Zelonedom Case Study Report: "Approaching" Zero Energy in the Pacific Northwest Marine Climate

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ABSTRACT

The Zelonedom is a 2400 ft^2 custom single story two bedroom home in Olympia, Washington ("Zelonedom" is phonetic spelling for the Polish term 'green home'.) Building America Industrialized Housing Partnership (BAIHP) staff at Washington State University and Florida Solar Energy Center provided technical assistance in the design, commissioning and monitoring phases of the project. This Northwest ENERGY STAR and Federal energy tax credit qualified home includes the following energy-efficiency measures:

- 4.5 kW photovoltaic array
- Ground source heat pump supplying domestic hot water and heat to an R15 radiant slab
- Hybrid low density spray foam / loose fill R-49 ceiling insulation
- R21 low density foam advanced frame walls
- Central energy recovery ventilator connected to a forced air handler filtration system
- Tankless electric hot water heater for master bath with efficient recirculation controls
- Sun tempering & Solar sunspace
- Energy Star windows, exhaust fans, lighting and appliances
- TED energy use feedback monitor

Home construction began in summer of 2005, and was completed in May of 2006; BAIHP staff conducted field testing and commissioning at that time. The data acquisition system was operational in 2007 and has since been monitoring home energy use since.

This paper presents modeled and measured overall home energy performance, and an evaluation of the innovative energy saving and PV systems. The home benchmark is roughly 54% - 69% whole house source and site savings without and with PV, respectively (Hendron 2004), (Hendron 2005). Source savings without PV is 164.7 Mbtu; with PV, the source savings is 208.2 Mbtu. The model estimates total electric use of 12027 kWh/year without PV, and 8237 kWh/year net with PV, using Energy Gauge USA version 2.8 (FSEC 2008).

Measured total electric use in 2007-08 without PV was 12,704 kWh/year and 7,750 kWh/year net with PV. The photovoltaic system is performing well, providing 4954 kWh/year or 1100 kWh/year per kW of installed PV. Of the total PV production, 2113 kWh/year was used by the house, and 2841 kWh/year returned to the utility. Monitoring results of the ground source heat pump, solar sunspace, field tests of building envelope and ventilation systems are presented along with suggestions to improve performance.

INTRODUCTION

Homes account for 37% of all U.S. electricity consumption and 22% of all U.S. primary energy consumption (EIA 2005). This represents a huge opportunity to reduce our energy consumption and make cleaner choices for the energy we consume. The U.S. 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. Program partners 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 for both technical feasibility, market readiness, and cost effectiveness in all climate zones.

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 (based on TMY2 data) 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

The Zelonedom project demonstrates and promotes innovative energy saving and renewable energy technologies while evaluating those technologies' energy performance. Technical support for the project's design, construction, commissioning, monitoring and analysis was funded by the U.S. Department of Energy's Building America Industrialized Housing Program (BAIHP). The project was featured in the March/April 2007 Solar Today Magazine (**Figure 1**) (Garst, 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)

Zelonedom partners included; Washington State University Extension Energy Program (WSU), Sam and Christine Garst (homeowners), Mort Staffors James (Architect), Barrett Burr of Polar Bear Construction, Smart Energy Systems (the installer of the 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. Homeowner's 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 they believe is "a stable long term energy investment." The Zelonedom project has helped BAIHP to move toward achieving net zero energy in marine climates.

DESIGN

Note: the following section is excerpted from Building America Best Practices Series for High Performance Technologies: Solar Thermal & Photovoltaic Systems in the Marine Climate 2008.

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. Consistent with the BA systems engineering approach, the homeowner 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."*

Even with a few weeks of weather-related delays, the homeowners were able to move in 9 months after breaking ground, ahead of neighbors who had started building 4 months earlier.

Barrett Burr summed up the project from the builder's perspective:

> *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 Zelonedom 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_p DC photovoltaic system using 24-190W Sanyo panels, and two Xantrex inverters. The system performance is monitored by both BAIHP and PSE. PSE has utility meters that monitor monthly total production and PV back to the grid, while the BAIHP meters monitor production on a 15 minute basis. There is enough roof space and inverter capacity to add another 12 panels, which is planned for summer of 2009. PV panels are oriented slightly to the Southwest, which optimizes performance after morning fog burn-off. Roof angle is 32 degrees to optimize PV production in the summer. The Sanyo HIT panels are rated at 190 watts, but have a higher "out of box" output of roughly 220W. 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; long tem monitoring is under investigation *(Nelson, 2008).*

- **Ground source heat pump (GSHP) -** The three ton Econar GSHP provides all domestic water (DWH) and space heating needs. A 300 foot long, 5 foot wide and 5 foot deep trench has a total of 1800 linear feet of 3/4" pipe and 1-1/4" manifolds. The highest loop is 3 feet below grade (see **Figure 2** for GSHP system design.) The GSHP supplies heat to an 80 gallon storage tank via plate heat exchanger and pump. The tankless electric water heater, designed as master bedroom backup has not been used since the first few months of occupancy. Metlund demand re-circulation pump control is used to ensure hot water at bath and kitchen fixtures, saving water and energy. The GSHP provides hot water to up to six independently controlled zones for the radiant floor heating system. The zone control allows for cooler temperatures in bedrooms and for infrequently used rooms like the guest room. Main living space and attic temperatures are maintained above 70F (**Figure 3**), and above 60F during the 3-1/2 days power outage resulting from 2007 ice storm. The radiant floor slab pump controls were modified to limit pump operation during no-heating months. The entire 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.
- **R15 radiant slab -** The floor is insulated to R15 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 R10.
- **Hybrid ceiling insulation** - R19 low density blown-in foam was employed above the ceiling drywall. An additional R38 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** - R21 blown low density foam was employed in the 2x6 24" o.c. advanced framing. R15 foam sheathing was employed on below grade walls.
- **Tankless hot water** - for master bath with efficient re-circulation controls
- **Sun tempering** - to maximize windows on south side of home
- **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 the exterior, using two 120 CFM exhaust fans on a cooling thermostat during non heating months. During the heating season another sunspace supply fan delivers 90 CFM of pre-heated sunspace air to the home and is estimated as providing roughly 450 kWh of useful heat to the home. The GSHP maintains the sunspace slab at 60°F to support growing lettuce in winter, as well as avocado and orange plants. The solar sunspace also adds significant aesthetic and functional value to the home. Homeowners have accepted the additional 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 windows were not available to optimize solar gains from south facing windows. Windows and three solartubes and skylights provide abundant natural light to each room. All the windows are operable to allow for cross ventilation for cooling during the summer.
- **Ventilation system -** Ducted kitchen and Energy Star bath exhaust fans provide spot ventilation to control indoor humidity levels. Whole house ventilation is provided by an Ultimate Air Re-Coupaerator ERV, connected to a fully ducted back-up Rheem #RBHC

air handler. This air handler supplies 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, homeowners decided to turn off the ducted ventilation system because:

- The envelope was not as tight as anticipated (around 4.0 ACH@50PA.)
- They perceive no added value in air tempering, filtering and mixing.
- No significant humidity levels observed with 2 occupants (see **Figure 4**).
- Central air handler with filter and ERV fans uses almost 300 watts when running
- Noise of the ERV and air handler

- **Energy Star Lighting -** the home employed 100% Energy Star screw-in CFL bulbs in a total of 21 fixtures (15 in main living space), and six additional exterior fixtures. Lighting design of the kitchen, which utilizes T-8 linear fixtures above and below cabinets, led to the elimination of many can fixtures. There is not an incandescent bulb in the home, and 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 feedback -** The Energy Detective (TED) was installed to help the homeowners evaluate miscellaneous end uses when the PV system was not operating. Confusion related to the TED arose from the PV net metering system. TED is developing new products for use with net metered PV systems. Monitoring of the media center revealed a standby loss of 84 watts continuous, mostly contributed by the cable. This is roughly 745 kWh per year. The homeowner is investigating the use of a manual switch to reduce standby power losses.
- **Other Green Features -** Sustainable "green" technologies were incorporated into Zelonedom that utilize recycled and durable materials, reduce indoor air pollutant sources, and provide rainwater management. A separate PV system powers a DC pump for operating a small waterfall. These technologies are part of an overall systems approach intended to improve energy, durability and environmental quality. The homeowner opted not to not pursue LEED certification due to cost, but did achieve the highest green building certification offered by the local builder association.

Specifications for each of these technologies are provided in **Table 1**. More information is available at: http://www.thegarsts.com.

FIELD TESTING & COMMISSIONING

Fan de-pressurization field tests were employed to determine the envelope leakage in accordance with ASHRAE Standard 119-1988 (ASHRAE 1988). Fan pressurization tests were employed to determine ERV and air handler filtration system duct leakage in accordance with ASHRAE Standard 152 (ASHRAE 2002). Bath fan and ERV flow rates were measured using a commercially available flow box, calibrated so that flow rates are determined from a differential pressure measurement across an orifice. The ERV measured supply flow was only 10CFM and exhaust 50CFM (**Table 2**).

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

DATA ACQUISITION

A data acquisition system was installed to determine home energy performance. The system was designed to allow disaggregation of the PV energy production and some end uses. A channel map of data collected is provided in **Appendix B**.

MONITORING RESULTS:

<u>Annual Electricity Use:</u> Measured overall home energy for a 12 month period is presented in **Figure 5**. Measured total electric use in 2007-08 without PV was 12,704 kWh/year and roughly 7,787 kWh/year net with PV. Regression analysis of space heat provided by the ground source heat pump versus temperature difference suggests a design load of roughly 31,000 btuh (see **figure 8.**)

<u>PV System:</u> Both the homeowner and BAIHP staff monitored the PV system. The system is performing well, with output measured at 4954 kWh/year or 1100 kWh/year per kW of installed PV. Of the total PV production, 2113 kWh/year was used by the house, and 2841 kWh/year returned to the utility. Ongoing investigations will focus on potential PV degradation over the next few years and the impact of the 12 additional PV panels.

<u>Ground Source Heat Pump</u>: In 2008, BAIHP staff began the process of analyzing the ground source heat pump. BAIHP staff collected one minute data on ground source heat temperature and flow to determine per cycle space and hot water COP (see **Figures 9 and 10**). COP estimates based on data logger measurements suggest highest (over 4 to 5) COP during space heating only conditions in early winter (see **Figure 11**.) Lowest COP of 2 to 3 were found during spring and entering into DHW only mode (see **Figure 12**.) **Appendix C** provides details on the methodology to determine the GSHP COP.

Ground loop flow rates were estimated to be 11.8 GPM based on 12 psi pressure drop measurements across the earth loop heat exchanger using manufactured 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, DHW loop pump, and slab pumps was conducted as shown in the table in **Figure 2** Efforts are underway to further evaluate COP and optimize piping design and pumping performance to improve COP, and evaluate use of de-superheater option.

<u>Solar Sunspace:</u> BAIHP staff 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 75F. **Figure** 6 shows warm air

(red) delivered to the house on two consecutive mild days in October (outside temperatures in yellow). As fan turns on (purple), sunspace temperatures (green) drop below the house temperature (blue) while staying above the outside temperature (yellow) providing solar gains to home. In summer all windows are opened and the exhaust fan turned on. The homeowner has been experimenting with white washing and shading of glazing to limit summertime temperatures; however, summer over-heating remains an unresolved comfort issue. Sixteen 55 gallon water drums are used as thermal mass in the sunspace, in addition to the floor and plant boxes. **Figure 7** shows the estimated 450 kWh per year from heat delivered form the sunspace to the home along with the fan energy of heating season supply fans and summer cooling exhaust fans. Simple modeling estimates the home with an unheated sunspace would use 4,320 kWh/year, 5,272 kWh/year with sunspace heated to home temperature and 5,272 kWh/year if not installed at all. Investigations are underway to further evaluate performance, and benefits of sunspace pre-heating supply air to house to offset potential mechanical ventilation (if used). The use of unglazed solar thermal panels in the peak of the sunspace may also be evaluated to reduce summertime sunspace temperature and exhaust fan energy use as well as pre-heat DHW for GSHP.

MODELING AND BAIHP BENCHMARK:

The benchmark estimated source and site savings derived from EGUSA version 2.8 are presented in **Table 3**. The home “as found” (case #2) benchmarks at roughly 54.4% and 68.8% whole house source and site savings without and with PV respectively. Source savings without PV is 164.7 Mbtu; with PV, the source savings is 208.2 Mbtu (see **Appendix G**.) **Table 3** also provides benchmark and end-load energy use, with total electric use of 12,027 kWh/year without PV and 8,237 kWh/year net with PV. A variety of parametric analyses were conducted to evaluate various envelope and equipment options, including PV. A best case was evaluated assuming optimum ventilation, tighter envelope, GSHP COP of 5.0 in space heating mode and additional PV. This best case (purple) benchmarks at roughly 55.4 % and 69.8% whole house source and site savings without and with PV respectively. Other measures that were discussed but not employed that would increase benchmark include adding R5+ wall foam sheathing to above grade walls and the use of triple pane windows. These measures were not evaluated in the best case. These measures may be less costly had different window frames and non-spray foam wall cavity insulation been used.

