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Energy Efficient, Cost Effective, Passive Solar House

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ABSTRACT

A house was constructed in Carbondale, IL, in the mixed humid climate region, using the best current construction methods with commonly available materials. Good passive solar characteristics were obtained by properly orientating the house to have many south-facing windows with proper overhangs which provided 23% of the energy needed for heating. The house also included 15 cm (6 in) thick insulated walls, insulated concrete forms for foundation walls, insulated rim joist, a ground-source heat pump, Energy-Star windows, clothes washer, refrigerator, and compact fluorescent bulbs (CFLs).

Electrical usage data was metered separately for heating, air conditioning, hot water, lights and appliances. The energy used by the actual house was compared to the same sized house built to the International Energy Code Council 2004 Residential Energy Code. The actual house used 7809 kWh (50%) less than the code house for an annual cost savings of $826. The annual on-site electricity used by the house was 19.8 kWh/m^2. Cost of the energy-efficient improvements in the actual house was $7,990. The house was very cost-effective by using commercially available materials and employing an on-site general contractor knowledgeable in maintaining the high energy-efficiency standards designed into the house, coordinating the work, and allowing the homeowners to perform manual tasks. This method resulted in a price of $1,062/m^2 ($99/ft^2) of finished floor area, noticeably less than a comparable house in the region.

INTRODUCTION

Is it possible to build energy efficient houses that are still cost effective? This article addresses this question starting with the design, construction, and performance of a very energy-efficient, cost-effective house using current best-construction methods. The house was constructed in Carbondale, IL, which is located in Southern Illinois in the mixed humid climate region. The typical annual weather in Carbondale, IL has 2,377 °C•days (4,279 °F•days) heating and 819 °C•days (1475 °F•days) cooling degree days. The average daily amount of solar radiation is 15.3 MJ/m^2.

The house consisted of an above-ground main level of 200.7 m^2 (2160 ft^2) with two regular bedrooms, master bedroom, study, living room, dining room, kitchen, dinette, two bathrooms, and a fully-conditioned basement beneath the main level with daylight windows. The house construction is energy-efficient from passive solar characteristics as well as additional insulation and air sealing. Also, energy efficient HVAC system, appliances, and lighting were used in the house. This type of construction should stimulate the housing market in providing reasonably priced, energy efficient houses resulting in affordable mortgages and low operating costs.

Others have successfully included passive solar characteristics into their building designs. Torcellini et al. (1999) described a design process for buildings that included passive solar characteristics compared to "solar neutral" buildings. Kehrig and Schoenau (1986) determined optimum values of glazing, insulation, and thermal mass of passive solar houses and used these results in residential designs in Dodge City, KS and Madison, WI. Olson and Suagee (1984) examined the advantages of passive solar houses under different utility schedules such as standard, time-of-day, and demand schedules. They found that passive solar houses had the least utility costs for all utility schedules and even more favorable with

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time-of-day rates, becoming more common in residential buildings.

DESIGN AND CONSTRUCTION

Building Envelope

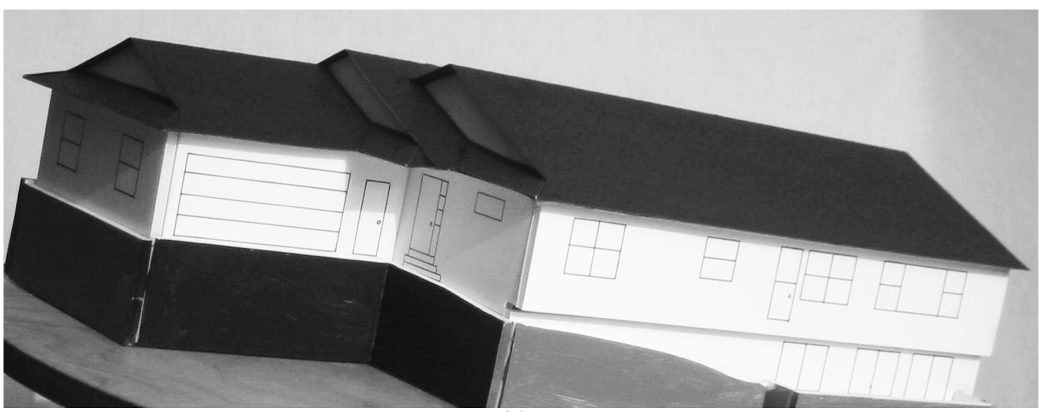
The passive solar house was initially designed using a heliodon to determine how the sun's rays shines on the house any time, day, and month of the year. The house was designed such that the south wall faced 12° east of south and the garage on the northwest corner blocked the north wind in the winter and afternoon sun in the summer. A 0.61 m (2 ft) overhang of the roof trusses shaded the south wall in the summertime and allowed direct sunlight onto it in the wintertime. Sun also shined through the windows of the basement south wall in the wintertime but was shaded in the summertime from the main level cantilevering over the basement wall by 0.41 m (1.3 ft).

