Approaching “Zero Energy” in the Pacific Northwest Marine Climate

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ABSTRACT

This case study focuses on an all-electric, 2400 ft^2 single-story home in Olympia, WA. Building America Industrialized Housing Partnership (BAIHP) staff has provided technical assistance in the design, commissioning, and monitoring phases of the project. This home includes numerous energy-efficiency envelope measures, including a 4.5 kW photovoltaic array (an additional 2.5 kW installed in 2008), ground-source heat pump supplying domestic hot water and space heat to a radiant slab, and solar sunspace. This paper presents modeled and measured overall home energy performance, and an evaluation of building envelope, space and water heating, ventilation, and PV systems.

Home construction began in summer of 2005, and completed field testing and commissioning in May of 2006; a data acquisition system was installed in 2007, which has since been monitoring home energy use.

The home’s US Department of Energy (DOE) Building America benchmark is roughly 52% to 68% whole-house site savings without and with PV. The home’s modeled total electric use is 11481 kWh/year without PV, and 7691 kWh/year net with PV.

Monitored total electric use for 2008 and 2009 averages 12845 kWh/year without PV and 6740 kWh/year net with PV; of PV production, roughly 47% was used by the house, 53% returned to the utility.

INTRODUCTION

Homes account for 38% of all US electricity consumption and 22% of all U.S. primary energy consumption (EIA 2010). This represents a huge opportunity to reduce our energy consumption and make cleaner choices for the energy we consume. The US Department of Energy’s Building America (BA) program is working to increase the energy efficiency of new and existing homes while increasing comfort and durability and reducing resource use. As part of this program, we pursue opportunities to research highly efficient homes with the goal of understanding what works, what doesn’t work, and what are the most economic ways to reach very high efficiency targets. The program aims to create cost neutral zero-energy homes by 2020. In pursuit of this goal, this home and other research homes around the country designed to approach or achieve the zero-energy goal are being built and studied.

In general, a zero-energy home is designed to produce as much energy as it consumes over the course of a full year. The BA program definition is more specific: a zero-energy home is designed to offset as much source energy as it consumes over a typical year using BA benchmark assumptions for typical occupant behavior. To achieve zero energy, the home exchanges energy with the utility power grid. It delivers energy to the grid when the photovoltaic (PV) system is producing more energy than is being used in the home, and draws from the grid when the PV system is producing less energy than needed in the home.

BACKGROUND

This project, called Zelonedom (the phonetic spelling for the Polish term for “green home”), demonstrates and promotes innovative energy saving and renewable energy technologies while evaluating those technologies’ energy performance

***Michael Lubliner** is the residential technical lead, **Andrew Gordon** is an energy specialist, and **Chris Fuess** is a computer programmer at the Washington State University Energy Program in Olympia, WA.*

Technical support for the project's design, construction, commissioning, monitoring and analysis was funded by the US Department of Energy's Building America Industrialized Housing Program (BAIHP). Zelonedom partners included Washington State University Extension Energy Program (WSU), Sam and Christine Garst, architect Mort Staffors James, Barrett Burr of Polar Bear Construction, Smart Energy Systems (the installer of the ground-source heat pump [GSHP]), PV installer Puget Sound Solar, and electric utility Puget Sound Energy. Additional project information can be found at http://www.thegarsts.com.

This project is a case study in the custom housing sector. The Garsts' willingness to finance the investment to address higher first costs while leveraging a combination of federal tax credits, state sales tax exemptions, and utilities incentives has led to what the Garsts believe is "a stable long term energy investment." Mr. Garst has been a renewable energy advocate since the 1970s, and an early adopter of innovative technologies and renewables. The Zelonedom project has helped BAIHP to move toward achieving net zero energy in marine climates.

The project was featured in the March/April 2007 *Solar Today Magazine* (Garst and Lubliner 2007). The project's preliminary case study was part of Building America Best Practices Series for High Performance Technologies: Solar Thermal & Photovoltaic Systems in the Marine Climate (Baechler et al. 2007). In 2009, a Building America Stagegate report was published, which included cost-benefit analyses, as well as detailed benchmarking analysis and details on ground source heat pump operation (Lubliner et al. 2009).

DESIGN

The Zelonedom was built with energy efficiency and renewable energy as a high priority, in an effort to evaluate proposed future energy efficiency targets for DOE's Building Technologies Program. Mr. Garst (2009) notes that planning ahead was critical to the project's success:

> With something this complex, you don't want to make it up as you go. We tried to do this all on paper before we started pouring concrete. We had the architectural plan, the landscaping plan, the lighting plan, even a furniture plan. We knew where we were going from the start. We knew how the systems were going to work together….Changes were very modest and were identified well in advance of finishing the house, so nothing was torn out and done again.

Designed by Morton Safford James III, AIA, Zelonedom fits the natural contours of the 3/4 acre building lot. Barrett Burr summed up the project from the builder's perspective (Garst 2009):

> This was a great project for my company. While the words "building green" may be new to the general public, building green is beginning to be understood as quality construction. Private, public and government organizations have been developing these ideas for the past twenty years. We have been adopting them all along. It has been called "Value based construction", "Model Conservation Standards", "Energy Efficient Building", "Energy Budget system design", "Eco-friendly/healthy homes". The Garst house allowed us to take the ideas from all these years of development and blend them with some of the newest available technologies. The result is a home that incorporates proven products and systems that benefit the environmental and homeowners.

