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Measured Whole-House Performance of TaC Studios Test Home

T. Butler, O. Curtis, and R. Stephenson
Southface Energy Institute
Partnership for Home Innovation (PHI)

December 2013

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Definitions

ACCA	Air Conditioning Contractors of America
ACH_{50}	Air changes per hour at 50 Pascals, infiltration measurement
AHRI	Air-conditioning, Heating, and Refrigeration Institute
AMY	Actual meteorological year
ASHP	Air-source heat pump
BEopt	Building energy optimization software
CFIS	Central fan integrated supply, ventilation method
CFL	Compact fluorescent lamp
CFM	Cubic feet per minute, air flow volume measurement
COP	Coefficient of performance, heating efficiency
DSH	Desuperheater
EER	Energy efficiency ratio, cooling efficiency
GSHP	Ground-source heat pump
HSPF	Heating seasonal performance factor, heating efficiency
HVAC	Heating, ventilation, and air conditioning
kW	Kilowatt, power measurement
kWh	Kilowatt hour, energy measurement
LFL	Linear fluorescent lamps
NREL	National Renewable Energy Laboratory
SEER	Seasonal energy efficiency ratio, cooling efficiency
SLA	Specific leakage area, infiltration measurement
TMY	Typical meteorological year

Executive Summary

As part of the Partnership for Home Innovation (PHI), Southface partnered with TaC Studios, an Atlanta-based architecture firm specializing in residential and light commercial design, on the construction of a new test home in Atlanta, Georgia, in the mixed-humid climate zone. This home serves as a residence and home office for the firm's owners, as well as a demonstration of their design approach to potential and current clients. Southface believes the home demonstrates current best practices for the mixed-humid climate, including a building envelope featuring advanced air sealing details and low density spray foam insulation, glazing that exceeds ENERGY STAR® requirements, and a high performance heating and cooling system.

Construction quality and execution was a high priority for TaC Studios and was ensured by a third-party review process through the project's involvement in the LEED for Homes program. Post-construction testing showed that the project met stated goals for envelope performance, an air infiltration rate of 2.15 ACH_{50}. The homeowners wished to further validate whole house energy savings through the project's involvement with Building America and this long-term monitoring effort. As a Building America test home, this home was evaluated to detail whole house energy use, end use loads, and the efficiency and operation of the ground source heat pump (GSHP) and associated systems. Given that the home includes many non-typical end use loads including a home office, pool, landscape water feature, and other luxury features not accounted for in Building America modeling tools, these end uses were separately monitored to determine their impact on overall energy consumption.

The home has been occupied since completion in September 2011. Short-term characterization testing was completed in October 2011, with long-term monitoring equipment installed in December 2011. This report includes analysis of the data collected through this effort, focusing on the six-month period from January 15 to July 15, 2012.

Monitored data for whole house energy consumption showed that the home exceeds projected energy consumption from Building America modeling tools, using roughly twice the energy expected; however, with the non-typical loads removed from the whole house total, the actual energy use is much more in line with BEopt outputs. The non-typical loads account for 48% of total energy consumption over the monitored period, with the pump associated with a landscape water feature making up three quarters of total non-typical use. Removing these non-typical loads results in consumption within 21% of weather-normalized BEopt projections. A closer examination of the data revealed that HVAC energy use exceeding modeled projections was primarily responsible for the difference in modeled and actual consumption.

Southface has found that GSHPs have considerable cachet value in the local residential market, and the question of real versus perceived value was a major research focus for this project. The research results showed measured efficiency values that fell below rated and manufacturer's published data, finding an average cooling efficiency of 14.3 energy efficiency ratio (EER) for the monitoring period. This measured efficiency does not greatly exceed the efficiency provided by currently available high efficiency air-source heat pump options, making the recommendation of GSHPs over more traditional options a hard sell on cost effectiveness alone. However, the long-term monitoring effort did reveal that the GSHP in this home may have insufficient loop

sizing to provide adequate ground heat exchange and other installation issues that contributed to this drop in performance. These findings and other issues with the home's HVAC and ventilation controls show that HVAC system design and installation best practices should remain focus areas for Building America.

This long-term monitoring effort will continue through early 2013, and Southface hopes to take that opportunity to determine measured heating efficiency for the home's GSHP, providing additional information on the cost effectiveness of these systems. Southface will also assist the homeowners with recommendations to reduce whole house energy consumption, particularly from the large loads associated with the home's pool and landscape water feature. The LEED Silver certified home continues to serve as a demonstration project for TaC Studios, Southface, and the Building America program, and has been featured in multiple home tours, regional conferences, and local newspaper articles.

Acknowledgements

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1 Introduction and Background

1.1 Introduction

Space conditioning represents the largest portion of residential energy consumption and has been a primary target for achieving substantial use reductions. Regarded as one of the most efficient system choices, ground source heat pumps (GSHPs) incorporate complex components and extensive infrastructures to reduce the impact of fluctuating ambient conditions for heat exchange and rely on sophisticated controls strategies to extract efficiency out of part-load conditions. Research and testing have documented efficiencies that exceed standard efficiency conventional air-to-air systems (Puttagunta & Shapiro, 2012), but in the case of this home, a GSHP system came at more than double the initial cost of high efficiency conventional systems. When this cost premium is considered along with the lowered space conditioning loads of high performance homes and the capabilities of the typical HVAC contractor to size, install and commission a GSHP, the question of cost effectiveness becomes a major issue in the choice of this technology over high efficiency traditional systems or emerging technologies such as variable refrigerant flow split systems.