COST DATA & MONTHLY CASH FLOW:

Table 4 provides an estimate of incremental cost relative to minimum code, assuming a 10% builder markup and 30 year mortgage at 7% interest. Simple Cash Flow without tax credits and utility rebates was found to be:

Without PV:
13110 kWh/year saved = $1180/year or $98.32/month
$169/month extra mortgage - $98/month saved at $0.09/kWh = $71 extra cost per month

With PV:
16945 kWh/year saved = $1525/year or $127/month extra

$378/month extra mortgage – $127/month saved at $0.09/kWH = $251 extra cost per month

The PV system received a $2400 initial utility rebate and a $750 /year 10 year production credit at $0.15/kWh (a $0.50/kWh credit would have been provided, had the PV modules been manufactured in Washington State (WAC 5101)). The homeowner also received a $2000 federal renewable tax credit and other incentives, providing a positive cash flow for over ten years.

Appendix A includes a discussion of cash flow economics and cost neutral variables. Cash flow analysis of PV systems with rebates, tax credits and incentives provide a positive cash flow for over ten years. Refinancing at lower interests rates, higher rebates and tax credits can further extend positive cash flow, especially if electricity rate increases continue and resale equity is considered. The homeowners are counting on higher fuel escalation and discount rates to address the negative cash flows in future years.
Appendix E provides the homeowner cash flow analysis spreadsheet, which considers utility rebates, and tax credits.

CONCLUSIONS:

The Zelonedom is a excellent example of a partnership between; owner, architect, builder and utility PV program with strong environmental values. The project has achieved 68% whole house source energy savings on the BA benchmark in a marine climate.

The project highlights the significant space and domestic water heating performance of an innovative ground source heat pump system. Lessons learned (see Appendix A) regarding “build tight and ventilate right” highlight the need for on-going BA field support and training as well as the importance of proper design and commissioning of ventilation systems.

There may also be a need to develop better simulation models for these high performance homes with GSHP radiant floor and DHW heating, as well as other innovative systems.

ACKNOWLEDGMENTS:

This work is sponsored in large part by the U.S. Department of Energy Office of Building Technology’s Building America Industrialized Housing program under cooperative agreement DE-FC36-99GO10478. Additional support has been provided by Danny Parker, Subrato Chandra, Janet McIlvaine and David Beal at the Florida Solar Energy Center, Luke Howard, Vicky Zarrell, Rob Penny and Todd Currier at the Washington State University Energy Program USDOE’s Building America Program, Northwest Energy Efficiency Alliance, and Energy Star Northwest Program.

Special thanks to: Sam and Cristine Garst, owners; Mort James & Christian Overby, architect; Barrett Burr, General Contractor; Jeremy Smithson, Solar Systems; Wayne Medrud, HVAC; Tom St. Louis, Product Consultant; Puget Sound Energy staff, utility; George James, USDOE; and Terry Gilbrith, Pacific Northwest Laboratory.

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

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Tables

Square footage	2400 sq. ft.
Number of bedrooms	2
Number of occupants	2
Design heating load	31 kbtu/hr @ 17° F out, 70°F in (based on regression)
Walls	R21 blown low density foam (Icynene) 2x6 24” o.c. advanced framing
Ceiling	R19 low density blown-in foam (Icynene) 19 blown-in fiberglass insulation (Owens Corning)
Floor (slab on grade)	R15 rigid foam 3” under slab R10 on side (Owens Corning)
Windows 25% glass/floor 2’ overhangs on south	U-factor = 0.33, SHGC = 0.33 Anderson, LowE-heat mirror model
Solar Sunspace w/mechanical fans Exhaust to home when heating season Exhaust to outside when not heating	U-factor = 0.4 summer interior shades 880 gallons of 55 gal drum water thermal mass
Combination DHW and Space Heating with Ground Source Heat Pump (GSHP)	Econar 3 ton GSHP to 80 gal tank via plate heat exchanger. Metlund hot water recirculation control Tankless DHW for master bedroom backup not used. GSHP to 80 gal tank for radiant slab to 5-6 zones
Whole House Ventilation, filtration and mixing (not used after 1st year)	Ultimate Air RecoupAerator ERV ducted to forced air-handler with filter. System and ducting located in conditioned mechanical room
Spot exhaust ventilation	Energy Star bath exhaust fans
Energy Star Lighting	Compact fluorescent fixtures and bulbs (100%)
Appliances	Energy Star clothes washer - Bosch #WFMC3200 Energy Star refrigerator - Jenn-Aire #JFC-2089HEP Energy Star dishwasher – Asko # D3251
Solar Electric	Nominal 4.5 kW_p DC photovoltaic system 24-190W Sanyo panels, 2-Xantrex inverters
Electricity Energy Monitoring	The Energy Detective (TED) - removed due to PV
Other Green Features	Low water use fixtures and appliances GreenGuard and GreenSeal Low VOC paints Moisture resistance wall drainage system & Timbor borax mold growth inhibitor 5000 gallon rain cistern for landscape & sunspace PV powered waterfall Recycled products include EcoSurface floor tiles, ceramic tile and bamboo. 50 year shingles to re-roof at PV replacement Smartwood & FSC certified and finger-jointed lumber Driveway with pervious concrete No impervious surfaces beyond the homes footprint.

Table 1 – Zelonedom, Energy Features

Run #	Ventilation Scenario	Vent Type	supply cfm	Exhaust cfm	Run time	watts	efficiency	ACH @50PA
1	no ventilation	none	0	0	0%	0	0	4.38
2	**as found not running**	**ERV+AH**	**10**	**50**	**0%**	**295**	**87**	**4.38**
3	**as found if run WSEC**	**ERV+AH**	**10**	**50**	**33%**	**295**	**87**	**4.38**
4	ASHRAE 62.2	HRV	35	35	100%	70	87	4.38
5	ASHRAE 62.2	NHRV exh	0	35	100%	10	0	4.38
6	ASHRAE 62.2 x 2	NHRV exh	0	70	100%	15	0	4.38
7	ASHRAE 62.2	NHRV sup	35	0	100%	250	0	4.38
8	WSEC 2006	NHRV exh	0	70	33%	15	0	4.38
9	ASHRAE 62.2	HRV	35	35	100%	70	87	3.01
10	ASHRAE 62.2	NHRV exh	0	35	100%	10	0	3.01
11	ASHRAE 62.2 x 2	NHRV exh	0	70	100%	15	0	3.01
12	ASHRAE 62.2	NHRV sup	35	0	100%	250	0	3.01
13	WSEC 2006	NHRV exh	0	70	33%	15	0	3.01

Table 2 - Benchmark Assumptions for Ventilation Scenarios

Run #	EGUSA Scenario	ACH	Site/ Source (%)	Site/ Source w/PV (%)	Total	Space Heat	Vent Fan	DHW	PV Gen	Net Use	Other
1	no ventilation	4.38	49.2	65.2	12035	4320	8	909	3790	8245	6114
2	Ventilation off	4.38	54.4	68.8	12027	4320	0	909	3790	8237	6114
3	WSEC 2006	4.38	49.5	64.5	12759	4306	745	909	3790	8969	6114
4	ASHRAE 62.2	4.38	51.3	66	12595	4347	537	909	3790	8805	6114
5	ASHRAE 62.2	4.38	50.5	65.9	12225	4441	77	909	3790	8435	6114
6	ASHRAE 62.2 x 2	4.38	52.1	66.4	12713	4764	244	909	3790	8923	6114
7	ASHRAE 62.2	4.38	46.7	61.3	13797	4139	1918	909	3790	10007	6114
8	WSEC 2006	4.38	52.3	67.2	12161	4374	80	909	3790	8371	6114
9	ASHRAE 62.2	3.01	52.6	67.3	12259	4016	533	909	3790	8469	6114
10	ASHRAE 62.2	3.01	53.9	68.5	11933	4149	77	909	3790	8143	6114
11	ASHRAE 62.2 x 2	3.01	53	67.3	12479	4529	243	909	3790	8689	6114
12	ASHRAE 62.2	3.01	47.8	62.5	13510	3860	1909	909	3790	9720	6114
13	WSEC 2006	3.01	53.5	68.4	11848	4063	79	909	3790	8058	6114
15	Sunspace Heated	4.38	50.2	64.7	13027	5272	0	909	3790	9237	6114
16	No Sunspace	4.38	51.1	65.7	12676	4972	0	909	3790	8886	6114
18	GSHP COP 5	4.38	57.5	72.5	10710	3003	0	909	3790	6920	6114
20	Add 2.5 kW PV	4.38	57.5	81.3	10710	3003	0	909	6011	4699	6114
21	Cases - 9,18,20	3.01	55.4	79.8	11182	3022	80	909	6011	5171	3790
	Measured Data (08-09)	4.38			12704	6786		1394	4917	7787	5021
2	Benchmark (2)	4.38	54.4	68.8	12027	4320		909	3790	8237	6114
	Measured vs. Benchmark (2)				677	2466		485	1127	-450	-1093

Table 3 – Benchmark (Energy Gauge USA) vs. measured

Measure	Minimum Code	Builder Standard	Zelonedom	Total Costs Increment (*)	Amortized Annual Cost $/month 7%, 30 yr)
Roof / Attic	R38 blown	R38 blown	R19 Icynene + R38 blown	2467 ft2 x $0.19/ ft2 x 3 x1.1 = $1547	$10.82
Walls	R21 batt	R21 batt	R19 Icynene	2000 ft2 x $0.19/ft2 x 3 x 1.1 = $1254	$8.78
Slab Floors	R10 below slab	R10 below slab	R15 below slab	2467 ft2 x $0.50/ft2 x 1.1 = $1357	$9.50
Foundation	R10	R10	R10	No cost	$0.00
Air Infiltration	7.0 ACH @50PA	5.0 – 7.0 ACH @50PA	4.0 ACH @50PA	$300 testing $200 caulking	$3.50
Glazing: *U-Factor*	0.35 vinyl	0.33 wood	0.33 wood	No cost	$0.00
Total Shell				$4658	$32.61
HVAC SYSTEM	Air source Heat Pump + DHW $7.5K	Air Source Heat Pump + DHW $7.5K	GSHP + Radiant $27K	$19,500	$136.50
DHW:	80 Gal Electric	80 Gal Electric	GSHP	GSHP Included	$0.00
Lighting	Incandescent w/CFL exterior	50% CFL bulbs	100% CFL bulbs & fixture	Zero with bulb + fixture rebate	$0.00
Appliances:	NEACA	Energy Star	Energy Star	Zero after $100 rebate	$0.00
PV:	n/a	n/a	$30 K	$30K after rebates	$210.00
Other	WH + spot Exhaust fans	WH + spot Exhaust fan	Central ERV (not used)	$2500 fully ducted (not used/included)	$0.00
Total Incremental Cost to Buyer				w/o PV = $24,158 w/PV = $54,158	w/o PV = $169.10 w/PV = $378.11