Highly efficient, cutting-edge technologies are detailed below.

4.5 kW Photovoltaic Array. The PV system is a 4.5 kW DC photovoltaic system using 24 190 W Sanyo panels, and two Xantrex inverters. The system performance is monitored by both BAIHP and Puget Sound Energy. The utility meters monitor monthly total production and PV back to the grid, while the BAIHP meters monitor production on a 15 minute basis.

PV panels are oriented slightly to the southwest, which optimizes performance after morning fog burn-off. Roof angle is 32° to optimize PV production in the summer. The Sanyo HIT panels are rated at 190 W, but have a higher measured rating, roughly 220 W. Two-thirds of the output is a result of the mono-crystalline silicon wafer and one-third from ultra-thin amorphous silicon layer. The amorphous layer is believed to reduce in performance by as much as 5% per year during the first five years, and long-term monitoring is under investigation (Nelson 2008).

An additional 12 panels, comprising an added 2.2 kW, were installed in February of 2009.

Ground-Source Heat Pump. This innovative design uses a 3 ton Econar GSHP, which provides all domestic water and space heating needs. A 300 ft (91 m) long, 5 ft (1.5 m) wide, and 5 ft (1.5 m) deep trench has a total of 1800 linear feet (549 m) of 3/4 in. (2 cm) pipe and 1 1/4 in. (3.2 cm) manifolds. The highest loop is 3 feet (0.91 meters) below grade (see Figure 1 for GSHP system design).

The GSHP supplies heat to an 80 gal (303 L) storage tank (DHW in Figure 1) via plate heat exchanger (HX-1 in Figure 1) and pump. The tankless electric water heater (not shown in Figure 1), designed as master bedroom backup, has not been used past the first few months of occupancy. A Metlund demand recirculation pump control is used to ensure hot water at bath and kitchen fixtures, saving water and energy. Some minimal thermosiphoning of hot water to the cold-water line was observed in summer when irrigating; a re-plumbing fix in the slab is not possible.

The GSHP provides hot water to a separate 80 gal (303 L) storage tank (ST-1 in Figure 1) to up to six independently controlled zones for the radiant heating system. The zone control allows for cooler temperatures in bedrooms and for infrequently used rooms like the guest room. As shown in Figure 2, regardless of ambient temperature, main living area temperatures are consistently above 70°F (21°C).

The radiant floor slab pump controls were modified to limit pump operation during non-heating months. The entire