The design and construction of the passive solar characteristics of the house agreed well. Figures 1a and 1b and 2a and 2b show the south wall of the house at noon during the winter (21 December) and summer (June 21) solstices of the house model on the heliodon and the actual house, respectively. The line of shade on the house during the summer solstice is visible on the garage and on the house farthest from the garage due to the large shade tree on the property. In addition, the passive solar characteristics and composition of the cantilever and overhang of the basement and main level walls are shown in Figures 3a and 3b.

After the house was properly orientated, it was designed in more detail. Figure 4 shows the layout of the house. The dinette, kitchen, dining room, and living room with larger windows faced south, the study and bedroom windows faced north, two master bedroom windows faced east, and front door sidelight and transom window faced west.

The basement was constructed with insulated concrete forms (ICFs) and the rim joist was insulated on the outside with 5.1 cm (2 in) thick polystyrene insulation (R-10), to eliminate condensation and consequently reduce mold and mildew.

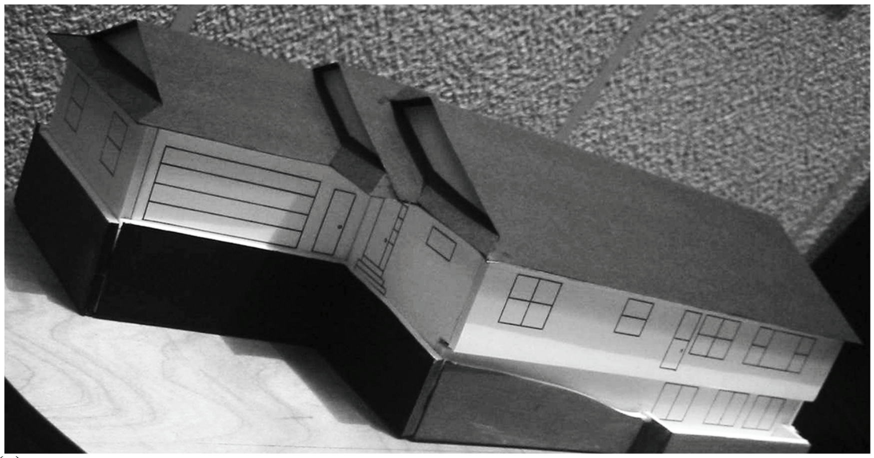
The upstairs, outside walls were constructed of wood framing with nominal dimensions of 5.1 cm by 15.24 cm (2 in by 6 in) placed every 61 cm (24 in) on center. Each outside wall cavity was caulked and typical paper-faced R-19 fiberglass-batt insulation was installed. Other insulation options of sprayed fiberglass, wet cellulose, or foam were investigated; however, these options were not chosen considering another study (Yuill and Yuill, 1997) that determined wall cavity insulation type had no measurable effect on overall tightness of the house, and drywall was the dominant air infiltration barrier of the wall. Caulking exterior cavities and fiberglass-batt insulation was significantly more cost effective, typically one fourth the cost of above mentioned options.