Table 4 – Incremental Cost and Monthly Cash Flow

Figures

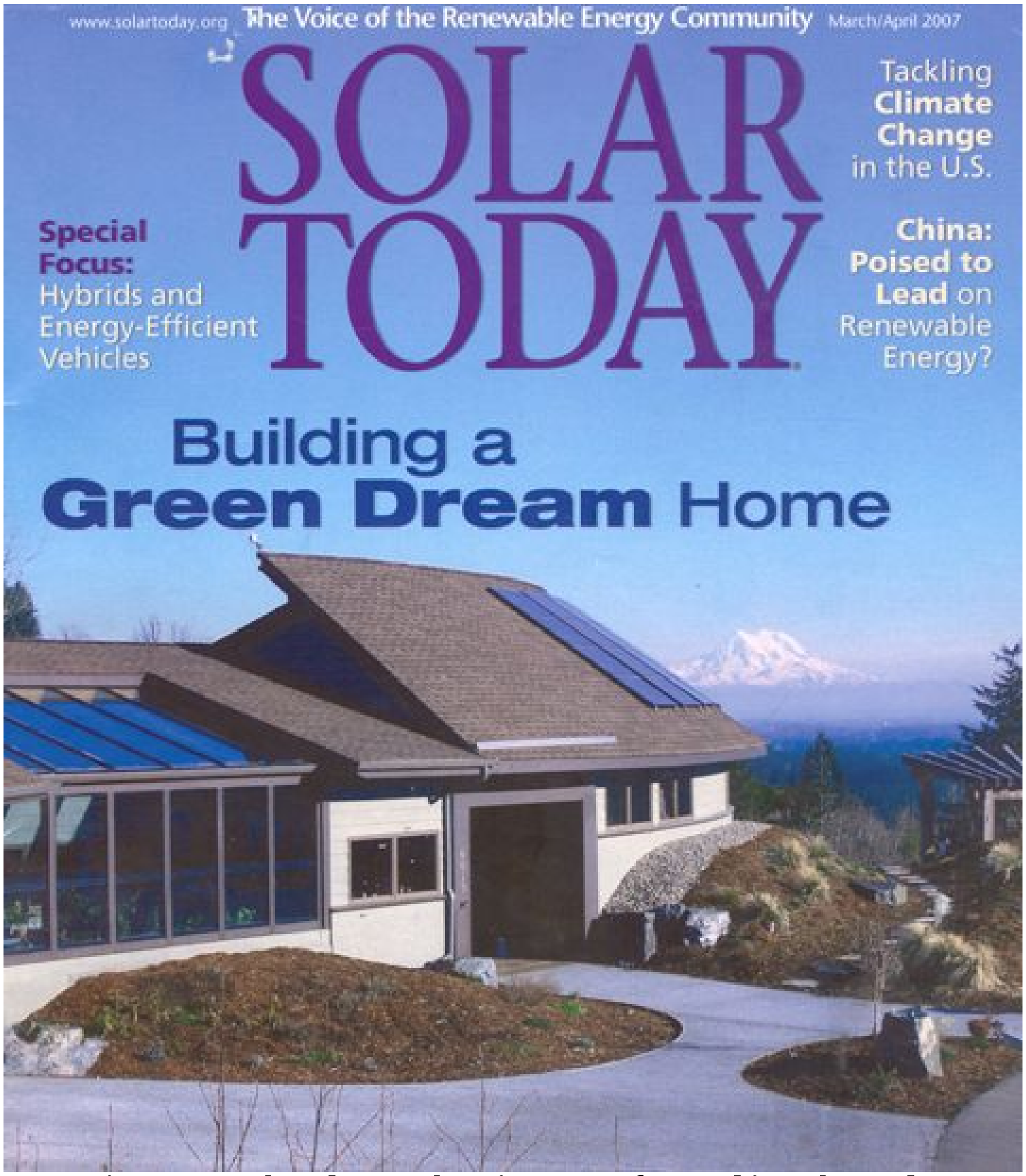


Figure 1 – Zelonedom – Olympia WA, as featured in Solar Today

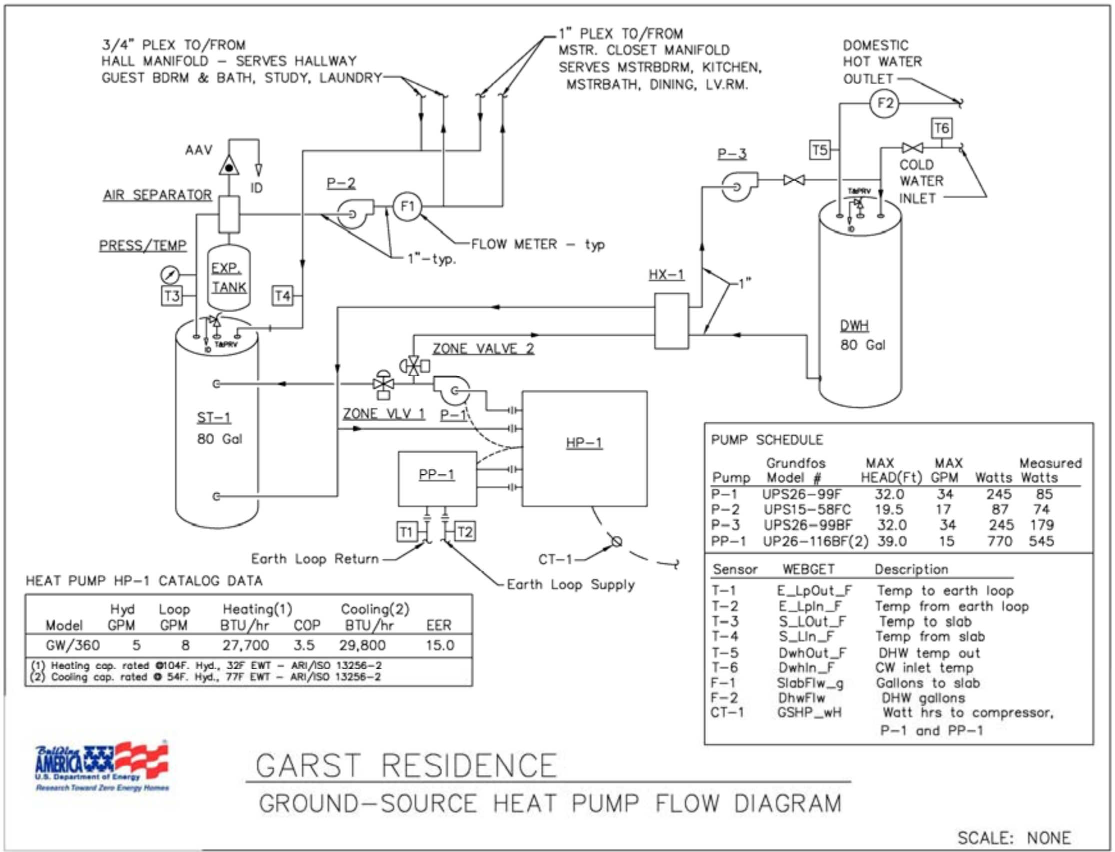


Figure 2 – Zelonedom Ground Source Heat Pump - Diagram, Specification & Monitoring Locations (see appendix for sequence of operation)

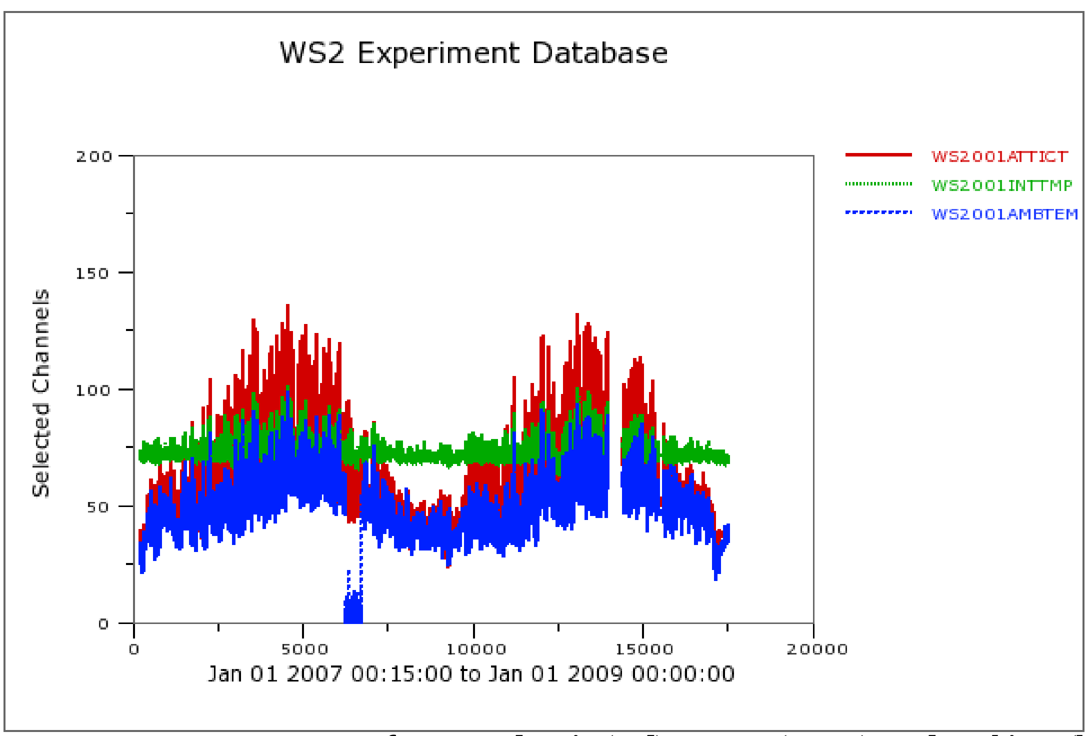


Figure 3 - Average Temperature for Vented Attic (red), House (green), and Ambient (blue)

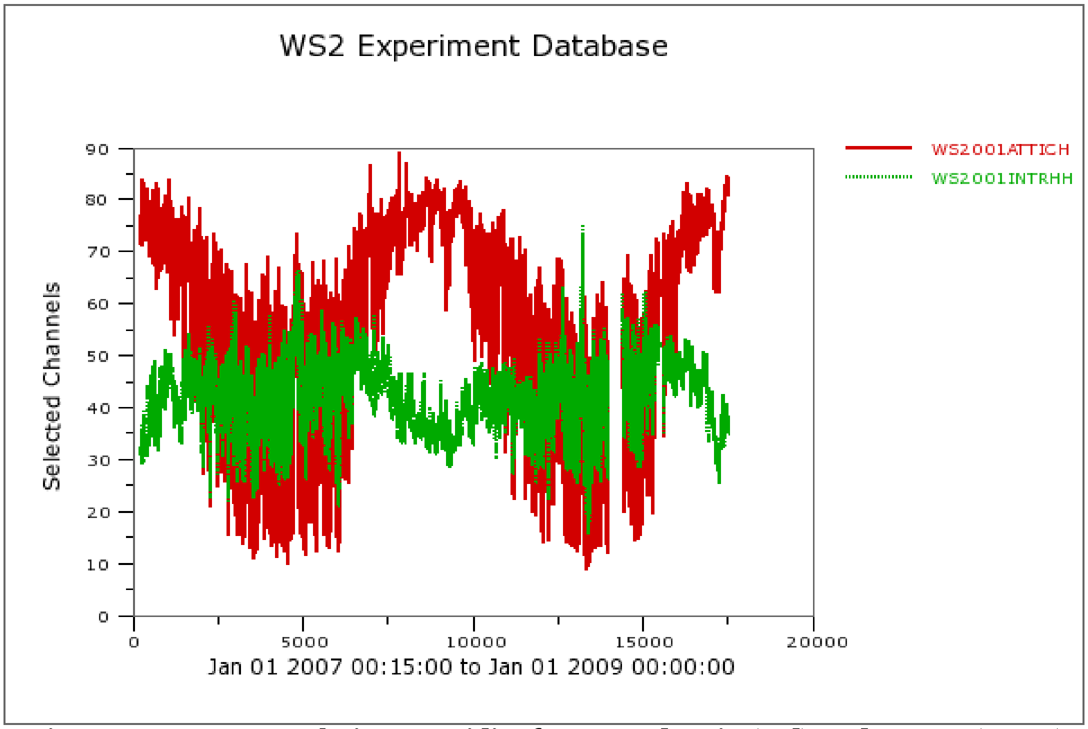


Figure 4 - Average Relative Humidity for Vented Attic (red) and House (green)

