrial wood*
** *For materials where specific primary energy and GWP data were not available, similar materials with complete data sets were substituted (for ceramic sinks "ceramic tile" data were used, and for latex in carpet and paint, "SBR" was used)*
*** *fabrication primary energy not included*
\+ *data not available*
++ *Other contradictory values for SBR and rubber were found: Rubber 67.7 MJ/kg[33], SBR 145.1 MJ/kg[34]*

Several building materials were composites. Carpet, for example, was assumed to be 58% nylon (PA6), 10% Polypropylene (secondary backing) and 32% Latex (binder)[35].

2.5 Home Maintenance and Improvements

To determine the contributions of maintenance and home improvements on life cycle energy consumption, a schedule of activities was created. It determines the interval of those maintenance activities that are needed to keep the home in good repair (e.g., repair of broken windows, or changing of light bulbs), as well as those of major home improvements (e.g., replacement of siding, carpet, roofing). Materials needed for these activities were quantified, and their life cycle energy and GWP added to the total. Table 2-4 provides an overview of home maintenance and improvement assumptions, based on a home life of 50 years. Data on the replacement rate of many items could not be found, and replacement frequencies were therefore estimated. Other sources are shown.

TABLE 2-4 Maintenance and Home Improvement Schedule for SH and EEH

Activity *(based on home life of 50 years)*	**Years occurring after Construction**	**Source**
Inside walls and door repair	25	Estimation
1st & 2nd floor internal re-painting	10, 20, 30, 40	Estimation
Exterior re-painting	10, 20, 30, 40	Estimation
PVC siding	25	Astro Building Prod.[36]
New roofing (asphalt shingles) for SH	20, 40	DEAM Data Base[37]
New refrigerator	15, 30, 45	Estimation
New garbage disposal	15, 30, 45	Estimation
New sump pump	15, 30, 45	Estimation
New water heater	15, 30, 45	Estimation
New range	15, 30, 45	Estimation
New range hood	25	Estimation
New A/C central unit	20, 40	Estimation
New dishwasher	20, 40	Estimation
New cloths washer	15, 30, 45	Estimation
New cloths dryer	15, 30, 45	Estimation
Kitchen and bathroom cabinet replacement	25	Estimation
Changing of all incandescent light bulbs for SH	every 3 years	*Calculation
Changing of all compact florescent light bulbs for EEH	every 5 years	*Calculation
Replacement of all vinyl floor tiles in house	20, 40	Estimation
Replacement carpet	every 8 years	Interface Inc.[38]
Replacement of all windows (includes breakage)	25	Estimation

* calculated using bulb life and annual hours of light usage

2.6 Life-Cycle Inventory of SH

2.6.1 Construction Phase

Material quantities for SH were determined by taking blue-print dimensions and performing field cross-checks. The Princeton home studied was a finished model home, with a similar unit under construction adjacent to it. By using these two sites, it was possible to verify all dimensions. Mass was determined by using material density data. When published data were unavailable, field weighing established material densities. Local vendors, subcontractors and product representatives were of great assistance in providing information (e.g., product dimensions, weights, material compositions).

Because many appliance manufacturers do not provide the weight of their products, appliance mass was determined by contacting local distributors and inquiring for shipping weight. Appliance material composition was checked against material composition data taken from a life cycle inventory study of a kitchen range[39]. Percentages of various materials (e.g., steel, aluminum, glass, plastic) in that study were used in estimating the percentage of materials in other appliances.

The database used to inventory material production and component manufacturing energy and GWP, accounted only for transportation to the manufacturer. Modes of transportation, and the distance from part/component manufacturer to the construction site had to be determined. Table 2-5 shows transportation data summarizing information provided by local suppliers. Due to the nature of the lumber data sets employed in this study,[40] it was not possible to separate wood transportation energy from total energy. However, the figures do reflect the “average transportation distance and mode”[41] for wood from western states to all other states.

TABLE 2-5 Transportation Distance and Mode Data

Material	Distance from Source	Mode of Transportation
Concrete	50 miles (80 km)	100% truck
Gravel	30 miles (48 km)	100 % truck
All Other	400 miles (640 km)	50 % truck, 50 % rail
Disposal of Demolished Materials	100 miles (160 km)	100% truck

2.6.2 Use Phase

Building energy consumption can be determined by taking measurements of the actual fuel and electricity consumed over an extended period, or by modeling simulations. Use of modeling software was selected for several reasons:

1) The project time limitations did not allow for actual site measurement. A full year of measurements would be needed. A survey of randomly selected Princeton home owners was taken, however (see Section 2.6.7).
2) Employing simulation software eliminates distortions from seasonal variations, calibration errors of heating/cooling control equipment, irregular occupant behavior, and abnormal weather conditions.
3) Modeling of SH with software made design of EEH easier. Parameters where established by running numerous scenarios to determine the energy consumption of various building envelope configurations.

2.6.3 Modeling of SH

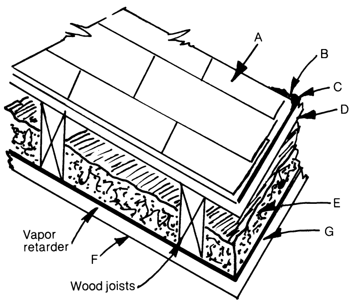
The Energy-10 software was used to model use-phase energy consumption. This software was developed in partnership by the Passive Solar Industries Council, the National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, and the Berkeley Solar Group, and distributed by the Passive Solar Industries Council[42].

Actual SH building characteristics modeled in Energy-10 were:

<u>walls</u>: 2x4 wood frame construction, 16” on center
3.5” of rolled bat glass wool insulation
0.5” drywall finishing on interior walls (0.75” for garage)
0.5” Orient strand board (OSB) and polyisocyanurate sheathing
PVC exterior siding

overall R-value of polyisocyanurate wall section = 14.9 (hr ft² °F/Btu)
overall R-value of OSB wall section = 12.2

roof/ceiling: prefabricated 2x4 wood trusses
8" of sprayed glass wool insulation ("E")
drywall finishing on interior ceiling ("F")
OSB sheathing on roof ("C")
asphalt roof shingles ("A")
#15 felt underlayment ("B")
overall R-value of ceiling = 22.9



floors 2x10 floor joists on 12" centers
0.75" OSB
carpet, vinyl and ceramic tile floor covering

windows: double-glazed double-hung windows with PVC frames
overall R-value (including frame) between 2.0-2.1
window glass thickness 1/8"

basement: f-factor for basement walls = 1.3 Btu/hr ft °F (used to calculate heat loss through the walls in an unheated basement)

infiltration: effective leakage area (ELA)[43] = 153 in²
0.67 house air changes per hour
fan air flow rate[44] = 302 cfm (ft^3/min)

other: occupancy: four people
South-East Michigan climate (Detroit, MI)
heating set point at 70°F with set-back point at 65°F,
cooling set point at 75°F with set-up point at 79°F
heating and cooling set-back/set-up occur between 11 pm and 7 am

2.6.4 SH Heating/Cooling Energy Use

Both heating and cooling energy were determined with Energy-10 for SH as well as for EEH. The program calculates the heat required to maintain the internal building temperature based on the following factors:

- averaged conductivity of the thermal envelope. R-values of the walls, ceiling, floor, foundation and windows are combined using the respective areas of each;
- outside temperature and wind speeds based on average Detroit weather data;

- internal temperature which includes setting the thermostat up or down depending on season and time of day;
- ventilation from outside air infiltration through gaps in the building envelope (ELA) and forced-air ventilation systems (ACH);
- internal heating from other sources (see Section 2.6.5);
- efficiency of the furnace and A/C systems, which take into account air duct placement and leakage, as well as fan efficiencies;
- solar heat gains through windows, which factors in glazing area and orientation to the sun, optical properties of the glazing, and shading effects from awnings .

2.6.5 Internal Heat Gains

Internal heat gains from lights, electrical appliances, hot water and occupants were determined separately and imported into Energy-10. These additional internal heat gains lower the natural gas heating requirement (but increase summer cooling energy requirements). Calculating internal heat gain was done in two steps:

1) Peak internal heat gains were calculated in W/ft^2 (as required by Energy-10). The peak load occurs when a specific source (e.g., stove or hot water heater) is operating at its highest "level" of performance, thus emitting the largest amount of waste heat.

2) The magnitude of internal heat radiating from different sources varies according to the time of day. Energy-10 timetables were used that allocate internal heat released into the building thermal envelope as a fraction of peak load. Lower daytime and continuous weekend occupancy was assumed.

Peak internal loads were determined by calculating the radiative energy from the total number of heat emitters at the time of maximum use. This was usually between 7-11 PM. This corresponds with maximum family usage of lights, electrical appliances, hot water, and with the maximum number of occupants in the building. These combined heat sources help heat the building. Consumption data for hot water usage, typical home electrical appliances and plug loads were based on "Household Energy Consumption and Expenditures 1993"[45]. The heat gain value used for occupants was 100 W/person[46].

2.6.6 SH Electrical Energy Use

Electrical energy consumption was determined independently from Energy-10. A list of appliances used in the building was determined, which consisted of standard household appliances and entertainment equipment. Appendix D-1 provides a list of those appliances modeled, and their annual energy use. Actual SH appliance manufacturers and model numbers were recorded. Those manufacturers were contacted and average annual energy consumption information collected. Other sources were used to determine annual energy use when model types were not known[47].

2.6.7 Survey of SH Heating Energy Consumption

To check Energy-10 generated results, seven survey forms were mailed to Princeton home owners in the subdivision studied. A sample of the survey form is given in Appendix A-1. Only one household responded to the survey. Visits to those homes not returning the survey were then conducted. It was revealed that most were renters, or had not lived in the home for more than one year. An Energy-10 calculation was performed and the results normalized for actual heating-degree days (HHD) in 1997-98[48]. Table 2-6 compares the Energy-10 calculation to the single survey result.

TABLE 2-6 Summary of Princeton Energy Use Survey

Source	Annual Natural Gas Costs	
Survey #1	$667.40	(HDD Normalized)
Energy-10	$637.00	(Actual)

The Energy-10 result was only 4.8% lower that the field survey result. The variation could be due to one or several of the following reasons:

- The average number of occupants in the Princeton homes surveyed is not 4
- Actual electrical usage was different because of varying numbers of appliances and use patterns
- Thermostat set-ups and set-backs varied

2.7 Life Cycle Inventory of EEH

EEH was modeled for greater energy efficiency to determine by what degree environmental impacts could be reduced, and at what incremental cost. It was also modeled to have the same floor plan and internal dimensions as the SH. The guiding principle in the design of EEH was to minimize life cycle energy. As reported in Section 3.2, 93.7% of SH life cycle energy consumption occurs in the use-phase. Thus, EEH design changes focused on minimizing use phase energy. Measures to reduce the material fabrication/construction (pre-use phase) energy by choosing materials with lower embodied energy were also taken.

Reductions in heating and cooling loads also allow for downsizing of furnace and A/C equipment which reduce overall cost. This is a secondary, but nevertheless significant benefit of a higher performance thermal envelope.

2.7.1 EEH Construction Phase

SH effective leakage area (ELA) was measured to be 153 square inches[49] (see Section 3.5.2). EEH was estimated to be 20 square inches[50]. This is based on thorough use of caulking, and the effects of sprayed-in cellulose insulation.

Building materials with lower embodied energy or higher durability were identified to replace SH materials with high embodied energy or with high replacement frequencies. In terms of embodied energy over the life cycle of the home, the major targets for reduction were polyamid (PA), concrete, asphalt shingles, steel, and polyvinylchloride (PVC). GWP reductions concentrated on concrete and steel because they make up a significantly high percentage of the building's mass.

Attention was given to those materials which effect both, use-phase and the embodied energy. Substitution of glass fiber heat insulation with cellulose insulation (made from 100% recycled newspaper[51]) is an example of this dual approach. Cellulose insulation has 87% less embodied energy per kg installed than fiberglass insulation. In addition, the R-value of sprayed-in cellulose insulation is 10% higher than that of fiber glass insulation. The life cycle inventory data sets used reflect both, the change in insulation mass, and embodied energy per kg. Based on the application technique, cellulose insulation also creates a tighter air infiltration barrier by filling in more voids in the wall cavity.

Careful consideration was given to wall design. Pierquet, et al.[52] evaluates the embodied energy of 12 different wall systems and compares them to annual energy savings based on varying R-values. Pierquet, et al. used a standard 2x4 stud wall with fiberglass insulation as the base case, and compared it with wall sections made of strawbale, structural insulated panels (SIPs), I-beam studs, 2x6 studs, autoclaved cellular concrete, and varying combinations of 2x4 construction and rigid foam insulation. Walls with very high R-values included the strawbale and double 2x4 walls. The strawbale wall had the lowest embodied energy. When the fiberglass insulation in the double 2x4 wall was replaced with cellulose, its embodied energy dropped to be almost equal with that of the strawbale wall.

Strawbale walls are not commonly used in northern climates. Special efforts must be made to protect the straw from moisture, and were therefore not considered. SIPs are relatively easy to build with and form a tight air seal. There is considerable embodied energy in the extruded polystyrene (EPS) foam insulation however. For this reason, SIPs were not considered. The double 2x4 wall with cellulose insulation was selected based on embodied energy and R-value criteria.

The concrete basement walls, having a high embodied energy due to their mass, were replaced with wood walls having a lower embodied energy. The wood walls also have a higher R-value. A bare 10" thick concrete basement wall has an R-value of 12 when the thermal insulating effects of the earth are included. A 2x8 wood frame wall (with CCA-treated studs and plywood to resist decay), insulated with cellulose, has an R-value of 39. There is also a net reduction of overall embodied energy of 2.5%. Wood basements are built in Michigan, and at least one local architect[53] uses them. One company in Detroit[54] specializes in wood basements, and has built them for many years.

It must be noted that the chromated copper arsenate (CCA) used to treat the wood is toxic. Manufacturing, use, and disposal of this product may generate serious environmental problems. Alternatives to CCA have showed only moderate success[55]. Another alternative to both cast-in-place concrete, and pre-treated wood foundation walls are pre-cast foundation blocks. These blocks may have lower life cycle energy characteristics. This study did not pursue this alternative.

Except for color (affecting solar absorptivity and reflectivity), roof cover materials have little or no effect on the heat gain or loss through the building envelope because the roof is un-insulated and the attic space is ventilated. However, the asphalt shingles used on SH, have a very high embedded energy per unit of mass. The BEES[56] database indicated that after 20 years, a second layer of asphalt shingles are placed on top of the original layer. At year 40, both shingle layers and the original felt underlayement are removed, and a new layer of shingles and felt underlayment applied. This makes the roof a very energy intensive part of the house. As an alternative, a product consisting of 50% post-industrial vinyl and 50% recycled post-industrial wood[57] was selected. It is similar in appearance to wood shingles. The manufacturer gives a 50 year warranty. This approach reduced the life cycle embodied energy of the roofing materials by 98 %. Another alternative with potentially lower embodied energy are sheet metal based roofing materials. This study did not examine the cost or life cycle energy of this building material.

Steel is a major component of SH GWP. The majority of the steel in the home is found in the duct system, appliances and assorted fasteners. No suitable alternatives to these steel products were identified.

Electrical appliances are complex systems containing many components and materials. A developing body of work in the Life Cycle Design community is dedicated to reducing the life cycle environmental impacts of such products. Because the pre-use phase energy of appliances contribute only a small fraction to the overall environmental burdens of the home, this study did not pursue strategies to reduce them. Determination of the material composition of EEH appliances used the same approach taken in Section 2.6.1 for SH appliances. Appliance mass was determined by requesting shipping weight information from local distributors and product manufacturers. Appliance material composition was checked against material composition data taken from a life cycle inventory study of a kitchen range[58]. Percentages of various materials (e.g., steel, aluminum, glass, plastic) in that study were used in estimating the percentage of materials in other appliances.

The effort to select appliances with lower life cycle energy consumption focused on the use phase. Appliances were selected that conserve electricity by being more efficient. The range and the clothes dryer were switched to run on natural gas because of the overall higher primary energy utilization of natural gas over electricity. About 30% of the power generated by burning fossil fuel in power plants actually reaches the home. This is because of accumulated energy conversion losses of fuel to heat, electrical generation and transmission.

2.7.2 Use Phase

To reduce energy consumption, efforts concentrated on reducing building envelope heat loss, increasing solar heat gain, reducing summer overheating, and employing higher efficiency heating/cooling equipment and appliances. Tables 2-7 through 2-21 list the various design scenarios considered, and detail the advantages and reductions in embodied energy, and state whether they were employed or not.

