The Winding Road Towards "Zero" Energy: Lessons from Monitoring Efficient Solar Homes

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ABSTRACT

Through U.S. Department of Energy's (DOE) Building America program, Steven Winter Associates, Inc. has been working with builders of efficient, solar homes around the country. The authors have performed energy modeling of the buildings and have installed detailed monitoring of several solar homes to evaluate – and to demonstrate – the energy performance of the building systems.

Monitoring of solar homes in South Chicago, IL; Atlantic City, NJ; Hadley, MA; and Madison, WI, showed solar electric systems providing between 10% and 76% of home electric loads. Solar thermal systems monitored provided 60-65% of annual domestic hot water loads. The results also highlighted several areas (including HVAC distribution, ventilation, lighting, occupant behavior, and commissioning) which have significant impacts on home energy performance and are sometimes overlooked by builders and designers. The authors present the results from these monitoring efforts in hope that they may be useful for others moving towards "zero energy."

Introduction

Over the last decade, there has been a growing interest in the building energy community about the prospect of "zero energy" buildings: buildings that combine energy efficiency and renewable energy so building systems generate all of the energy that consumed by the building and its occupants. In 1998, the Florida Solar Energy Center (FSEC) evaluated one of the first near-zero energy homes built in Lakeland, FL, where energy-efficient features reduced building loads by 70%; a photovoltaic system provided 73% or the remaining load, for a total reduction of 92% compared to a standard home over the course of a year (Parker 2000). The U.S. Department of Energy (DOE) has been a strong proponent of the "zero energy" concept, and it has become a predominant focus of DOE's Building America program. Over several years, Building America teams and others have been involved in design and research of homes approaching "zero energy" (Farhar 2004; Keesee 2005; NAHBRC 2004; Norton 2005).

Largely through DOE's Building America program, Steven Winter Associates, Inc. has been working with builders of efficient, solar homes around the country. For most of these advanced homes, the authors performed energy modeling of the buildings and energy systems. As homes were nearing completion, the authors were able to install detailed monitoring of several homes to evaluate – and to demonstrate – the energy performance of the building systems.

The authors believe that monitoring energy performance of advanced systems is key in the move towards "zero energy" homes. Information from monitored homes can expose shortcomings in systems design and operation as well as highlight areas where energy modeling can be improved. In addition, the authors have found that "real-world" demonstrations and data from high-performance homes often have more credibility with builders, trades, the general public, and others.

This paper summarizes the monitoring results from four solar home projects located in Chicago, IL; Atlantic City, NJ; Hadley, MA; and Madison, WI.

The Homes

It's important to note that none of the homes monitored achieved zero net energy consumption. For many of these homes, "zero energy" was not an identified goal; rather they were efficient homes incorporating solar systems.

Figure 1. Images of Homes Monitored

Left to right from upper left: South Chicago, IL; Atlantic City, NJ; Hadley, MA; and Madison, WI

South Chicago, IL

In South Chicago, IL, Claretian Associates (a non-profit developer) and South Chicago Workforce (a non-profit builder) have teamed to build 26 affordable homes in a low-income neighborhood. Key features include:

- SIP construction,
- ENERGY STAR® windows,

- Condensing furnaces,
- ENERGY STAR® appliances,
- Compact fluorescent lighting (~50%), and
- 1.2-kW PV systems on the first 12 homes.

SWA monitored overall electricity consumption in the homes, energy produced by the PV systems, and performance of several ventilation systems.

Atlantic City, NJ

The Casino Reinvestment Development Authority (CRDA) leads several community development initiatives in Atlantic City, NJ. In 2003-2004, CRDA finished construction of six solar homes on vacant lots in Atlantic City. The homes feature:

- Modular construction,
- Passive solar space heating,
- Mini-split, ductless air conditioning,
- Combination boiler/water heater and hydronic baseboard heating,
- CFLs in all fixtures, and
- 2.8- or 4-kW PV systems.

SWA was able to monitor electricity use and generation and environmental conditions at one home for the first year of occupancy.