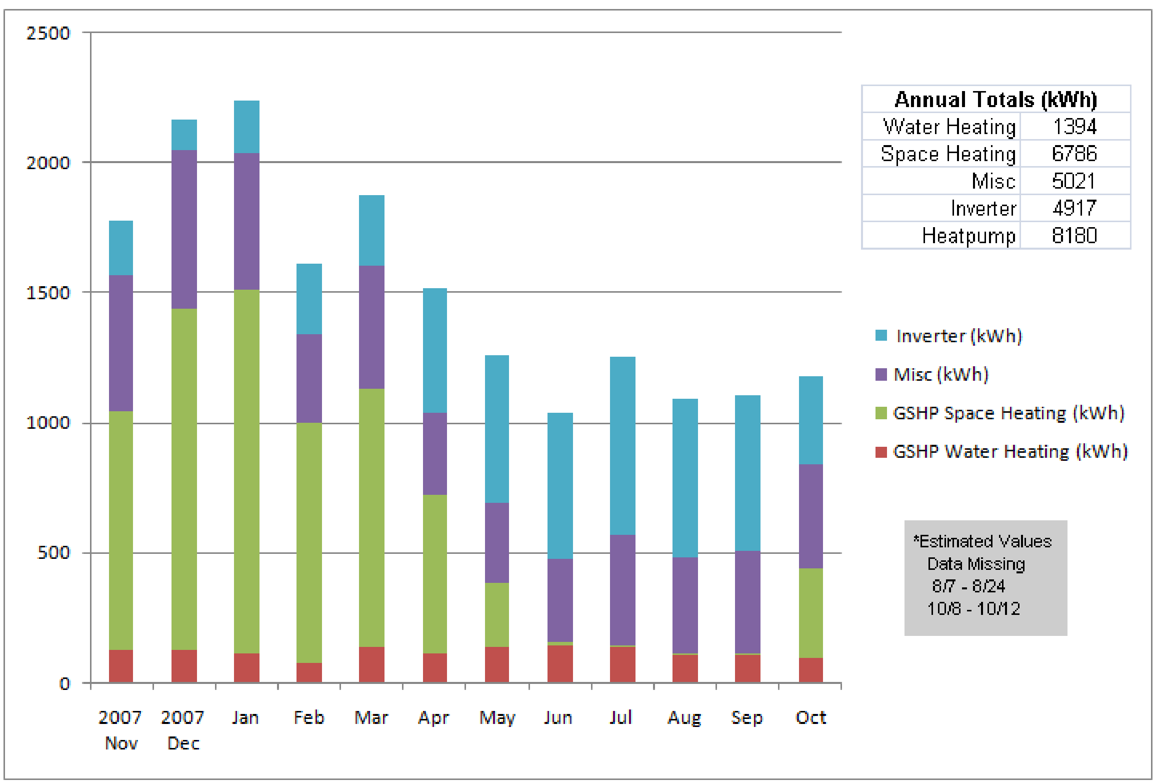


Figure 5 - Measured Monthly Energy Use, including PV to grid

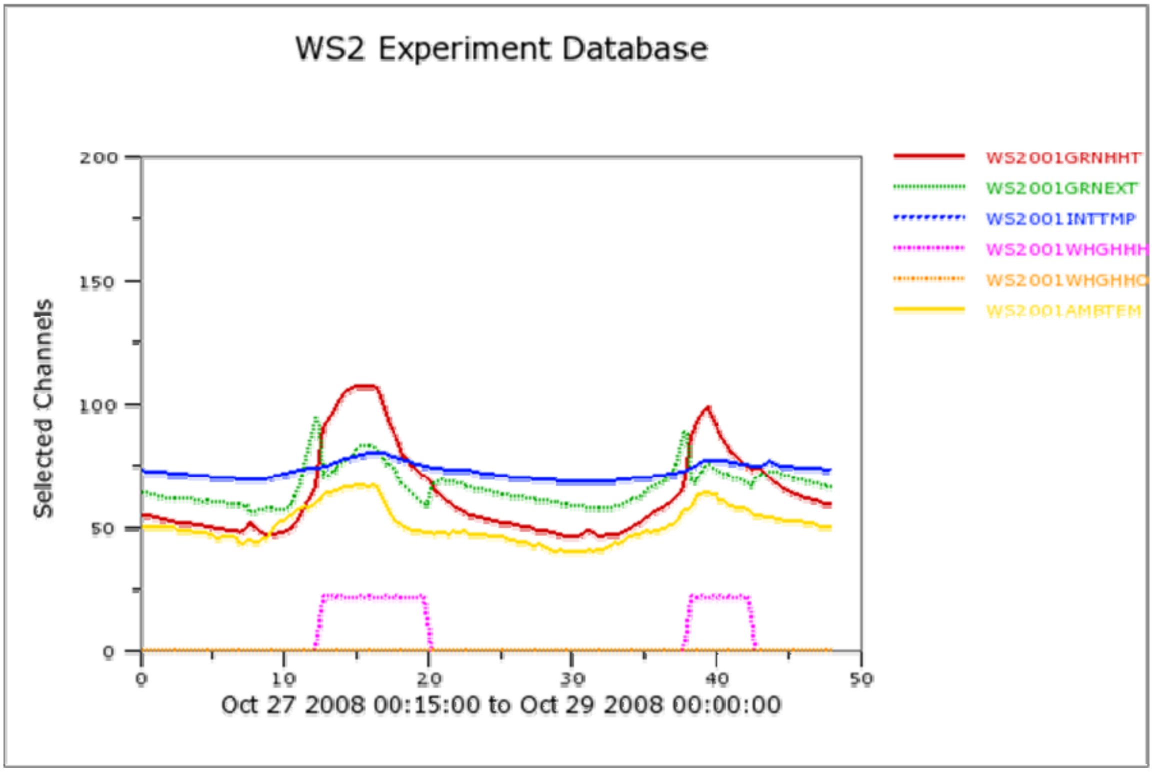


Figure 6 - Solar Greenhouse Operation on Two Sunny Fall Days

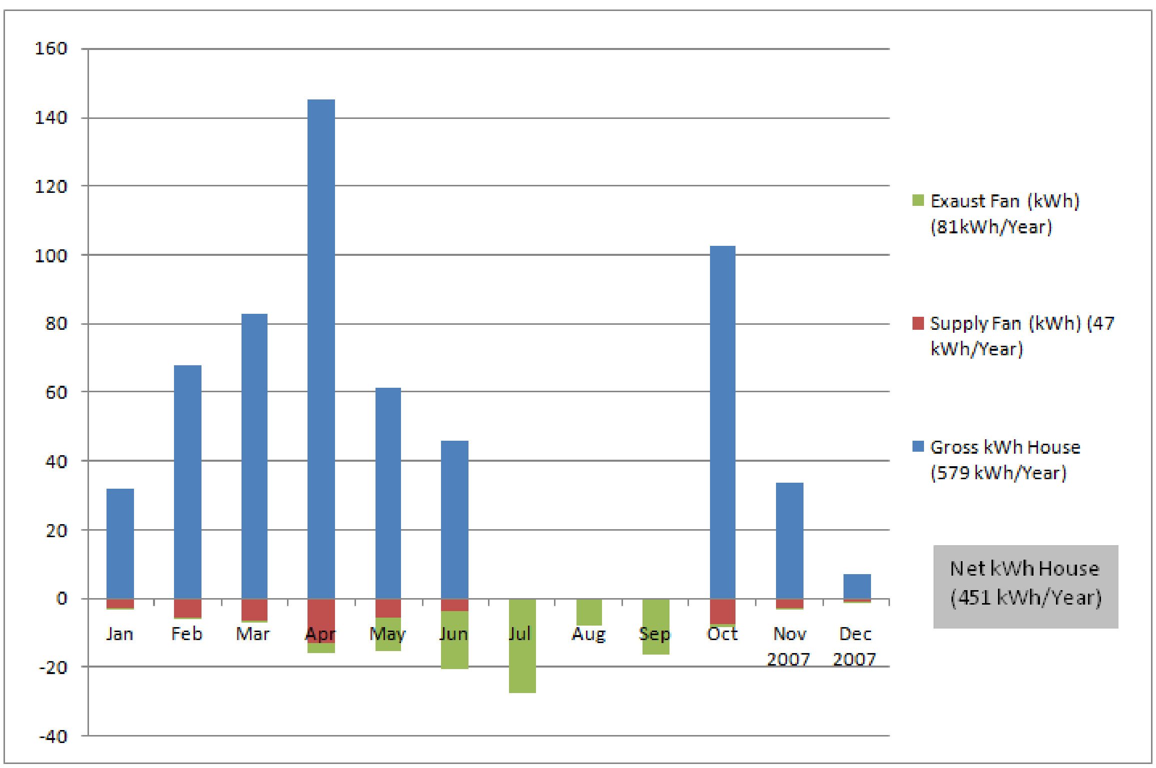


Figure 7 - Greenhouse/Sunspace Space Heat & Fan Energy:

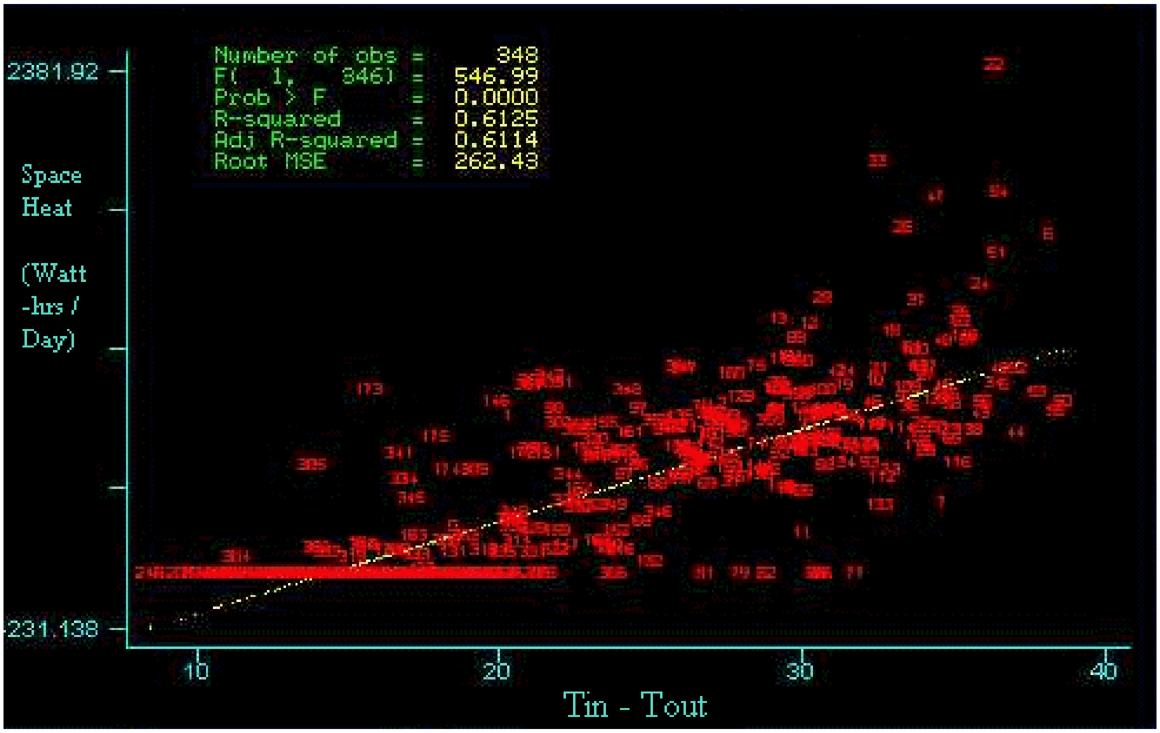


Figure 8 – Ground Source Heat Pump Space Heat vs. Delta Temperature
(Slope = 147.4 btu/hr/°F)

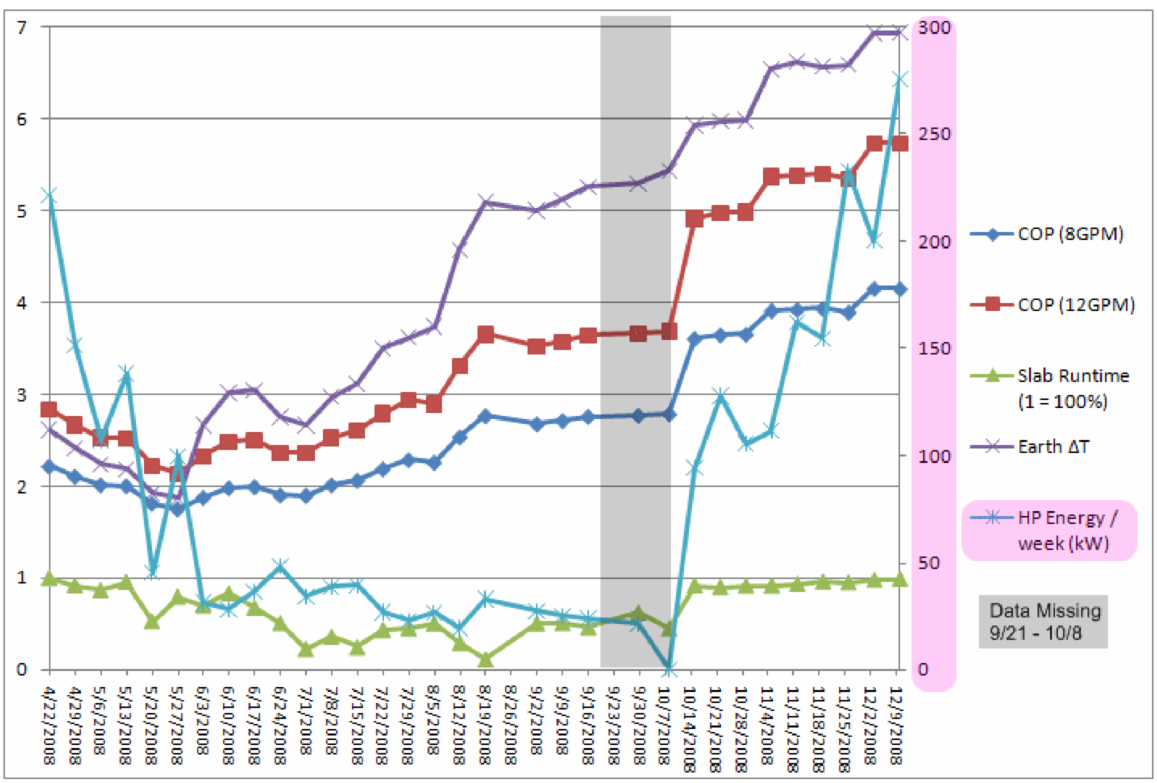


Figure 9 – Ground Source Heat Pump Monthly COP
April 22 – December 9, 2008

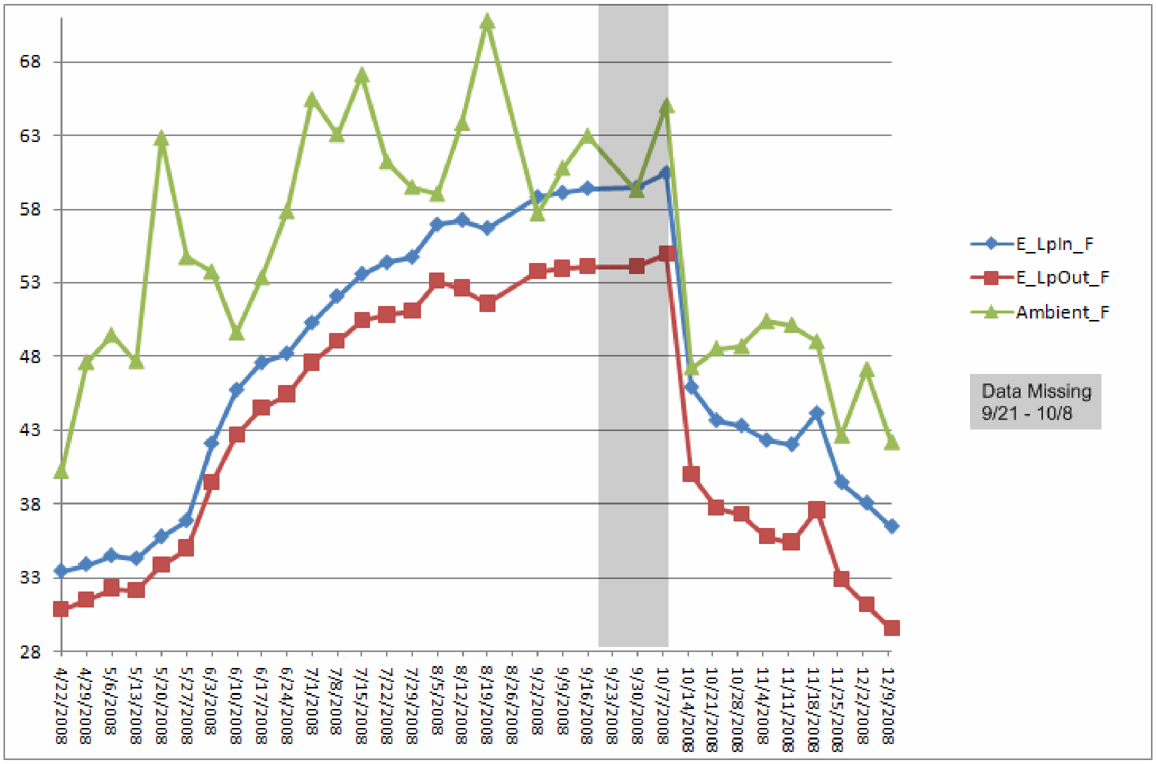


Figure 10 – Ground Source Heat Pump Monthly Conditions
April 22 – December 9, 2008