TABLE 2-7 Energy Efficient Strategy Walls/Insulation

WALLS - INSULATION	
Strategy:	substitute fiberglass insulation with cellulose, and increase thickness by creating a double 2x4 wall (See sketch of Saskatchewan wall section Figure 2-7)
Advantage:	improve thermal performance of envelope, reduce embodied energy of insulation per kg, increase recycled content
SH materials deleted:	fiberglass bat insulation
SH Mass, wood/fiber glass (50 yr.):	12,297 kg
SH Embodied energy (50 yr.):	78,027 MJ
EEH materials added:	additional wood studs, cellulose insulation
EEH Mass, wood/cellulose (50 yr.):	18,807 kg
EEH Embodied energy (50 yr.):	108,577 MJ
Increase of Embodied Energy (50 yr.)	39%
Comments:	**EMPLOYED** A major cause for use-phase energy consumption reductions

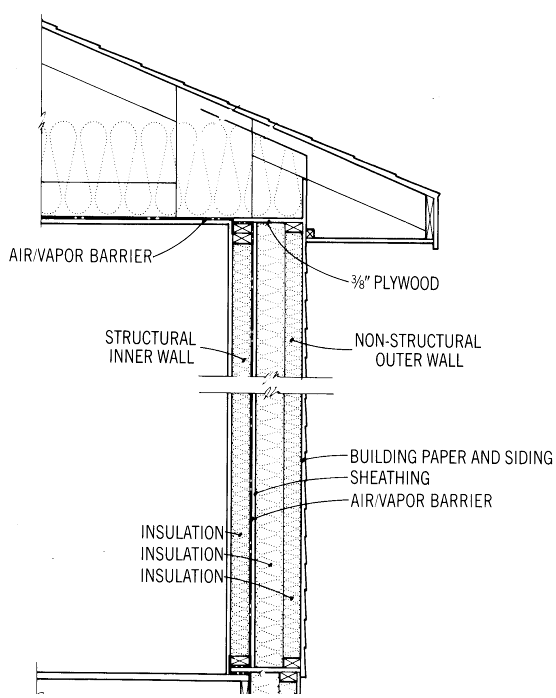


FIGURE 2-7 EEH Saskatchewan Wall System [59]

TABLE 2-8 Energy Efficient Strategy Walls/Infiltration

WALLS - INFILTRATION	
Strategy:	reduce infiltration from average of 0.67 ACH, to 0.35[60] with caulking, sprayed-in cellulose, (see Figure 2-8)
Advantage:	reduce use-phase energy consumption
SH materials deleted:	n/a
SH Mass (kg for 50 yr.):	n/a
SH Embodied energy (MJ)	n/a
EEH materials added:	negligible (caulking)
EEH Mass (kg for 50 yr.):	negligible
EEH Embodied energy (MJ)	negligible
Reduction of Embodied Energy (MJ)	n/a
Comments:	**EMPLOYED**

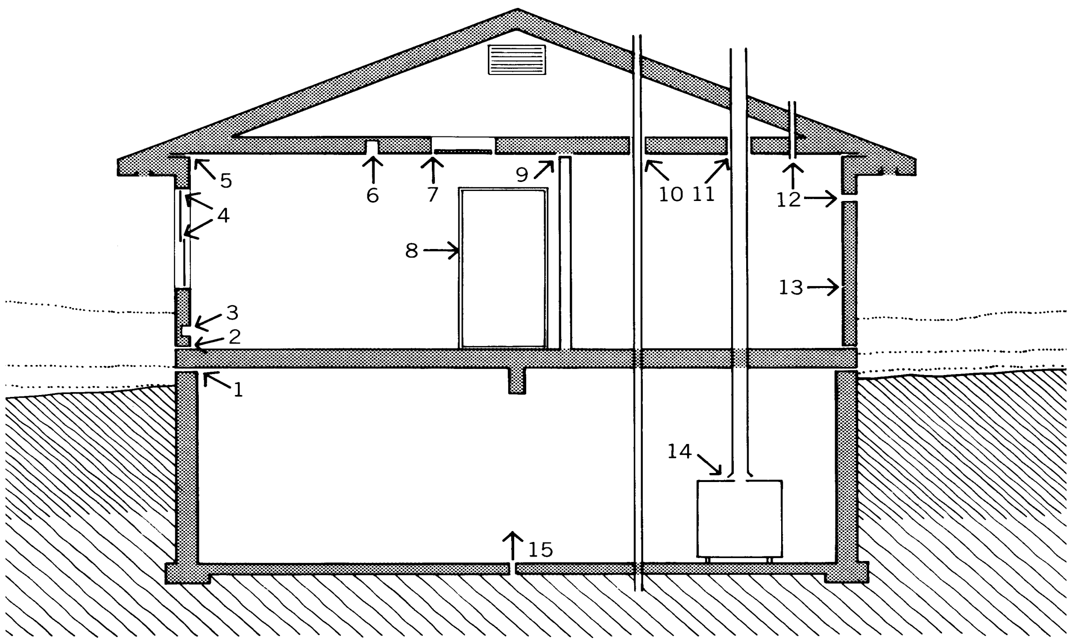


FIGURE 2-8 Typical Air Leakage Spots [61]

Legend:
- 1-joints between joists and foundation
- 2-joints between sill and floor
- 3-electrical boxes
- 4-joints at windows
- 5-joints between wall and ceiling
- 6-ceiling light fixtures
- 7-joints at attic hatch
- 8-cracks at doors
- 9-joints at interior partitions
- 10-plumbing-stack penetration of ceiling
- 11-chimney penetration of ceiling
- 12-bathroom and kitchen ventilation fans
- 13-air/vapor barrier tears
- 14-chimney draft air leaks
- 15-floor drain

TABLE 2-9 Energy Efficient Strategy Walls/Sheathing

WALLS - SHEATHING	
Strategy:	replace polyisocyanurate with oriented strand board (OSB)
Advantage:	reductions in life cycle energy, increased use of renewable resources, additional structural strength
SH materials deleted:	polyisocyanurate, steel wind bracers
SH Mass OSB, polyisocyanurate, steel wind bracers (50 yr.):	1,660 kg
SH Embodied energy (50 years)	10,430 MJ
EEH materials added:	OSB
EEH Mass OSB (50 yr.):	2,536 kg
EEH Embodied energy (50 years)	8,622 MJ
Reduction of Embodied Energy (50 years)	17%
Comments:	**EMPLOYED**

TABLE 2-10 Energy Efficient Strategy Walls/Exterior Siding

WALL - EXTERIOR SIDING	
Strategy:	substitute PVC siding with wood
Advantage:	reduces embodied energy over the life cycle of the house
SH materials deleted:	PVC siding panels (77.4 MJ/kg for PVC)
SH Mass (kg for 50 yr.):	1,098 kg
SH Embodied energy (MJ)	93,210 MJ
EEH materials added:	wood siding board (6 MJ/kg), water-based paint (77.6 MJ/kg)
EEH Mass (kg for 50 yr.):	1,041 kg (including paint)
EEH Embodied energy (MJ)	28,120 MJ (including repainting every 5 years)
Reduction of Embodied Energy (MJ)	65,090 MJ
Comments:	**NOT EMPLOYED** because of higher maintenance requirements, and low amount of wood suitable for recycling

TABLE 2-11 Energy Efficient Strategy Roof/Insulation

ROOF INSULATION	
Strategy:	substitute fiberglass insulation with cellulose, and increase thickness (attic), modify roof truss to accommodate for additional ceiling insulation (see Figure 2-9)
Advantage:	SH ceiling is R-23 EEH ceiling is R-49. Cellulose has better air infiltration properties and lower EE.
SH materials deleted:	blown-in fiberglass
SH Mass (50 yr.):	476 kg
SH Embodied energy (50 yr.):	11,735 MJ
EEH materials added:	blown-in cellulose
EEH Mass (50 yr.):	1,506 kg
EEH Embodied energy (50 yr.):	5,599 MJ
Reduction of Embodied Energy (50 yr.):	52%
Comments:	**EMPLOYED (although there may be added construction difficulties)**

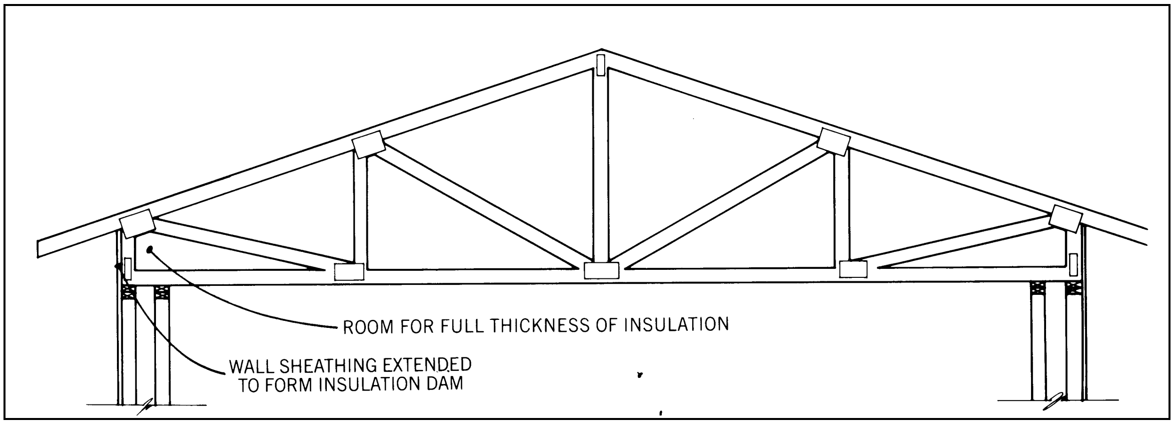


FIGURE 2-9 Raised Roof (to accommodate sufficient ceiling insulation)[from 62]

TABLE 2-12 Energy Efficient Strategy Roof/Shingles

ROOF - SHINGLES	
Strategy:	substitute asphalt shingle roofing with recycled plastic/wood fiber shingles[63]
Advantage:	lower embodied energy
SH materials deleted:	asphalt shingles and No. 15 Felt underlayment
SH Mass (50 yr., 2 replacements):	8,862 kg
SH Embodied energy (50 yr. 2 replacement):	142,587 MJ
EEH materials added:	recycled-plastic/ wood composite shingles
EEH Mass (50 yr., no replacement):	441 kg
EEH Embodied energy (50 yr., no replacement):	3,023 MJ
Reduction of Embodied Energy (50 yr.):	98%
Comments:	**EMPLOYED**

TABLE 2-13 Energy Efficient Strategy Basement/Walls

BASEMENT - WALLS	
Strategy:	replace 10” concrete foundation wall with 2x8 wood frame wall with cellulose insulation
Advantage:	increases thermal insulation and reduces embodied energy
SH materials deleted:	10” concrete basement walls, drywall inside
SH Mass concrete foundation wall/floor slab, damp proofing (50 yr.):	172,060 kg
SH Embodied energy (50 yr.):	285,641 MJ
EEH materials added:	2x8 wood studs (12" on center), 8" thick sprayed-in cellulose, plywood, PE foil, and drainage gravel outside, drywall inside
EEH Mass wood structure, cellulose, drainage gravel, concrete footing/floor slab (50 yr.):	190,075 kg
EEH Embodied energy (50 yr.):	276,001 MJ
Reduction of Embodied Energy (50 yr.):	3.4%
Comments:	**EMPLOYED**

TABLE 2-14 Energy Efficient Strategy Basement/Insulation

BASEMENT - INSULATION	
Strategy:	insulate foundation
Advantage:	Reduces heat losses through basement walls
SH materials deleted:	10” concrete basement walls
SH Mass concrete foundation wall/floor slab, damp proofing (50 yr.):	172,060 kg
SH Embodied energy (50 yr.):	285,641 MJ
EEH materials added:	Foam board insulation
EEH Mass (50 yr.):	not calculated
EEH Embodied energy (50 yr.):	not calculated
Reduction of Embodied Energy (50 yr.):	not calculated
Comments:	**NOT EMPLOYED** (Wood basement used)

TABLE 2-15 Energy Efficient Strategy Floors/Tiling & Thermal Mass

FLOORS - TILING & THERMAL MASS	
Strategy:	install tile floors and specify limited use of throw-down rugs
Advantage:	create thermal storage mass, reduce embodied energy consumption of carpet
SH materials deleted:	2x10 floor with carpet
SH Mass carpet first floor (50 yr.):	3,284 kg
SH Embodied energy (50 yr.):	403,972 MJ
EEH materials added:	2x12 rafters, 12" on center, OSB, 3" concrete, 0.75" tiles, (carpet only in bedroom and closet/closet hallway)
EEH Mass concrete/tiles/mortar (50 yr.):	27,445 kg
EEH Embodied energy (50 yr.):	134,736 MJ
Reduction of Embodied Energy (50 yr.):	67%
Comments:	**NOT EMPLOYED** heating energy actually increased with the above arrangement at an additional cost for concrete/tile floor of about $19,000. Only when insulation was put underneath the concrete, did the heating energy decrease to the value of a 2x10 floor with fiberglass insulation.

TABLE 2-16 Energy Efficient Strategy Floors/Alternate Covering Material

FLOORS - ALTERNATE COVERING MATERIAL	
Strategy:	replace carpet with material with lower embodied energy
Advantage:	lower embodied energy
SH materials deleted:	carpet
SH Mass carpet entire home (50 yr.):	n/a
SH Embodied energy (50 yr.):	n/a
EEH materials added:	e.g., cork
EEH Mass (50 yr.):	n/a
EEH Embodied energy (50 yr.):	not available
Reduction of Embodied Energy (50 yr.):	n/a
Comments:	**NOT EMPLOYED** best alternative appeared to be cork, but was considered to be too expensive (although provides large savings in embodied energy). Initial installation cost were approximately 2.5 times higher than carpet, although life cycle

	cost was 10% lower, due to a lower replacement rate and less maintenance.

TABLE 2-17 Energy Efficient Strategy Windows/Glazing Area

WINDOWS - GLAZING AREA	
Strategy:	Increase window area from 337 ft^2 (using double lowE/argon in EEH) to 490 ft^2 (double lowE/argon in EEH)
Advantage:	Increases solar gain while reducing heating (and possibly cooling loads)
EEH original Mass (50 yr.):	923 kg (from glazing area of 337 ft2)
EEH original Embodied energy (50 yr.):	36,603 MJ
EEH materials added:	LowE glass, argon, (additional 153 ft2)
EEH new Mass (50 yr.):	1,342 kg
EEH new Embodied energy (50 yr.):	23,559 MJ
Increase of Embodied Energy (50 yr.):	7,356 MJ
Comments:	**LOW-E COATING EMPLOYED, INCREASED GLAZING AREA NOT EMPLOYED** Additional glazing area is not effective because of increased annual primary energy consumption. See section 3.5.1 for additional explanation.

TABLE 2-18 Energy Efficient Strategy Appliances

APPLIANCES	
Strategy:	Where feasible, replace appliances using electricity with appliances that use natural gas. Install highest-efficiency appliances everywhere else
Advantage:	Using natural gas reduces primary energy consumption by a factor of about 3, Higher efficiency appliances lower use phase energy
SH Appliances:	Refrigerator, Garbage Disposal, Water Heater, Range, A/C Central Unit, Dishwasher, Clothes Washer and Dryer, and Furnace
Appliances not used in EEH anymore:	Garbage Disposal (composting or vermiculture assumed)
Appliances in EEH with increased efficiency:	Refrigerator, Furnace, Water Heater, Range, A/C Central Unit, Dishwasher, Clothes Washer and Dryer
Reduction of Embodied Energy (50 yr.):	no change assumed
Reduction of Use-Phase Energy	40%
Comments:	**EMPLOYED**

TABLE 2-19 Energy Efficient Strategy Lighting

LIGHTING	
Strategy:	Replace all incandescent bulbs with florescent bulbs.
Advantage:	Reduces use phase energy
SH materials deleted:	All incandescent bulbs
EEH materials added:	Compact and tube florescent bulbs
Reduction of Use-Phase Energy (50 yr.):	686 kWh/year reduction (73% reduction)
Comments:	**EMPLOYED**

TABLE 2-20 Energy Efficient Strategy Building-Integrated Shading

BUILDING-INTEGRATED SHADING	
Strategy:	Provide for optimum overhang on all windows (see Figure 2-10), based on Ann Arbor's latitude
Advantage:	Allows full winter sun access but cuts out significant amounts of summer sun, reducing summer heat gain
SH materials deleted:	None
SH Mass (50 yr.):	None
SH Embodied energy (50 yr.):	None
EEH materials added:	roof truss lumber, OSB roof sheathing, shingles
add'l EEH Mass OSB, 2x4 lumber, plastic/roof roof shingles (50 yr.):	260 kg
EEH Embodied energy (50 yr.):	17,872 MJ
Increase of Embodied Energy (50 yr.):	17,872 MJ
Comments:	**EMPLOYED**

TABLE 2-21 Energy Efficient Strategy Hot Water Heat Exchanger

HOT WATER HEAT EXCHANGER	
Strategy:	Recover waste heat from disposed-of hot water, utilizing a heat transfer coil that passes collected waste hot water around the hot water intake supply line.
Advantage:	Reduces the natural gas consumption for water heating by 40% (preheating water to the hot water heater)
SH materials deleted:	None
SH Mass (50 yr.):	None
SH Embodied energy (50 yr.):	None
EEH materials added:	copper tubing, solder
EEH Mass (50 yr)	not calculated
EEH Embodied energy (50 yr.):	not calculated
Increase of Embodied Energy (50 yr.):	not calculated
Comments:	**EMPLOYED reduces annual consumption of natural gas by 211 kg/yr.**

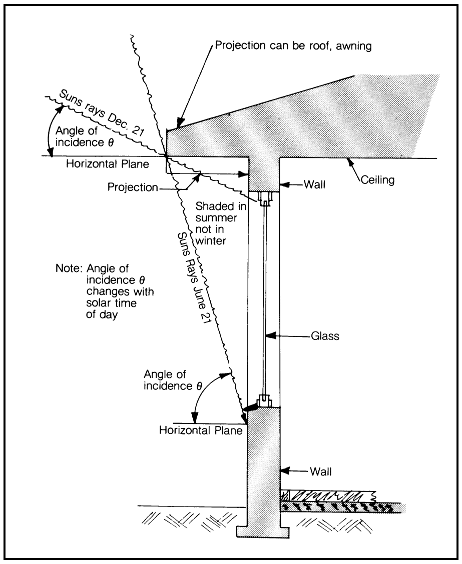


FIGURE 2-10 Optimum Window Overhang Design [64]

Solar orientation was also considered. The Princeton (SH) was built with the greatest amount of windows facing north (see Figures 2-1 and 2-4). In an Energy-10 simulation, the SH with true orientation was compared with an SH rotated 180°. Rotating the building reduced annual energy heating by 8/10 of a percent. Because this incremental increase in solar gain was obtained at no additional material cost, the EEH was modeled with a 180° rotation.