Hadley, MA

In 2003, SWA began working with Western Massachusetts Electric Company (WMECO) to evaluate utility costs and benefits of homes approaching "zero energy." The first result of this research effort was construction of a single-family home in Hadley, MA, featuring:

- Stick-framing (2x6) with dense-blown cellulose insulation,
- 100% of lighting is fluorescent,
- Efficient appliances,
- ENERGY STAR® oil boiler providing hydronic heat and hot water,
- 2.6-kW PV system, and
- Solar DHW system with 64 ft^2 of collector and 80 gallons storage.

The authors are monitoring performance of both solar systems, electricity consumption, oil/biodiesel consumption, and environmental conditions.

Madison, WI

Through the Building America program, the authors have worked with Veridian Homes in Madison, WI, for over four years. The latest prototype home, completed in 2004, features:

- 2x6 construction with high-density, blown-in fiberglass insulation,
- R-50 attic insulation,
- Condensing furnace with an efficient fan motor,
- SEER-14 air conditioning,
- Tankless gas water heater,
- 100% fluorescent lighting,
- All ENERGY STAR® appliances,
- Electricity monitoring & feedback system, and
- Solar DHW system with 64 ft^2 of collector and 80 gallons storage.

The authors are monitoring detailed electricity consumption in the home as well as environmental conditions and performance of the solar thermal system.

Energy Modeling and Monitoring

For most of the homes, the authors performed Building America "benchmark" analyses using the protocols developed by the National Renewable Energy Laboratory (NREL 2004). Hourly energy simulations of the homes and energy systems were performed primarily with Energy Gauge USA software. Benchmark analyses predict reductions in source energy consumed at the home using national averages for site-source energy ratios. A true net zero energy home, using this analysis procedure, is a home that, over the course of a year, requires no net consumption of source energy (primarily fossil energy).

Monitoring of home energy systems was accomplished primarily with Campbell Scientific datalogger systems. Electricity watt and watt-hour transducers (provided by FlexCore and Continental Control Systems) were used to measure AC electricity consumption and generation. Temperature measurements were made with 25 kΩ NTC thermistors; humidity measurements were made with capacitive transducers manufactured by Humirel. Water flow measurements were made with turbine meters provided by Omega Engineering. The authors installed flow meters to measure natural gas consumption in homes with natural gas, but these sensors proved unreliable. Where possible, natural gas consumption was obtained from utility bills. In the Massachusetts home, a float-level transducer in the oil tank provided more detailed oil consumption data. All datalogger systems included a telephone modem, and SWA collected data bi-weekly via telephone.

Modeled vs. Monitored Energy Use

For analysis purposes, the authors have considered home electricity consumption separately from fossil fuel consumption. While the two can be closely linked, it's very common to see homes that use very little fossil fuel but consume a tremendous amount of electricity (and vice versa). For each home described above, SWA does have some measure of overall electricity consumption. As Table 1 shows, electricity use varies considerably among the homes.

Table 1. Average Electricity Consumption (Over One Year) from Monitored Homes

Home	Average Electricity Use [kWh/day] Modeled	Monitored
South Chicago 1	na	37.2
South Chicago 2	na	24.1
South Chicago 3	19.9	17.4
Atlantic City	na	15.8
Hadley, MA	33.8	9.7
Madison	18.8	21.0

SWA was not able to collect detailed natural gas consumption data for the Atlantic City, Madison, or South Chicago homes. For the Madison and two of the South Chicago homes, however, SWA has obtained gas utility bills. In the Hadley home, SWA was able to collect detailed oil consumption values.

The differences between measured and modeled fossil fuel consumption is much less than with electricity (Table 1). Space heating – the largest piece of fossil fuel consumption in each home – can be predicted by modeling quite well. The fossil fuel variations come primarily from hot water use patterns, laundry and cooking habits, and weather conditions over the monitoring period; these uses are more difficult to model accurately.