(a)

(b)

Figure 1 *(a) Model of south wall of house on winter solstice and (b) actual house.*



(a)

(b)

Figure 2 *(a) Model of south wall of house during summer solstice and (b) actual house.*

To minimize air infiltration, sheeting was applied such that all seams occurred on the center of all framing members. Air tight electrical boxes were used upstairs on the exterior walls and ceiling. All penetrations out of the thermal envelope such as holes for electrical wires, plumbing, and venting were caulked providing a tight seal and a continuous piece of housewrap was used around the entire house. These air infiltration reduction measures were successful as a blower door test on the completed house resulted in air infiltration of only 0.28 air changes per hour (ACH) at 4 Pa pressure difference.

Double-pane, argon-filled, low-emissivity coated windows were used throughout the house. High solar gain windows and additional thermal mass were not used in the construction of the house as the intent was to construct a very cost effective, energy efficient house using best standard practices with no additional support or modifications for thermal mass and no specialty ordered windows.

The roof consisted of energy trusses with a 12 inch heel, allowing blown cellulose insulation to a value of R-40 throughout the entire ceiling area.

Heating and Cooling System

A two-stage, ground source heat pump (GSHP) and a desuperheater provided the heating, cooling, and a portion of the hot water to the house. The smallest GSHP unit was chosen because the favorable passive solar characteristics of the house reduced the amount of heating and air conditioning required. This consequently reduced the initial cost of the GSHP and of the vertical ground wells. The average performance of the GSHP stated by the manufacturer for the specified ground loop configuration was 4.11 for heating COP and 16.9 EER for cooling. Six vertical loops were drilled 15.2 m (50 ft) deep and 3.0 m (10 ft) apart with the loops connected together in parallel 1.2 m (4 ft) below the surface.

Appliances and Lighting

The occupants purchased Energy-Star rated front-loading clothes washer and side-by-side refrigerator-freezer. Compact fluorescent lights (CFLs) were installed in all fixtures throughout the house except 1.2 m (4 ft) long T-8 fluorescent lights were installed in the kitchen. CFLs were installed in enclosed light fixtures by leaving an unnoticeable gap between the globe and fixture allowing air to circulate keeping the electronics of the CFL from overheating.

Data Collection

Totalizing electrical meters measured the electricity consumed by the electric resistance heat, heating and cooling