2.7.3 EEH Electrical Energy Use

EEH electrical energy consumption was determined in an identical fashion to SH. Appendix D-1 provides a list of those appliances modeled and their annual energy use.

2.8 Life Cycle Cost Analysis

The life cycle cost of SH was determined by adding the accumulated home finance payments (down and mortgage payments), annual utility payments, and scheduled maintenance and improvement costs. These represent all costs borne by the homeowner excluding items outside the study scope (e.g., furniture, landscaping, home insurance, property taxes).

The mortgage down-payment was assumed to be 15% of the home purchase value. Monthly mortgage payments were determined using an annual interest rate of 7% over a mortgage period of 30 years, payable at the first of the month. No refinancing was assumed, and these costs did not vary over the 30 year period.

The cost of EEH was calculated by:

1. determining the constructed cost of SH by dividing out the developers profit first, assumed to be 20%[65], and then subtracting the cost of the property, $55,000[66]. This gives the construction value of SH,

2. determining appropriate material and labor unit rates and contractor overheads for Michigan[67]; adjusting cost data (if more that one year old) using a 3% annual escalation rate,
3. defining which SH systems were to be replaced by more energy efficient systems, determining material quantities and installed cost; subtracting this cost from the construction value of SH in step 1,
4. defining new EEH systems and determining material quantities and installed costs; adding this cost to the result of step 3,
5. adding back property cost, and then the developer's profit used in step 1.

EEH annual mortgage costs were then determined using the same finance assumptions for SH.

Yearly home maintenance and improvement costs for both SH and EEH were based on the replacement timetable given in Table 2-4. Material quantities were determined for each task, and future labor and material unit rates calculated using a 3% annual escalation factor.

Year-one annual energy costs for SH were determined by first calculating annual natural gas usage (from energy-10 modeling) and electricity usage based on annual consumption data for home appliances (refer to Appendix D), and then multiplying by Ann Arbor utility rates of \$0.462/therm and \$0.08/kWh (residential rates[68]). Year one annual energy costs for EEH were determined by using the same approach except that energy consumption data for electrical appliances was selected from a list of most energy efficient equipment on the market[69].

Annual utility rates vary over time depending on numerous economic and political factors and have traditionally defied prediction. The task of estimating future natural gas and grid electric unit rates for the next 50 years was therefore not attempted. Instead, four energy rate scenarios were used to determine sensitivity of changing rates over time. The scenarios are summarized in Table 2-22 below:

TABLE 2-22 Utility Rate Escalation Scenarios

Scenario	Description of Scenario	Source
1	Natural gas rates remain constant for 50 years Electricity rates remain constant for 50 years	Base Case
2	Natural gas rates decline 1.1 %/yr. from 1998 up to 2010, rises 0.03% /yr. up to 2020. Does not change from 2021 to 2048 Electricity rates decline 1 %/yr. From 1998 up to 2010, declines an additional 0.58%/yr. until 2020. Does not change from 2021 to 2048	EIA DOE[70]
3	Natural gas rates escalate 4.2 %/yr. from 1998 until 2010. This gives an increase of 63% at year 2010. Annual escalation between 2011 and 2048 assumed to be 1%. Electricity rates escalate 4.2 %/yr. from 1998 until 2010 This gives an increase of 63% at year 2010. Annual escalation between 2011 and 2048 assumed to be 1%.	Wefa Inc.[71]
4	Natural gas costs \$0.721/therm in 1998 and increase annually 1% until 2048. Electricity costs \$0.127 \$/kWh in 1998 and increase annually 1% until 2048.	German[72]

3.0 RESULTS

3.1 Life Cycle Mass

The total life cycle mass of all construction and maintenance/improvement materials of SH, consumed during its assumed 50-year life-time, was determined to be 305.9 metric tons. Figure 3-1 shows the 10 SH materials with the largest life cycle mass contributions (the materials shown represent 89.4% of SH mass over 50 years).

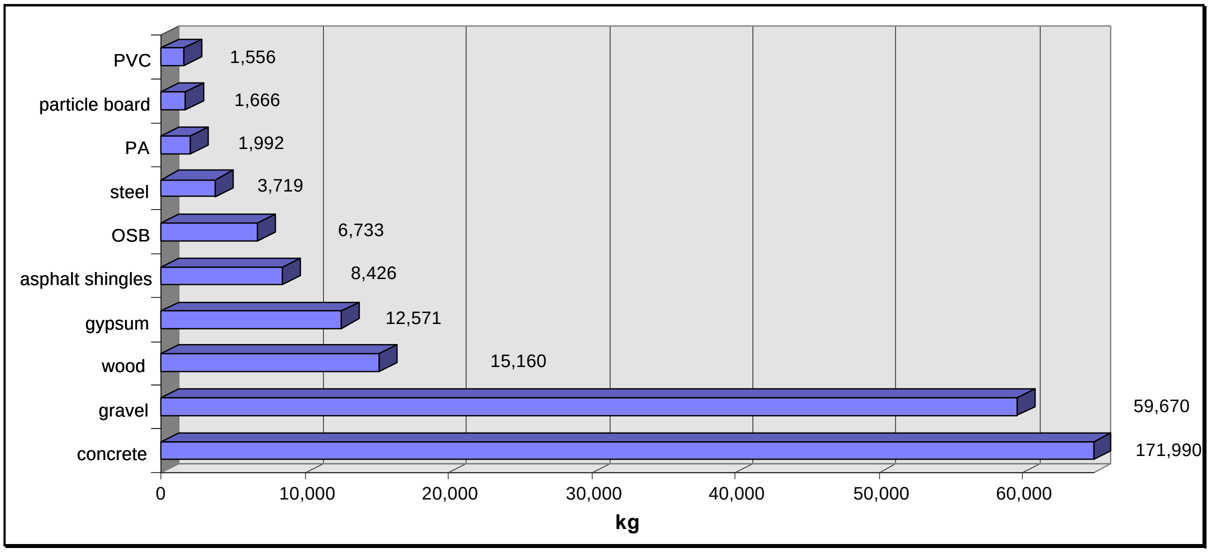


FIGURE 3-1 Mass Distribution SH, top-ten materials, total life cycle (incl. all building materials and appliances, new and replacements)

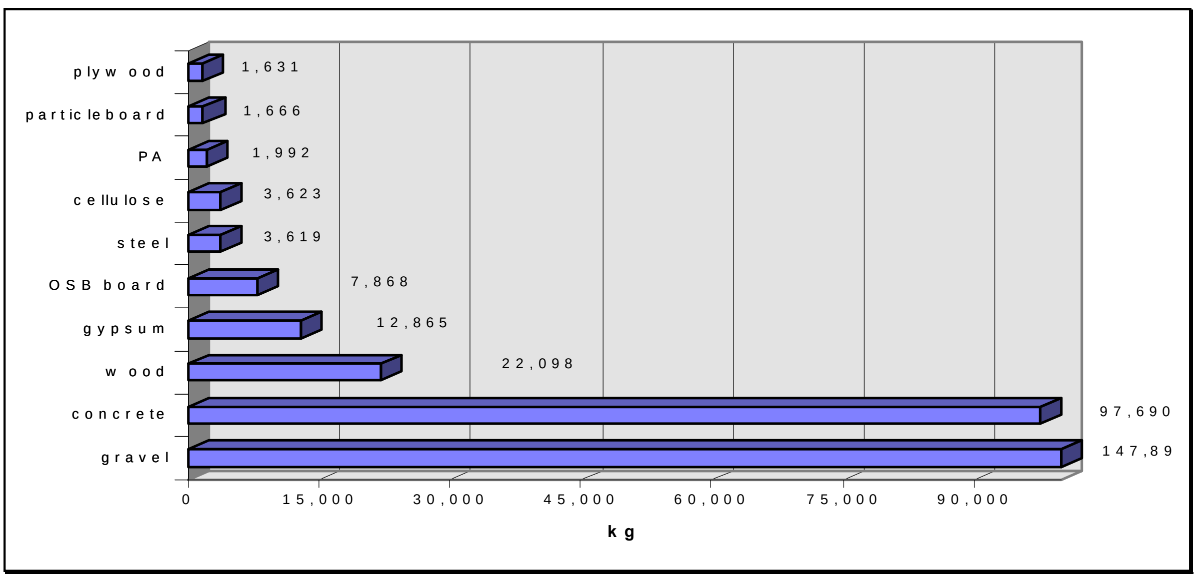


FIGURE 3-2 Mass Distribution EEH, top-ten materials, total life cycle (incl. all building materials and appliances, new and replacements)

The total life cycle mass of all construction and maintenance/improvement materials of EEH, consumed during its assumed 50-year life-time, was determined to be 325.6 metric tons.. Figure 3-2 shows the 10 EEH materials with the largest life cycle mass contributions (the materials shown represent 92.4% of EEH mass over 50 years). EEH is more massive because the additional weight of gravel and lumber exceed the weight of deleted concrete. Figure 3-3 shows the weight of the top-10 materials for SH that are used in the initial construction of the home. The total weight of SH after construction is 277.4 metric tons, while the weight of all maintenance and improvement materials in SH is 28.3 metric tons.

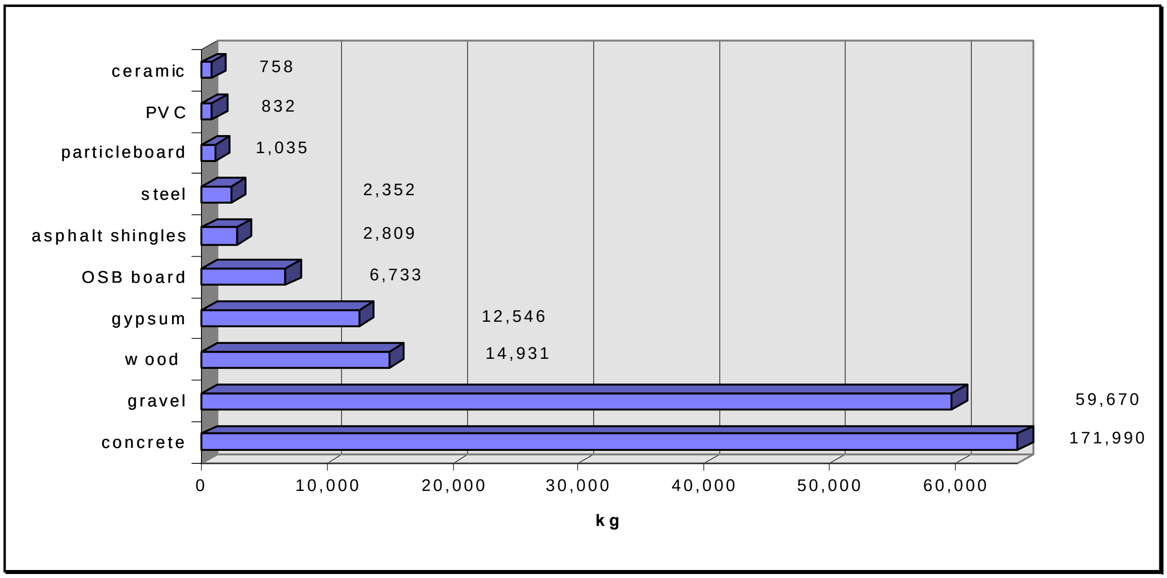


FIGURE 3-3 Mass Distribution SH, top-ten materials, year 0 (incl. all building materials & appl.)

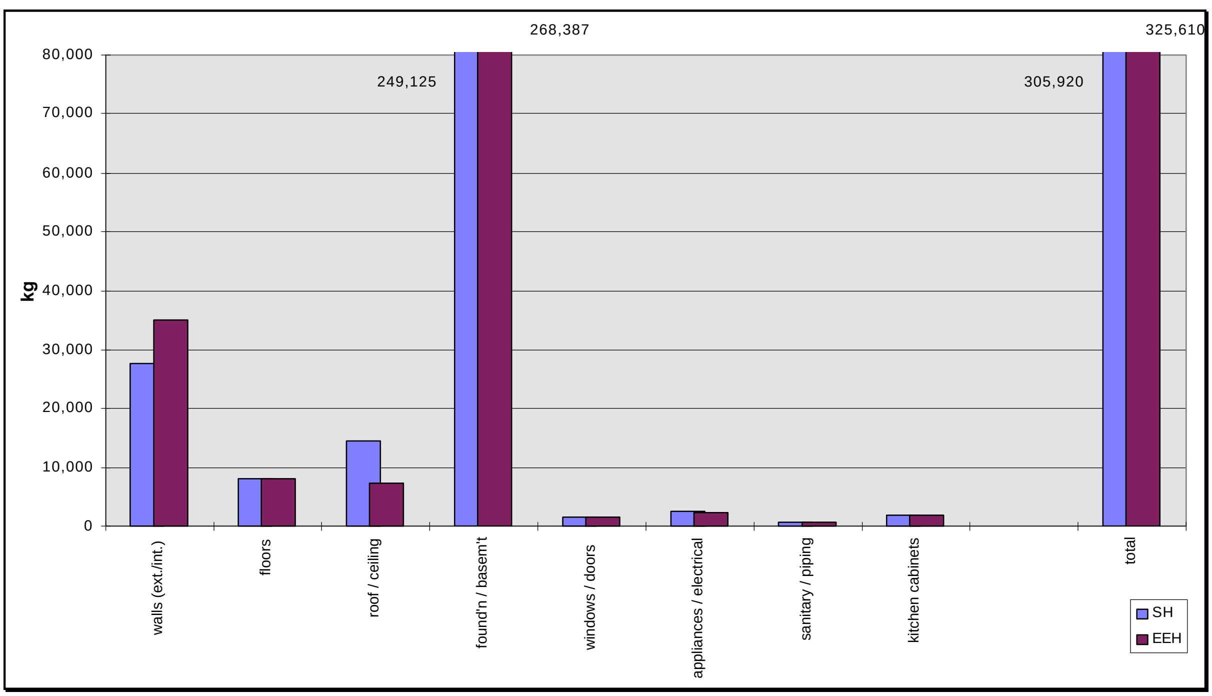


FIGURE 3-4 SH/EEH Mass Comparison by System, total life cycle (incl. all building and appliances, new and replacements)

Figure 3-4 shows the SH and EEH life cycle materials by home system as defined in 2.6. Figures 3-5 and 3-6 provide a percentage breakdown of all materials in both SH and EEH. Four basic material types were identified: minerals (e.g., gravel, gypsum, limestone), metals, petroleum based (e.g., plastics, solvents), and timber. Minerals include all materials extracted from the earth that are used without excessive processing including gravel, gypsum and concrete. Petrochemicals include all plastics, solvents and adhesives.