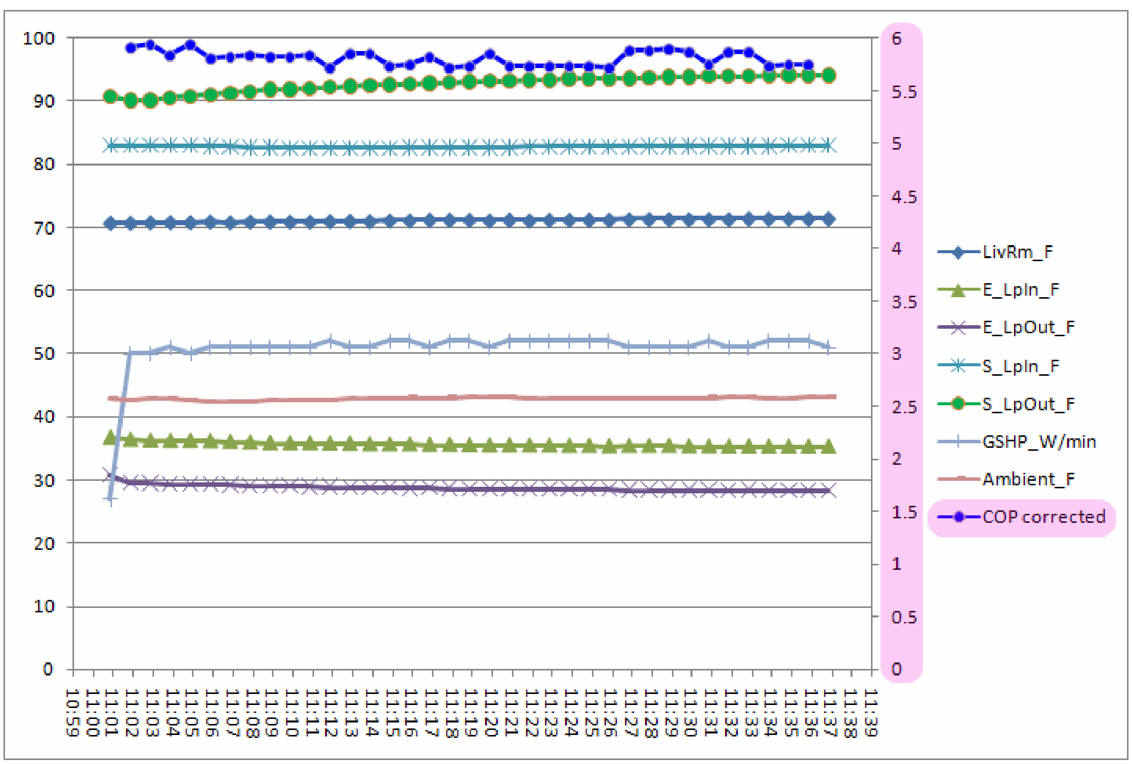


Figure 11– Ground Source Heat Pump in Winter Space Heat Mode
Dec 4, 2008

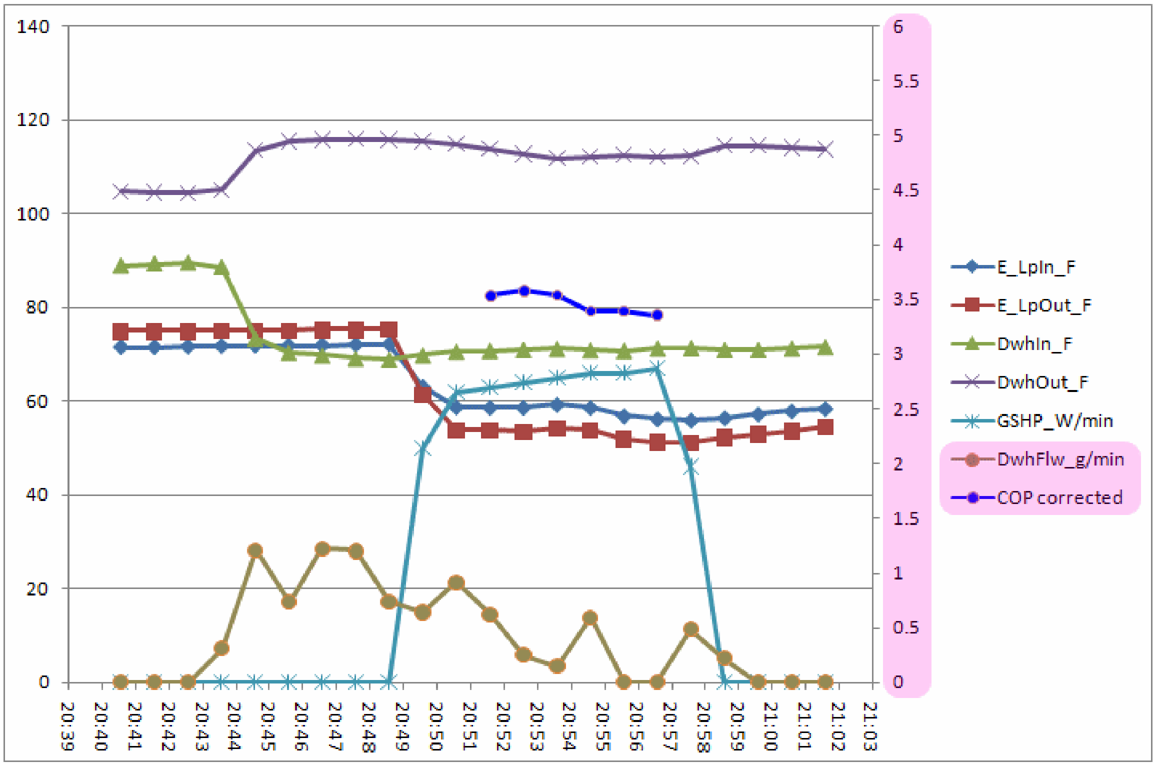


Figure 12– Ground Source Heat Pump in Summer DHW Mode
August 14, 2008

Appendix A

Evaluation of Project Stage-gate Criteria

Within the Building America process, the Stagegate process is used to evaluate overall project success, potential for continuation and refinements to research and development.

Within the process are "must meet" and "should meet" criteria. Each of these criteria are examined relative to the Zelonedom residence in the marine climate of Olympia, WA (HDD 5710, CDD 341).

"Must Meet Criteria"

Detailed Site and Source Energy Savings

We used the *EGUSA Version 2.8* software to evaluate the source energy savings of the net zero energy home design. The software predicted a 54.5% source and site energy savings without PV and a 65.8% site energy savings with PV versus the BA Benchmark for the installed measures. Source savings without PV is 164.7 Mbtu without PV, and 208.2 Mbtu with PV (See **Appendix G**.)

Characteristic	Annual Electricity Use (kWh)
Benchmark Total Energy Use	25182
Zelonedom: (simulation w/o PV)	12027
Zelonedom (monitored)	12704
Zelonedom (simulation w/PV)	7787
Zelonedom (monitored)	8237
Zelonedom Savings: Simulated w/o PV	13155
Zelonedom Savings: Simulated w/PV	16945

While there seems to be overall agreement, a number of factors need to be considered in single home case study end-load predicted vs. measured comparisons:

- Net of PV power produced was roughly: 3800 kWh simulated; 4900 kWh measured with 2100 to home and 2800 to grid.
- Measured space heating was 6786 kWh while simulation estimated 4320.
- Measured DHW was 1394 kWh while simulation estimated 909 kWh.
- Measured "Other" non space heating/cooling and DHW use was 5021 while simulation estimated 6114 kWh

Quality Assurance

Quality assurance was a key focus during design, installation and commissioning phases of the project. Both builder and owner effectively followed up on a number of unusual construction and specification issues including Built Green, Energy Star NW, and BAIHP technical assistance. Blower door tests and field testing during construction identified key air leakage and thermal bypass issues. Commissioning of GSHP and ventilation systems should be a key component to these QA practices.

Market Coverage

The home has received considerable press, and was featured in America Society of Solar Energy (ASES) Solar Today magazine in April 2007. The property borders on state forest land at 500 ft elevation.

Homeowner feedback on comfort, energy performance, and return on energy efficiency investment has been positive overall. Based on this feedback, we believe that the home is a potential model for other custom homes and is likely to meet the Market Coverage “Must Meet” criteria. It should be pointed out, however, that this assessment is very homebuyer specific, depending on homebuyer’s environmental values and economic priorities.

Should Meet Criteria

Neutral Cost Target
The incremental cost of energy measures, HVAC upgrades, PV system and sunspace was roughly $260/ft2, or $54,158 higher than more than a similar custom home built to the current Washington State Energy Code. One problem the homeowner notes is that the appraisal had no similar homes to compare with, so that the appraised value was roughly $100,000 less than.

The PV system cost roughly $27,000, the GSHP system $19,500 more than a ducted air source heat pump. The remaining energy efficiency measures cost roughly $4700 more than minimum code homes, (Table A.1). The initial cost of the PV system was $5.97/watt. An additional 12 collectors will be installed in 2009, using the same inverters from the original system. These additional collectors are expected to cost $8.00/watt (includes estimated labor cost). Without utility rebates and tax credits the entire home envelope, HVAC system and PV was estimated to be roughly $54,158.

Measure	Minimum Code	Builder Standard	Zelonedom	Total Costs Increment (*)	Amortized Annual Cost $/month 7%, 30 yr)
Roof / Attic	**R38 blown**	**R38 blown**	**R19 Icynene + R38 blown**	**2467 ft2 x $0.19/ ft2 x 3 x1.1 = $1547**	**$10.82**
Walls	**R21 batt**	**R21 batt**	**R19 Icynene**	**2000 ft2 x $0.19/ft2 x 3 x 1.1 = $1254**	**$8.78**
Slab Floors	**R10 below**	**R10 below**	**R15 below slab**	**2467 ft2 x $0.50/ft2 x 1.1**	**$9.50**

	slab	**slab**		**= $1357**	
Foundation	**R10**	**R10**	**R10**	**No cost**	**$0.00**
Air Infiltration	**7.0 ACH @50PA**	**5.0 – 7.0 ACH @50PA**	**4.0 ACH @50PA**	**$300 testing $200 caulking**	**$3.50**
Glazing: *U-Factor*	**0.35 vinyl**	**0.33 wood**	**0.33 wood**	**No cost**	**$0.00**
Total Shell				**$4658**	**$32.61**
HVAC SYSTEM	**Air source Heat Pump + DHW $7.5K**	**Air Source Heat Pump + DHW $7.5K**	**GSHP + Radiant $27K**	**$19,500**	**$136.50**
DHW:	**80 Gal Electric**	**80 Gal Electric**	**GSHP**	**GSHP Included**	**$0.00**
Lighting	**Incandescent w/CFL exterior**	**50% CFL bulbs**	**100% CFL bulbs & fixture**	**Zero with bulb + fixture rebate**	**$0.00**
Appliances:	**NEACA**	**Energy Star**	**Energy Star**	**Zero after $100 rebate**	**$0.00**
PV:	**n/a**	**n/a**	**$30 K**	**$30K after rebates**	**$210.00**
Other	**WH + spot Exhaust fans**	**WH + spot Exhaust fan**	**Central ERV (not used)**	**$2500 fully ducted (not used/included)**	**$0.00**
Total Incremental Cost to Buyer				**w/o PV = $24,158, w/PV = $54,158**	**w/o PV = $169.10 w/PV = $378.11**

Table A.1 Incremental Cost and Amortized Cost of Improvements

Assuming an incremental cost of $4700 for envelope and $19,500 HVAC upgrades and a 7%, 30 year mortgage the added monthly annual payments is approximately $169 per month. The benchmark analysis indicated a savings of 13,110 kWh per year using EGUSA or an estimated utility saving of $98 per month or $1180 per year at current rates of $0.09/kWh. The cost neutral point utility cost would be roughly 12-13 cents per kWh. At current electric rates the incremental cost for the envelope and HVAC efficiency upgrades would have to be $14,000 or roughly $10,000 less. Cost neutral would have also been achieved with financing rates of roughly 2.75%. Interest rate was 6.25% or $148/month, so he is paying roughly $50 more per month than his current energy savings produce.

The owner is a financial analyst, and developed a simple model for the pay backs and cash flow for the PV solar system under three scenarios: (see appendix D)

1) total system
2) the initial installation, and
3) a stand alone secondary install of 12 collectors (2.3 kW).