Table 2. Summary of Modeled and Measured Fossil Fuel Use

Home	Annual Fossil Fuel Use Modeled	Measured
South Chicago 1	na	514 therms
South Chicago 3	740 therms	556 therms
Hadley, MA	967 gallons	1022 gallons
Madison	603 therms	630 therms*

* The measured value from the Madison home is extrapolated from 11 months of utility data

Monitored and modeled electricity data vary considerably. In the home in Hadley, MA, for example, actual electricity consumption is less than 30% of the benchmark prediction. In Madison, actual consumption was 10% more than the prediction. Although both homes have similar occupancies and were built with similar appliances, energy use varied considerably. An inspection of the Madison home revealed a spare refrigerator (approx. 20 years old)and freezer in the basement. Also, the owners installed a dehumidifier in the basement that was operated continuously. The owners were observed to have several televisions operating, and they also maintain a home office stocked with computers, fax, and printer, that were powered continuously. A spot inspection of the Hadley home, by contrast, showed very few additional appliance loads and the owners appeared to be conscientious about turning off lights and appliances.

Such variability is a concern for builders and designers of homes nearing “zero energy.” Home residents certainly have a significant responsibility in operating homes in an efficient manner, and the authors believe that addressing occupant behavior (with feedback or education regarding energy use) is a key component in reaching zero energy.

Monitored Data from Building Systems

HVAC Distribution

Air handler energy. While energy consumption habits differ widely, building designers have at least some control over the efficiency and energy use of heating and cooling systems. Designers are generally well aware of the effects of superior envelopes, high-SEER and right-sized air conditioners, and efficient boilers or furnaces, but the distribution of heating or cooling is often overlooked. In the homes SWA has monitored, the homes in South Chicago and Madison are heated and cooled with central forced air. Homes in Hadley, MA, and Atlantic City utilize hydronic heating (primarily baseboard convectors).

Unfortunately, the South Chicago homes present excellent examples of how *not* to distribute air in efficient homes. While these homes use condensing boilers (AFUE of 92.5%), the fans alone consume 700-800 Watts. The effects of these inefficient fans are compounded in that two of the South Chicago homes (nos. 1 and 2) use the air handlers as part of fresh air ventilation systems. The first South Chicago home also has central air conditioning (homes 2 and 3 do not have AC). Table 3 shows average daily electricity use of air handlers in the Chicago and Madison homes. In the Madison home, where an efficient air handler with a brushless, permanent magnet (BPM) motor consumes 200-300 Watts, the air handler is used for heating and cooling only; ventilation is accomplished separately.

While the authors did not collect electricity consumption data from the hydronic distribution systems, the average total electricity consumption of the two homes during winter months (12.8 kWh/day in Hadley and 12.5 kWh/day in Atlantic City) suggest that the hydronic distribution did not contribute greatly to the total electric load. While pump power consumption varies, most residential circulators consume between 40 and 200 Watts; typically less than even the most efficient air handlers. Complicated hydronic systems can, however, utilize many circulators.

Table 3. Summary of Electricity Consumed by Central Air Handlers

Home	Average AHU Elec. Use [kWh/day]
South Chicago 1	10.8
South Chicago 2	10.3
South Chicago 3	3.4
Madison	0.8

An alternative to forced air cooling in Atlantic City. The savings possible from efficient hydronic heat (distribution of hot water rather than hot air) may be negated by the need for ducted air conditioning distribution. Few homes incorporate separate distribution systems for heating and cooling – this is often cost-prohibitive and impractical. The designers of the Atlantic City homes chose to stay with hydronic heating (baseboard convectors) and install a separate ductless, mini-split air conditioning system. A single condensing unit serves two fan coils in the Cape home: one fan coil is in the living room; the other is upstairs in the central hall between the two bedrooms. Consumption of each fan-coil unit is listed at 20-30 Watts.

One major concern for builders and designers considering mini-split air conditioners is adequate distribution and comfort. In the home in Atlantic City, the authors installed temperature and humidity sensors in downstairs living areas and in each upstairs bedroom. The upstairs bedrooms are not cooled directly, as the fan coil unit is located in the hallway between the bedrooms. Surprisingly, the temperature sensors showed relatively consistent, comfortable temperatures throughout the home. An interview with the homeowner revealed that occupants were very comfortable during summer months, though bedroom doors were often left open to allow for more consistent temperatures. While evaluation of comfort in one home has limited value, it does suggest that more evaluation of the necessity of heating and cooling distribution in very efficient homes is warranted.