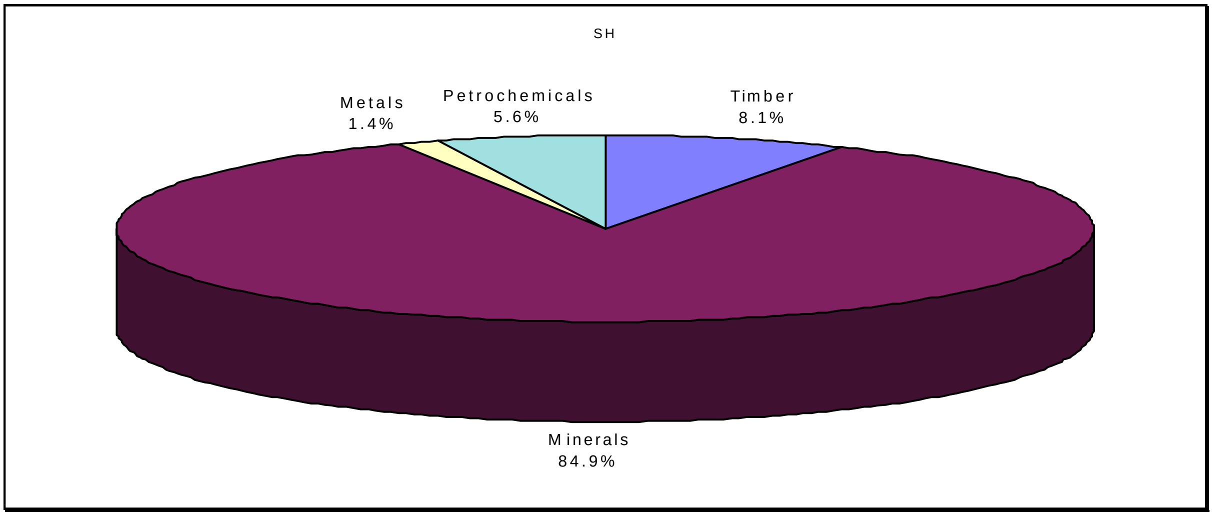


FIGURE 3-5 SH Mass Breakdown by Material Groups, total life cycle (incl. all building materials and appliances, new and replacements)

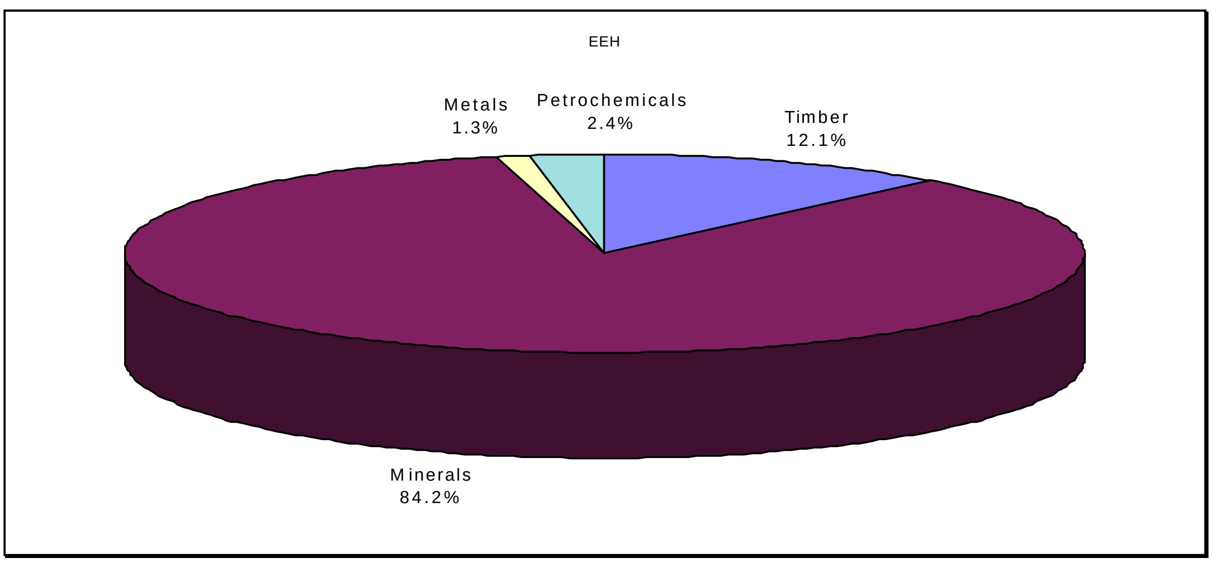


FIGURE 3-6 EEH Mass Breakdown by Material Groups, total life cycle (incl. all building materials and appliances)

3.2 Life Cycle Energy Consumption

The total life cycle energy consumption of SH is 15,455 GJ (equal to 2,525 barrels of crude oil). This takes into account the embodied energy of all construction and maintenance/improvement materials, all use phase energy, as well as demolition and transportation energy. SH raw material extraction/production and construction (pre-use phase) energy is 942 GJ or 6.1% of total life cycle energy use, while its use phase energy is 14,482 GJ (93.7%), and its end-of-life phase energy amounts to 31 MJ (0.2%).

The total life cycle energy of EEH in contrast is 5,653 GJ (equal to 927 barrels of oil). Raw material extraction/production and construction (pre-use) phase energy is 905 GJ (16.0%), use phase energy is 4,714 GJ (83.4%) and end-of-life phase energy is 34 GJ (0.6%). EEH life cycle energy consumption is 9,802 GJ less than the SH, which is a reduction of 63% (or 1,598 barrels of oil). Figure 3-7 graphically illustrates the percentage of pre-use, use, and end-of-life phase energy in both SH and EEH.

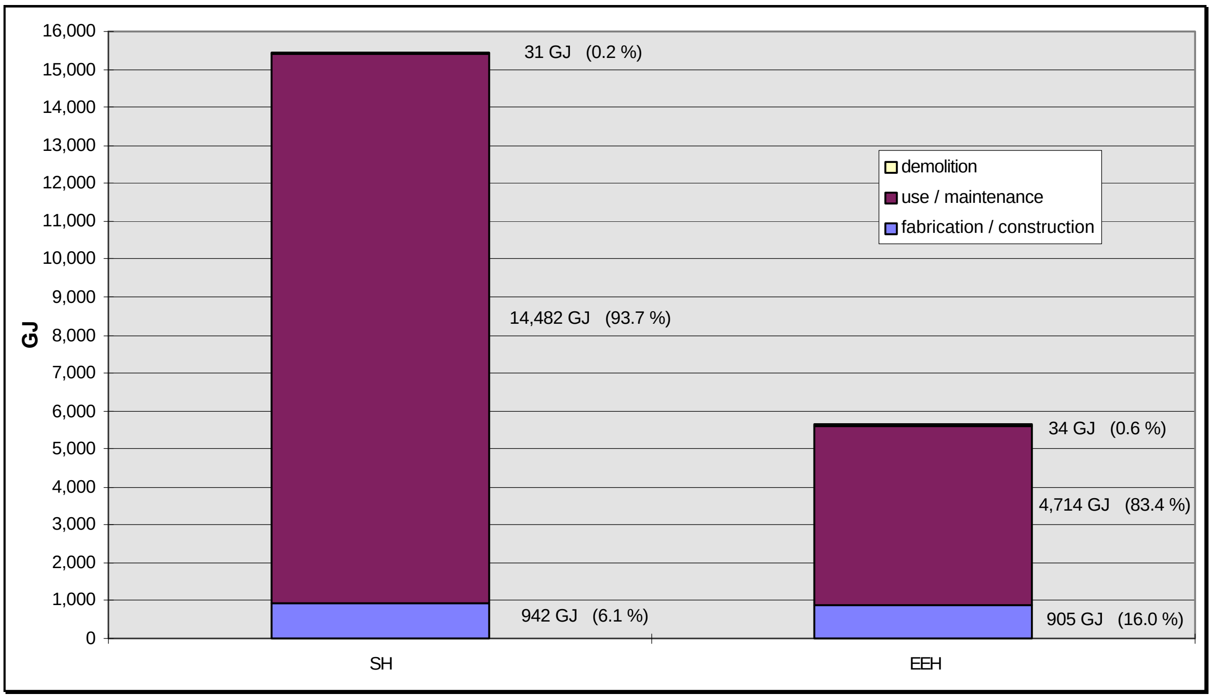


FIGURE 3-7 SH and EEH Primary Energy, total life cycle (incl. all building materials, appliances, and utility energy consumption)

SH energy consumption due to heating, cooling, and electricity consumption contributed 95.8% (13,877 GJ) to the use-phase number. The remaining 4.2% (605 GJ) came from replacement and home improvement materials. The same break-down for EEH on the other hand shows that 89% (4,195 GJ) of the use-phase primary energy is also consumed as natural gas and electricity, while 11% (519 GJ) went into replacement and home improvement materials.

Figures 3-8 and 3-9 show the total life cycle primary energy of the 15 most energy intensive materials in SH and EEH, respectively. In both houses, PA (polyamid) as a main constituent of carpet, consumes the most energy. This is a result of the high embodied energy of PA, the large amount of carpet used, and the fact that the carpet has a high replacement rate (every eight years). Alternative flooring materials with lower embodied energy were explored.

Cork tiling and parquet wood flooring do have lower embodied energy, and also have other aesthetic properties. The higher cost of these alternatives led to their being disqualified however. The initial installation cost of a cork floor covering , replacing all carpet and tiles on the first and second floors would be 2.4 higher than that for carpet. However, over the full life cycle of the house, cork would be approximately 10% less expensive, using established cost estimation data[73]. This is because with proper care (sanding and application of two layers of lacquer every 10 years), it does not need to be replaced over the 50 year life of the home[74]. Another alternative to carpet is tongue-and-groove wood flooring. This option was not investigated.

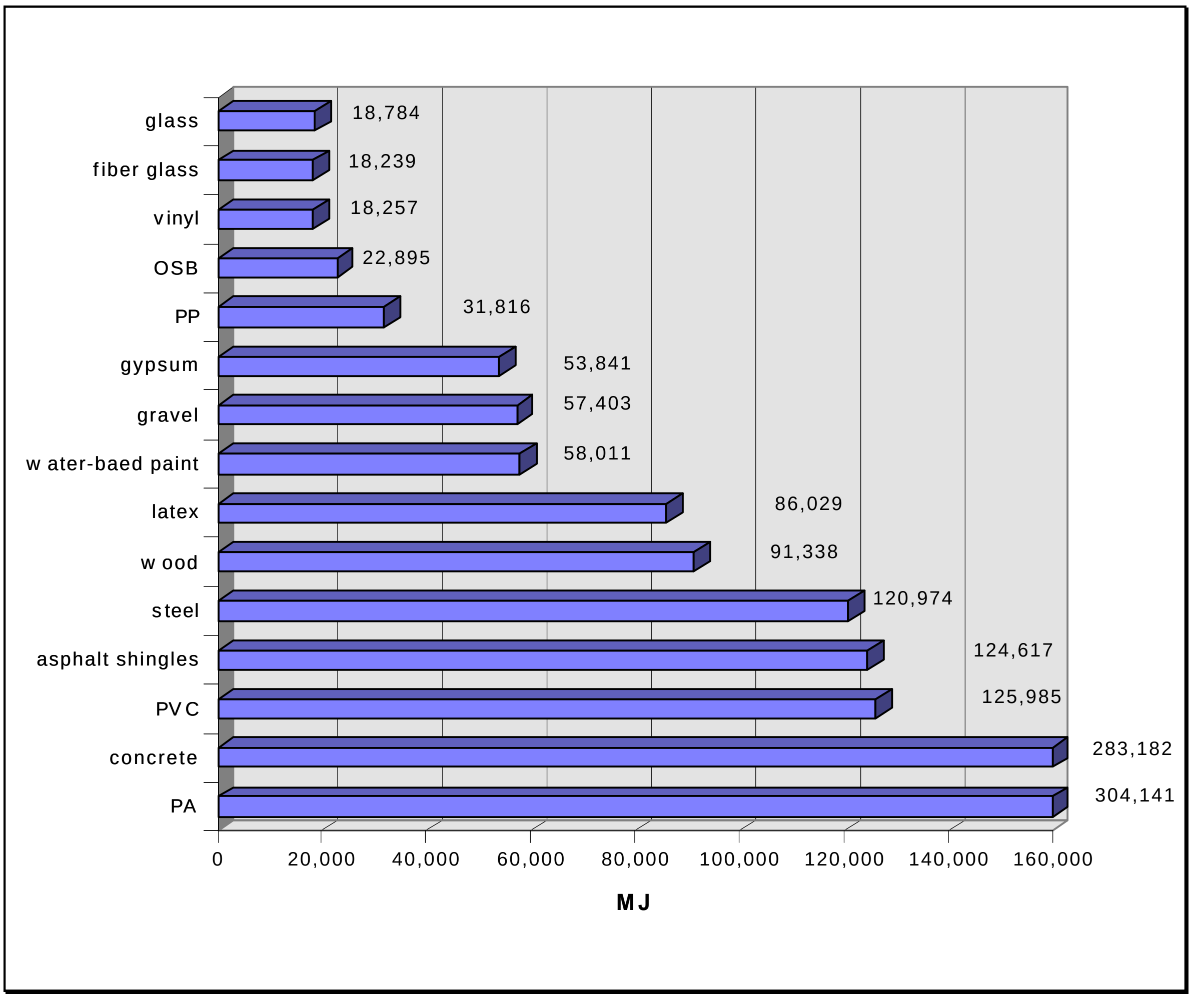


FIGURE 3-8 SH Primary Energy Consumption of top 15 materials, total life cycle (incl. all building materials and appliances)

Redesign of the EEH foundation has reduced concrete life cycle energy consumption by nearly half, and has more than doubled gravel life cycle energy. As a result of the EEH roof redesign, asphalt has been eliminated altogether, and its replacement (plastic/wood composite) is not even in the list of the 15 most energy intensive materials.

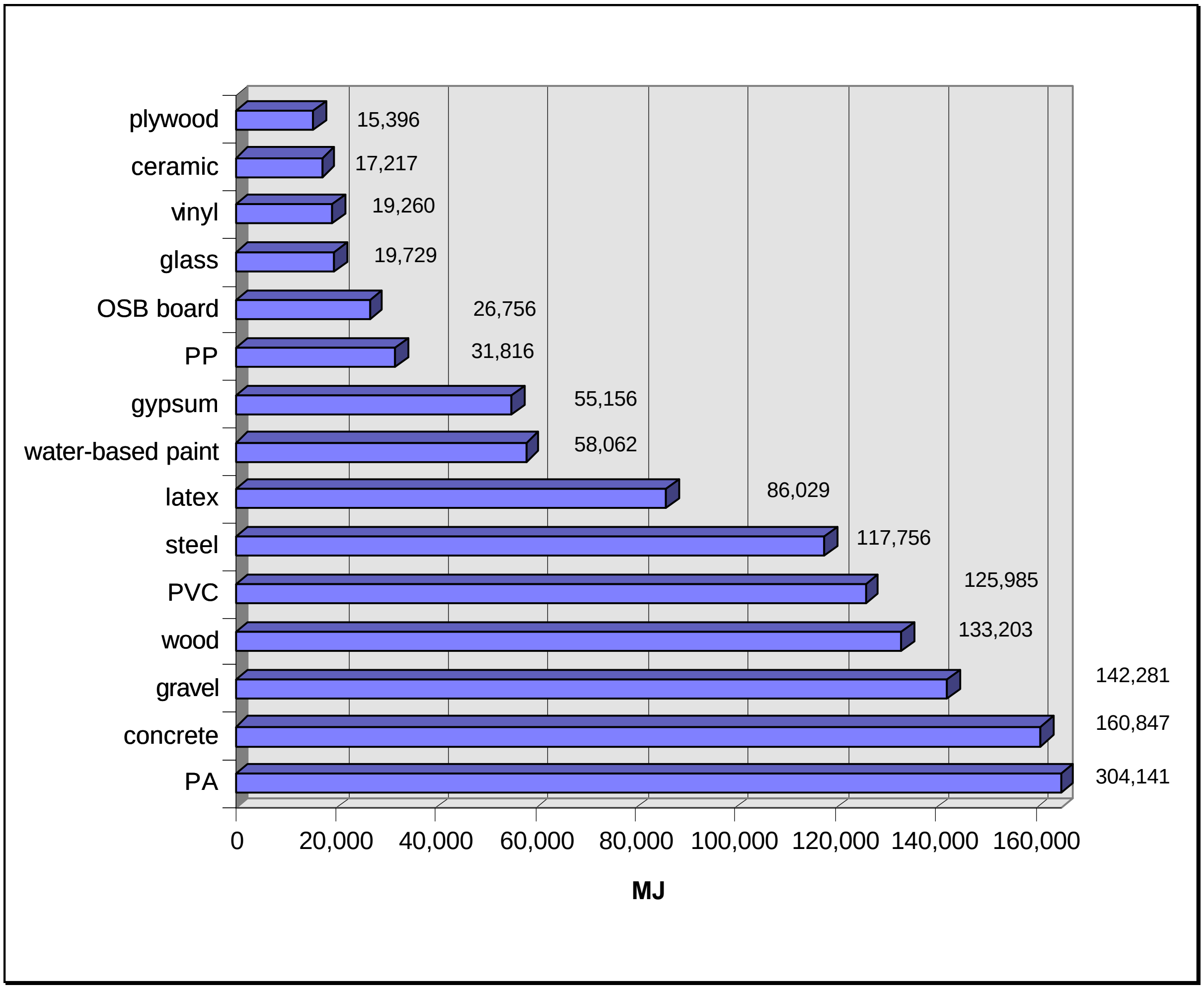


FIGURE 3-9 EEH Primary Energy Consumption of top 15 materials, total life cycle (incl. all building materials, and appliances)

Figure 3-10 shows annual natural gas use for both SH and EEH. The dramatic decrease in natural gas consumption is due to the greatly improved thermal envelope, a much more efficient HVAC system, causing a decrease in heating natural gas consumption of 91.8%, and a hot water heat recovery unit (providing a decrease of 40%). While EEH uses natural gas for the stove and dryer (which is not the case for SH), EEH total annual natural gas use is only 21% that of SH.