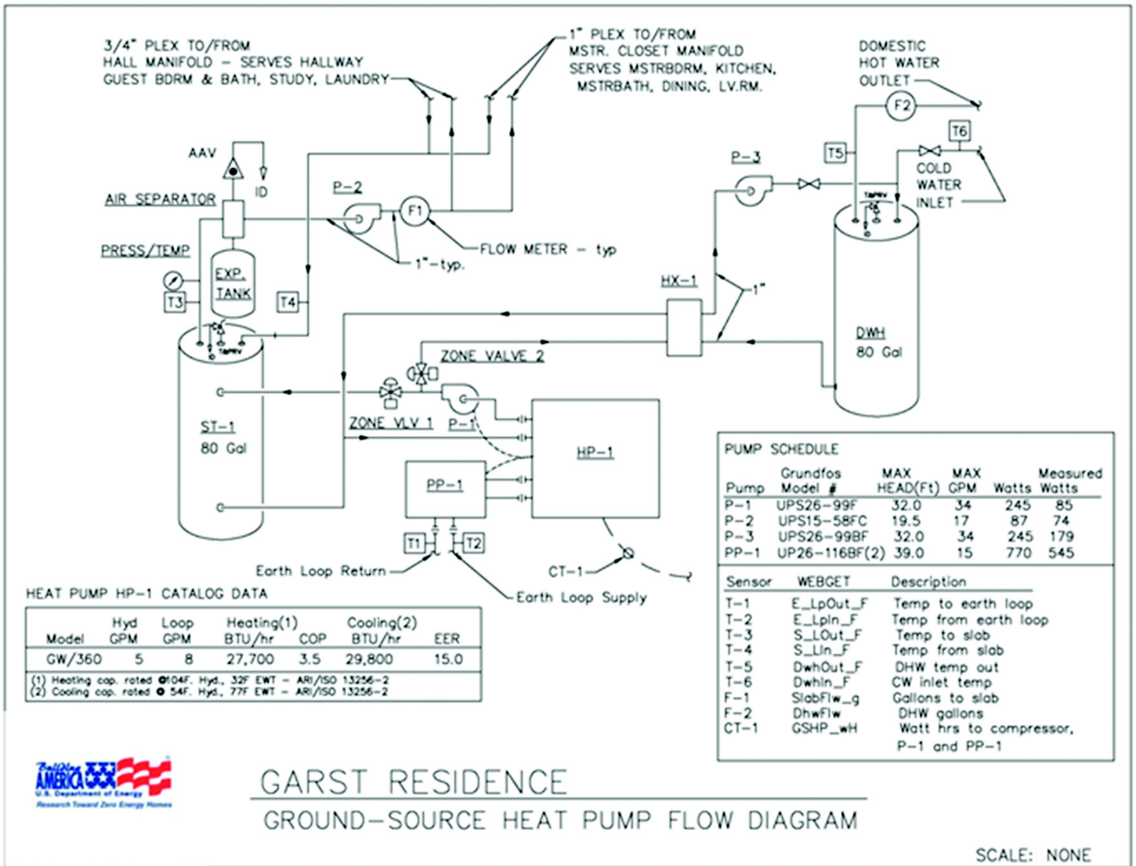

Figure 1 *Ground-source heat pump design.*

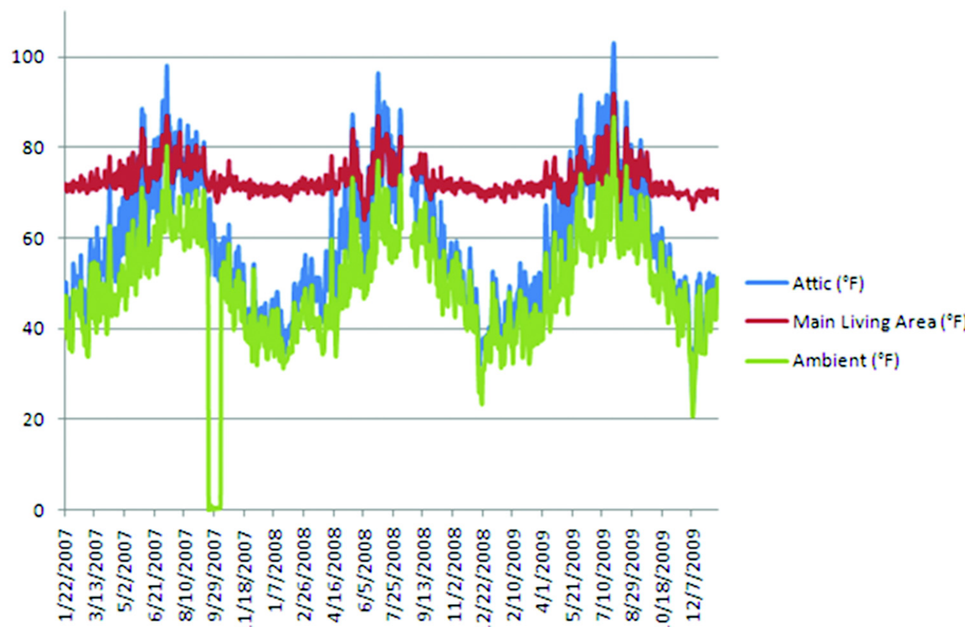

Figure 2 *Average temperature for vented attic (blue), house (red), and ambient (green).*

GSHP system is located in a partially buffered conditioned mechanical room between the garage and home. The mechanical room is conditioned by standby losses of GSHP system.

R-15 Radiant Slab. The floor is fully insulated to R-15 under the entire slab and perimeter. Current Building America benchmarking does not account for radiant slab heating systems and higher insulation levels. Washington state code required all radiant floors be fully insulated to a minimum of R-10.

Hybrid Ceiling Insulation. R-19 low-density blown-in foam was used above the ceiling drywall. An additional R-38 of blown-in fiberglass insulation was then installed above. The use of the spray foam reduced ceiling air leakage and improved the effectiveness of the entire ceiling insulation systems.

Foam Advanced Frame Walls. R-21 blown low-density foam was used in advanced framed walls. R-15 foam sheathing was used on a small section of bermed below-grade walls.

Central Energy Recovery Ventilator. This was connected to a forced air handler filtration system and filtration.

Tankless Hot Water. A tankless hot-water heater supplies the master bath.

Sun Tempering and Solar Sunspace. The home is designed with sun tempering to add more southern double pane glazing and a solar sunspace for solar gain. The sunspace is shaded and mechanically vented to outside with two 120 CFM (0.06 m^3/s) exhaust fan on a cooling thermostat, during non-heating months. During the heating season, another sunspace supply fan delivers 90 CFM (0.04 m^3/s) of preheated sunspace air to the home and is estimated to provide roughly 450 kWh of useful heat to the home. The GSHP maintains the sunspace slab at 60°F (16°C) to support growing lettuce in winter, as well as avocado and orange plants. The solar sunspace also adds significant aesthetics and functional value to the home. Garst has accepted the additional estimated 950 kWh of energy use associated with heating the sunspace as a lifestyle choice.

Energy Star® Windows. Wood clad windows were employed with a NRFC 0.33 U-factor and 0.33 SHGC. Higher SHGC were not available to optimize solar gains from south facing windows. Windows and skylights provide abundant natural light to each room. All the windows are operable to allow for cross ventilation for cooling during the summer. Unexpected leakage was revealed during blower door smoke stick testing; however, the Garsts note no comfort related drafts issues.

Ventilation System. An Ultimate Air Re-Couperator energy recovery ventilator (ERV) is connected to a fully ducted back-up Rheem #RBHC air handler to supply filtered fresh air and exhaust stale air from the home. This system is located in a partially buffered conditioned attic mechanical room; ductwork is covered by attic insulation.

After a few months, the Garsts decided to turn off the ducted ventilation system and rely only on the spot exhaust ventilation system for the following reasons:

- The envelope was not as tight as anticipated (around 4.4 ACH at 50 Pa).
- They perceived no added value in air tempering, filtering, and mixing. This perception seems to be confirmed by monitored relative humidity levels in the main living area (Figure 3); with few exceptions, humidity levels remained between 35% to 55% throughout the two-year monitoring period, regardless of outside conditions. This suggests that the spot exhaust is providing adequate ventilation.
- Central air handler with filter and ERV fans uses almost 300 W when running, a significant energy penalty.
- Noise of the ERV and air handler was undesirable.