Ventilation. Most building scientists agree that providing mechanical ventilation is a necessity in a high-performance home (ASHRAE 2004). Mechanical ventilation does consume electricity and often results in thermal penalties. In the three South Chicago homes, SWA compared the performance of three different ventilation systems: an energy recovery ventilator (ERV), an Air Cycler (supply ventilation using the central air handler with a duct from outdoors to the return plenum), and a controlled exhaust fan in each of two bathrooms.

Because both the ERV and Air Cycler used an inefficient central air handler, this study found that the efficient exhaust fans were by far the least energy intensive. In larger homes, however, one or two central exhaust fans cannot be expected to provide adequate fresh air distribution. Exhaust-only strategies may also not be appropriate where natural-draft combustion appliances are present (because of interference with exhaust draft) nor in hot, humid climates (because of moisture management concerns).

In cold climates, the least energy-intensive ventilation system is often an ERV or HRV utilizing a dedicated distribution system (i.e., not the central air handler; Aldrich & Vijayakumar 2006). If a central air handler is part of a ventilation system in an efficient home, this air handler should be very efficient. In the South Chicago homes, the inefficient furnace fans caused very high electricity consumption in what could otherwise have been very efficient homes (Table 1 and Table 3).

Lighting

One of the simplest and most effective specifications for efficient homes is: all fixed lighting to be fluorescent (or compact fluorescent). If a builder or designer wants to do more to guarantee home efficiency, an improved specification is: all spaces to be lighted with efficient, fluorescent fixtures. To save costs, builders often do not install light fixtures in bedrooms, and minimal lighting is provided in living rooms, offices, and other work spaces. In the South Chicago homes, for example, homeowners installed halogen torchieres and incandescent lamps to augment the modest amount of fixed, fluorescent lighting. The authors believe this contributed to the higher electricity loads.

In three of the homes (Atlantic City, NJ; Hadley, MA; and Madison, WI) 100% of the fixed lights were fluorescent or compact fluorescent (CFL). While the actual lighting load itself was not measured, the authors believe that the low overall electricity consumption in the Hadley and Atlantic City homes (9.7 and 15.8 kWh/day, respectively) is largely due to efficient lighting.

Solar Systems and Progress Towards Zero Energy

Hadley, MA. The 2.64-kW_{DC} photovoltaic system in the Hadley home generated 2,682 kWh during 2005, providing 76% of the electricity consumed in the home. Because of the shallow elevation of the array (18°) and snow cover, winter electricity production was much lower than summer production. The solar water heating system provided 61% of domestic water heating energy in 2005; average hot water use was 64 gallons per day.

Figure 2. Summary of Electricity Generation and Consumption in the Hadley, MA, Home

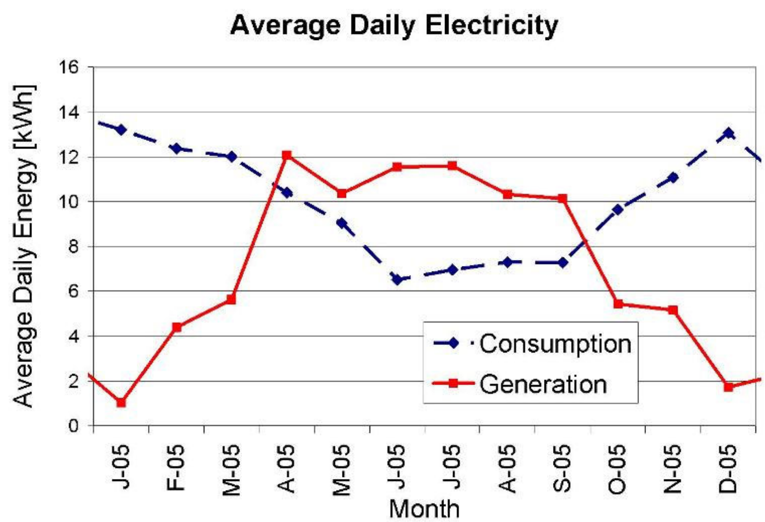
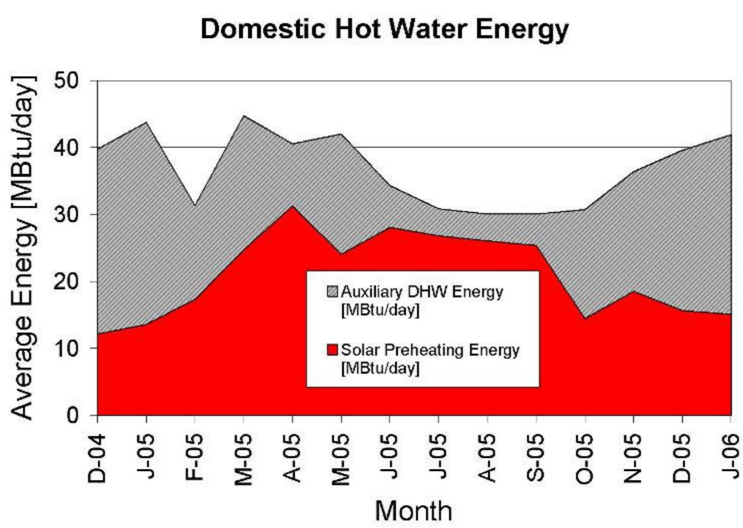


