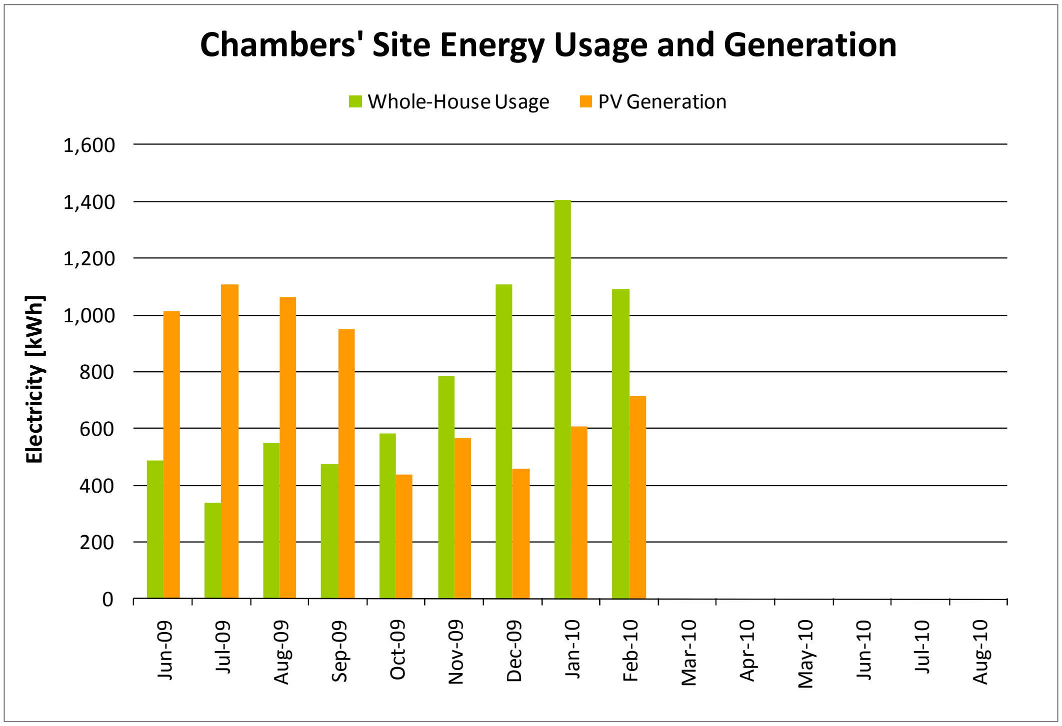
WPPI's GreenMax – Chambers Long Term Monitoring Summary To Date

Steven Winter Associates Inc. (SWA) is partnering with WPPI Energy to monitor the energy performance of the Chambers' GreenMax house for a period of at least 12 months. Energy monitoring enables the tracking of the energy performance of the house and analysis of the energy consumption data gives an indication of how much energy is saved due to the energy efficiency measures included in this project. This data is being used to commission and fine tune the various systems within the home.

SWA engineers set up a data logger and sensors that collect real time energy consumption data for the various domestic appliances including washer/dryer, microwave oven, coffee maker, range/stove and dishwasher (the refrigerator is currently not collected separately, so it is accounted for in the Miscellaneous Category); lighting and plug loads in the kitchen, living room, bedroom, bathrooms and garage; HVAC equipment including ground source heat pump (GSHP) and other integrated systems like the desuperheater, water heater, drain water heat recovery, and energy recovery ventilator. This GreenMax home is an all-electric home. The PV arrays are also being monitored to collect energy generation data. Data collection began in June of 2009.

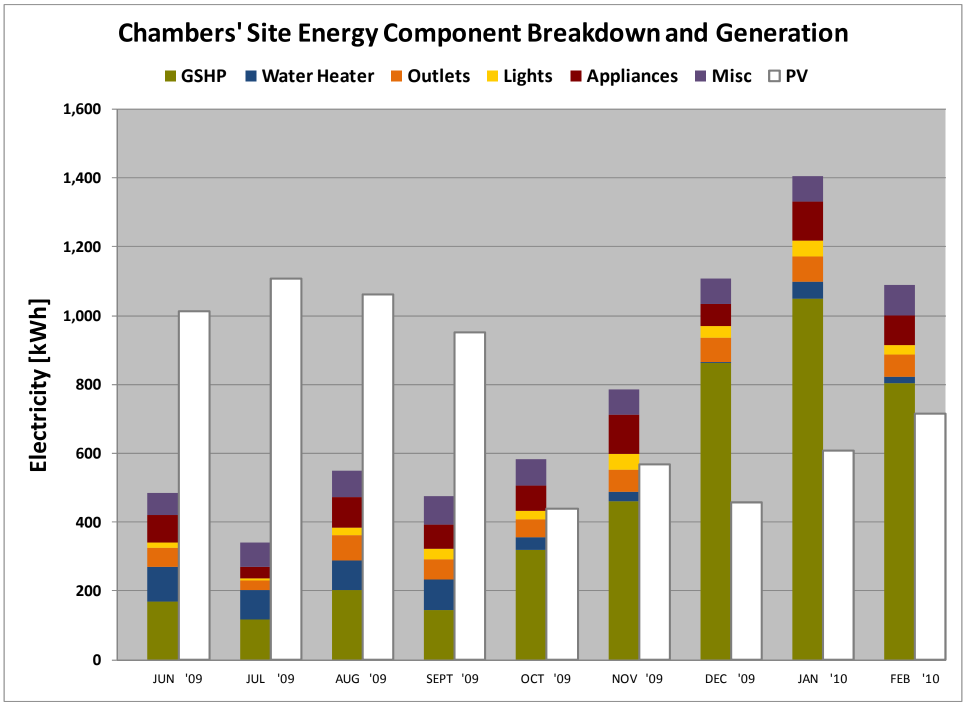


Above is a monthly chart showing whole house electrical usage and generation. Based on nine months of data, the home is net-zero in terms of electrical energy consumption (6,924 kWh generated versus 6,823 kWh consumed). According to the 2000 Energy Center of Wisconsin's "Energy and Housing in Wisconsin" Study, the average Wisconsin home uses 9,960 kWh annually and 1,026 therms of natural gas annually. This study also reports that the average usage of all electric homes (less than 5% of Wisconsin homes, versus 70% of homes heated by natural gas) is 24,000 kWh annually. Over this initial nine month span, the average monthly electricity usage for the Chambers' GreenMax home has been 758 kilowatts-hours of electricity. If this average is maintained, these homeowners are utilizing roughly 62% less energy than the average Wisconsin all-electric household. It should be noted that this is a new energy-efficient home, fairly small at 1,800 square feet of finished living space (3,100 square feet of conditioned space including unfinished basement area), a household of two, and they were away for the majority of the month of July.