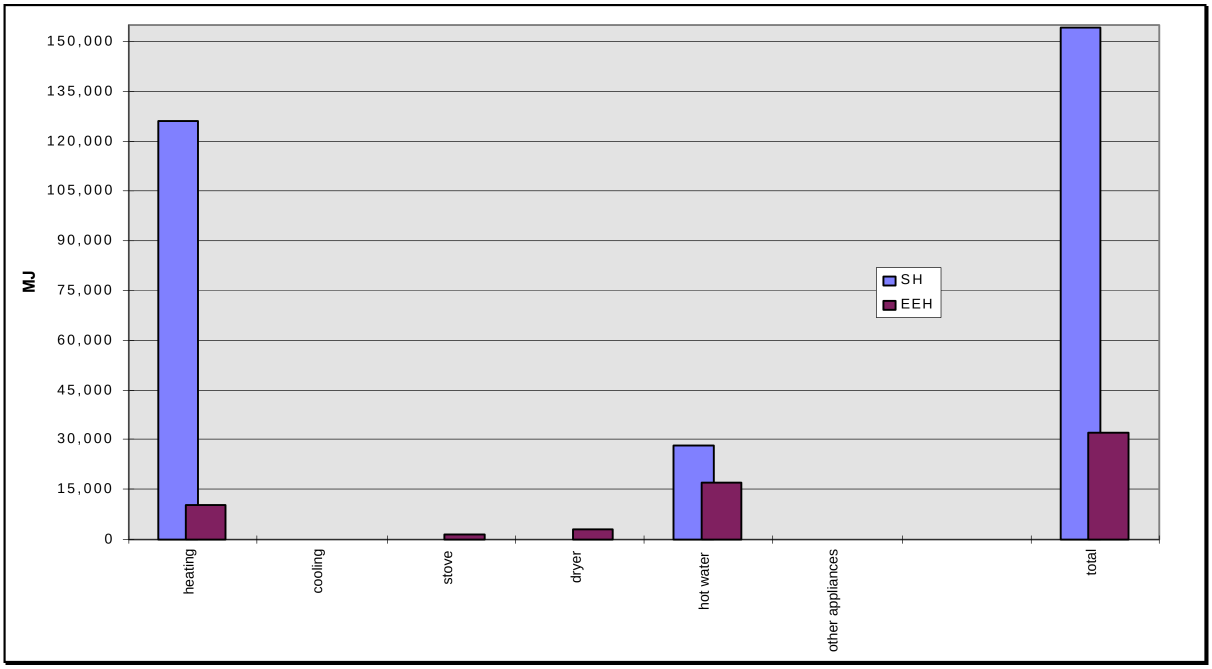


FIGURE 3-10 SH/EEH Annual Natural Gas Energy Use

Annual electricity use for both, SH and EEH is shown in Figure 3-11. EEH electricity use for cooling is approximately half of that for SH, again due to an improved thermal envelope, and a much more efficient HVAC system. SH uses electricity for the stove and dryer. EEH electricity use for other appliances is also almost half due to more efficient lights and appliances. EEH annual electricity use is reduced to only 58% that of SH.

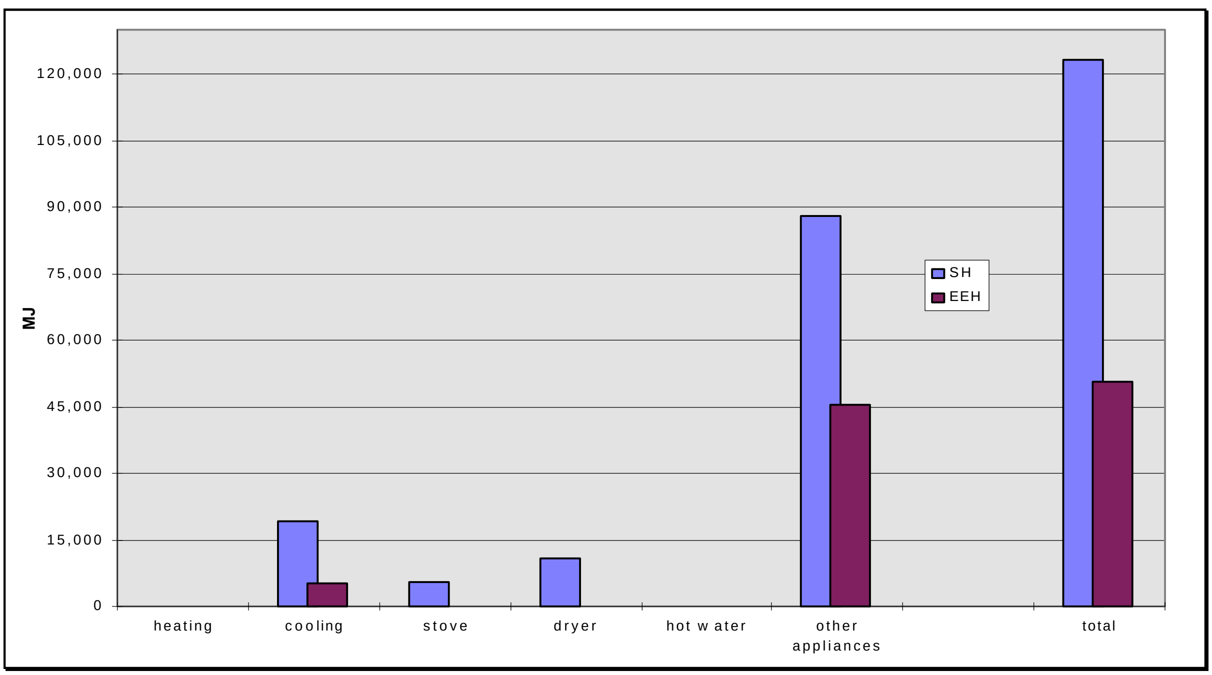


FIGURE 3-11 SH/EEH Annual Electrical Energy Use

Energy-10 determined that the annual heating energy requirement of SH was 120 MJ based on a value of 46.4 kBtu/ft2. This value was compared to the average 1993 heating energy for Midwest homes (average size 1,880ft^2) of 97 MJ[75]. Normalized for SH floor area, this is equal to 127 MJ which is within 6% of the calculated SH annual heating energy.

Figure 3-12 provides life cycle energy of all systems (including embodied energy of construction and maintenance/improvement materials) for both SH and EEH. For both houses, floors and foundation/basement are the two highest energy consumers with walls being the third highest. The SH roof is the fourth largest energy user.

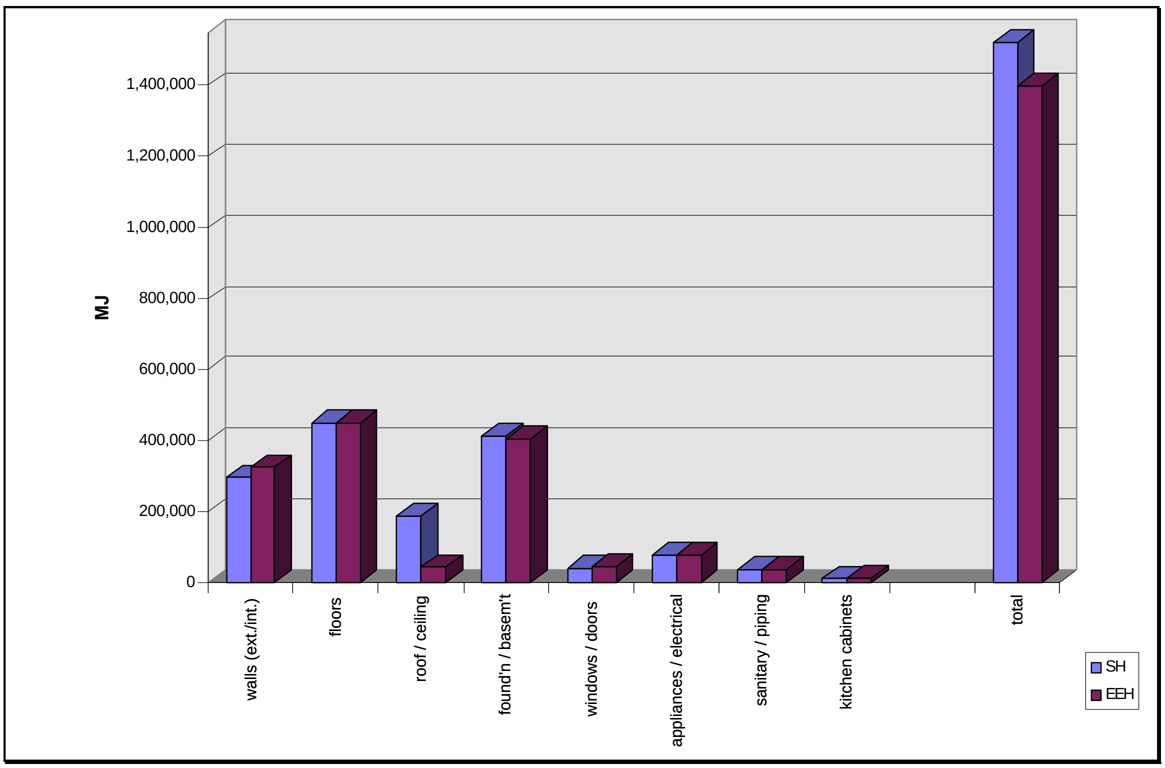


FIGURE 3-12 SH/EEH Life Cycle Energy Comparison by System (incl. only building materials and appliances, not utility energy consumption)

3.3 Life Cycle Global Warming Potential

The total global warming potential for SH (see Figure 3-13) was determined to be 1,013 metric tons of CO_2 equivalent. This includes all GWP gases emitted to the atmosphere during:

- extraction and processing of raw materials
- manufacturing and assembly of construction components and finished goods
- transportation of all materials in the pre-use phase (rail and truck),
- construction of the home
- use phase (home heating and power plant emissions generating electricity for the home)
- end-of-life demolition
- disposal transportation to landfill/recycling centers

The total global warming potential for EEH on the other hand was determined to be only 374 metric tons of CO_2 equivalent. The design changes therefore brought about a reduction of 639 metric tons of GWP gases over the 50 years period. This is a 63% reduction.

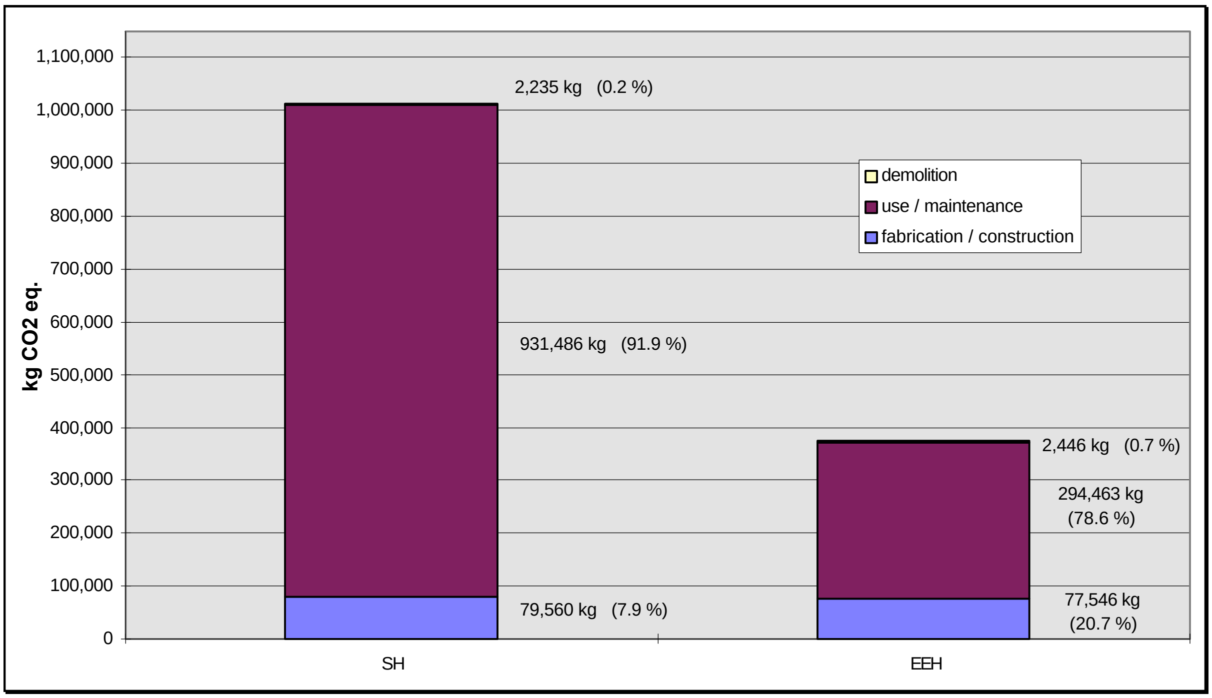


FIGURE 3-13 SH/EEH Life Cycle GWP (incl. all building materials, appliances, and utility energy consumption)

Figures 3-14 and 3-15 show life cycle GWP emissions of the fifteen materials contributing the largest quantities of GWP gases in SH and EEH.

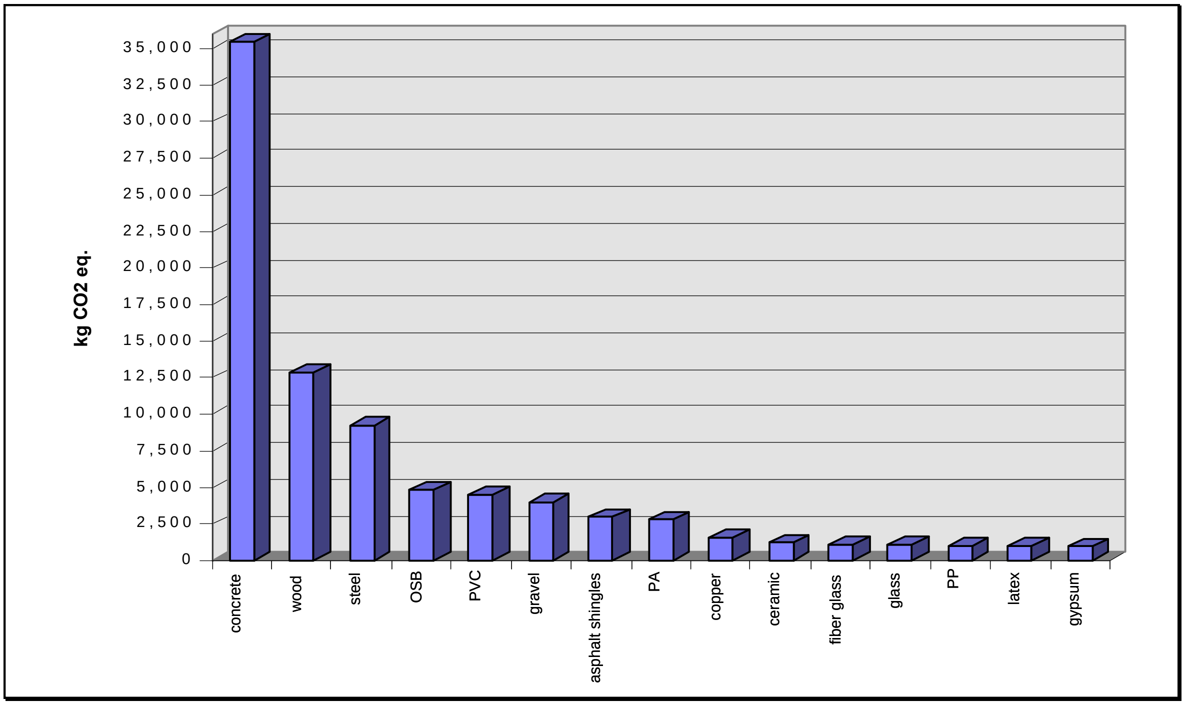


FIGURE 3-14 SH Global Warming Potential of the top-15 materials, Total Life Cycle (incl. all building materials, and appliances)

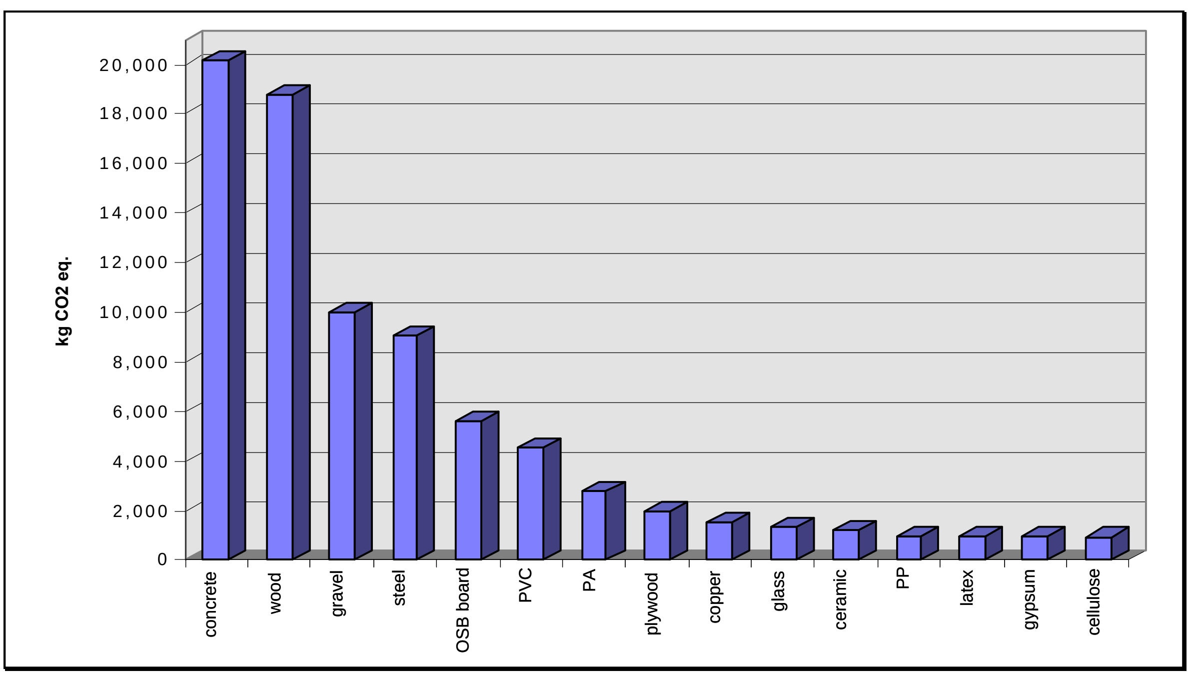


FIGURE 3-15 EEH Global Warming Potential of the top-15 materials, Total Life Cycle (incl. all building materials, and appliances)

Figure 3-16 compares life cycle GWP for construction and maintenance/improvement materials for the eight systems in SH and EEH (use-phase-utility related GWP not included). EEH walls produce more life-cycle GWP because of the additional wood in the thicker wall. Pre-use phase GWP for EEH is 2,014 kg less than SH.