Figure 3. Summary of Domestic Water Heating Energy in the Hadley, MA, Home

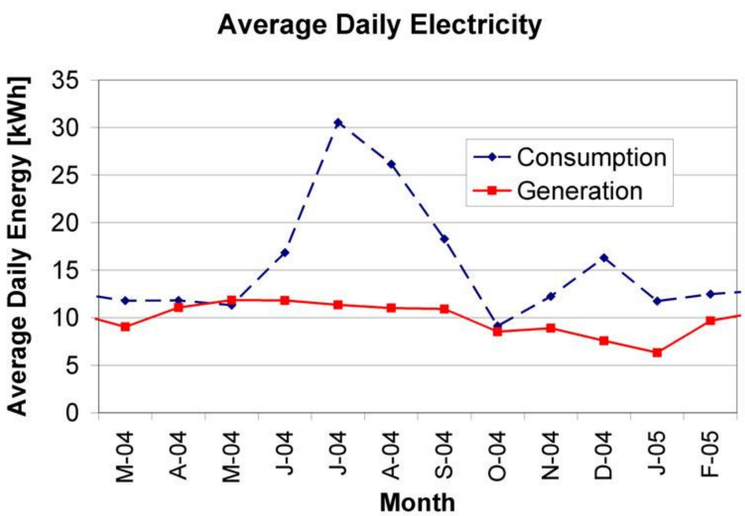


While the electric performance of the Hadley home was excellent, the thermal performance was far from "zero energy" as the occupants consumed 1,022 gallons of oil (approximately 143 MMBtu of fuel). While the cellulose wall and ceiling insulation (R-19 and

R-40) is fairly typical (or slightly above-average) for the region, the basement insulation (R-13 batts between the first floor and basement) is less than regional standards. Improving the envelope – e.g., installing 1” of rigid foam as a thermal break on exterior walls – would reduce thermal loads substantially. Such measures would also be much more cost-effective than either solar system. To truly reach “zero energy” in such climates, a larger investment is probably necessary for higher insulation levels and possibly in passive or active solar space heating as well.

Atlantic City, NJ. Passive solar heating was incorporated by the designers of the Atlantic City homes. Unfortunately, the large area of clear, southern glass has no fixed shading to reduce summer gains. As a result, electricity use in the summer doubles relative to winter months (see Figure 4). Throughout the non-cooling months, the output of the 2.85-kW_{DC} PV system is almost equal to consumption. The annual solar electric fraction was 62% for the 12 months monitored; 3,562 kWh were generated, 5,715 kWh were consumed. Clearly, better solar control during the summer is one feature that would bring the home closer to “zero energy.”