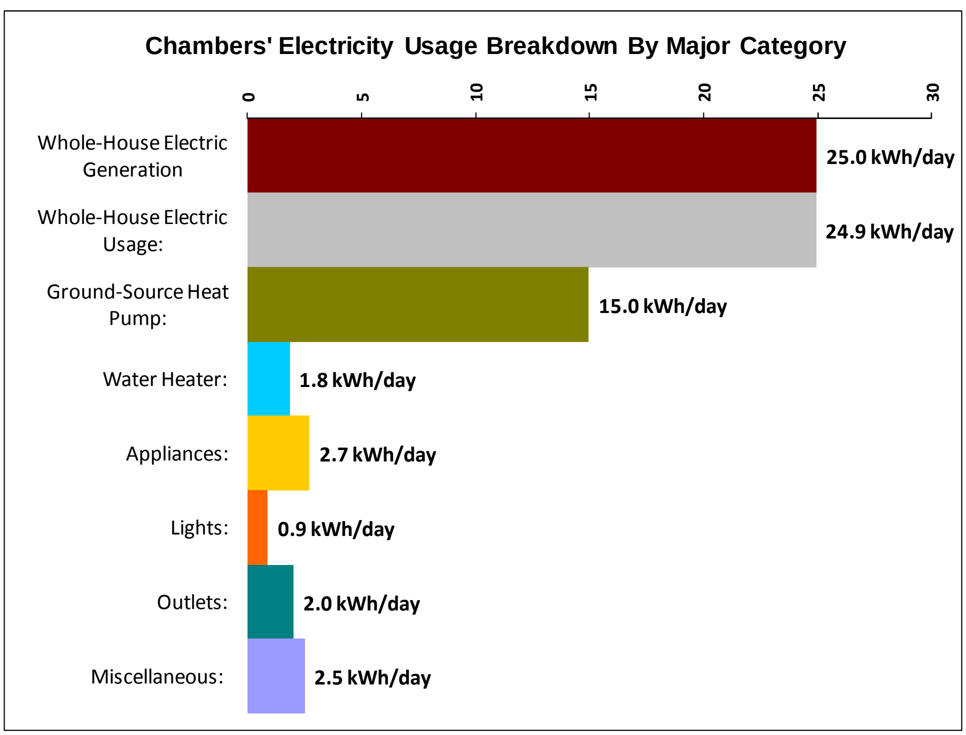
The actual PV generation is tracking fairly consistent with the anticipated PV generation based on energy modeling. The National Renewable Energy Laboratories' PVWatts calculator was used with Eau Claire, WI as the representative city for Black River Falls, WI (roughly 50 miles away). A DC to AC derate factor of 0.83 was utilized based on SWA's extensive PV monitoring experience for systems with limited or no shading. The results of the modeled PV generation versus actual generation are shown in the table below. Over the past nine months, the difference between actual and estimated PV generation is less than 1.6% for that period. The estimated vs actual generation for October and November seemed askew at first glance, but the weather for these two months in this region also flip-flopped. October was colder and saw more rain than typical, while November was warmer and saw minimal precipitation compared to historical data. If the Chambers' maintain their average monthly electrical usage from the past nine months over the next three months, they will maintain a net-zero energy home.

	Estimated		Actual
Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	AC Energy (kWh)
Jan	4.03	651	609
Feb	5.64	804	714
Mar	6.40	983	
Apr	6.30	900	
May	7.94	1,131	
Jun	8.40	1,118	1,013
Jul	8.33	1,150	1,108
Aug	7.36	1,002	1,063
Sep	6.00	805	952
Oct	4.59	664	440
Nov	2.83	406	567
Dec	2.80	436	457
Total	-	10,050	

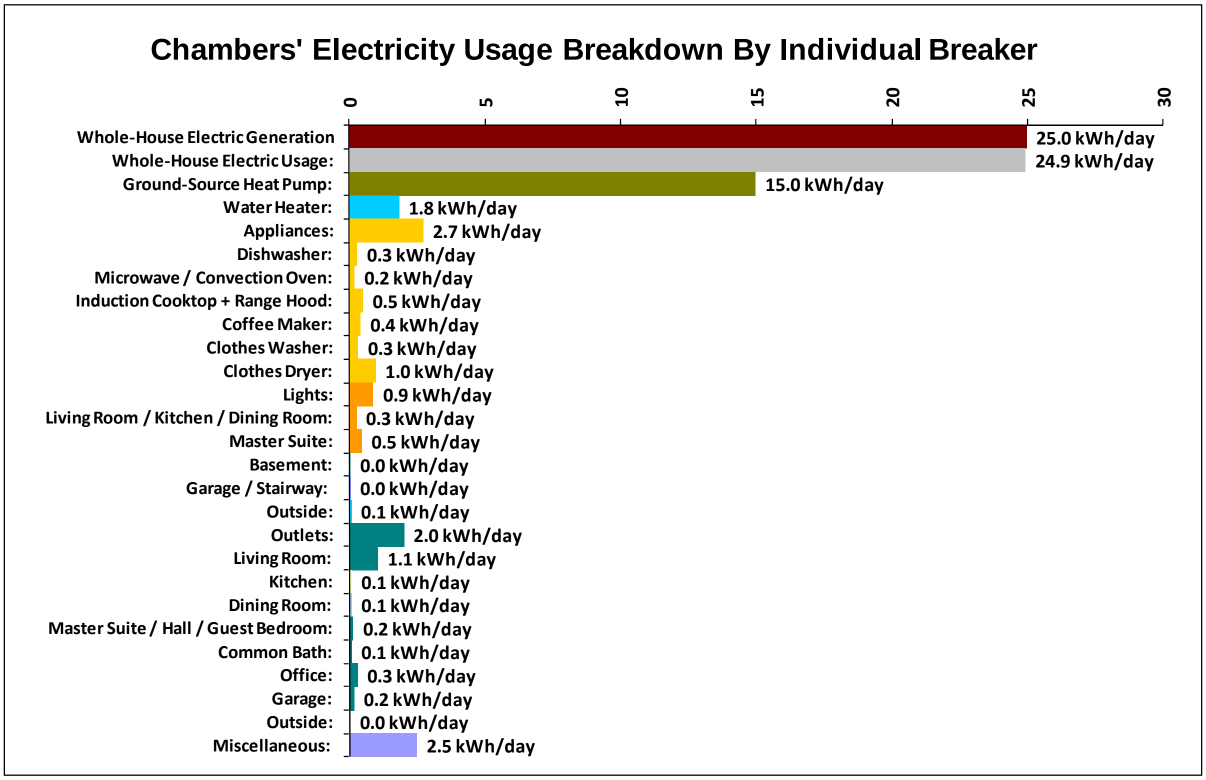
To get a better idea of how electricity is being consumed in the Chambers' residence, the following chart shows the electricity consumption breakdown by major component. As would be expected, the ground-source heat pump is the largest energy user. As this is providing space heating/cooling and a significant portion of water heating, it is understandable that the GSHP accounts for 60% of the daily energy usage on average. Use of CFL lights throughout the house keeps the lighting loads to a minimum while Energy Star rated appliances enable the monthly appliance loads (excluding the refrigerator, which is lumped with Misc currently) to be kept to a minimum.