Energy Star Lighting. The home uses 100% Energy Star screw-in CFL bulbs in a total of 41 fixtures (15 in main living space), and six additional exterior fixtures. Lighting design of the kitchen, which uses T-8 linear fixtures above and below cabinets, allowed elimination of many can fixtures. The hall and walk-in closet lights are turned on and off by motion sensors. The lamps near the motion sensors have prematurely failed, likely due to high cycling rates.

Energy Star Appliances. All appliances are Energy Star, including the clothes washer, refrigerator, and dishwasher

Energy Use Monitoring. The Energy Detective (TED) was installed to help the Garsts evaluate miscellaneous end loads when the PV system was not operating. Confusion related to TED arose from PV net metering system. TED is developing new products for use with net metered PV systems (TED 2010). Monitoring of the media center revealed a continuous standby loss of 84 W, mostly contributed by the cable. This is roughly 745 kWh per year. The Garsts are investigating the use of a manual switch to reduce standby power losses.

Other Green Features. Sustainable “green” technologies that use recycled and durable materials, reduce indoor air quality pollutant sources, and provide rainwater management were incorporated into Zelonedom. A separate PV system powers a DC pump for operating a small waterfall. These technologies are part of an overall systems approach that Zelonedom takes towards improving energy, durability, and environmental quality

More information is available at http://www.thegarsts.com.

FIELD TESTING AND COMMISSIONING

Fan depressurization field tests were used to determine the envelope leakage in accordance with *ANSI/ASHRAE Standard 119-1988 (RA 2004), Air Leakage Performance for Detached Single-Family Residential Buildings*. Fan pressurization tests were performed to determine ERV and air handler filtration system duct leakage in accordance with *ANSI/*

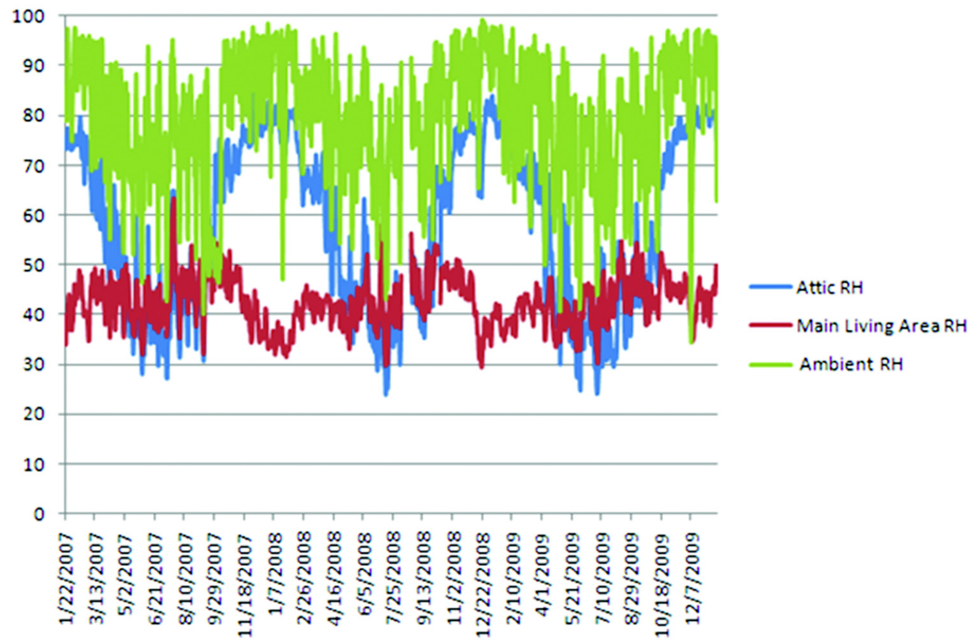

Figure 3 *Average relative humidity for vented attic, main living area, and ambient.*

ASHRAE Standard 152-2004, Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems. Bath fan and ERV flow rates were measured using a calibrated flow box; however, it was very difficult to get a reliable flow rate using this equipment due to the location and configuration of the outside termination fittings and impacts of wind during testing. The ERV measured supply flow was only 10 CFM (0.004 m^3/s); exhaust flow was 50 CFM (0.02 m^3/s).

Although caulking of all seams, plumbing, and wiring penetrations was conducted, blower door testing revealed significant leakage of the windows and some leakage at the slab to wall bottom plate. These leakage paths resulted in higher than anticipated envelope leakage of 4.4 ACH at 50 Pa.

DATA ACQUISITION

A data acquisition system was installed to determine home energy performance (FSEC 2009). The system was designed to allow disaggregation of the PV energy production and some end uses.

Monitoring Results

Annual Electricity Use. Monitored overall home energy usage for November 2007 through February 2010 is presented in Figure 4. Monitored total electric use for 2008 and 2009 averages 12845 kWh/year without PV and 6740 kWh/year net with PV. A detailed comparison of usage with the original 4.5 kW of PV and additional 2.2 kW is presented in a later section on Modeled and Actual Energy Usage.