Figure 4. Summary of Electricity Generation and Consumption in the Atlantic City Home



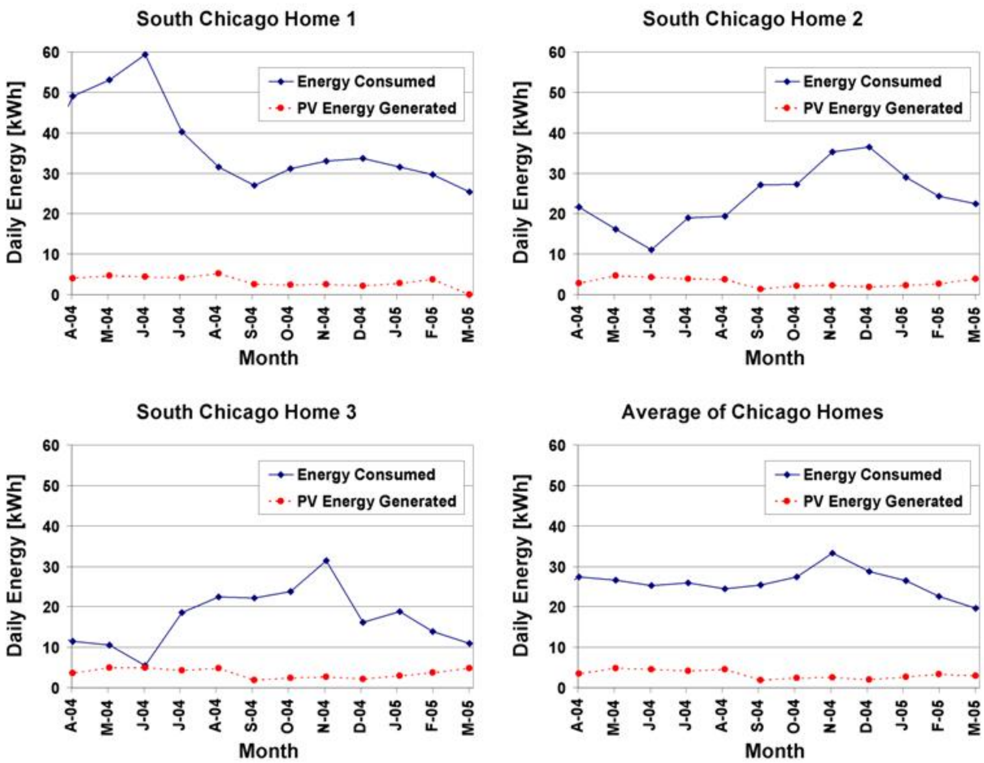
No data on fossil fuel consumption are available from this home. In an interview with home residents, they maintained that the passive heating is quite useful. Homeowners report almost no boiler operation during the day and greatly reduced operation at night.

South Chicago, IL. In the Hadley and Atlantic City homes, the PV systems appear to be sized to provide most of the homes’ electric loads (76% and 62% respectively). In the South Chicago homes, the PV contributions are much smaller; the 1.2-kW systems only provide a small part of the electric load (10%, 13%, and 20% in homes 1, 2, and 3). As discussed above, the main cause of elevated electricity use is the inefficient furnace fans. SWA suspects less efficient lighting is also a cause of higher electricity use.

SWA calculated that the electricity savings from a proposed \$500 - \$1,000 furnace fan upgrade would be almost twice as much as the electricity produced by the \$13,000 PV systems (for homes 1 and 2 where the furnace fan is used for ventilation). The authors impressed upon the builder and developer the importance of these numbers. In this development, however, the PV systems are paid for entirely by a combination of state, city, and utility funds. There are no such incentives for efficient furnace fans, and the additional \$500 - \$1,000 per home is beyond the budget for these homes.

While the electric performance of the homes is poor, the thermal performance is quite good. The tightly-sealed SIP envelopes, low-e windows, and condensing furnaces resulted in space heating gas usage of 383 and 478 therms per year for homes 1 and 3 (gas data were not available for the second home). Water heating, cooking, and gas dryers consumed an additional 131 and 78 therms per year respectively.