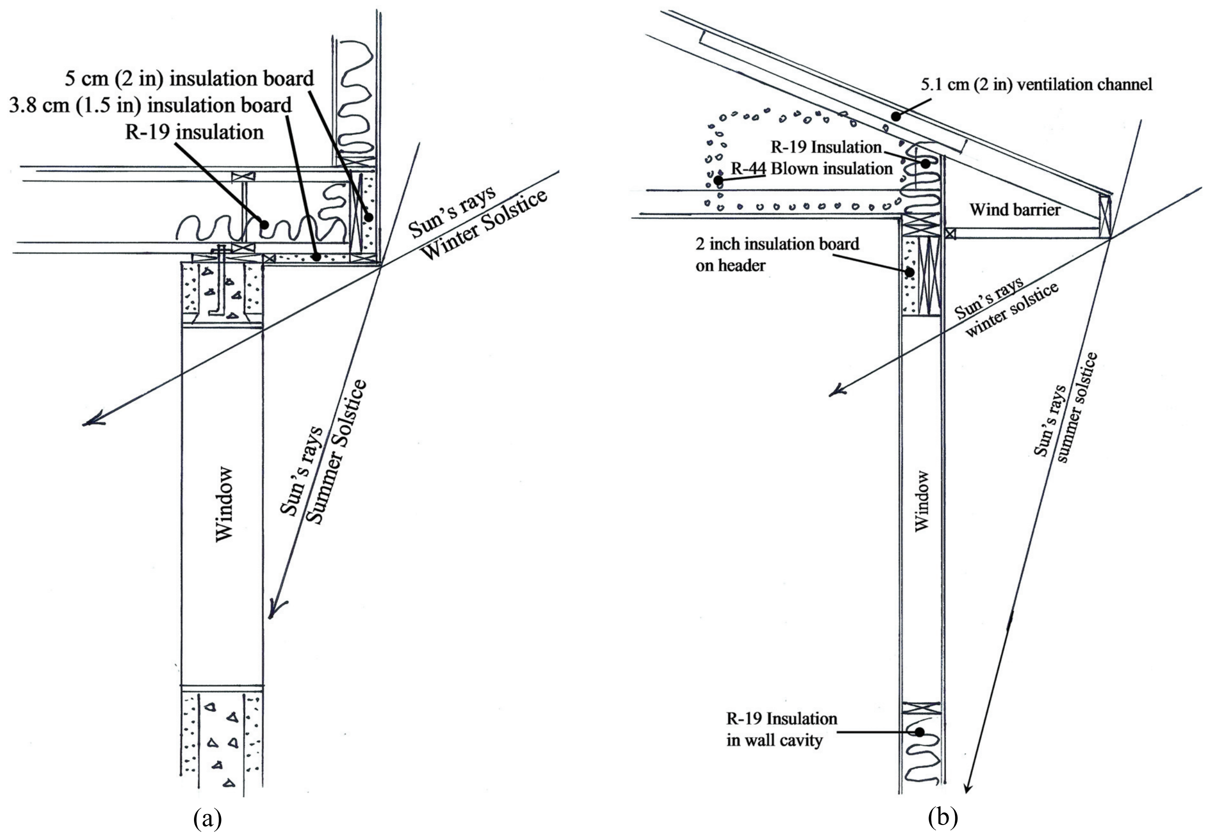


Figure 3 *(a) Passive solar characteristics and (b) composition of cantilever and overhang.*