Looking at this same data on a daily average basis, the electrical usage breakdown by major category is as follows. The Miscellaneous category currently includes the refrigerator energy usage, but this will be isolated as a separate appliance beginning from March 2010. The Energy Guide Label for the installed refrigerator estimates electrical usage at 470 kWh/yr or 1.29 kWh/day. This is roughly half of the Miscellaneous electrical consumption being monitored.



As each individual electrical breaker is being monitored, it is possible to refine these major categories further to get a better understanding of the specific appliance, zoned lighting, and zoned outlet usage.



In terms of appliances, the clothes dryer uses the most energy. The lighting in the Master Suite and the outlets in the Living Room are the major sources of electrical usage for these two major components. The outlets in the Living Room are comprised of the home entertainment center, so it is not surprising that this represents half of the plug loads.

	Monthly Appliance Electrical Usage [kWh]					
Month	Dish-washer	Speed Oven	Induction Cooktop	Coffee Maker	Clothes Washer	Clothes Dryer
Jun '09	14	4	10	11	10	30
Jul '09	5	0.5	8	7	4	9
Aug '09	10	2	18	14	13	34
Sept '09	8	5	14	13	12	19
Oct '09	7	8	10	13	9	26
Nov '09	11	13	17	15	15	45
Dec '09	7	7	10	12	4	23
Jan '10	9	9	26	15	13	41
Feb '10	8	5	20	14	9	31
Total	79	54	133	114	89	258

Appliance	Daily Standby Watt-hours
Dishwasher	37
Speed Oven	5
Induction Cooktop	190
Coffee Maker	155
Clothes Washer	25
Clothes Dryer	0
Total	411

The July data when the Chambers weren't home actually provides some interesting information about the electrical usage of the various appliances when not operating. Essentially this is the daily standby-by energy usage. If an electric rate of $0.10/kWh is assumed, this standby energy only amounts to a $15 additional per year for the appliances.

In terms of the lighting and outlets, the only consistent standby energy usage was the garage outlets. This circuit breaker averages 133 Wh/day when there is no home occupancy. Again not significant, but it would be interesting to determine what is drawing this standby power. Is it simply the garage door opener? Or it may be that the home's internet wireless router is plugged into this circuit (even though located in the basement near the electrical panel).

Ground-Source Heat Pump Monitoring

This horizontal closed loop, pressurized slinky GSHP system consists of two 300 foot trenches at a depth of 8 feet and separated by 8 feet. Environol 1000 solution (21.4% ethanol) is circulated between the ground coils and a 3-ton dual capacity Water Furnace Synergy 3-D heat pump (model SDV038A121CTL) located in the unfinished portion of the basement. This unit also has a third mode of water heating that goes to a 50 gal buffer tank prior to the 80 gal electric water heater. A desuperheater runs directly to the electric water heater. A passive ERV (with no internal fans; it uses the air handler to move air through it) was connected to the central duct system, but this has been replaced with a typical HRV with internal fans (currently not interlocked with the GSHP air handler fan).

SWA is extensively monitoring this GSHP system. SWA also leads the Department of Energy's Building America working group on GSHPs. Through those efforts, SWA has developed a monitoring protocol for GSHPs to effectively quantify the whole-system performance of these units that account for the ground loop pump, ductwork, and desuperheater. The following equations represent how system efficiency has been defined for this project.

Coefficient of Performance (COP): The coefficient of performance of a heat pump is the ratio of the useful heating energy outputted by the system to the net energy inputted to the system.

Heating Coefficient of Performance is:

$$COP = \frac{useful\ heating\ energy}{net\ energy\ input} = \frac{Q_h + (W_{fan} + W_{comp} + W_{DHW,pump}) \times 3.413\ \ Btu/Wh}{(W_{comp} + W_{fan} + W_{pump} + W_{DHW,pump}) \times 3.413\ \ Btu/Wh}$$

where:

COP	= coefficient of performance of the complete system [dimensionless]
Q_h	= useful heat extracted from ground loop [Btu]
W_{comp}	= energy consumed by the compressor [Wh]
W_{fan}	= energy consumed by the fan [Wh]
W_{pump}	= energy consumed by the ground-loop pump [Wh]
$W_{DHW,pump}$	= energy consumed by water heater/desuperheater pump, if appropriate [Wh]

Domestic Hot Water Mode Coefficient of Performance is:

$$COP = \frac{useful\ \ heating\ \ energy}{net\ \ energy\ \ input} = \frac{Q_h}{(W_{comp} + W_{pump} + W_{pump-2}) \times 3.413\ \ Btu/Wh}$$

where:

W_{pump-2} = energy consumed by the DHW pump [Wh]

Energy Efficiency Ratio (EER): The Energy Efficiency Ratio of a heat pump is the ratio of the useful cooling energy output by the system to the net energy input to the system.

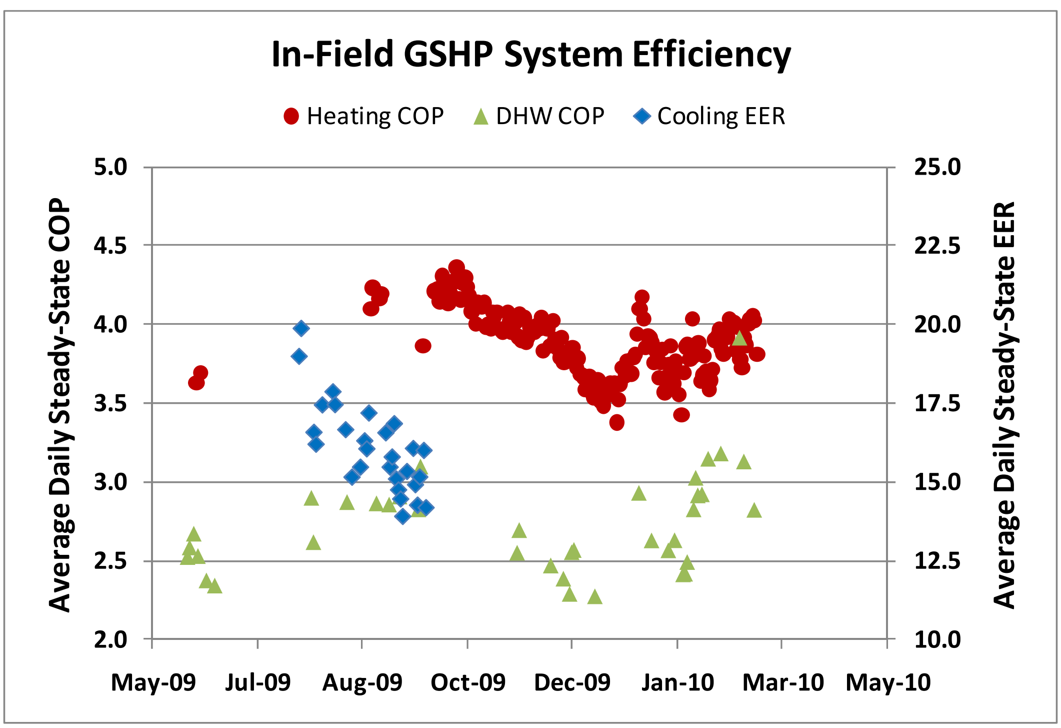
Cooling Energy Efficiency Ratio is:

$$EER = \frac{useful\ \ cooling\ \ energy}{net\ \ energy\ \ input} = \frac{Q_c + Q_{DSH} - (W_{fan} + W_{comp}) \times 3.413\ \ Btu/Wh}{W_{comp} + W_{fan} + W_{pump} + W_{DSH,pump}}$$

where:

EER	= energy efficiency ratio [Btu/Wh]
Q_c	= heat dumped to ground loop [Btu]
W_{comp}	= energy consumed by the compressor [Wh]
W_{fan}	= energy consumed by the fan [Wh]
W_{pump}	= energy consumed by the ground-loop pump [Wh]
Q_{DSH}	= heat transferred to DWH by desuperheater [Btu]
$W_{DSH,pump}$	= energy consumed by the desuperheater circulator [Wh]

For the nine month period, the overall heating COP was 3.51, the DHW COP was 2.60 and the cooling EER was 17.11. This accounts for all energy usage of the GSHP regardless of whether the system is supplying conditioned air or not. The heating COP also included all standby electrical usage. If this standby usage is removed, the overall heating COP was 3.70.



Looking at the data (table below) when the system is on and running at "steady-state", the system has a better heating COP performance. Steady-state is defined here as system operation for the full 15 minute logging period (measurements are taken at a 10 sec execution interval). The total average in the table below is actually not an average of the monthly averages, but an average for the entire heating period (which is mostly at the lower incoming fluid temperature <45°F).

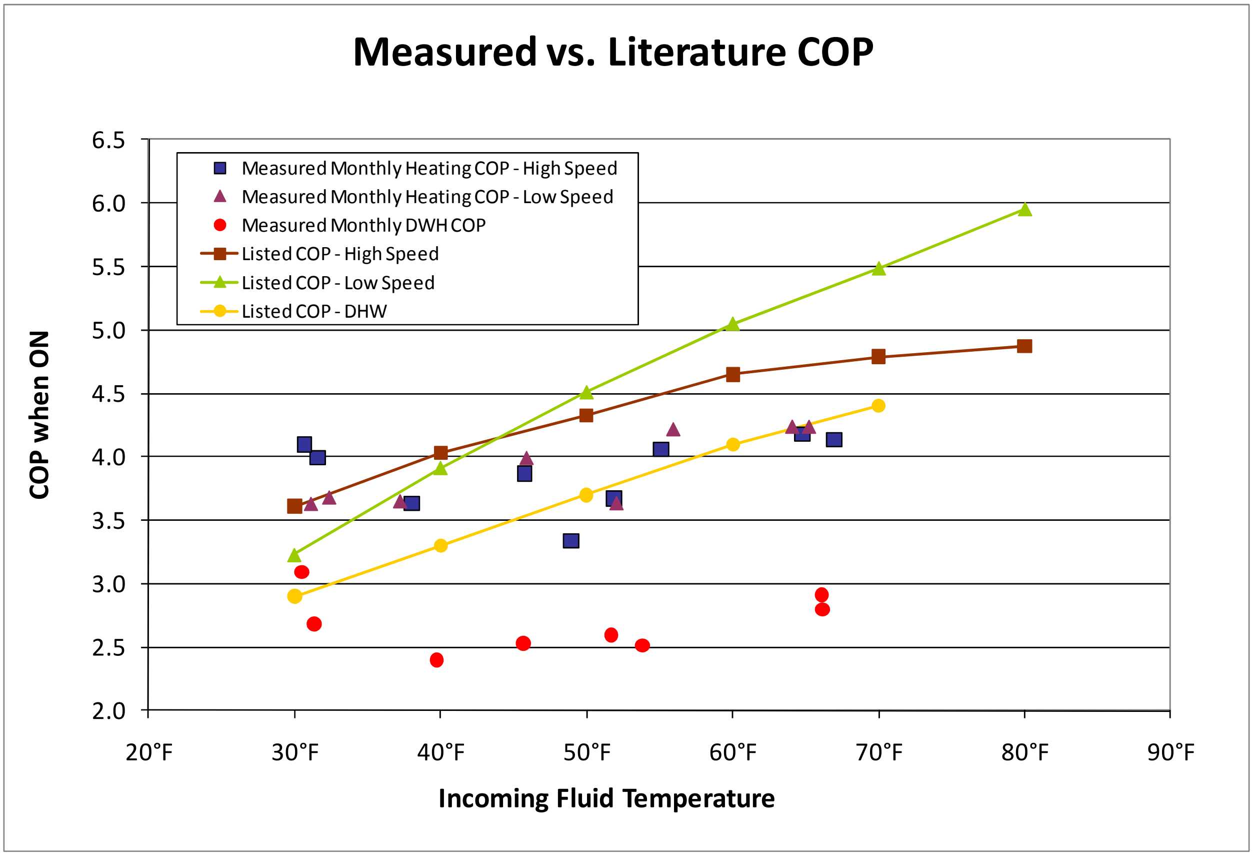
The steady-state cooling EER is slightly lower, but this might be due to there not being many instances of steady-state operation during the cooling cycle. This system is sized for the dominant heating load, so it is oversized in terms of cooling capacity (even at part-load capacity), resulting in the system short-cycling during the cooling season.