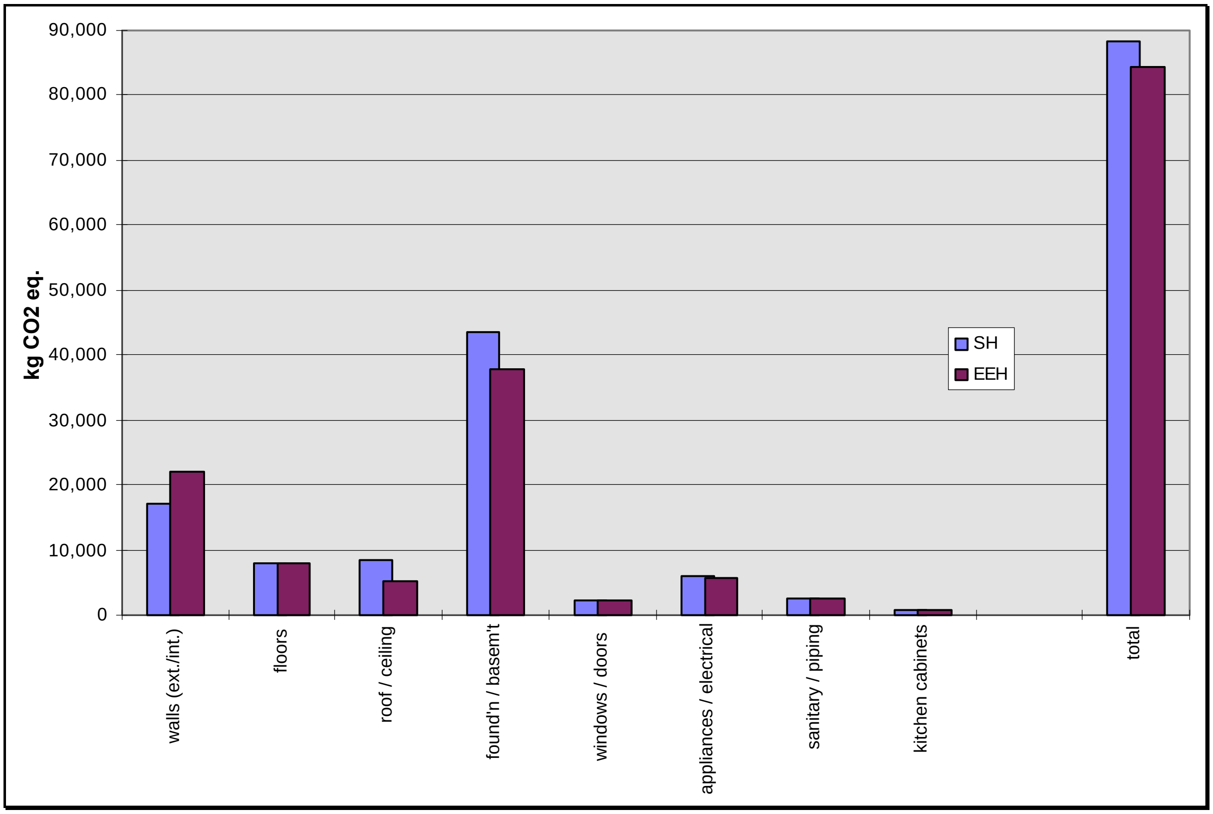


FIGURE 3-16 SH/EEH Life Cycle GWP by System (only for construction/maintenance materials, and appliances; no utilities)

3.4 Life Cycle Cost Analysis

3.4.1 Description of Scenarios

As explained in Section 2.8, four energy cost escalation scenarios were established to determine how both, discounted present value cost and un-discounted cumulative life cycle cost vary with changes in future energy prices. Following are more complete descriptions of the various scenarios:

Scenario 1 *Constant Energy Costs*

To provide a baseline for the other energy cost comparisons, scenario 1 was run with rates for the natural gas, and grid-supplied electricity remaining at 1998 levels for 50 years.

Scenario 2 *DOE Projection[76] (falling energy costs)*

The DOE projection foresees falling energy costs of utility-supplied natural gas and electricity due to the increased efficiency of new power plants built to replace aging lower efficiency power plants, and due to utility deregulation. Natural gas prices fall 1.1% annually between 1998 and 2010, and thereafter rise 0.03% annually between 2010 and 2020. It was assumed that prices stabilize between 2021 and 2048. Electricity prices fall 1% annually between 1998 and 2010, and thereafter decline only 0.48% annually between 2011 and 2020. It was assumed that prices stabilize between 2021 and 2048.

Scenario 3 *Wefa Projections for Global Warming[77] (Rising Energy Costs)*

Wefa Inc., a Pennsylvania-based consulting firm, performed a study to determine the impact of global warming legislation on US utility rates. The study assumes rapidly escalating energy prices as a result of US energy policies to meet the CO_2 reduction targets outlined in the Kyoto Agreement. The projection assumes both natural gas and electricity costs rise 4.2% annually between 1998 and 2010. It is assumed that energy costs escalate 1% annually thereafter until 2048.

Scenario 4 *Current German Energy Costs*

To provide a broader perspective on the impact of higher utility costs, a fourth scenario was run using 1998 energy rates in Germany. Utility-supplied energy in the City of Dresden costs $0.127/kWh and $0.721/therm for electricity and natural gas respectively[78]. Both of these values are approximately 59% higher than US energy prices. The scenario assumes energy prices rise 1% annually between 1998 and 2048.

3.4.2 Summary of Present Cost Analysis

The time value of money makes investments made in the future worth less today at a given discount rate. The additional cost of EEH was determined to be $22,801 (see appendix E page 153, for a complete breakdown of differential costs between EEH and SH). To determine if this additional $22,801 spent on EEH energy efficient enhancements would be economically justifiable, the present value of both SH and EEH was calculated for comparison. 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. This provides a means of comparing the two options as if they were investments. Table 3-1a below summarizes the present value of SH and EEH for the four utility escalation scenarios. For comparison, the same calculation was performed using a 10% discount rate (see Table 3-1b).

TABLE 3-1a 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 3-1b 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

Tables 3-1a and 3-1b indicate that the higher initial cost of $22,801 for EEH energy efficient enhancements do not pay for themselves (from a present value perspective) at falling or constant energy prices during the next 50 years. At escalating energy prices (Wefa-scenario) EEH is marginally better at a 4% discount rate and, worse at 10% discount rate. If the US adopted German energy prices that continued to escalate, EEH would be a marginally better investment.

3.4.3 Accumulated (un-discounted) Life Cycle Costs

Life cycle costs in this study consists of accumulated mortgage, natural gas, electricity and maintenance/improvement costs over the assumed 50 year life of the home. The accumulated, un-discounted summation of these costs are presented in Figures 3-17 through 3-20 based on the energy-price escalation scenarios. Tables 3-2 through 3-5 summarize the major components of life cycle cost for each scenario. The linear portion of each curve (year 1 through 30) indicates constant annual costs. The slope change after year 30 represents completion of mortgage payments. Abrupt slope changes throughout the curves represent home maintenance and improvement payments with large expenditures at years 25 and 40.

Scenarios 1 and 2 are relatively close, indicating that constant and falling energy rates affect life cycle cost comparisons between EEH and SH little. Scenarios 3 and 4 are also relatively similar, indicating that the Wefa energy cost projection would bring US energy costs more in line with those in Germany or Europe in general.

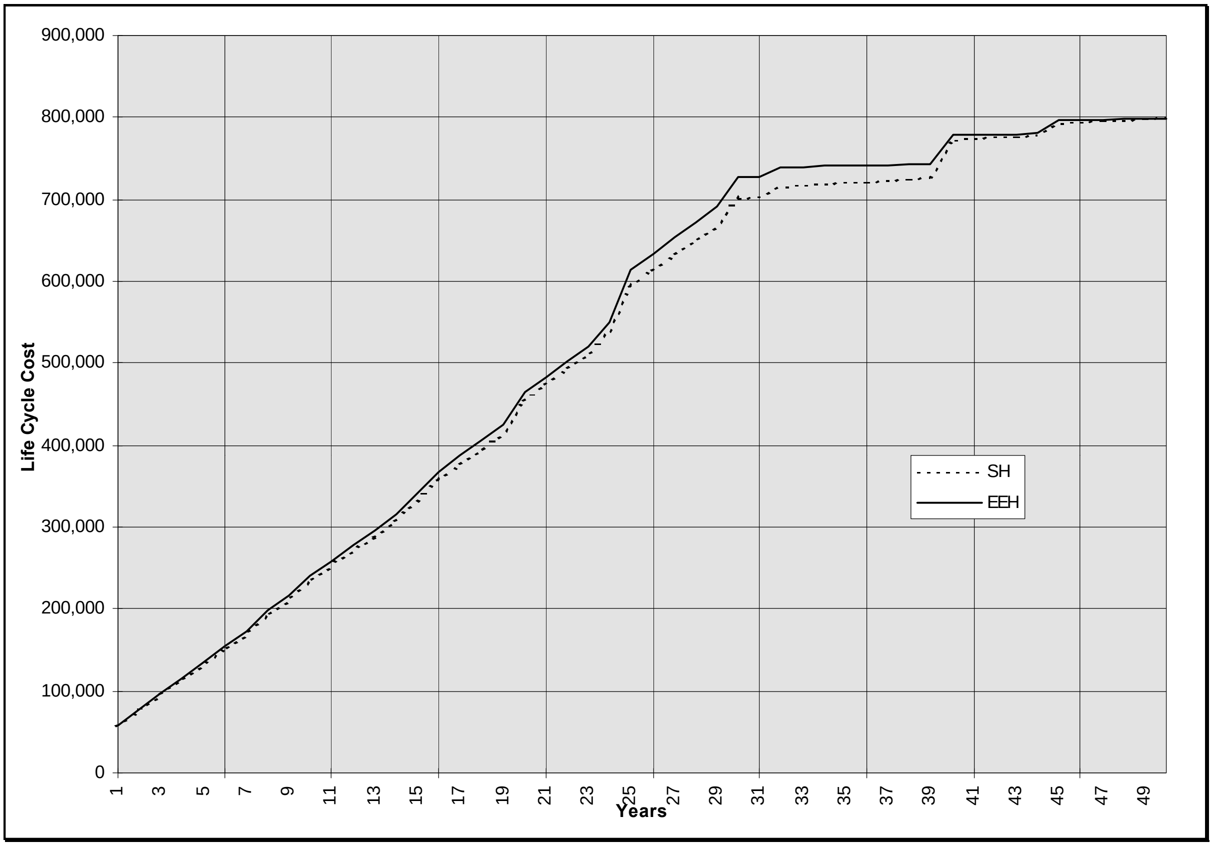


FIGURE 3-17 Life Cycle Costs Using Utility Escalation Scenario 1

The accumulated life cycle costs of scenario 1 are higher in EEH up until year 48, and are $1,054 (or 0.1%) less at year 50.

TABLE 3-2 Life Cycle Cost Elements for Utility Escalation Scenario 1

LIFE CYCLE COST ELEMENT	SH		EEH	
	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%

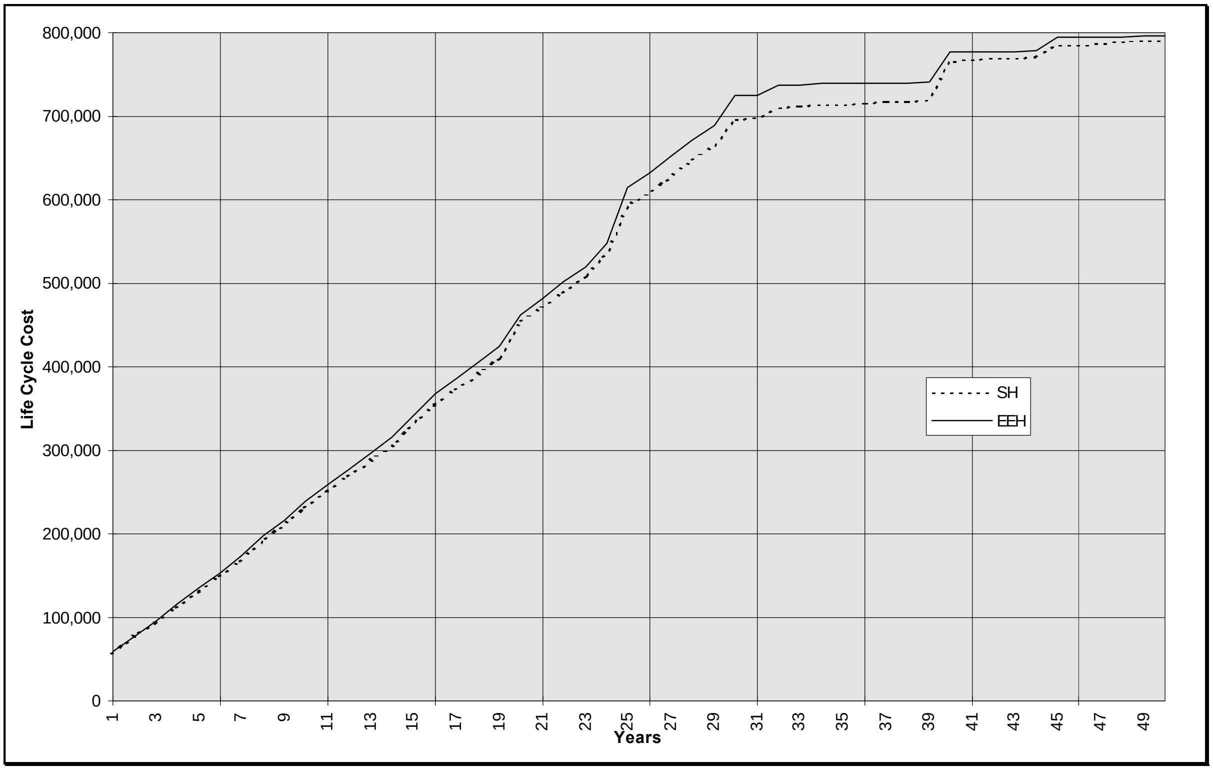


FIGURE 3-18 Life Cycle Costs Using Utility Escalation Scenario 2

The accumulated life cycle costs of scenario 2 are slightly higher in EEH throughout the assumed 50 year home life, being $4,783 higher (0.6%) than SH at year 50.