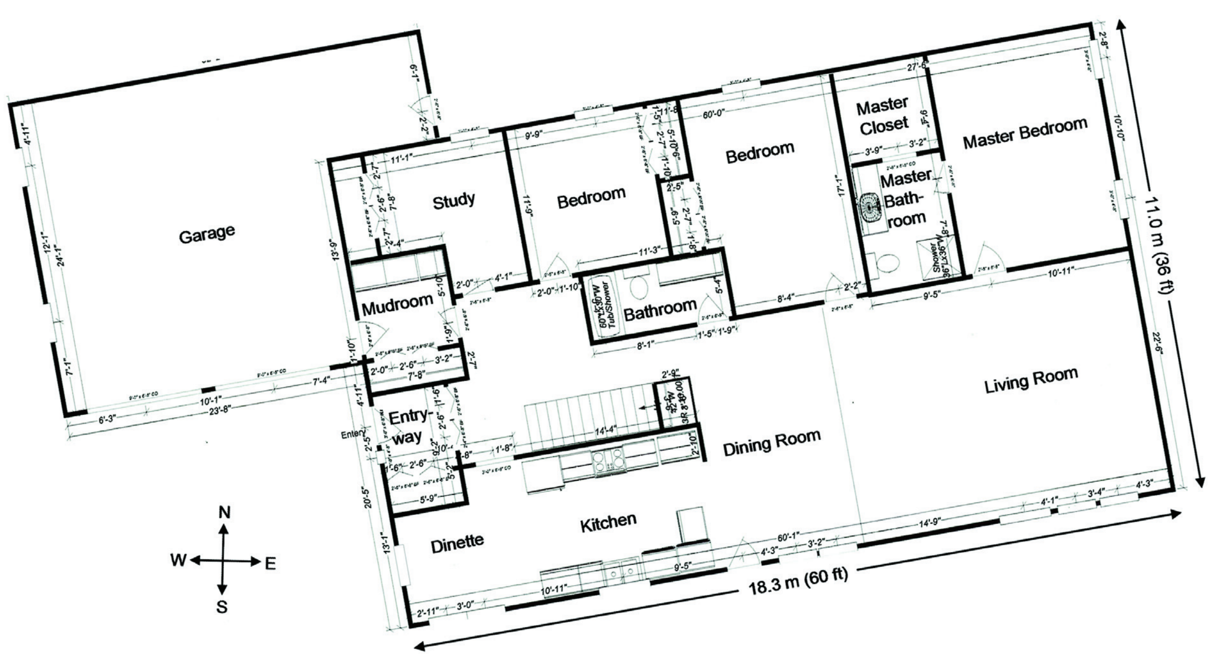


Figure 4 *Layout of the passive solar house.*

by the GSHP, hot water, and total. The electricity consumed by the lights and appliances was obtained by subtracting the other meters from the total electricity consumed. The homeowners, a family of four, almost daily recorded the electrical usage measured by the meters, for an entire year beginning 15 January 2007 and recorded details such as when the heat pump was heating, cooling, or off. The homeowners felt comfortable setting the thermostat during the summer and winter at 26.1°C (79°F) and 18.9°C (66°F), respectively. The thermostat setting during the summer was acceptable due to ceiling fans installed in the bedrooms, living room, and kitchen operating at medium speed. The winter thermostat setting was appropriate due to the thicker, warmer walls decreasing the amount of radiant heat transfer from the body.

RESULTS AND DISCUSSION

Energy

Electricity was the only source of energy to the house and a commercial software program was used to simulate the actual electricity use of the house through detailed inputs of lighting, appliances, bathing, and washing schedules. Consequently, an electricity usage model of the house was calibrated with these inputs. The model then was altered to simulate a house of the same size that just meets IECC 2004 code (ICC, 2004), maintaining the same operating conditions as the actual house, thus removing the effect of occupant behavior. The commercial software program used the average weather data for Carbondale, IL. The actual heating and cooling degree days during the year beginning 15 January 2007 were 2,393 °C•days (4307 °F•days) and 908 °C•days (1634 °F•days), respectively. These values are greater than the average conditions, given in the Introduction section, by less than 1% and approximately 10%, respectively. The same average weather data were used for the actual passive solar house and code house; consequently, the weather effect was removed during calibration of the actual house.

Table 1 shows the annual energy savings of the actual house compared to the code compliant house. The thermal heating and cooling savings of the above grade walls, R-28 insulated basement walls, windows, and insulated rim joist were obtained from the previously mentioned commercial software program. The program predicted substantially more heat transfer through the windows of the code house in the cooling season because equally sized windows were placed in all directions without properly designed overhangs. The electricity savings of the GSHP of the actual house compared to an air source heat pump of federal minimum efficiency (8.5 hspf

Table 1. Increased Price and Annual Energy Savings of Actual Versus Code House

Actual house	Simulated code house	Increased price of actual house	Annual energy savings of actual house (E) = Electricity (kWh) Thermal: (H) = Heating (GJ) (C) = Cooling (GJ)
Passive solar orientation	Windows equally distributed all directions	$0	Not determined
15 cm (6 in) thick insulated above grade walls	10 cm (4 in) thick insulated above grade walls	$290	(H) 2 (C) ≈ 0
Double pane, argon filled, low-e windows; U=0.3	Double pane windows; U=0.4	$699	(H) 2 (C) 7.7
Rim joist insulated to R-10	Uninsulated rim joist	$157	(H) 0.4 (C) ≈ 0
Insulated concrete forms R-28 for basement walls	Block basement walls with R-10 continuous insulation	$1,754	(H) 3 (C) -0.4
Ground source heat pump	Air source heat pump	$4,518	(E) 2502 during heating (E) 168 during cooling (E) 2670 Total
CFL in all light fixtures	Incandescent light bulbs	$42	(E) 1,762
Energy-star front loading clothes washer also providing reduced drying time, and side-by-side refrigerator	Same size and features standard clothes washer and refrigerator	$530	(E) 44 refrigerator (E) 78 clothes washer (E) 94 clothes dryer (E) 216 Total
Totals		$7,990	(H) 7.4 (C) 7.3 (E) 4,648

heating and 14 EER cooling) as specified by code, was determined by the difference in electricity used of these two heat pumps to heat and cool the code house. The electricity savings of the energy star refrigerator was obtained from the difference between the electricity used of an average and the energy star refrigerator, obtained from the energy guide of the actual refrigerator.