Month	Average Incoming Fluid Temp.	Heating COP when ON - High Speed	Heating COP when ON - Low Speed	DHW COP when ON	Cooling EER when ON - High Speed	Cooling EER when ON - Low Speed
June 2009	53°F	3.7	3.6	2.5	-	-
July 2009	70°F	-	-	-	-	19.3
August 2009	72°F	4.1	4.2	2.8	15.7	17.3
September 2009	71°F	4.2	4.2	2.9	14.5	15.0
October 2009	55°F	4.1	4.2	-	-	-
November 2009	46°F	3.9	4.0	2.5	-	-
December 2009	38°F	3.6	3.6	2.4	-	-
January 2010	32°F	4.0	3.7	2.7	-	-
February 2010	31°F	4.1	3.6	3.1	-	-
Avg.	55°F	3.9	3.7	2.7	15.1	16.1

ISO/ARI Rated Heat Pump Efficiency		Actual System Efficiency When ON		Performance Difference	
low stage [COP / EER]	high stage [COP / EER]	low stage [COP / EER]	high stage [COP / EER]	low stage [COP% / EER%]	high stage [COP% / EER%]
4.5 / 23.7	4.0 / 18.5	3.7 / 16.1	3.9 / 15.1	17.8% / 32.1%	2.5% / 18.4%

This ground-source heat pump is ISO/ARI rated as EER 23.7/COP 4.5 for low stage and EER 18.5/ COP 4.0 for high stage. Though the measured monthly system COP is lower than the rated COP from the engineering data, this is not unexpected. The literature COP does not account for the external piping resistance (the ground loop pump energy) and rates the equipment at a blower external static pressure (ESP) of 0 in. w.c. (or no ductwork). The table above right shows the performance difference between the unit's rating and actual system performance. It should be noted that this table shows the higher steady state COP (not the average COP). Still, the overall efficiency of this GSHP system is significantly higher than alternative space conditioning methods.

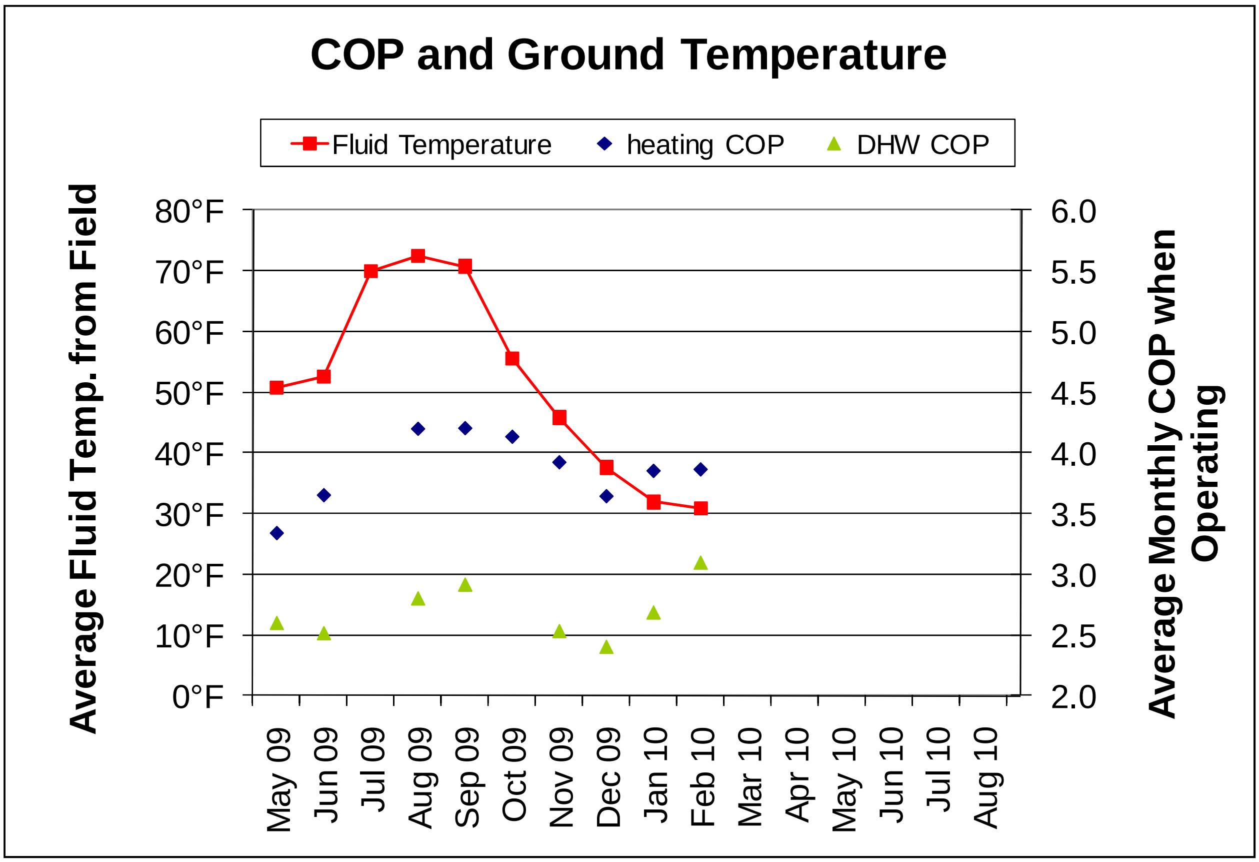
This difference between the rated efficiency of a heat pump unit and the in-field system efficiency is important when performing energy modeling to estimate home performance. The rated equipment COP entered into common modeling tools is ultimately taken as the effective COP of the modeled system – i.e. there is no compensation made by the modeling tools for any additional fan or pumping energy. The manufacturers are not necessarily to blame, because they can only rate the portion of the product that they manufacture; therefore designers – and even contractors – need to acknowledge the difference between a rated efficiency and a system efficiency. Below is a chart showing the average monthly measured COP of the *system* vs. the manufacturer listed COP for the *heat pump only*. This system utilizes a single speed ground loop pump that is operating at roughly 7.4 gpm. The listed COPs in the chart above are based on ground loop flow rates of 7 gpm for high stage and an interpolated 7 gpm for low stage (manufacturer data provided performance ratings at 6 gpm and 8 gpm). The listed DHW COP is also based on 7 gpm ground loop flow rate.