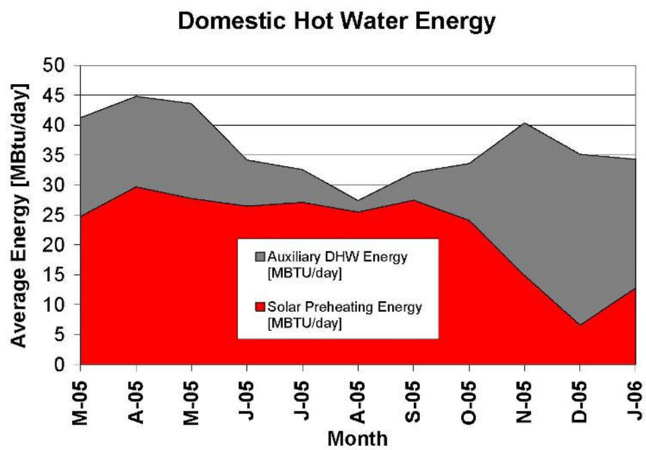
Figure 5. Summary of Electricity Generation and Consumption in the Three South Chicago Homes



Madison, WI. As shown in Table 2, the overall fossil fuel consumption of this home was low as predicted by benchmark analysis. The solar thermal system worked well; it provided 62% of water heating energy through the eleven months monitored. The combination of the tankless water heater and the solar system also appeared to work well, but proper operation required several commissioning visits by the plumber, the solar contractor, and SWA.

In the Madison home, the builder made sensible, cost-effective steps towards superior efficiency and incorporation of renewable energy. While the builder did not install PV, they did choose to provide blown-in insulation, extensive air sealing, 100% fluorescent lighting, superior ENERGY STAR® appliances, a condensing furnace, an tankless water heater, and a solar thermal system. The builder did make the first, lowest cost (and probably most cost-effective) steps towards "zero energy."

Figure 6. Summary of Domestic Water Heating Energy in the Madison Home



Summary

All of the homes described here are quite far from producing 100% of the energy that they consume, but they do demonstrate some significant features (and some pitfalls) on the way to "zero energy." Most importantly, designers of homes that truly want to target zero net energy should implement cost-effective energy efficiency measures before considering active solar systems. Solar systems cannot bridge the gap between a moderately efficient home and a zero energy home. Envelopes must be very well insulated, all lighting and appliances must be very efficient, and HVAC distribution energy must be minimized.

Table 4. Summary of Modeling and Monitoring for the Six Solar Homes

Home	Avg. Electricity [kWh/day] Modeled Use	Measured Use	Measured Generation	Solar Elec. Fraction	Annual Fuel Use Modeled	Measured	DHW Use [gallons per day]	Solar Thermal Fraction
South Chicago 1	na	37.3	3.6	10%	na	514 therms	-	-
South Chicago 2	na	24.0	3.0	13%	na	na	-	-
South Chicago 3	19.9	17.2	3.5	20%	740 therms	556 therms	-	-
Atlantic City, NJ	na	15.8	9.8	62%	na	na	-	-
Hadley, MA	33.8	9.7	7.3	76%	967 gallons	1022 gallons	63.6	61%
Madison, WI*	18.8	21.0	-	-	603 therms	630 therms	70.7	62%

* Only 11 months of data were available for the Madison, WI home

In addition to efficient design and construction, home resident behavior must be addressed. Education or energy feedback devices may be necessary to provide information to home residents, with whom the ultimate responsibility for reaching "zero energy" resides. As the wide disparity in energy use indicates, the consumption patterns of many Americans are not compatible with the operation of a zero energy home. As the data presented here show, a 2-4 kW_{DC} PV system is capable of providing most or all of the electricity needs for an efficient home with conscientious residents.

This study also highlighted the need for efficient HVAC distribution in a "zero energy" home. Electricity used by pumps and fans can be considerable if systems are not designed, installed, and commissioned carefully. In the relatively cold climates discussed here, even homes with efficient envelopes have substantial space heating loads. A combination of passive and active solar is one viable route for meeting heating loads in zero energy home, but because of high costs and non-standard systems, builders rarely consider active solar space heating. The authors believe that further research, design, and evaluation of simple, lower-cost solar heating systems are appropriate to help close the gap to "zero energy" in heating-dominated climates.

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