The electricity savings of the energy star, front loading clothes washer was obtained the same way as the refrigerator; however, it was adjusted by the difference in the actual number four loads washed each week, compared to eight loads used by the energy guide to predict electrical usage. The electricity savings of the dryer resulted from the energy star clothes washer reducing the drying time from 45 to 35 minutes and was adjusted for the four weekly loads. The electricity saved by CFLs was established by actual lighting usage of the occupants and using 13 W CFL instead of 60 W incandescent bulbs.

Figure 5 shows the predicted electricity use of the simulated house built to IECC 2004 code as well as the electricity use of the actual house. The simulated house assumes equal windows on all four cardinal headings thus requiring greater heating, due to less solar gain. The simulated house uses an air-source heat pump requiring more energy than the actual house using a ground source heat pump. The simulated house also requires significantly more electrical use in lights and appliances resulting from incandescent bulbs and "average" appliances, instead of high-efficiency appliances. In addition, the homeowners reported using less lights in the passive solar house due to the significant amount of direct light entering in the heating season and noticeable indirect light entering during all other seasons, also reported elsewhere (Torcellini et al., 1999). This effect is unaccounted for in this comparison because the results in Figure 5 contain the same lighting usage pattern. In conclusion, there is a 50% decrease in total electrical use of the actual passive-solar house compared to the simulated house.

In the actual house, the GSHP energy efficiently satisfied the heating and cooling requirements of the house while using a negligible amount of backup electric resistance heat, less than 0.5% of the total electricity was used for purely resistance heating. The lights and appliances section was the largest use of electricity; however, the electrical use for lighting was decreased by the passive solar features of the house, as discussed previously. The high efficiency appliances also reduced the electrical usage, for example the front loading clothes washer ended each cycle with a high-speed spin of 1050 RPM, extracting more water than typical and greatly reducing drying time. The annual electrical usage per conditioned area of the house is 19.8 kWh/m^2, while the primary energy usage is 59.3 kWh/m^2 obtained by multiplying electrical usage by the factor of 3, accounting for the efficiency of the electrical generation cycle.

The amount of heating obtained through the passive solar features of the house was determined through a correlation of (1) daily electricity consumed by the GSHP, (2)

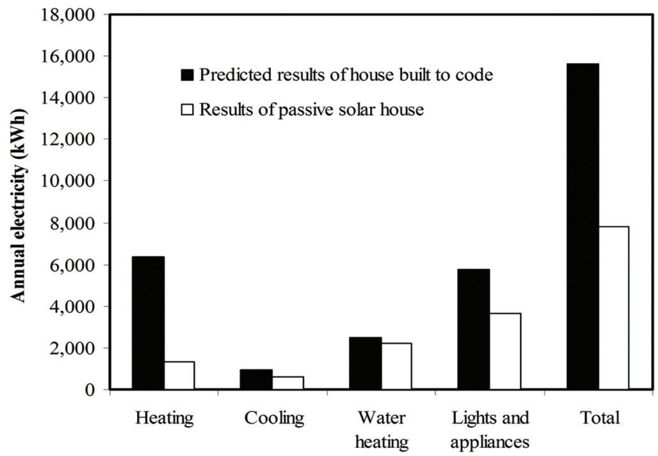
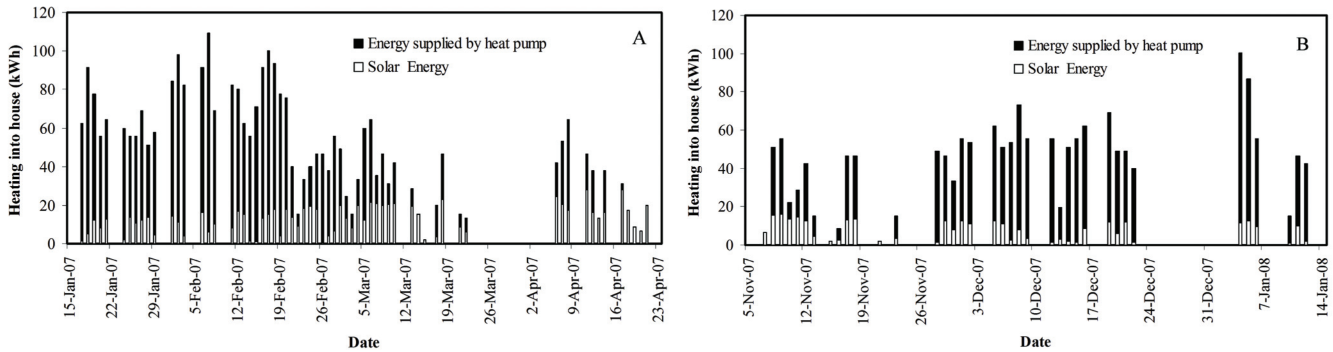