Regression analysis was employed to help separate space and water heating performance. Figure 5 plots the watt-hours per day against the ΔT between indoors and outdoors, as a means of inferring the home energy performance with the ground-source heat pump for space heating. The analysis suggests a heat loss rate of 147 Btu/h· °F (834 W/h·K), with an R^2 of 0.61.

PV System. The photovoltaic system is performing well. From March 2008 through February 2009, performance was measured at 4538 kWh, or 1008 kWh per kW of installed PV. Of the total PV production, roughly 47% was used by the house, and 53% returned to the utility.

For the same months in 2009–2010, with the additional 2.2 kW of PV, performance was measured at 7765 kWh, or 1158 kWh per kW of installed PV.

GSHP. In 2007, investigators began the process of analyzing the innovative ground source heat pump design. One-minute data on ground-source heat temperature and a one-time flow measurement were used to determine per-cycle space and hot water coefficient of performance (COP) (see Figure 6).

Measurements of ground-loop flow rates ranged from 8 gal/min to 12 gal/min (30 L/min to 45 L/min), so the COP was calculated with the low and high rates of flow. In Figure 6, the slab runtime series shows the percentage of time that the ground-source heat pump operated in water-heating and/or space-heating mode. The earth ΔT represents the temperature drop across the earth loop when the system is operating.

The COP was calculated as

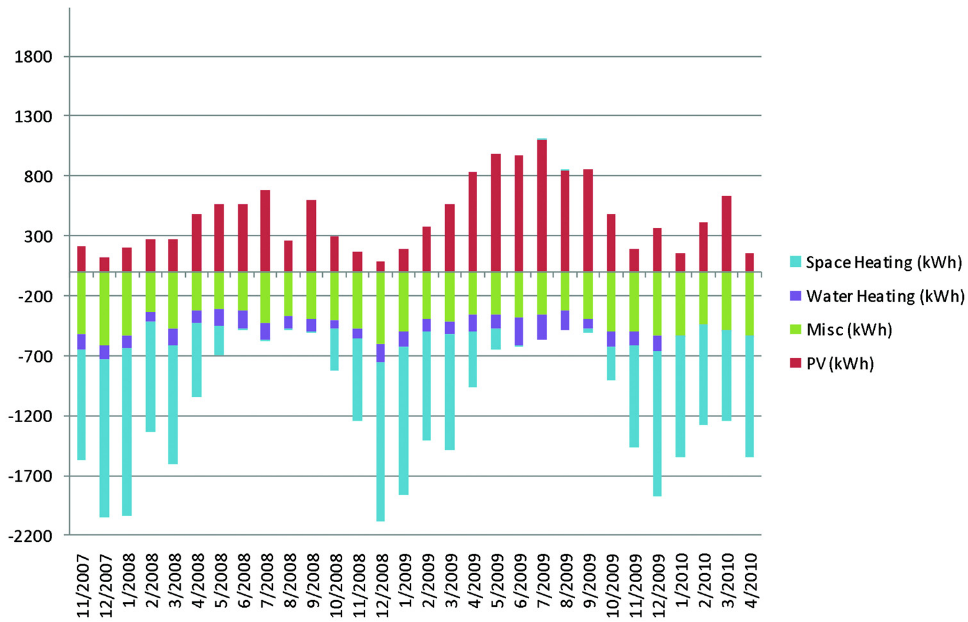

Figure 4 *Monthly energy use, including PV to grid, November 2007–April 2010.*

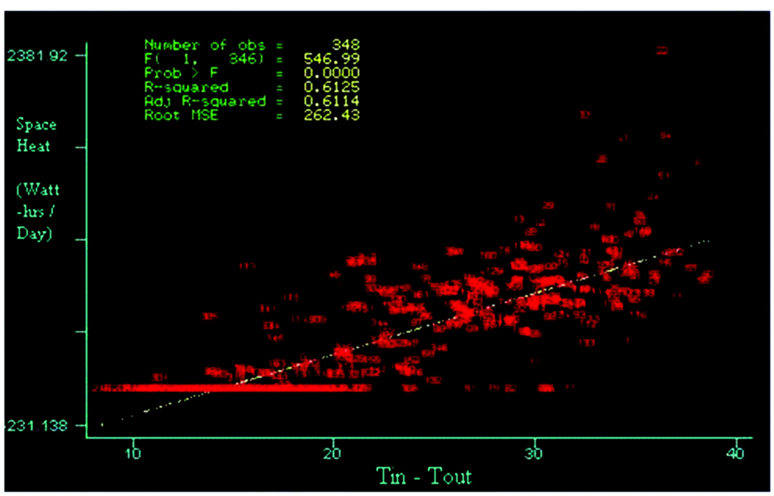

Figure 5 *Ground-source heat pump space heat vs.* ΔT *(slope = 147.4 Btu/h·°F).*

$$COP = \frac{Q_{earth} + Q_{compressor} + Q_{pumps}}{Q_{compressor} + Q_{pumps}} \quad (1)$$

where

Q_{earth} = energy extracted from ground loop, Btu/hr

$Q_{compressor}$ = electrical energy provided to heat pump compressor

Q_{pumps} = electrical energy provided to ground loop, and pump to storage tanks (PP-1, P-1, and P-3, as shown in Figure 1**)**

Additional detail on the COP calculation method can be found in the Garst Stagegate report, Appendix C (Lubliner et al. 2009).