TABLE 3-3 Life Cycle Cost Elements for Utility Escalation Scenario 2

LIFE CYCLE COST ELEMENT	SH		EEH	
	Amount	Percent	Amount	Percent
MORTGAGE COSTS	$546,314	69.0%	$598,216	75.1%
NATURAL GAS COSTS	$29,208	3.7%	$6,279	0.8%
ELECTRICITY COSTS	$35,183	4.4%	$14,772	1.9%
MAINTENANCE COSTS	$180,828	22.8%	$177,049	22.2%
TOTALS	$791,533	100.0%	$796,316	100.0%

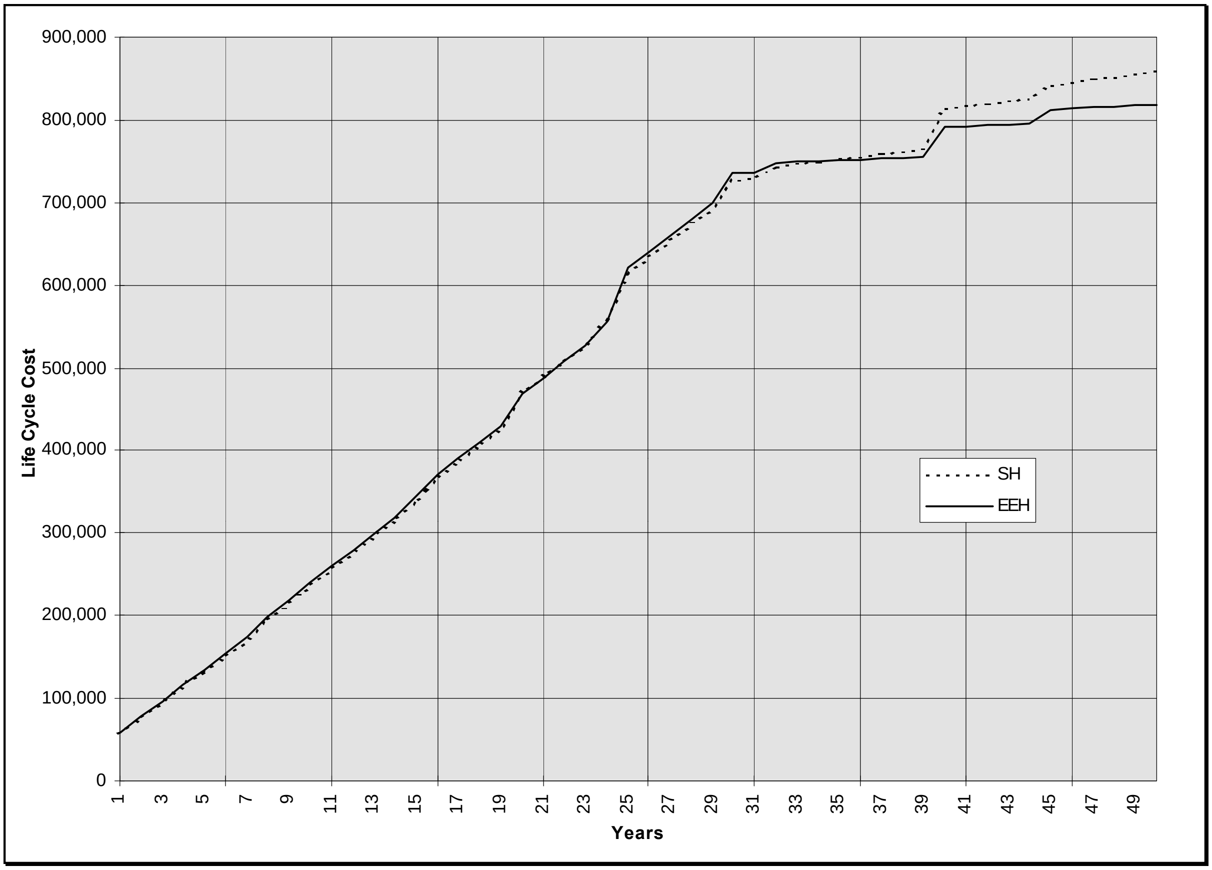


FIGURE 3-19 Life Cycle Costs Using Utility Escalation Scenario 3

The accumulated life cycle costs are slightly higher in EEH up until year 35, and are significantly lower thereafter, being $40,874 (or 4.8%) less than SH at year 50.

TABLE 3-4 Life Cycle Cost Elements for Utility Escalation Scenario 3

LIFE CYCLE COST ELEMENT	**SH**		**EEH**	
	Amount	Percent	Amount	Percent
MORTGAGE COSTS	$546,314	63.6%	$598,216	73.1%
NATURAL GAS COSTS	$59,177	6.9%	$12,721	1.6%
ELECTRICITY COSTS	$73,332	8.5%	$30,790	3.8%
MAINTENANCE COSTS	$180,828	21.0%	$177,049	21.6%
TOTALS	$859,650	100.0%	$818,776	100.0%

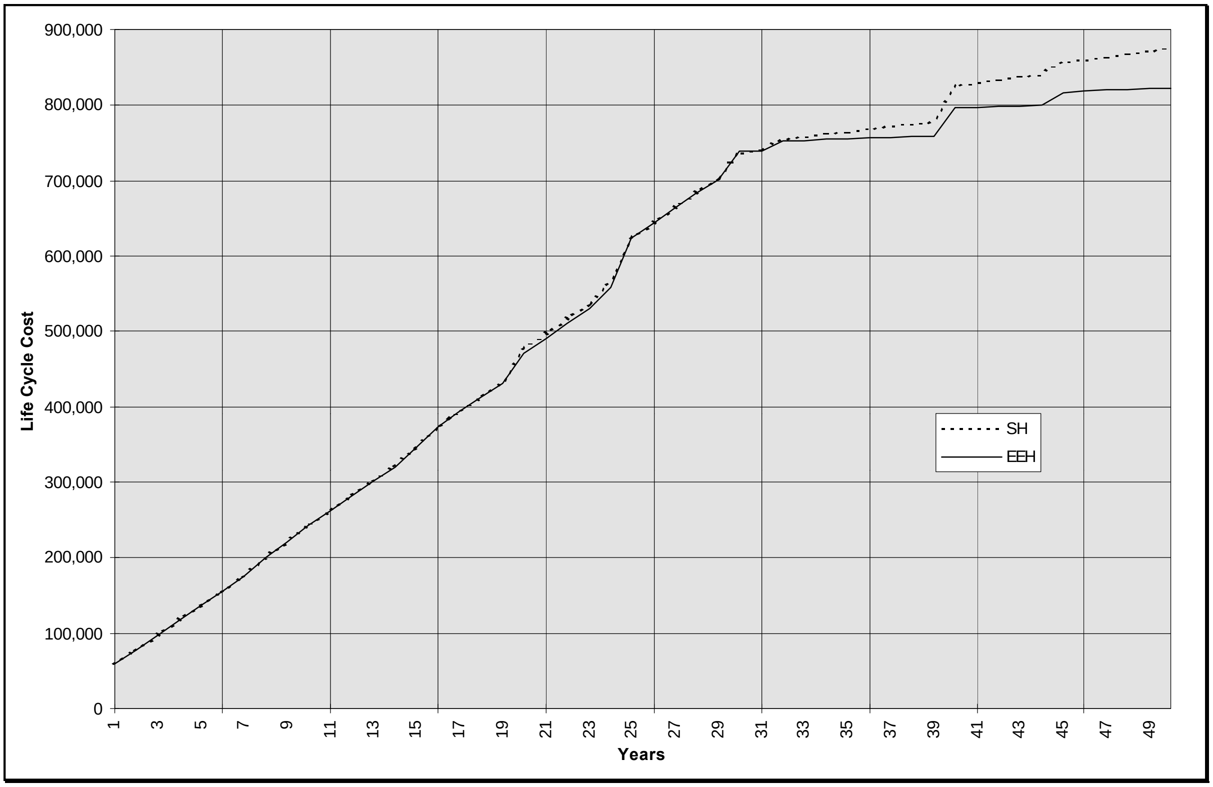


FIGURE 3-20 Life Cycle Costs Using Utility Escalation Scenario 4

The accumulated life cycle costs are almost equal between years 1 to 30, and diverge thereafter, with EEH being $51,761 (or 5.9%) less than SH at year 50.

TABLE 3-5 Life Cycle Cost Elements for Utility Escalation Scenario 4

LIFE CYCLE COST ELEMENT	SH		EEH	
	Amount	Percent	Amount	Percent
MORTGAGE COSTS	$546,314	62.4%	$598,216	72.6%
NATURAL GAS COSTS	$66,416	7.6%	$14,277	1.7%
ELECTRICITY COSTS	$82,302	9.4%	$34,557	4.2%
MAINTENANCE COSTS	$180,828	20.6%	$177,049	21.5%
TOTALS	$875,859	100.0%	$824,098	100.0%

3.4.4 Energy Efficient Mortgages

Energy efficient mortgages (EEM) are financial strategies that allow home owners to increase their housing debt-to-income ratio and total debt-to-income ratio, by two percentage points. These ratios are typically 28% and 36% respectively, and can be raised to 30% and 38% for EEM's[79]. The logic behind this is that with energy efficient measures, the home owner's combined housing related debt consisting of principle, interest, property tax and insurance (PITI) and utility costs will be equal to or less than that for a less energy efficiency home. EEM's qualify home owner's for bigger mortgages.

Table 3-6 below calculates the annual income required to secure a mortgage for both SH and EEH. Even though the EEH purchase price is $22,801 more than that for SH, because of lower annual utility rates and the two point mark-up on the home debt/income ratio, the annual income required to qualify for an EEH mortgage is $1,874 less than that required for an SH mortgage.

TABLE 3-6 Calculation of Required Annual Incomes using Energy Efficient Mortgages

Compenent	SH	EEH
Home Price	240,000	$262,801
Down Payment	36,000	$39,420
Mortgage Amount	204,000	223,381
Interest Rate (annual)	0.075	0.075
Term (Years)	30	30
Monthly Mortgage Payment	$1,417.54	$1,552
Monthly Taxes = 0.167% of property value	$400.80	$438.88
Monthly Insurance = 0.017% of property value	$40.80	$44.68
PITI (mortgage + taxes + insurance)	$1,859.14	$2,035.77
Monthly Energy Bills	$122.03	$40.07
PITI + Energy bill	$1,981.17	$2,075.84
Home debt/income ratio	0.28	0.3
Monthly Income Required	$7,075.61	$6,919.45
Annual Income Required	$84,907.31	$83,033.44

3.5 Other EEH Design Scenarios

3.5.1 Glazing Area Sensitivity

Of particular interest in the design of EEH was the total glazing area. SH glazing area is 337 ft^2. EEH design for glazing looked at two alternatives; a) 337 ft^2 lowE argon and b) 490 ft^2 lowE argon. The 490 ft^2 value was based on window-to-wall ratios recommended by Energy-10. However, Energy-10 simulations of EEH with 490 ft^2 lowE argon windows resulted in an increase of 352 MJ/yr (primary energy) more than the EEH with 337 ft^2 lowE argon windows. The increase in glazing area of 153 ft^2 lowered heating energy requirements by 501 MJ/yr because of increased solar gain. However, this was offset by increased heat gains requiring additional cooling energy inputs of 853 MJ.

The recommended Energy-10 glazing to floor area for optimal solar gain were:

- North Wall 4% of home floor area
- East Wall 4% of home floor area
- South Wall 12% of home floor area
- West Wall 2% of home floor area

Most likely, these recommendations are for standard 2x4 stud wall construction, and may also not be applicable for areas with low insolation (solar radiation), such as Michigan’s. Standard walls have R-values of between 12 and 14. EEH walls have an R-value of 35. Double glazed windows used in this study have an R-value of 2. This means that a window in a standard wall is a reduction in R-value of about 10 to 12. A window in the EEH wall would be a reduction in R-value of 33. Thus, the higher the insulative value of the wall, the less glazing is desired to reduce winter heat losses and summer heat gains.

Another likely explanation is the fact that South-East Michigan has insufficient insolation during a period when it would be most beneficial for passive solar heating.

3.5.2 HVAC and Infiltration Sensitivity

The air changes per hour (ACH) was modified from 0.67 in SH to 0.4 in EEH. The ACH value used for the EEH Energy-10 simulation however, was set at 0.1. This value was used to reflect a four-fold decrease in ventilation heat loss, achievable with the heat recovery system which would have otherwise not been possible to model in Energy-10. Given the volume of the house (22,500 ft^3), the actual air exchange rate translates into an airflow of 131 cfm. This is the value used by Energy-10 to calculate the electricity consumption of the ventilation fan.

The effective leakage area (ELA) of SH was determined by a blower-door test[80]. A blower-door test is a measure of the total air leakage area in a building. The standard procedure is to set up a variable speed fan in the doorway, close all windows, and induce a vacuum in the building . A manometer is set up to measure the pressure differential between the outside and inside of the building. The fan is calibrated so the flow rate can be determined. The air flow rate exiting the building is equal to the air flow rate entering the building through gaps, vents and various holes in the building envelope. Air flow is measured at differential pressures of 10, 20, 30, 40, 50 and 60 Pascal. Table 3-7 below provides flow rates from the Princeton-Home (SH) test.

TABLE 3-7 Princeton (SH) Blower-Door Test Data

House Pressure (Pa)	Fan Pressure (Pa)	Air Flow (cfm)	Fan Configuration
60	74	4,118	Open
50	47	3,290	Open
40	36	2,884	Open
30	27	2,501	Open
20	95	1,720	Ring A
10	39	1,107	Ring A

The data were extrapolated to determine the air flow into the building at a negative pressure differential of 4 Pascal, which is what Energy-10 assumes to be the ambient pressure differential in a residential home under average wind conditions. The ELA for SH was determined to be 153 in^2. The estimated natural infiltration rate was determined to be 242 CFM (or 0.48 air changes per hour). EEH ELA on the other hand, was set at 20 in^2. This appears to be the lowest level achievable with present construction methods[81].

3.5.3 Analysis of the Effectiveness of Energy Efficient Strategies

Figures 3-21 through 3-24 are Energy-10 outputs showing the relative effectiveness of various energy efficiency strategies in achieving reduced cost and energy consumption in EEH. Energy-10 starts with SH, and adopts one energy-efficient strategy, determining the energy and cost savings realized. All other strategies are then sequentially employed individually. Figure 3-21 presents the savings of each of those strategies. It must be noted that the sum of all bars in Figure 3-21 does not equal the total energy savings between SH and EEH. This is because the inclusion of one strategy in most cases decreases the effectiveness of others. Figure 3-21 shows that the most effective strategy for reducing overall annual energy costs is installation of a high efficiency HVAC system. Use of insulation was ranked second and is almost as effective in reducing annual cost.

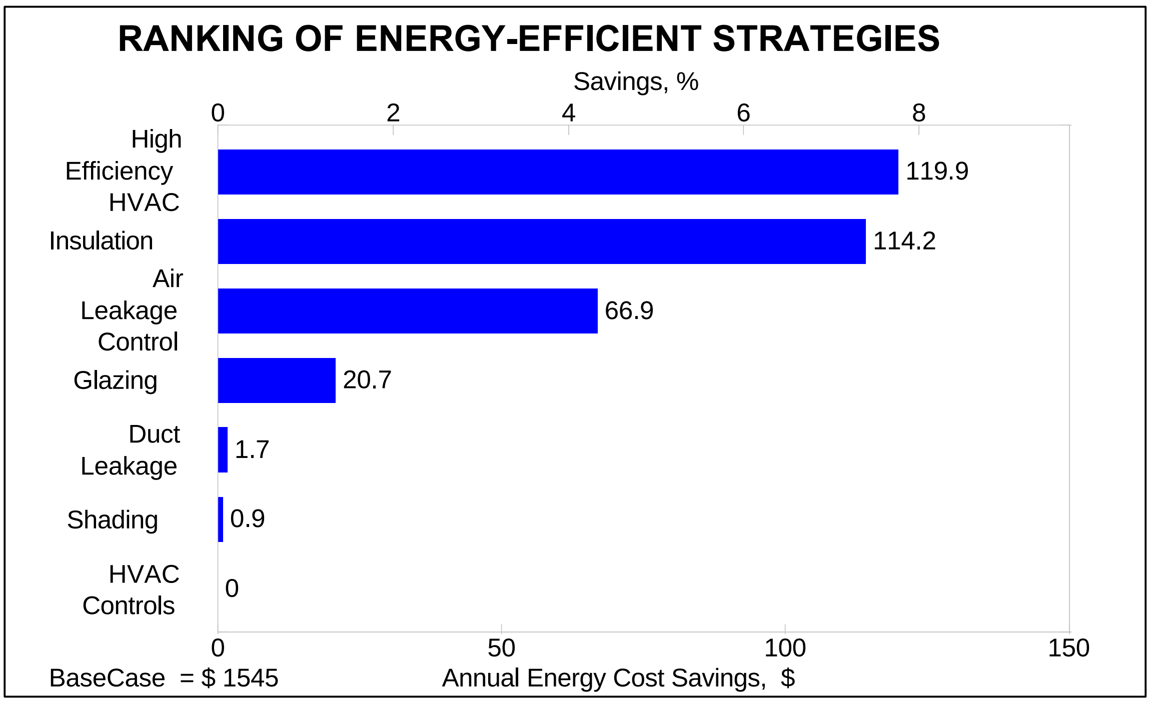


FIGURE 3-21 Annual Energy Cost Savings Ranking EEH Energy Efficient Strategies

The annual cost savings attributable to the energy efficient strategies displayed in Figure 3-21, were compared with the cost differential of installing each strategy. For example, an annual cost savings of $119.90 results from high efficiency HVAC, which is comprised of a higher efficiency furnace and A/C unit and an air-to-air heat recovery unit.

To determine the pay-back period for each system, the differential installment cost was divided by the annual savings. Table 3-8 provides calculations for seven different (but not all) systems that lend themselves to such comparison. Walls, ceiling and foundation were lumped into one group to allow for comparison with the Energy-10 insulation-savings number.

Table 3-8 Pay-back Period for Energy Efficient Strategies

		INSTALLATION COSTS			ANNUAL SAVINGS	PAY-BACK PERIOD/YR.
NO.	SYSTEM	SH	EEH	EEH-SH		
1	FOUNDATION	$19,778	$17,818	-$1,960		
2	FLOOR	$58	$0	-$58		
3	WALLS	$2,976	$13,668	$10,692		
4	CEILING	$7,722	$8,741	$1,018		
	subtotal (1-4)			**$9,692**	$114.2	**84.9**
5	WINDOW/DOOR	$4,259	$5,318	$1,059	$20.7	**51.2**
6	HVAC	$1,800	$7,700	$5,900	$119.9	**49.2**
7	APPLIANCES	$2,730	$4,830	$2,100	$223.4	**9.4**
	TOTALS	$39,324	$58,075	$18,751		

The additional cost of EEH improvement (before developer profit) is $22,801. As can be deduced from the life cycle cost determinations in Section 3.4, the pay-back period for all EEH improvements is less than 50 years, given than EEH life cycle costs are nearly equal or less than SH life cycle costs. Thus, the greater pay-back time for insulation improvements is combined with the shorter pay-back time for appliance improvements. The air leakage pay-back period was not calculated because the differential cost of improved air leakage prevention was assumed to be absorbed in the additional cost of the wall design.