Using a mortgage of 6.25%, the homeowner estimates that the total system goes cash flow negative in 2018. However, the homeowner notes that if he refinanced at 5.0% over a new 15 year mortgage with added cash taken out of equity for the additional PV the cash flow for interest only is quite positive. The homeowner believes he has a good investment without amortization at a 4% annual increase in utility rate and the return on cash of 3%. Had the homeowner been able to purchase WA state built PV panels he would have received a 50 cent per kWh produced incentive (rather than the 15 cent per kWh he did receive) which would have further extended his positive cash flow on the PV system. (WAC)

Marketability

The fact that this is a one of a kind custom home with very satisfied homeowner/builder, indicates that others with similar environmental values and may do the same. However, it cannot be ignored that the elevated price of the homes with their efficiency and renewable energy features would remain a deterrent to those with less financial resources and environmental values.

Builder Commitment

The Builder, Polar Bear Construction, continues to build custom energy efficient homes with advanced framing and other efficiency measures in the Olympia community, well beyond local green building and Energy Home program levels. Both The homeowner and Polar bear construction and have strengthened their commitment based on lessons learned from BAIHP experiences.

Gaps Analysis /Lessons Learned

A number of lessons were learned within the Zelonedom project:

- The GSHP system worked exceedingly well providing comfortable radiant floor space and ample DHW heating with low power. COP of overall GSHP performance is lowest in late spring and summer where the majority of heating is for DHW, and earth loop ground temperatures are lowest.

- Solar PV system is performing better than expected in the first few years of monitoring. Continuing monitoring of the system is proposed to see if PV system performance reduces to rated output over time.

- Solar sunspace system worked well to offset some space heating loads especially if the sunspace was not heated with the GSHP. Integration of the sunspace supply fan into the ventilation control strategy may be a viable option to pre-heat ventilation air.

- Strategies that utilize summertime waste heat from sunspace for solar thermal DHW pre-heating are under investigation, as a way of reducing sunspace temperature and associated exhaust fan energy.

- Occupants were able to use energy feedback to better understand the impact of lifestyle choices, and are currently exploring ways to reduce 86W standby energy use of media center, and understand impacts of wintertime sunspace heating.

- Cash flow analysis of PV systems with $2400 PSE initial rebate, $750 /year 10 year production credit at $0.15/kWh, $2000 federal renewable tax credits and other incentives provide a positive cash flow for over ten years. Refinancing at lower interests rates, higher rebates and tax credits can further extend positive cash flow, especially if electricity rate increases continue and resale equity is considered. The homeowners are counting on higher fuel escalation and discount rates to address the negative cash flows in future years.

Identified gaps within the research process:

- Need low standby energy products for hardwired items in a net zero energy home (doorbells, garage door openers, appliances and HVAC electronics).

- The use of tighter vinyl triple glazed windows instead of double paned wood windows and use of exterior R5-10 foam sheathing on above grade walls in lieu of expensive spray foam in wall cavities should be considered.

- Additional engineering optimization, GSHP commissioning and use of multi-speed GSHP system pump(s) may improve GSHP COP. However, since the system is not providing AC the pump energy penalty is not as large. Multi speed pump control may be warranted for future projects to reduce this consumption.

- Solutions to eliminate problems identified associated with interaction of the net metering of PV system and the TED feedback device are underway.

- The ventilation system was not well designed, installed or operated, and other, more effective systems are available, especially if the home had been built with a tighter envelope. Just because cavity foam insulation was used doesn’t make the home tight. Attention to air leakage paths (windows in particular) is critical.

- The homeowner chose to have large window areas, increasing home space heat use, first cost and air leakage but also provided enhanced views and improved day-lighting.

- Advanced construction techniques in the project were successful at reducing heating loads. Investigations into higher than predicted space and DHW heating are also underway.

1

Appendix B

Channel Map & Sensor Descriptions

WEBGET Channel Map:

ChannelMap

1	Array	
2	Year	
3	Day	
4	Time	
5	BATVOL	Logger Battery Voltage
6	ATTICT	Attic Temperature (F):
7	ATTICH	Attic Relative Humidity (%RH):
8	GRNHHT	Green House to House Temperature (F)
9	GRNHHH	Green House to House Relative Humidity
10	GRNEXT	Greenhouse Exhaust to Outside Temperature
11	GRNEXH	Greenhouse Exhaust to Outside Relative Humidity
12	INTTMP	Main Living Area Temperature
13	INTRHH	Main Living Area Relative Humidity
14	ERVSUT	Supply Air from ERV Temperature
15	ERVSUH	Supply Air from ERV Humidity
16	ERLINT	Earth Loop Inlet Temperature
17	ERLOUT	Earth Loop Outlet Temperature
18	SLLINT	Slab Loop Inlet Temperature
19	SLLOUT	Slab Loop Outlet Temperature
20	DHWINT	Hot Water Tank Inlet Temperature
21	DHWOUT	Hot water tank Outlet Temperature
22	WHGHHH	Watt-hours Greenhouse Heat to House
23	WHGHHO	Watt-hours Greenhouse Heat to Outside
24	WHGHHP	Watt-hours Heat Pump Compressor
25	WHPAN1	Watt-hours Panel 1A

26	WHERVA	Watt-hours ERV / Air Handler
27	WHPAN2	Watt-hours Panel 1B
28	WHINVO	Watt-hours PV Inverter Output
29	WHDHWP	Watt-hours Hot Water Pump (not working)
30	FLSLAB	Slab Loop Flow Rate (gallons)
31	FLODHW	Hot Water Tank Flow Rate (Gallons)
32	AMBTEM	Ambient Temperature
33	AMBRHH	Ambient Relative Humidity
34	PYWAVG	Flux Density
35	PYKJTO	Total Flux (ignore)
46	PUMPON	DHW Pump run percent (Inverted 1=Off, 0=On)

Monitoring System Sensor Descriptions:

Attic Temperature (F):
Description: Temperature in the attic
Logger Channel: Attic_F_AVG
WebGet Channel: 6 (ATTICT)
Sensor Location: In attic halfway between ceiling and roof joists.
Good Data: 1/11/2007 - Current

Attic Relative Humidity (%RH):
Description: Humidity in the attic
Logger Channel: Attic_RH_AVG
WebGet Channel: 7 (ATTICH)
Sensor Location: In attic halfway between ceiling and roof joists.
Good Data: 1/11/2007 - Current

Green House to House Temperature (F)
Description: Temperature in the ductwork between the greenhouse and the main living space
Logger Channel: GrnHsH_F_AVG

WebGet Channel: 8 (GRNHHT)
Sensor Location: In the exhaust vent in the green house leading to the main living space.
Good Data: 1/11/2007 - Current

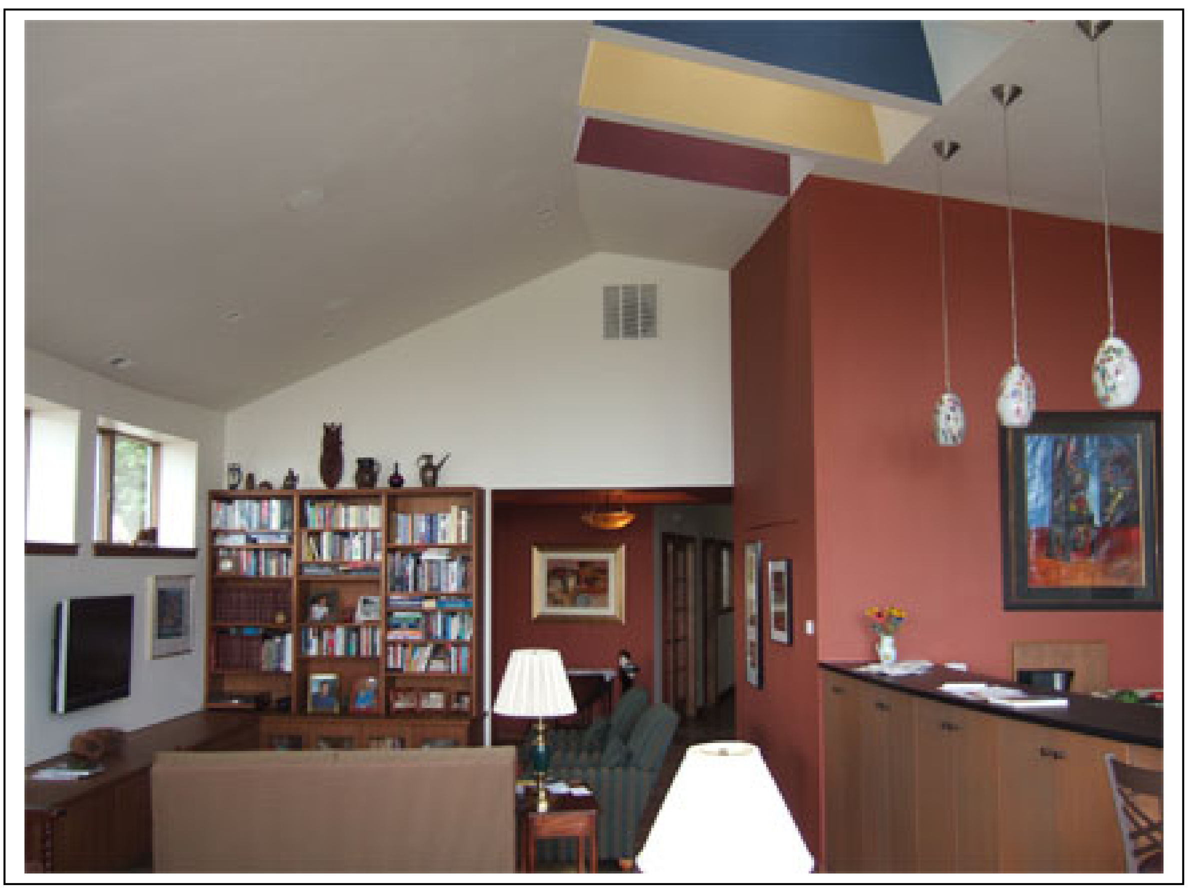
Green House to House Relative Humidity
Description: Humidity in the ductwork between the greenhouse and the main living space
Logger Channel: GrnHsH_RH_AVG
WebGet Channel: 9 (GRNHHH)
Sensor Location: : In the exhaust vent in the green house leading to the main living space.
Good Data: 1/11/2007 - Current

Greenhouse Exhaust to Outside Temperature
Description: Humidity in the ductwork between the greenhouse and the exterior
Logger Channel: GrnHsO_F_AVG
WebGet Channel: 10 (GRNEXT)

Sensor Location: : In the exhaust vent in the green house leading to exterior of the house.
Good Data: 1/11/2007 - Current

Greenhouse Exhaust to Outside Relative Humidity
Description: Humidity in the ductwork between the greenhouse and the exterior
Logger Channel: GrnHsO_RH_AVG
WebGet Channel: 11 (GRNEXH)
Sensor Location: : In the exhaust vent in the green house leading to exterior of the house.
Good Data: 1/11/2007 - Current

Main Living Area Temperature
Description: Temperature in the ductwork between the main living space and the ERV system.
Logger Channel: LivRm_F_AVG
WebGet Channel: 12 (INTTMP)
Sensor Location: : In the exhaust vent in the living space leading to the ERV system.
Good Data: 1/11/2007 - Current



Main Living Area Relative Humidity
Description: Humidity in the ductwork between the main living space and the ERV system.
Logger Channel: LivRm_RH_AVG
WebGet Channel: 13 (INTRHH)
Sensor Location: : In the exhaust vent in the living space leading to the ERV system.
Good Data: 1/11/2007 - Current

Supply Air from ERV Temperature
Description: Temperature in the ductwork between the ERV system and the main living space
Logger Channel: ERV_F_AVG
WebGet Channel: 14 (ERVSUT)
Sensor Location: : In the ductwork to the living space from the ERV system.
Good Data: 1/11/2007 - Current