It should be noted that the COP calculation focused on in-situ equipment performance and does not include distribution system losses associated with the mechanical room equipment or radiant floor.

COP estimates based on data logger measurements suggest the highest COP occurs during space-heating-only conditions in early winter. As seen in Figure 7, the COP is running above 5.5 in heating mode early in the heating season,

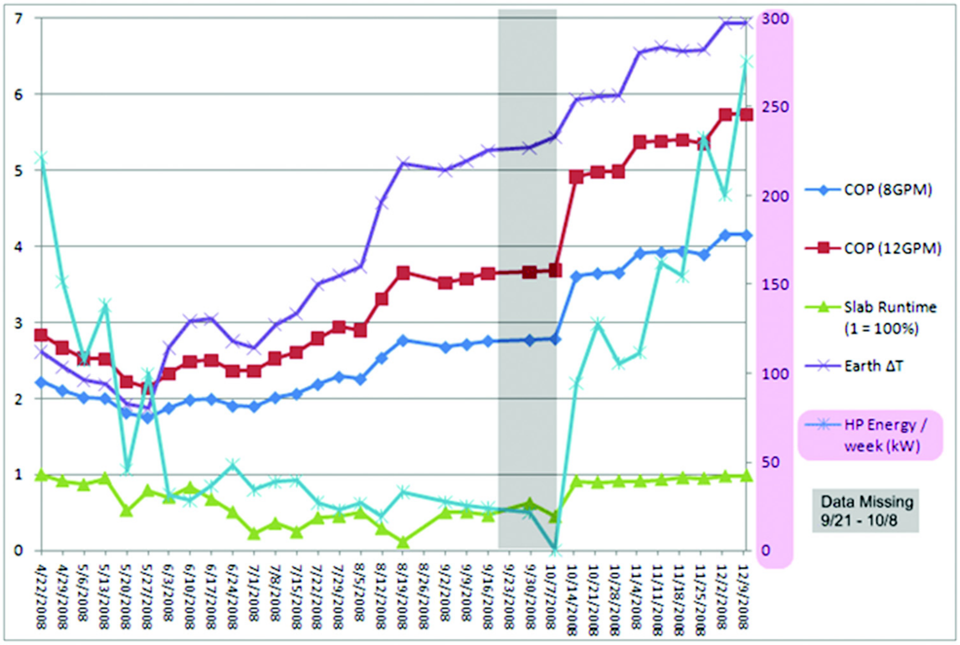

Figure 6 *Ground-source heat pump weekly COP, April 22–December 9, 2008.*

as a result of warmer ground temperatures and a higher percentage of space heat usage relative to hot-water usage.

The lowest COPs (2 to 2.5) were found during spring and entering into DHW-only mode, when the ground is coldest, as a result of wintertime heating. As shown in Figure 8, the COP is roughly 3.5 when the system is in water-heating-only mode after a number of months of not heating.

Ground-loop flow rates were estimated to be 11.8 gpm (45 L/min), based on 12 psi (83 kPa) pressure drop measurements across the earth-loop heat exchanger using manufacturer-supplied flow versus pressure drop engineering data and adjusting flow rates to reflect the 20% methanol ground loop heat transfer loop mixture. A one-time wattage measurement of the earth-loop dual-pump pack, domestic hot-water (DHW) loop pump, and slab pumps was conducted, as shown in the table in Figure 1. Efforts are under way to further evaluate COP and optimize piping design and pumping performance to improve COP.

Solar Sunspace. Investigators are evaluating using the home's sunspace to provide solar gain benefits to the house during the heating season via a thermostat-controlled exhaust fan that delivers heat to the home when the sunspace reaches roughly 75°F (24°C). Sixteen 55 gal (208 L) water drums are used as thermal mass. Figure 9 attempts to provide a snapshot of how the sunspace contributes to space heating in the house; warm air (red) is delivered to house on two consecutive mild days in October (outside temperatures in yellow). As fan turns on (purple), sunspace drops to temperatures (green) above outside and below house temperature (blue), providing solar gains to the home.

Figure 10 attempts to quantify the overall benefit of the sunspace throughout the year, showing the estimated 450 kWh per year from heat, less supply fan energy delivered from the sunspace to the home, along with the fan energy to exhaust heat in summer (note that only one of the exhaust fans was monitored—the other was assumed to operate at the same rate, and with the same energy use).

Simple modeling estimates the home with an unheated sunspace would use 4320 kWh/year, 5272 kWh/year with sunspace heated to home temperature, and 5272 kWh/year if not installed at all. Investigations are underway to further evaluate performance, and benefits of sunspace preheating supply air to house to offset potential mechanical ventilation (if used).

MODELED AND ACTUAL ENERGY USAGE

Table 1 compares simulated energy use, using Energy Gauge 2.8 (FSEC 2008) versus measured energy use from utility data. The period of March through February was chosen to compare annual electricity use before and after installation of the additional 2.2 kW of PV in February 2009.