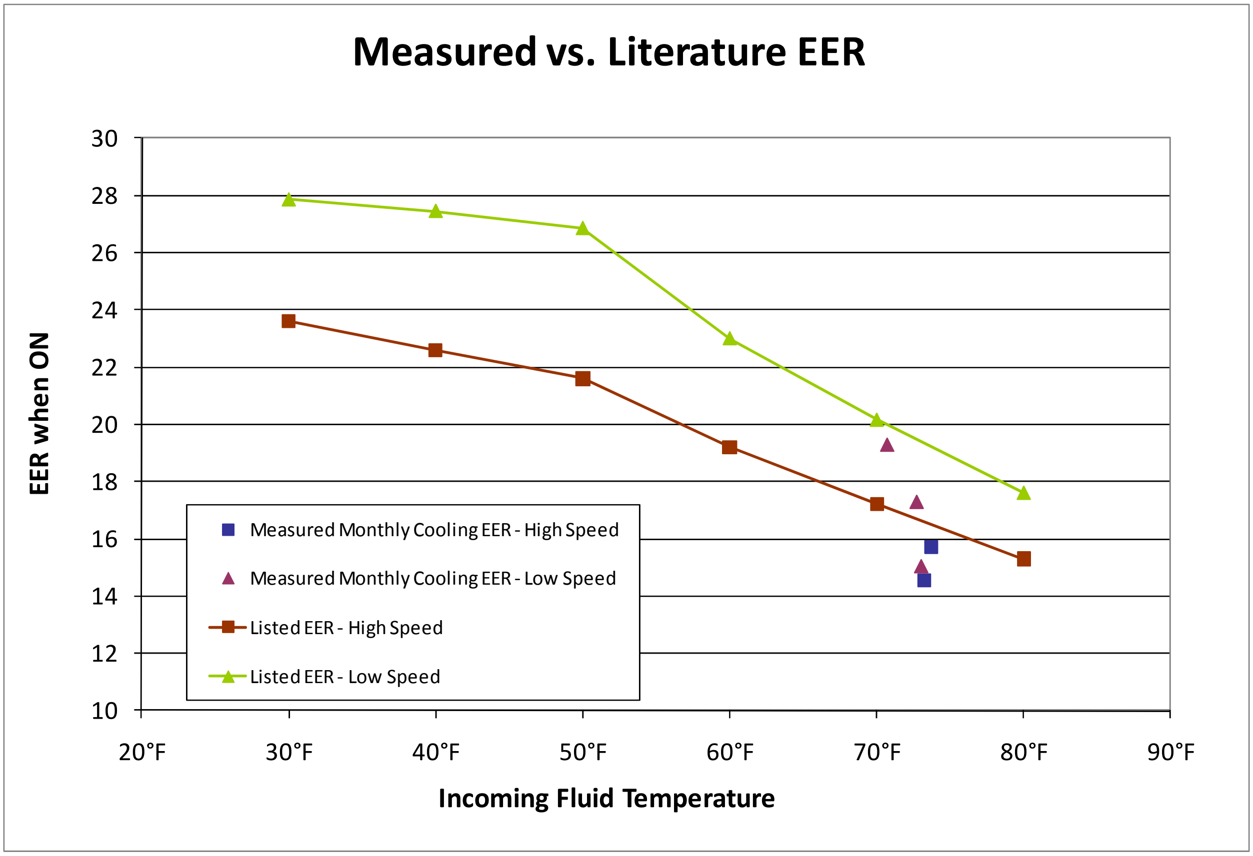
SWA often hears GSHP contractors talk about not worrying about oversizing because of the overall efficiency increase due to higher rated COPs at low stage. Depending on the incoming fluid temperature, there may be a benefit from low stage operation, but nothing comparable to the advertised benefit from the manufacturing data. For this system design, the average COP on high speed (or full-load capacity) is better than when on low speed; what do we make of this? That is the opposite of what most would expect and what the manufacturer specs would indicate. The above chart may be slightly misleading as we are looking at monthly averages of steady-state operation, but as this system is a horizontal unit, the incoming fluid temperature from the ground field is going to be fairly low during the heating season. If you look at the manufacturer's data, at low incoming fluid temperatures, the high speed actually performs better. The "Measured vs. Literature COP" chart doesn't distinguish the number of steady-state heating periods that took place during each month.

The DHW COP is also consistently lower than the rated performance and is not as significantly benefited by higher incoming fluid temperatures as depicted in the manufacturer's data. It is currently unclear why the system DHW COP is varying more from the listed unit DHW COP than the space heating COP. Though in February, the DHW COP performed in line with the rated efficiency. It may be due to February having the lowest entering mains temperature, allowing for more useful heat to be transferred to the buffer tank. SWA will continue to investigate this. Regardless of the listed DHW COP, the DHW mode is a highly efficient method of water heating.

As this is a horizontal ground loop configuration, the efficiency is being affected by outdoor conditions (see chart below). The in-coming fluid temperature from a vertical field loop is more consistent throughout the year due to the smaller ground temperature variation as you go roughly 8 feet or more below grade.



Though there haven't been many months of cooling data, a chart showing the average monthly measured EER of the system vs. the manufacturer listed EER for the heat pump only is provided below. The listed EERs depicted are based on ground loop flow rates of7 gpm for high stage and an interpolated 7 gpm for low stage (manufacturer data provided performance ratings at 6 gpm and 8 gpm).



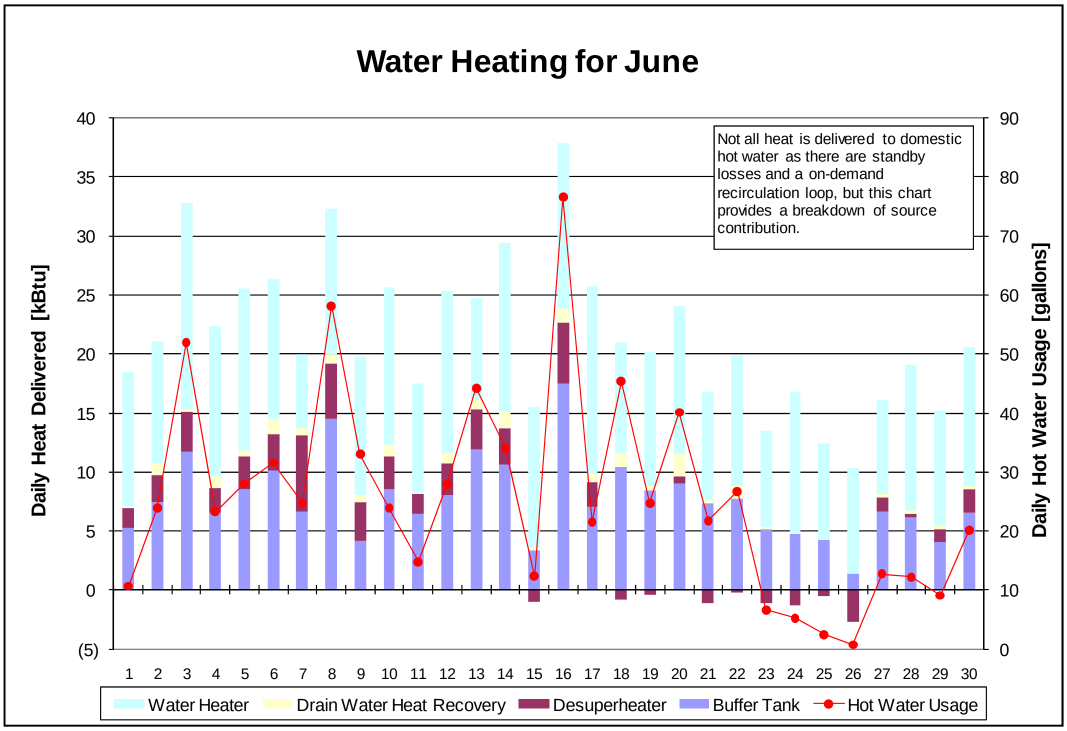
An interesting aside for this installation was evaluation of the desuperheater. Typical operation of a desuperheater provides water pre-heating during cooling mode operation, but during heating mode, it robs heating capacity from the space conditioning to water providing pre-heating. A reversing valve or smarter control logic (available in some newer GSHP models) is needed to avoid the space heating penalty, if this is of concern.