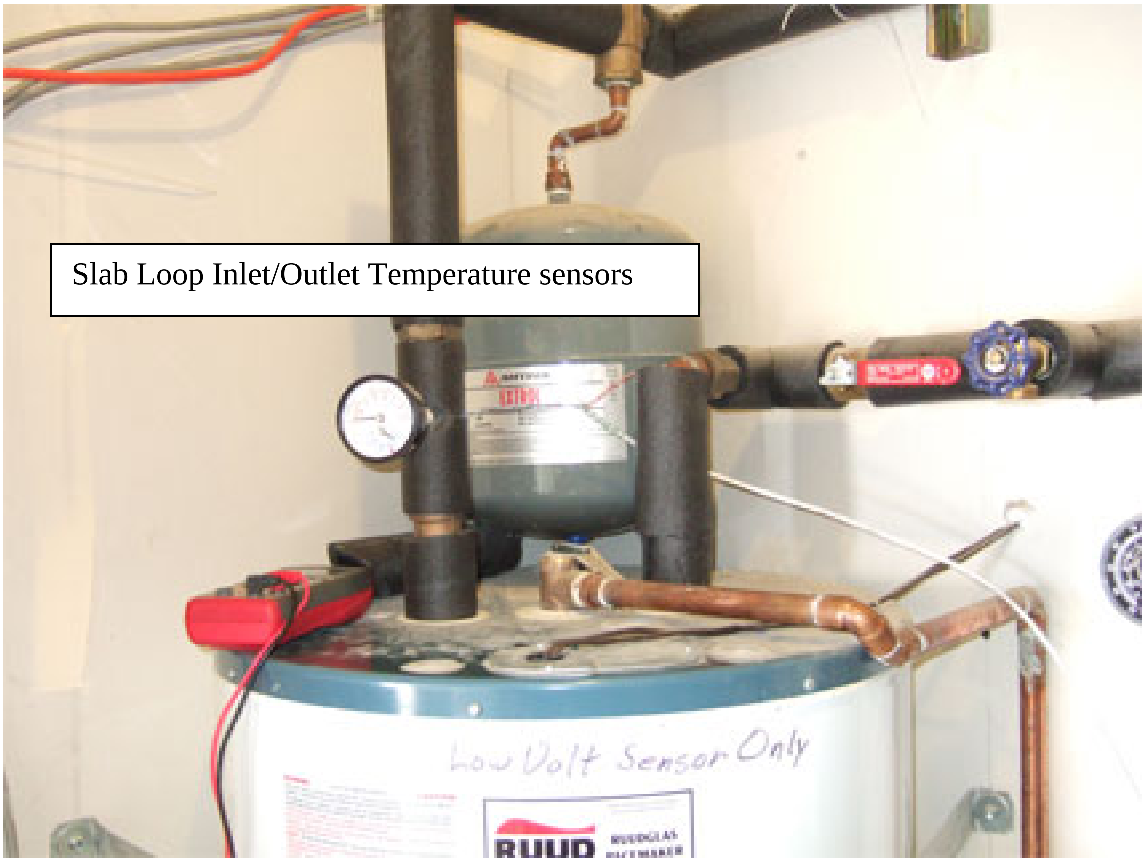
Supply Air from ERV Humidity
Description: Temperature in the ductwork between the ERV system and the main living space
Logger Channel: ERV_RH_AVG
WebGet Channel: 15 (ERVSUH)
Sensor Location: : In the ductwork to the living space from the ERV system.
Good Data: 1/11/2007 - Current

Earth Loop Inlet Temperature
Description: Temperature of the water coming from the earth loop.
Logger Channel: E_LpIn_F_AVG
WebGet Channel: 16 (ERLINT)
Sensor Location: On the pipe leading into the heat pump from the ground loop.
Good Data: 1/11/2007 - Current


Inlet and Outlet Ground Loop Temp sensors

Earth Loop Outlet Temperature
Description: Temperature of the water being injected back into the earth loop.
Logger Channel: E_LpOut_F_AVG
WebGet Channel: 17 (ERLOUT)
Sensor Location: On the pipe leading back to the ground loop from the heat pump.
Good Data: 1/11/2007 -
03/23/2007 02:15 PM - Current

Slab Loop Inlet Temperature
Description: Temperature of the water going to the radiant floor slab loop.
Logger Channel: S_LpIn_F_AVG
WebGet Channel: 18 (SLLINT)
Sensor Location: On the pipe that leads to the slab loop from the storage tank.
Good Data: 1/11/2007 - Current



Slab Loop Outlet Temperature
Description: Temperature of the water coming from the slab loop back to the storage tank.
Logger Channel: S_LpOut_F_AVG
WebGet Channel: 19 (SLLOUT)
Sensor Location: On the pipe that leads back to the storage tank from slap loop.
Good Data: 1/11/2007 - Current

Hot Water Tank Inlet Temperature
Description: Temperature of the water going to the house from the storage tank.
Logger Channel: DwhIn_F_AVG
WebGet Channel: 20 (DHWINT)
Sensor Location: On the pipe that leads back to the storage tank from slap loop.
Good Data: 1/11/2007 - Current

Hot water tank Outlet Temperature
Description: Temperature of the cold water going into the storage tank.
Logger Channel: DwhOut_F_AVG
WebGet Channel: 21 (DHWOUT)
Sensor Location: On the cold water pipe that goes into the storage tank.
Good Data: 1/11/2007 - Current

Watt-hours Greenhouse Heat to House

Description: Energy use by the fan that moves hot air from the green house to the living area. Fan runs when a thermostat is set to move warm air into the house. This blows warm air over the cement slab in the foyer.
Logger Channel: GrnHsH_wH_TOT
WebGet Channel: 22 (WHGHHH)
Sensor Location: On the wire in the fan's junction box.
Good Data: 1/11/2007 - Current

Watt-hours Greenhouse Heat to Outside
Description: Energy use by the fan that moves hot air from the green house to the exterior. This keeps the greenhouse from overheating.
Logger Channel: GrnHsO_wH_TOT
WebGet Channel: 23 (WHGHHO)
Sensor Location: Located in the Attic, on the wire in the fan's junction box.

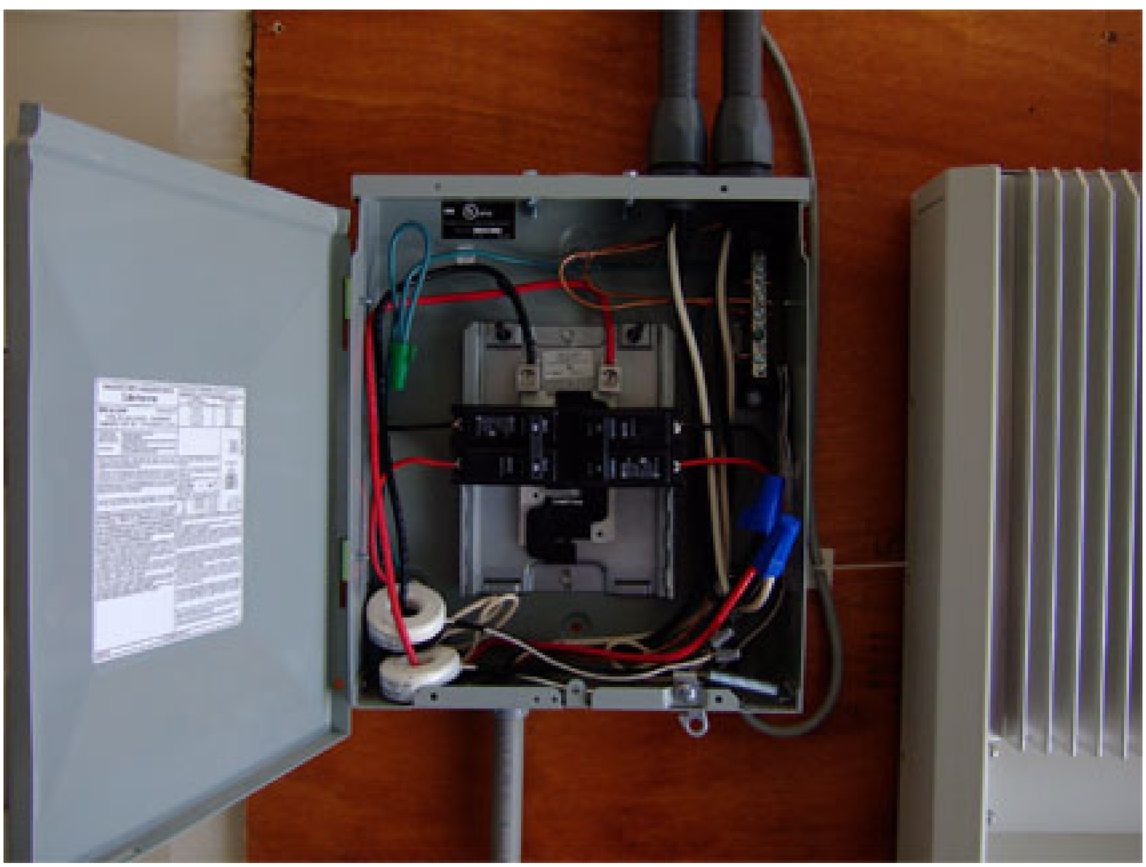
Watt-hours Heat Pump Compressor
Description: Energy use by the heat pump.
Logger Channel: GSHP_wH_TOT
WebGet Channel: 24 (WHGHHP)
Sensor Location: In panel A on both of the wires.
Good Data: 03/21/2007 02:00 PM - Current

Watt-hours Panel 1A
Description: Energy use by the Panel A (including the heat pump and the ERV).
Logger Channel: PnlA_wH_TOT
WebGet Channel: 25 (WHPAN1)
Sensor Location: In panel A.
Good Data: 03/23/2007 03:00 PM - Current

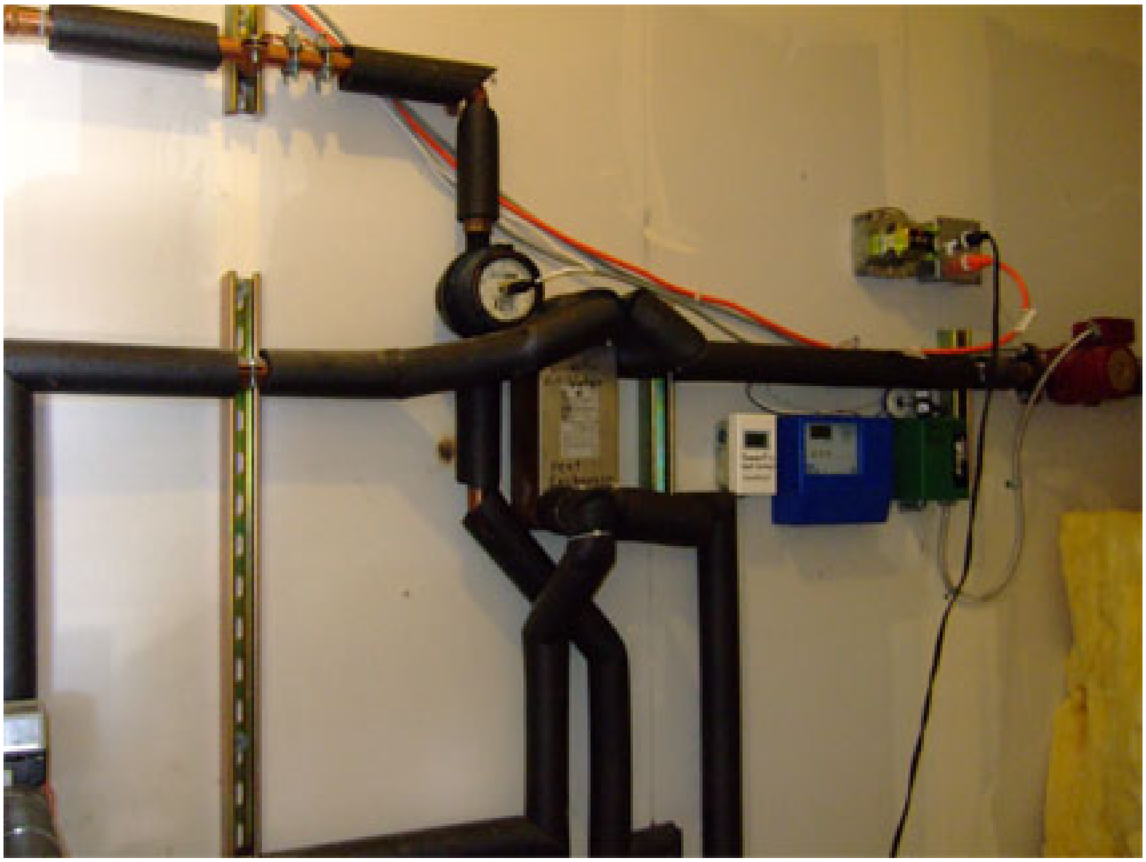
Watt-hours ERV / Air Handler
Description: Energy use by the ERV
Logger Channel: ERV_wH_TOT
WebGet Channel: 26 (WHERVA)
Sensor Location: In panel A on both phase wires
Good Data: 03/30/2007 03:45 PM - Current

Watt-hours Panel 1B
Description: Energy use by panel B loads
Logger Channel: PnlB_wH_TOT
WebGet Channel: 27 (WHPAN2)
Sensor Location: In panel B
Good Data: 03/23/2007 02:30 PM - Current

Watt-hours PV Inverter Output
Description: Energy use by panel B loads
Logger Channel: Solar_wH_TOT
WebGet Channel: 28 (WHINVO)
Sensor Location: In breaker box that back feeds on panel B (2 phase)
Good Data: 03/21/2007 01:30 PM - 06/21/2007 11:30 AM
10/10/2007 07:30 AM - Current



Slab Loop Flow Rate
Description: Flow in the slab in gallons
Logger Channel: SlabFlw_g_TOT
WebGet Channel: 29 (FLSLAB)
Sensor Location:



Hot Water Tank Flow Rate (Gallons)
Description: Flow of domestic hot water in gallons
Logger Channel: DwhFlw_g_TOT
WebGet Channel: 30 (FLODHW)
Sensor Location:

Ambient Temperature
Description: Temperature outside the house
Logger Channel: Out_F_AVG
WebGet Channel: 31 (AMBTEM)
Sensor Location: sensor located on roof.

Good Data: 1/11/2007 - Current

Ambient Relative Humidity
Description: RH outside the house
Logger Channel: Out_RH
WebGet Channel: 32 (AMBRHH)
Sensor Location: sensor located on roof.
Good Data: 1/11/2007 - Current

Flux Density
Description: Solar radiation
Logger Channel: OutSlr_W_AVG
WebGet Channel: 33 (PYWAVG)
Sensor Location: sensor located on roof.