While there seems to be overall agreement, a number of factors need to be considered when comparing the predicted versus measured energy use:

- Net of PV power produced was 3790 kWh simulated (842 kWh/year per kW of PV); 4538 kWh measured

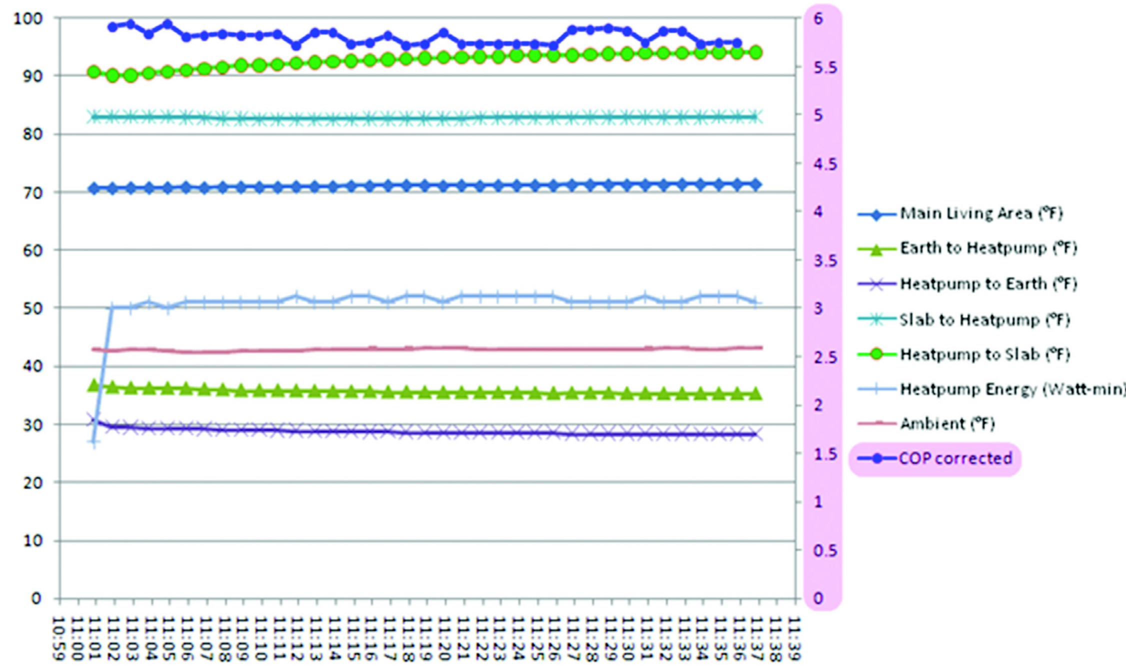

Figure 7 Ground-source heat pump in winter space heat mode, December 4, 2008.

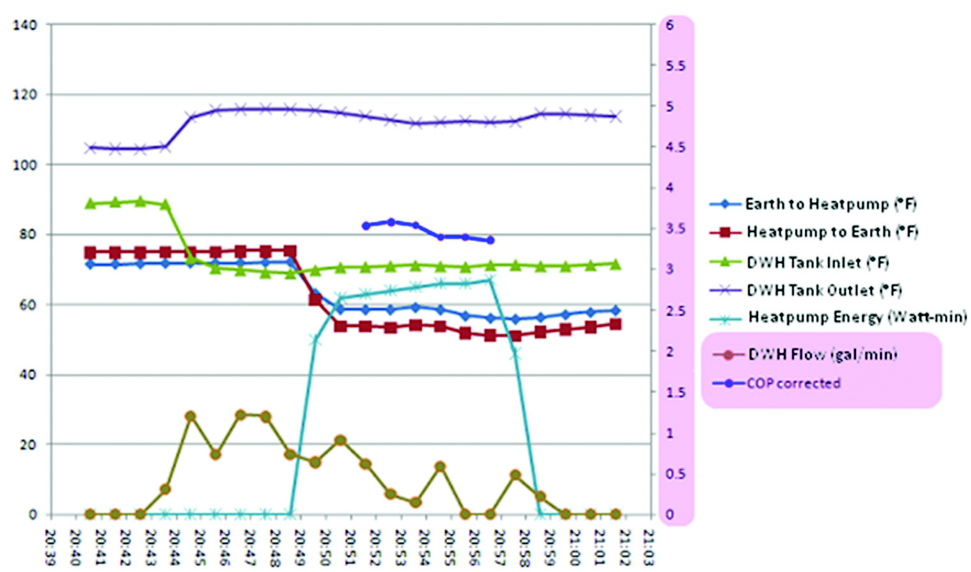

Figure 8 Ground-source heat pump in summer water heat mode, August 14, 2008.

(1008 kWh/year per kW of PV) with roughly 47% to home and 53% to grid (for 4.5 kW system).

- Measured space heating was 6386 kWh, while simulation estimated 4320 kWh.
- Measured DHW was 1422 kWh, while simulation estimated 909 kWh.
- Measured "other" non-space and DHW use was 4971 kWh, while simulation estimated 6114 kWh.