Figure 5 *Annual energy use in kWh of simulated house built to code and actual house.*

outdoor air temperature, and (3) solar radiation. The daily average outdoor air temperature and solar radiation were obtained from a weather station within 4.8 km (3 mi) of the house. The correlation optimized the variables of indoor balance temperature, coefficient of solar gain, and thermal transmittance. The correlation closely matched the annual data and resulted in a 23% solar gain for the passive solar house. Figures 6a and 6b show the heat obtained by solar radiation and by the GSHP when data were available. The heat supplied by the heat pump was calculated by multiplying the electricity used by the heat pump and the weighted average heating Coefficient of Performance (COP) of the heat pump predicted by the manufacturer for the specified ground loop system and local climate.

The accuracy of the correlation was determined by comparing the actual electricity used by the GSHP to that predicted by the correlation. The square of the Pearson product moment correlation coefficient, R-squared value, was 0.88, meaning that the correlation accounted for 88% of the variation of the electricity used by the heat pump for heating. Figure 7 shows the electricity used for heating predicted by the correlation versus the actual electricity used. In addition, the residuals obtained from the difference of the correlation and actual electrical usage data were plotted versus time, outdoor air temperature, and solar radiation. The residuals in all plots were random, verifying that the residuals appear to come from normally distributed data.

It was difficult to determine the reduction of electricity for air conditioning the passive solar house. This was determined by using the thermal transmittance (ASHRAE, 2005), cooling degree days, and weighted average of the cooling COP of the GSHP resulting in a 43% reduction in electricity for air conditioning of the passive solar house. The reduced electricity required for cooling is influenced by a number of factors which include: 1) roof overhang to shade the southern wall of



(a) (b)

Figure 6 *Heating energy supplied by the (a) GSHP and (b) passive solar.*

the house. 2) orientation of the southern wall facing 12 degrees east of south and shading the south facing windows in the late afternoon. 3) house was placed next to a large oak tree that shades the south wall and the garage shades the house in the late afternoon. 4) the south-facing windows allow indirect sunlight in the summer, reducing the heat from artificial lighting. 5) ceiling fans circulate the air allowing the thermostat to be set in the summer at 26.1°C (79°F) and still be comfortable, reducing the heat transfer into the house.

The GSHP contained a desuperheater intended to provide a portion of the hot water. The HVAC installer suggested only one hot water tank that is electrically energized be used in the system to interact with the desuperheater and provide hot water. The electric hot water heater was examined to determine what portion of hot water was provided by the GSHP. Changes in estimated incoming water temperature accounted for 30% of the changes in electrical usage of the hot water heater and there was no correlation between operation of the heat pump and electrical usage of the hot water heater. Consequently, since the analysis included the time when the heat pump was off, it was determined that the desuperheater did not provide any hot water to the house.

After one year of data collection ended, the occupants learned of an improved hot water thermostat setting allowing the desuperheater to provide some energy to the hot water. The occupants also learned about the two tank setup; the first tempering or preheater tank only obtains energy from the desuperheater to heat up the coldest water, while the second tank, or tankless inline heater, is electrically heated. This modified setup could significantly increase the energy into the hot water from the desuperheater, by allowing it to heat colder water, and decouple the amount of energy provided by the desuperheater and the preferred hot water temperature selected by the homeowners.