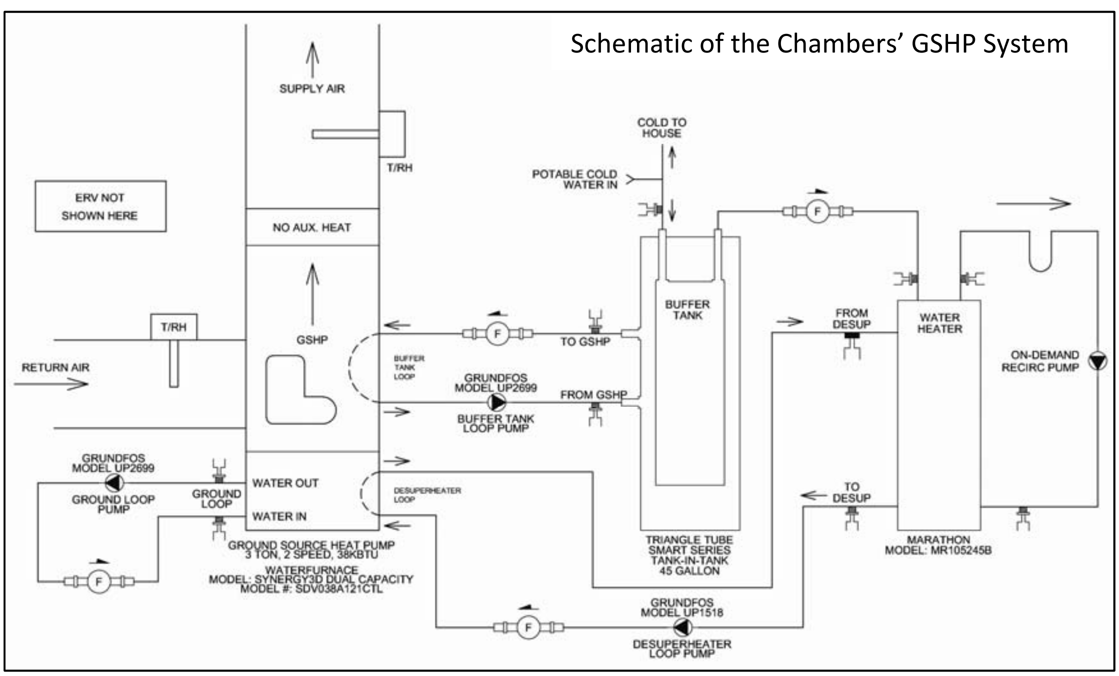
SWA recommends to all contractors to pipe the desuperheater to a pre-heat tank and not directly to the electric resistance water heater. The ideal use of a desuperheater is for pre-heating water. In this home, it is being directly plumbed to the water heater that has independent controls set to maintain heat at roughly 110°F. In January, an on/off switch was installed on the desuperheater pump in case it needed to be shut off to optimize whole-house system performance.

In general, the desuperheater was acting as anticipated - essentially "robbing" heating capacity from the space conditioning to provide water heating during heating/DHW mode. During the coldest winter months, there is minimal operation of the electric resistance water heater.

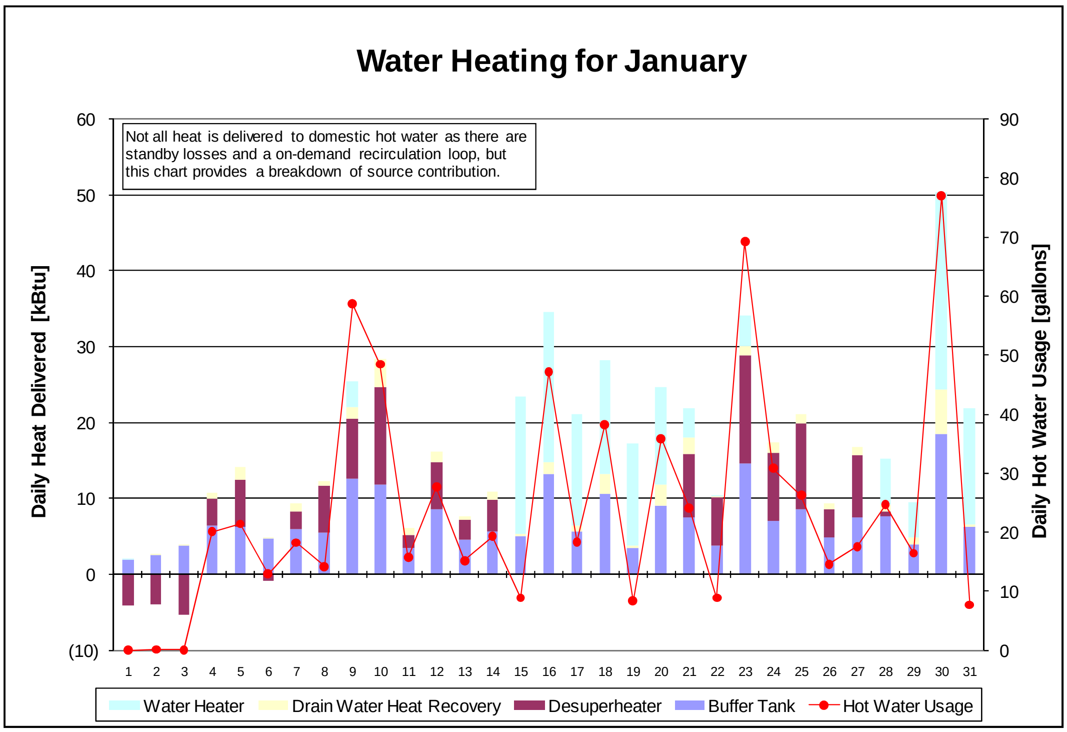
In cooling mode, the desuperheater is having a negative impact due to it being plumbed to the primary water heater instead of the pre-heat tank. The energy taken from the water heater is dumped to the ground as waste heat. The positive contribution from the desuperheater during the June period shown in the chart below was when the GSHP was operating in the DHW mode. On a whole for the cooling months, the desuperheater is more beneficial in DHW mode compared to the negative impact in cooling mode. Therefore, the desuperheater shouldn't be shut off during the cooling mode.