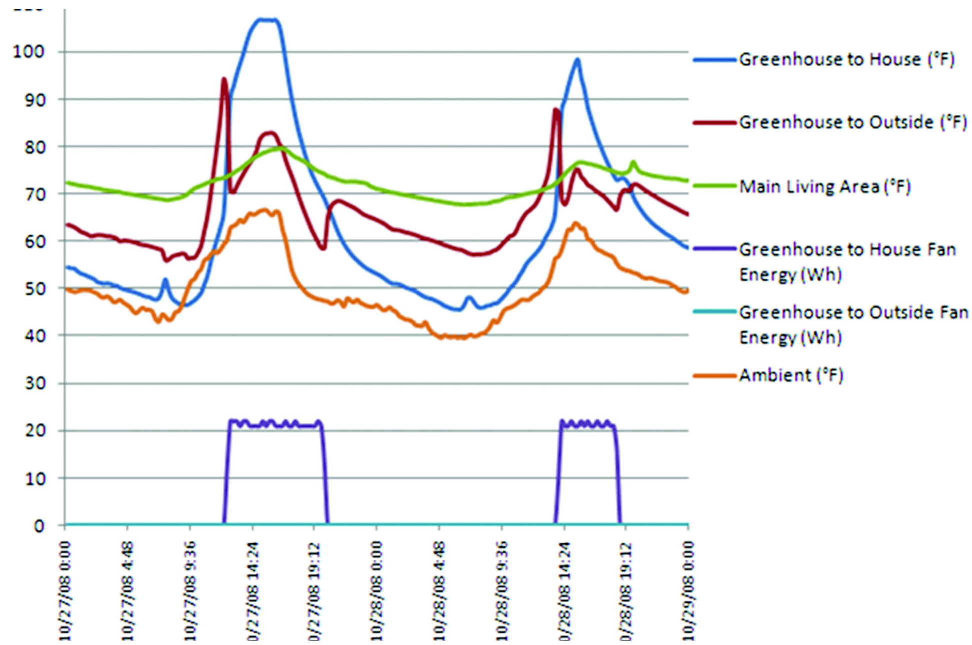

Figure 9 *Solar sunspace operation on two sunny fall days.*

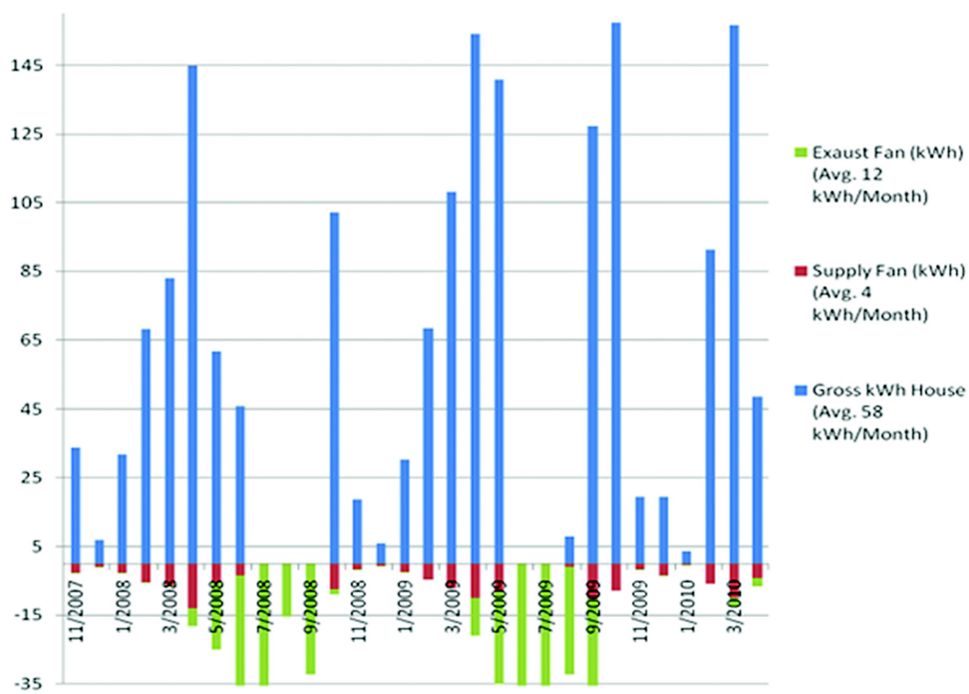

Figure 10 *Solar sunspace space heat and fan energy.*

Table 1. Modeled vs. Actual Energy Usage

Characteristic	Annual Electricity Use, kWh
Without PV	
Simulation	11,481
Utility Data	
3/08–2/09	12,784*
3/09–2/10	12,343
Savings simulated w/o PV (08–09)	12,212
Savings measured w/o PV (08–09)	10,909
With PV	
Simulation	7691
Utility Data	
3/08–2/09	8246*
3/09–2/10	4578
Savings simulated w/PV (08–09)	16,002
Savings measured w/PV (08–09)	15,447

*Differs from monitored data, due to data loss.

ACKNOWLEDGMENTS

This work is sponsored in large part by the US Department of Energy Office of Building Technology's Building America Industrialized Housing program. Additional support has been provided by Danny Parker; Subrato Chandra and David Beal at the Florida Solar Energy Center; Ron Major, Bill Kingrey, Luke Howard, and Todd Currier at the Washington State University Energy Program; the Northwest Energy Efficiency Alliance; and the Energy Star Northwest Program.

Special thanks to Sam and Christine Garst, owners; Mort James and Christian Overby, architects; Barrett Burr, general contractor; Jeremy Smithson, Solar Systems; Wayne Medrud, HVAC; Tom St. Louis, product consultant; Puget Sound Energy staff, utility; George James, US DOE; and Terry Gilbrith, Pacific Northwest Laboratory.

More information on US DOE's Building America Industrialized Housing Partnership can be found at http://www.baihp.org.

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