06/22/2007 04:00 AM - 09/18/2007 11:30 PM
10/10/2007 06:15 AM - Current

Total Flux (not important)
Description: Solar radiation accumulation
Logger Channel: OutSlr_kJ_TOT
WebGet Channel: 34 (PYKJTO)
Sensor Location: sensor located on roof.

Appendix C
Ground Source Heat Pump COP Calculation Method

A channel data acquisition system takes measurements every 15 seconds, averages them over 15 minutes and saves them to FSEC's WEBGET database. WEBGET is used to evaluate overall home performance and PV production. For the analysis of the GSHP COP, one minute data was collected from May to November 2009 data into a spreadsheet which was then used to analysis GSHP performance and determine in-situ COP.

The COP of a GSHP is defined as:

$$\frac{Q_{earth} + Q_{compressor}}{Q_{compressor} + Q_{pumps}}$$

Q_{earth} was calculated by doing a one-time measurement of the flow rate of the ground loop, measuring the temperature difference between inlet and outlet temperatures and adjusting for the thermal capacity of the 20% methanol mixture in the earth loop, which was calculated at 0.921 BTU/lb x °F.

Qearth (BTU/hr) = m x Cp x Cv x (Tin – Tout)

Where m is the mass flow rate of the fluid in lb/hr.; so m = 11.8 gpm x 8.33 lbm/gal = 98.3

Energy to the compressor, earth loop and hydronic system pumps is monitored by the data logger. Energy to the auxiliary pumps (space heat and domestic hot water circulation pumps) was measured (one time) and added to the energy measured by the logger for periods when they are running.

Flow rate in the earth loop was calculated thus:

$$Q = Cv\sqrt{H}$$

Where Q=flow rate in gpm
Cv = valve factor, gpm flow that causes a 1 psi pressure drop
H=heat in psi

The Manufacturer lists flow vs. head for the earth loop heat exchanger. At the design flow rate of 8 gpm the pressure drop is 5.5 psi, plugging these values into the equation above yields a Cv of 3.41. Using this value of Cv, we can calculate the flow at any head - in this case $Q = 3.41x\sqrt{12}$ =11.8 gpm.

The measured flow then is nearly 50% higher than the factory-recommended flow rate of 8 GPM. The effect is to increase heat output by approximately 8% while increasing the energy use (in the compressor only) by 2%. Investigations are underway to further evaluate earth loop flow rates on overall system efficiency.

Other Notes:

1) The estimate of COP was done for each GSHP cycle. To help evaluate the steady-state performance and the first two minutes and last minute of cycle data was filtered out of the calculation estimate.

2) Adjustments to COP were also methanol/water mixture in the earth loop as follows: The fluid used in the ground loop consists of a mixture of 20% methanol and 80% water. Methanol has a Specific Gravity (at 20 deg. F) of .7915 and a heat capacity of 0.604 BTU/(deg.F x Lb); water has a specific heat of 1 BTU/(deg.F x lb) and a specific gravity of 1.0. For a 20% mixture of methanol and water, the mixture will contain 0.2 parts of methanol and .8 parts of water. The specific gravity of the mixture is then 0.2 x 0.7915 + 0.8 x 1.0 = 0.9582. The specific heat of the mixture is 0.2 x 604 + 0.8 x 1.0 = 0.1208 + 0.8 x 1 = 0.921.
Calculated the specific heat = .92 is multiplied by 8.33 #/gal and by the delta t of earth loop.

3) The correction factor for measurements of various fluid densities - the formula is the square root of 1/specific gravity times the gauge reading. A specific gravity of .9581 indicates a correction factor of 1.021 - a 2% increase in actual flow.

Appendix D

Ground Source Heat Pump Sequence of Operation

SEQUENCE OF OPERATIONS
HVAC SYSTEMS SERVING THE ZELONEDOM RESIDENCE

General

The system provides ventilation and space heat for several radiant floor zones and domestic hot water (DHW). System components include an Econar ground-source heat pump with the factory pump pack (two pumps) serving the earth loop, a main circulation pump (P-1), Space heat pump P-2, domestic water heater pump (P-3), two zone valves, A system hot water storage tank, a domestic hot water storage tank and two Tekmar controllers, a Tekmar 150 for domestic hot water control and a Tekmar 260 with outdoor reset.

Heat Pump

The heat pump consists of an Econar two-ton water to water heat pump. The heat pump is a water to water unit with two "source" circulating pumps which move water through the earth loop and a "load" circulating pump which circulates heating water through either the domestic water heat exchanger or the heating water storage tank (ST-1), depending on the position of the system zone valves.

The heat pump is started and stopped by end switches on the two zone valves. The zone valves are energized and de-energized by the Tekmar controllers. Upon a call for heat from the space heat sensor or the domestic hot water storage tank sensor, circulating pump P-1 and the two pumps serving the earth loop (Pump Pack-1) are energized and run until the call for heat is satisfied. If both DHW and space heat systems are simultaneously calling for heat, the domestic water heater has priority and runs until its load is satisfied before providing for the space heat load. When changing from domestic water heating mode to space heating mode, the heat pump shuts down momentarily until ZV-1 opens fully and its end switch energizes the heat pump.

Domestic Water Heating

When the temperature in the domestic hot water storage tank (DHWST) drops 2°F below the set point (adjustable and currently set at 117°F - 120°F) zone valve - 1 (ZV-1) is closed, ZV-2 opens and pump P-3 is energized. When Z-2 is fully open, an end switch starts the heat pump if it is not already running. When the temperature in the DHWST rises to 2°F above the set point, the call for domestic hot water heating is satisfied, ZV-2 closes, ZV-1 opens and, if the space heat zone is satisfied, the heart pump and all hydronic pumps shut down.

Space Heating

The Tekmar 260 controller provides space heat control functionality for the heat pump. The controller senses outdoor temperature, indoor temperature and the heating water storage tank (ST-1) temperature and uses this information to set the temperature of the water supplied to the radiant floor. As the outside temperature falls, the controller increases the heating water temperature, raising the temperature of the water in ST-1 and the water used in heating the floor loop. The ratio between the rise in the heating water temperature as the outdoor temperature falls is called the reset ratio. The Zelonedom system is currently setup with an indoor temperature of 68°F – 70°F and a reset ratio of 1:1 - i.e., as the outside temperature rises from 20°F to 60°F, the heating water temperature drops from 120°F to 60°F.

The heating control system is actuated by the indoor sensor connected to the Tekmar 260 and located in the main living area (which includes the open living area, master closet, laundry, and bathrooms). Heating sub-zones are provided for the office, guest bedroom, sunroom, reading room and master bedroom. Each area has a thermostat connected to an actuator on one of the supply heating manifolds. The actuator shuts down heating water flow heat to its sub-zone when a call for heat in the area is satisfied. A summer lock-out circuit is provided to shutdown the hydronic pump whenever the outside temperatures exceed 70°F. (adjustable).

Radiant Floor Loop

The radiant floor is a 4 inch concrete slab with ¾” PEX tubing on 9 inch centers except for the edges where the first 3-4 passes are on 6 inch centers. Bathrooms also have tubing installed on 6” centers including the areas under the bathtub and shower. Tubing was not placed under the pantry or lower cabinets.

Each heating circuit in the floor is connected to a heating water supply or return manifold. There are two sets of manifolds – one in the master bedroom closet, the other in the hall closet. Each manifold has a shut-off valve for each supply and return circuit and on the supply manifold, a flow meter and balancing valve for each circuit.

Ground Loop Heat Exchanger

The ground loop heat exchanger consists of 1,800 ft. of buried ¾” polyethylene piping (PEX) in a 300 ft long by 5 ft. deep trench on the east side of the building. Two additional passes of PEX are run on the south side of the house. These loops terminate in the garage near the heat pump.

Ventilation System (not operating)

The ventilation system consists of a Rheem™ 600 CFM air handling unit with a Honeywell HEPA filter and a 200 CFM heat recovery ventilator (HRV). The air handler distributes filtered air throughout the house via 8 diffusers and two return air grilles. The HRV is connected to the air handler return air ductwork with the exhaust air connection upstream of the outside air outlet The HRV flow is set (via a fan speed controller) at slightly over 1/6 of the house’s ACH rate. A de-humidistat is located near the entry and is wired to boost the fans speed to high speed if the humidity in the area exceeds the set point. A second switch shuts down the heat exchanger’s heat-transfer wheel when the temperatures exceed 50-70 °F.

Appendix E

Cost-effectiveness spreadsheet (attached electronically)

Appendix F

Ground Source Heat Pump (WSU will deliver 344MB spreadsheet file on CD)

See link: <\\dfsc0\shared\IND\Build America\Build America\Garst\COPCalc20090112_ToMike.xls>

Appendix G

Building America Site and Source Savings

Building America

Site Energy Summary 2008

Sam & Christine Garst
6015 Maranatha Lane
Tumwater, WA 98512-

Project Title:
Garst final 2

Climate: WA_OLYMP
2/10/2009

End Use:	Benchmark kWh	Therms	Gal	MBTU	Cost	Prototype kWh	Therms	Gal	MBTU	Cost	Saving Si
Total Space Heating:	13031	0	0	44.462	1042	4320	0	0	14.740	345	66.8
Heating:	11265	0	0	38.436	901	3427	0	0	11.693	274	
Heating Fan:	1766	0	0	6.026	141	893	0	0	3.047	71	
Total Space Cooling:	535	0	0	1.825	42	79	0	0	0.270	6	85.2
Cooling:	455	0	0	2	36	61	0	0	0	5	
Cooling Fan:	80	0	0	0.273	6	18	0	0	0.061	1	
Total Hot Water:	4064	0	0	13.867	325	909	0	0	3.101	73	77.6
Lighting Subtotal:	2783	0	0	9.496	223	1443	0	0	4.924	115	48.1
Wired Lighting:	2297	0	0	7.838	184	957	0	0	3.267	77	58.3
Plug Lighting:	486	0	0	1.657	39	486	0	0	1.657	39	0.0
Appliance Subtotal:	5760	0	0	19.653	460	5276	0	0	18.002	421	8.4
Refrigerator:	669	0	0	2.283	54	480	0	0	1.638	38	28.3
ClothesWasher:	105	0	0	0.358	8	69	0	0	0.235	6	34.3
ClothesDryer:	835	0	0	2.849	67	601	0	0	2.051	48	28.0
Dishwasher:	206	0	0	0.703	16	181	0	0	0.618	14	12.1
Cooking:	605	0	0	2.064	48	605	0	0	2.064	48	0.0
Other Appls:	3340	0	0	11.396	267	3340	0	0	11.396	267	0.0
Ceiling Fan:	0	0	0	0.000	0	0	0	0	0.000	0	
OAVentilation Fan:	200	0	0	0.682	16	0	0	0	0.000	0	100.0
Total:	26373	0	0	89.985	2108	12027	0	0	41.037	961	54.4
Generation(PV):	0	0	0	0	0	-3790	0	0	-12.931	-303	
Net:	**26373**	**0**	**0**	**89.985**	**2108**	**8237**	**0**	**0**	**28.105**	**658**	**68.8**

EnergyGauge USA 2.8

Building America

Source Energy Summary 2008

Sam & Christine Garst
6015 Maranatha Lane
Tumwater, WA 98512-

Project Title:
Garst final 2

Climate: W
2/16/2009

End Use:	Benchmark					Prototype				
	kWh	Therms	Gal	MBTU	Cost	kWh	Therms	Gal	MBTU	Cost
Total Space Heating:	13031	0	0	149.614	1042	4320	0	0	49.600	345
Heating:	11265	0	0	129.338	901	3427	0	0	39.347	274
Heating Fan:	1766	0	0	20.276	141	893	0	0	10.253	71
Total Space Cooling:	535	0	0	6.143	42	79	0	0	0.907	6
Cooling:	455	0	0	5	36	61	0	0	1	5
Cooling Fan:	80	0	0	0.919	6	18	0	0	0.207	1
Total Hot Water:	4064	0	0	46.661	325	909	0	0	10.435	73
Lighting Subtotal:	2783	0	0	31.953	223	1443	0	0	16.569	115
Wired Lighting:	2297	0	0	26.376	184	957	0	0	10.993	77
Plug Lighting:	486	0	0	5.577	39	486	0	0	5.577	39
Appliance Subtotal:	5760	0	0	66.134	460	5276	0	0	60.577	421
Refrigerator:	669	0	0	7.681	54	480	0	0	5.511	38
ClothesWasher:	105	0	0	1.206	8	69	0	0	0.792	6
ClothesDryer:	835	0	0	9.587	67	601	0	0	6.900	48
Dishwasher:	206	0	0	2.365	16	181	0	0	2.078	14
Cooking:	605	0	0	6.946	48	605	0	0	6.946	48
Other Appls:	3340	0	0	38.349	267	3340	0	0	38.349	267
Ceiling Fan:	0	0	0	0.000	0	0	0	0	0.000	0
OAVentilation Fan:	200	0	0	2.296	16	0	0	0	0.000	0
Total:	26373	0	0	302.800	2108	12027	0	0	138.088	961
Generation(PV):	0	0	0	0	0	-3790	0	0	-43.514	-303
Net:	**26373**	**0**	**0**	**302.800**	**2108**	**8237**	**0**	**0**	**94.573**	**658**

EnergyGauge USA 2.8

Appendix H

Building America Benchmark Analysis Site and Source Savings ENB Files (attached electronically)