ECONOMICS

Table 1 shows the increased cost of the energy efficient modifications. The improvements in the actual house of

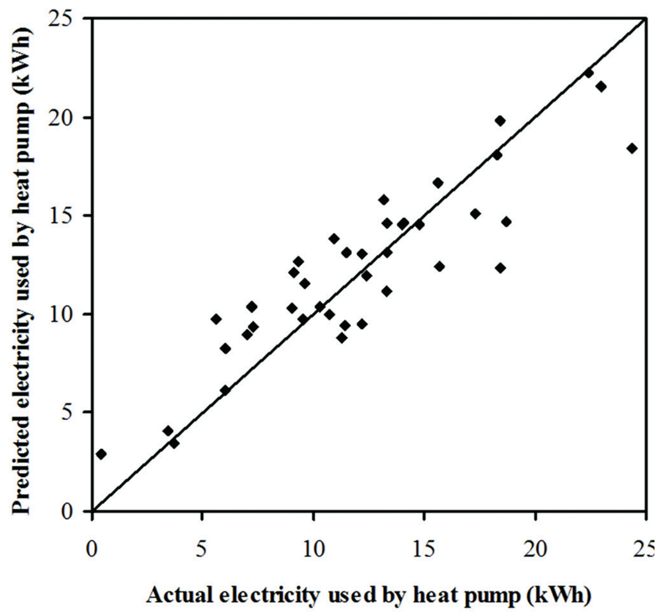


Figure 7 *Predicted versus actual electricity used by heat pump for heating.*

passive solar orientation, thicker walls and insulation, CFLs, and insulated rim joist, each increased the price $200 or less and did not take any more labor than a typical house except insulating the rim joist. The improved Energy Star appliances reduced electrical use and in addition, because of the final high speed spin of the clothes washer, the reduction of electricity used by a standard clothes dryer was estimated. Improved windows greatly assisted in decreasing heating and cooling costs since windows have the lowest R-value of the walls or ceilings, therefore improving windows can make a large reduction in heat transfer. Triple-pane windows were considered; however, they were not chosen because energy savings did not justify the increased cost. Insulated concrete forms were selected because of the superior insulating ability and also the insulated concrete forms were assembled by the general contractor and homeowners. The installation of the GSHP was the largest increase in price of any of the improvements but, it provided the greatest reduction in energy use. Modifications to obtain 50% of the hot water as promoted by the HVAC manufacturer would significantly improve the cost effectiveness of it.

The current electric rate in Carbondale, IL is \$0.106/kWh providing an annual cost savings of \$826 for the actual house, resulting in a simple payback time of 9.7 years. Including interest but removing inflation results in a payback time of 10.5 years. The total cost of the house including all material, land, on-site general contractor, and subcontractor costs resulted in a final price of \$1062/m^2 (\$99/ft^2) of finished floor area, while a similar house in the same city would cost approximately 1345 to 1507 \$/m^2 (125 to 140 \$/ft^2). The significant reduction in price of the actual house is due to the homeowners performing the routine manual labor as directed by the on-site general contractor.

CONCLUSIONS

Current best building practices of residential houses were used to construct a passive solar house that was energy efficient and cost effective. Solar radiation provided a noticeable amount (23%) of the energy needed for heating. The GSHP successfully provided the heating and cooling needed; however, unfortunately no correlation was noticed between GSHP operation and electricity used for hot water, indicating the desuperheater of the GSHP, in the tested configuration and thermostat setting, provided little or no hot water. A modification was proposed to significantly improve the amount of hot water provided by the GSHP. The Energy Star appliances, in particular the front loading clothes washer, decreased the energy used for hot water as well as drying. Cumulatively, the energy efficient improvements likely were cost effective as demonstrated by the payback period. The cost effectiveness will improve if electricity prices increase as proposed in the Carbondale, IL region or if the occupants family increase in number requiring more electricity for bathing and washing. Significant cost effectiveness also resulted from employing an on-site general contractor knowledgeable in energy conservation practices and who allowed the homeowners to provide much of the labor resulting in a very energy efficient house at a much lower price than a comparable house with similar features.

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