In terms of reducing annual energy consumption, insulation was the most effective strategy followed by high efficiency HVAC and air leakage control (see Figure 3-22 below).

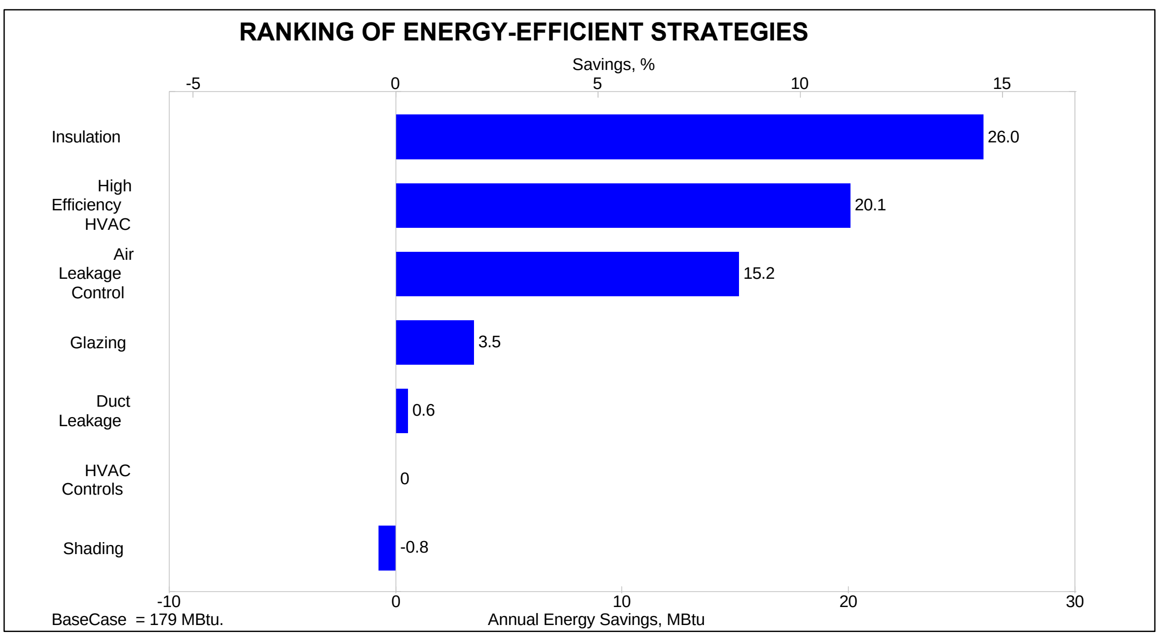


FIGURE 3-22 Annual Energy Savings Ranking EEH Energy Efficient Strategies

While insulation saves more energy, more efficient HVAC systems save more money. This is because per unit of energy delivered to the home, electricity is more expensive than natural gas. Figure 3-23 shows the effectiveness of various strategies in reducing annual heating costs. It reiterates the fact that insulation is much more effective in reducing natural gas space heating requirements. Increased glazing provides some additional savings, while the use of window shading devices (i.e., roof overhangs) actually increase heating requirements (by limiting potential fall/spring heat gains).

Figure 3-24 shows which strategies are most effective at reducing cooling loads. By far the most effective strategy is an efficient HVAC system, consisting of a higher efficiency air conditioning unit, and air-to-air heat exchanger. Window shading is the second best strategy while improved window glazing surfaces (low emissivity) are the next best. Air leakage control has a negative effect on house cooling. More infiltration actually assists in releasing unwanted internal heat gains during warmer periods of the year. Of the strategies tested, added thermal insulation was the most detrimental to home cooling. However, the overall contribution that insulation makes to home energy savings is better understood by observing the scale factors of Figures 3-22 (26 million Btu) and 3-24 (483 thousand Btu).

Figure 3-23 indicates that the most effective strategy employed in the modeling of EEH was added thermal insulation in the building envelope. Energy-10 effectively turned off all other energy efficiency strategies and compared an SH version with EEH thermal insulation with SH. The energy reduction was 26%. With the furnace efficiency increasing from 80 to 95%, it becomes the second most effective measure with about 20% heating energy reduction.

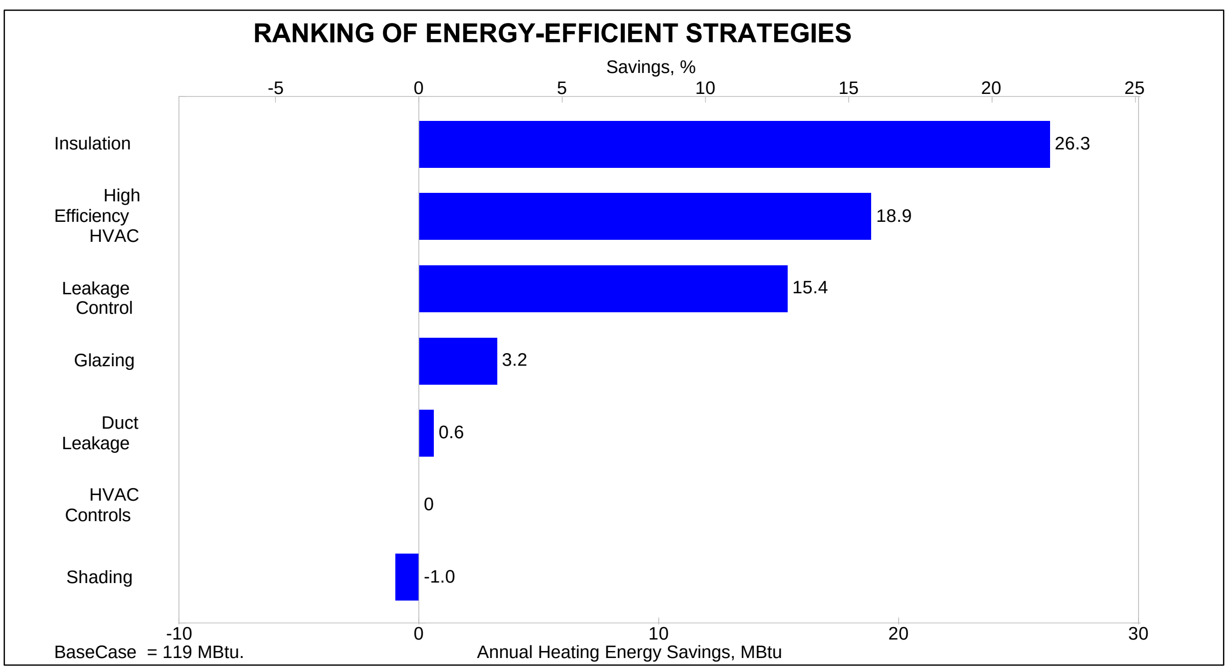


FIGURE 3-23 Annual Heating Energy Savings Ranking EEH Energy Efficient Strategies

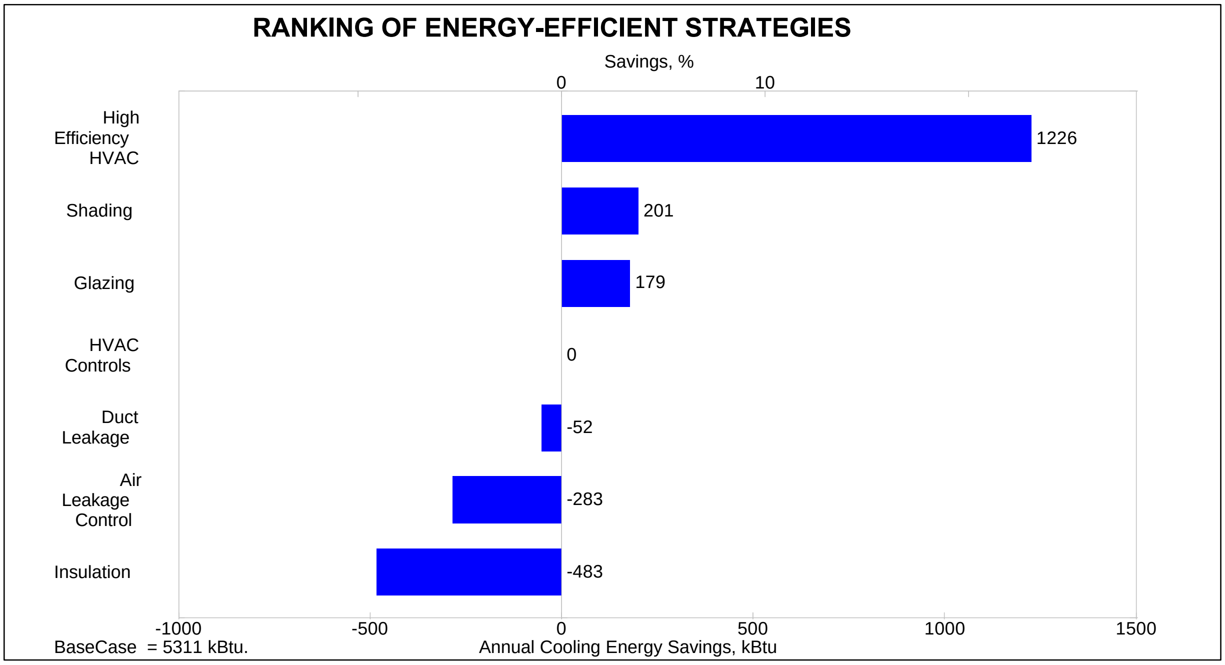


FIGURE 3-24 Annual Cooling Energy Savings Ranking EEH Energy Efficient Strategies

3.5.4 Comparison to Other Research

Table 1-1 below compares the results of this study (Princeton SH and EEH) with the four homes analyzed by Cole[82].

TABLE 3-9 Other Studies Determining Percentage of Construction and Use Phase Energy

Building		Size ft2	% of Total Life Cycle Energy		
Status	Name		Pre-Use Phase	Use Phase	Life Cycle Period of Study (years)
Original	Princeton (SH)	2,450	6	94	50
	Cole (Conventional Vancouver)[I]	3,750	15.8	84.2 [III]	50[II]
	Cole (Conventional Toronto) [I]	3,750	12.2	87.8 [III]	50[II]
Improved	Princeton (EEH)	2,450	15	85	50
	Cole (Energy Eff. Vancouver) [I]	3,750	26.3	73.7 [III]	50[II]
	Cole (Energy Eff. Toronto) [I]	3,750	20.7	79.3 [III]	50[II]

[I] *Conventional homes: 2x4 stud walls with R-24 roof, energy efficient homes: 2x6 stud walls with R-42 roof, additional glazing on south elevation and added thermal mass.*
Construction energy includes material manufacturing, transportation and home construction.

[II] *Cole's study provided annual heating energy, not life cycle energy. A 50 year life cycle was therefore assumed to normalize percentage results for comparison.*

[III] *Cole did not provide electrical energy consumption. This would make use phase percentages higher.*

The embodied energy in the original houses analyzed by Cole are higher than that of SH

than that of EEH (20.7-26.3% vs. 15%).
The reason(s) for these discrepancies are not clear. Most likely, Cole used different

have used include:

- exclusion of electricity consumption
- use of different life cycle inventory data sets
- possible inclusion of the embodied energy of wood
- less comprehensive material inventory
- use of different replacement frequencies, or omission of maintenance and improvement materials altogether

4.0 CONCLUSIONS

4.1 General

The most startling result of this study is that total life cycle energy of a new residential home can be reduced by a factor of 2.8 by making incremental design changes that reduce the embodied energy, and the use-phase energy consumption of the home. This was achieved largely with an improved thermal envelope, and an improved HVAC system, and with energy efficient appliances.

While the main focus of this study was life cycle energy and GWP, which are closely linked and mostly parallel functions of each other, mortgage payments are one of the most important factors to a home buyer. The cost analyses performed in this study were based on design modifications made to lower life cycle energy. The EEH model was developed for analytic purposes and would need more engineering design, and cost analysis before it could be used in the market place. The analysis does show that despite a 9.5% increase in the purchase price of an energy efficient home, lower annual energy expenditures make the present value (discounted at 4% over 50-years) nearly equivalent to the more energy consumptive version. Additional sensitivity runs are also needed to find optimal wall thickness, glazing area, and ventilation parameters, both in terms of costs, and environmental impacts. Reductions in the amount of structural framing lumber can also be made.

The applied EEH design modifications employ practices not yet widely used in the US. References to the Saskatchewan wall system used fiber-glass, not cellulose insulation. Wood basement walls lower the embedded energy of the home unit, but most home buyers might be suspect of wood's ability to last the life of the home. Wood basements have been built in Michigan for a number of years however. There is considerable opportunity in the residential home construction industry for cost effective construction methods integrating the energy efficient strategies (refer to tables 2-7 through 2-21) discussed in the study.

Given that life cycle energy use and global warming potential can be reduced by a factor of nearly three without compromising the home as a financial investment, it is natural to ponder why it is not happening. Several possibilities are:

- The home buying market does not consider reduction of environmental burdens as a significant element in evaluating home selection.
- Given that over the life of the home reduced energy costs compensate for higher financing costs, home buyers, who on an average, move about every eight years, do not believe the added cost of energy efficiency will be appraised in future transactions.
- There are no "green" regulatory or market incentives to motivate property developers.
- There is an insufficient volume of low energy homes being built to force the home design and construction industries into developing lower cost, higher efficiency homes. If there was a sufficiently high volume, the market would quickly focus on the life cycle energy savings of EEH- type residences.

4.2 Potential Follow-on Research

Several follow-on research projects, building on the work presented here, are suggested below. Each would need to investigate performance, life cycle energy and cost.

- Thermal envelope - Optimization of high thermal resistance properties, lower cost, material intensity, ease of construction, and reduced air infiltration

- Glazing - For a given weather region and home layout, determine the glazing area for optimal solar heat gain (winter) and shading (summer), window material embodied energy, overall installed cost and functionality.

  One EEH scenario increased EEH glazing by 100% to determine natural gas heating and electrical cooling cost changes. The incremental cost of installing the windows was $7,000. The additional windows reduced heating energy due to increased solar heat gain. This was offset however by an increase in electricity for space cooling. The combination of heating and cooling costs led to an overall life cycle cost increase of $360. The present value increase (discount-rate = 10%) of the additional windows is $2,200. If window replacement (in 25 years) is factored in, the discounted (10%) present value increase of additional windows is $4,600. Impacts to GWP were not calculated.

- Ventilation - exploring the life cycle energy of more sophisticated passive solar heating and natural convection systems. What are the economic limits in Michigan for minimizing natural gas heating and ventilation fan power while maintaining adequate fresh air circulation standards?

- Solar hot water heating - EEH reduced the natural gas space heating load by 92%. After these reductions, the largest consumer of natural gas is the water heater. What would be the life cycle impacts of solar hot water heating?

- Radiant Floor Heating - Design a combined total floor heat radiating system in combination with an air ventilation system and compare life cycle energy with a standard central furnace heating and ventilation system.

4.3 Analysis Tools

More thorough cost/benefit design iterations are needed, comparing functionality, durability, marketability, life cycle energy, and cost. This requires a greater understanding of the architectural design and construction process. The spreadsheets developed during this project combined material quantities, embodied energy data for specific materials, annual heating and electrical requirements, life cycle energy, GWP data, and cost. These were somewhat cumbersome to use, and made analysis of design changes time consuming. Needed is a software program designed to allow greater flexibility in comparing various options while keeping track of different scenarios and maintaining consistency of units.

Such an ideal product would have the following features:

- Graphical Interface - Most homes built today are not shoe boxes and tend to have a complicated geometry. At a minimum, the program should be able to create the floor plan and deal with multi-story arrangements. Developers of Energy-10[83] plan to develop a basic graphical interface to supplement the present data entry format required to specify building dimensions. A more sophisticated design engine like 3D Home Architect® Deluxe[84] that can create floor plans, cross sections and 3D views of a building would be very useful. Integration of a full design software tool like AutoCAD®[85] would allow for complete design detailing.

- Quantity Take-off Capability - The graphical interface should be capable of producing a complete material take-off of the design. Both, 3D Home Architect® Deluxe and AutoCAD® have this capability. 3D Home Architect® Deluxe is however limited to standard framing conventions and lacks the sophistication to create unique framing solutions.

- Cost Estimation Capability - Estimating the cost of a building requires both a complete list of building materials and an up-to-date library of material and labor rates for thousands of different materials and construction techniques. National Estimator ’97[86] is one software program that provides much of this, although the materials must be input from the user’s material list. Variations in regional pricing, escalation of costs, and specific trade profit mark-ups are critical factors.

- Life Cycle Energy Inventory Capability - A generic library consisting of the embodied energy and manufacturing energy of numerous construction materials, and other environmental impact catgories on a per mass basis is critical. Transportation energy is specific to home location, transportation mode (rail, truck or combined) and the location of the source material. Team/Deam™, BEES[87] and LCad[88] are some of the software programs that provide both an energy data base and format to construct the various material and energy flows related to a product.

Development of a software program that meets these overarching requirements would be costly. But without it, the process of assessing design changes in terms of life cycle energy and cost, are extremely laborious and prevent many architects from doing so.

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