The chart below shows the daily heating contribution of the various components (electric water heater, drain water heat recovery, desuperheater, and buffer tank, which refers to the GSHP DHW mode) that heat water for this home. Daily hot water usage is also shown on the 2nd y-axis.





When there is no demand for hot water and the GSHP is providing space heating (see the first three days of January in the chart below, similar results for the last nine days of December), the desuperheater is having a negative impact to water heating, but this just means it is "robbing" heat from the water heater which increases heating capacity (the return temperature from the desuperheater loop was higher than the supply temperature during heating). Without any water demand, the primary tank temperature is not losing heat except for standby loss. At some point, the tank temperature is hot enough that the energy provided by the desuperheater will not be useful and the desuperheater return temperature is actually returning hotter than it was leaving the GSHP. When there are draws for hot water, the tank temperature drops (from the incoming mains water temperature) and the desuperheater once again is able to provide useful energy.



If the desuperheater was plumbed to a buffer tank rather than the primary tank, how would the performance change? It is not clear how a reconfiguration of the desuperheater to the buffer tank would benefit over the current set-up (especially with it set at 110°F, versus 125°F). Going to the buffer tank with a lower tank temperature on average means more heat can be transferred by the desuperheater, but it is also a smaller volume tank, so it may still heat this tank high enough to reduce the overall effectiveness of the desuperheater in the long run. Again, as this system is "robbing" heat from the forced air side, either way you would still benefit (just either water heating or spacing heating would be enhanced). To get a clear answer, the desuperheater would need to be connected to the buffer tank with a diverter valve, so SWA could test both configurations and see how the system works. Unless more research is done, it is recommended to leave the desuperheater plumbing in its current configuration.

Domestic Water Heating

According to the 2000 Energy Center of Wisconsin's "Energy and Housing in Wisconsin" Study, the average Wisconsin home (28% of homes have electric water heaters) uses 3,250 kWh/yr to heat hot water. The GreenMax home utilized 799 kWh over this initial nine months to heat water. Extrapolated for a full year, this is roughly a 67% reduction in electrical consumption for water heating over typical homes.

As seen in the previous two charts, water heating is being accomplished through a multitude of sources: drain water heat recovery, GSHP DHW mode, GSHP desuperheater, and electric resistance water heating. Over the nine month monitoring period, each component is contributing to water heating as follows:

Domestic Hot Water			
Component	Energy Delivered [kBtu]	% of Overall DHW	Energy Consumed [kWh]
Drain Water Heat Recovery	207	4.2%	-
GSHP DHW Mode	1,936	39.3%	245
GSHP Desuperheater	1,048	21.3%	46.3
Electric Water Heater	1,732	35.2%	508
Total	4,923	100%	799

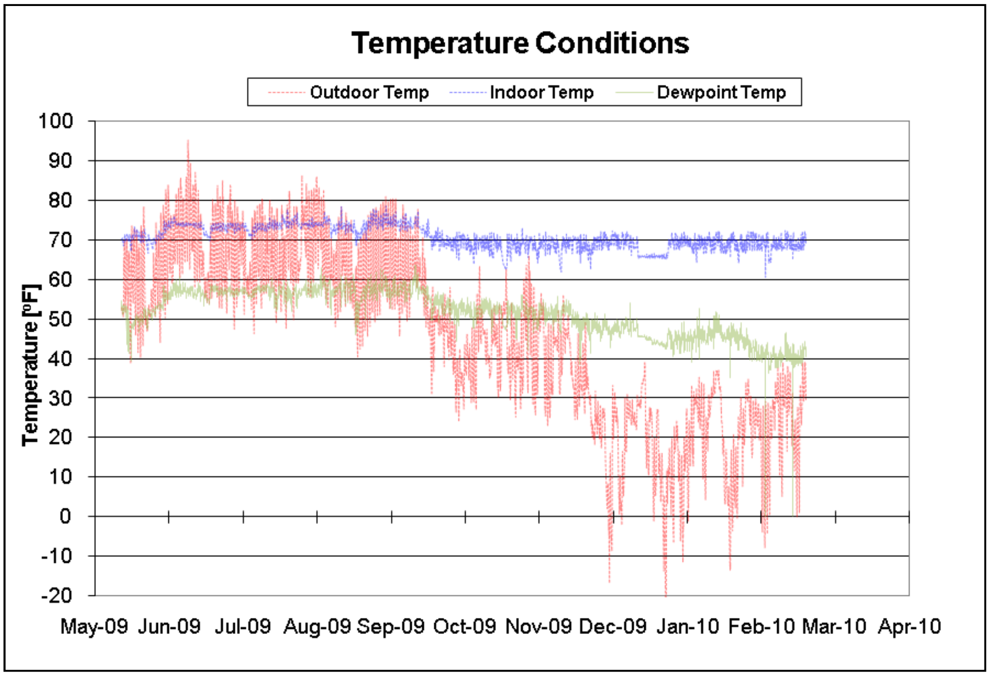
It should be noted that not all heat is delivered to the house as there are standby losses and distribution losses from the on-demand recirculation loop.

Indoor Comfort

The GSHP is able to maintain the indoor temperature at desirable levels all year round. During the summer, the indoor temperature was fairly consistently controlled at 75°F and never exceeded 78.5°F. In the winter, the indoor temperature was maintained between 68-70°F and never dropped below 62°F.

Over the summer, the homeowners expressed concern with what they perceived to be high relative humidity in their home. The sensible cooling load of this home is fairly small, so there isn't a continuous call for cooling by the GSHP. This is the sole method of mechanical dehumidification designed into this home. As the system is not required to run for extensive periods of time to address the sensible load, it likely won't be able to adequately control the building's latent load.

In addition, the homeowners open up the house (window and rear sliding doors) often in the summer to promote natural ventilation and cooling when outdoor conditions are suitable. The ERV was set up to provide whole-house mechanical ventilation without consideration for natural ventilation. The homeowners decided to turn off the ERV during the summer and found the home to be comfortable and the home was able to maintain relative humidity below 60%. Further analysis of the indoor conditions was performed to ensure that there was no potential for condensation. The chart below shows the indoor temperature and dewpoint temperature. Based on the building envelope construction, it is unlikely that any interior building surface will be cold enough to result in condensation.



There were periods during the summer when the relative humidity spiked to a high of 67%, but on average it was 55% for the summer months. This is at the upper end of the desirable humidity levels. Again, as the GSHP is sized for the dominant heating load, it is oversized in terms of cooling capacity (even at part-load capacity), resulting in the system short-cycling during the cooling season. This doesn't allow the system enough time to properly remove the moisture from the air stream. The use of a whole-house dehumidifier during the summer might be warranted to compensate for the minimal operation of the GSHP in cooling mode.