Currently, the market has demonstrated that the high price, technological complexity, available tax incentives, and acoustic/aesthetic benefits of GSHPs from the elimination of exterior condensers have given the system a cachet value in the high-end residential market, similar to marquee kitchen appliances and luxury automobiles. As with more traditional durable consumer goods, an appreciable improvement in performance and comfort may be seen; however, given the less tangible and more personal factors associated with thermal comfort and indoor air quality, it remains to be seen if these improvements represent real value to overall home energy efficiency.

This test home provided the opportunity to gather real world performance data for a GSHP system, and the primary research focus of this study is the evaluation of the GSHP performance against rated efficiency values and previous studies. Monitoring equipment installed in the home gathered the data necessary to complete this evaluation, as well as whole house energy use and the isolation of non-typical loads found in this home including a home office, pool, landscape water feature, and other luxury features not accounted for in Building America modeling tools. The long-term monitoring results provided data to address the question of real versus perceived value.

1.2 Background

As part of the Partnership for Home Innovation (PHI), Southface partnered with TaC Studios, an Atlanta-based architecture firm specializing in residential and light commercial design, on the construction of a new Building America test home in Atlanta, Georgia, in the mixed-humid climate. This home serves as a residence and home office for the firm's owners, as well as a demonstration of their design approach to potential and current clients.

The three-story design has 3,570 ft^2 of conditioned floor area over a sealed crawlspace foundation. The first floor includes the kitchen, dining, and living areas with a half bath and an attached garage (564 ft^2). The second floor includes two bedrooms, a library, three full baths, and a home office that has the flexibility to function as two bedrooms at a future date. The third floor includes a small entertaining space with access to a roof top deck. Ceilings are 10 ft at the first floor and 9 ft at the second floor. The third floor ceiling is sloped. The home's modern architecture includes many unique overhang and cantilevered details that required special attention in the air sealing and insulation design, and installation. Luxury features that are not included in the Building America Benchmark include a pool, landscaping water feature, electric radiant floor heat, home office, and an all-electric gourmet kitchen.

Figure 1. TaC Studios residence.

The home has been occupied since the completion of construction in September 2011. Short-term characterization testing and system commissioning was completed in October 2011, with long-term monitoring equipment installed in December 2011.

1.3 Home Specifications

This home incorporated features to improve the overall thermal performance of the building envelope, provide high performance space conditioning and domestic hot water (DHW) delivery, and bring mechanical components within conditioned space. Table 1 lists the building specifications for the home, with further detail provided on the home's HVAC system below. Building America 2010 Benchmark specifications have been included for reference.

Table 1. TaC Studios Residence Building Specifications.

Measure	B10 Benchmark	TaC Studios Residence
Foundation	Sealed Crawlspace	Sealed Crawlspace
Foundation Insulation	R-5	R-7, continuous open cell spray foam, interior
Wall Construction	2×4	2×6
Wall Insulation	R-13	R-13, partial fill open cell spray foam
Ceiling Construction	Vented Attic	Cathedral attic, with flat roof trusses
Ceiling Insulation	R-30	R-20 open cell spray foam to underside of sheathing
Cantilever Floor	R-30	R-19, open cell spray foam

Insulation		to underside of sheathing with floor trusses
Window Ratings	U-0.40, SHGC-0.30	Varies: U-0.34, SHGC-0.26 max U-0.28, SHGC-0.19 min
Infiltration	6.6 ACH_{50}	2.5ACH_{50}
Heating Efficiency	7.7 HSPF	3.9 COP
Cooling Efficiency	13 SEER	18 EER
Supply Duct Location	65% crawlspace, 35% conditioned space	50% crawlspace, 50% conditioned space
Return Duct Location	100% crawlspace	50% conditioned space, 50% crawlspace
Duct Leakage	15% total	< 15% total
Ventilation	Exhaust 100% ASHRAE 62.2	Central fan integrated supply, 100% ASHRAE 62.2
Hot Water Efficiency	0.86 EF, electric	0.92 EF, electric (DSH)
Lighting	66% incandescent, 21% CFL, 13% LFL	100% incandescent w/ automated dimming
Appliances	Benchmark	Induction cooktop, ENERGY STAR

The primary system investigation in this home includes researching the HVAC system. The GSHP included in this project presents an opportunity to evaluate the cost effectiveness and in-field efficiency of this technology in a ground loop application. Per AHRI/ISO 13256, this dual stage GSHP is rated at 18.0 EER and 3.9 COP at full load with full load cooling and heating capacities of 67.6 kBtuh and 45.8 kBtuh, respectively. At part load, it is rated at 25.6 EER and 4.2 COP, with 51.1 kBtuh and 36 kBtuh of heating and cooling capacity respectively. The unit also includes a desuperheater (DSH) to provide water pre-heating. The ground exchange loop for the system includes five 250 ft deep vertical wells. The home was designed with four separate HVAC zones, shown in Figure 2, all served by this single unit. Characterizing the operation of the unit during part load conditions, when a single zone calls for conditioned air for example, was a research priority for this study.

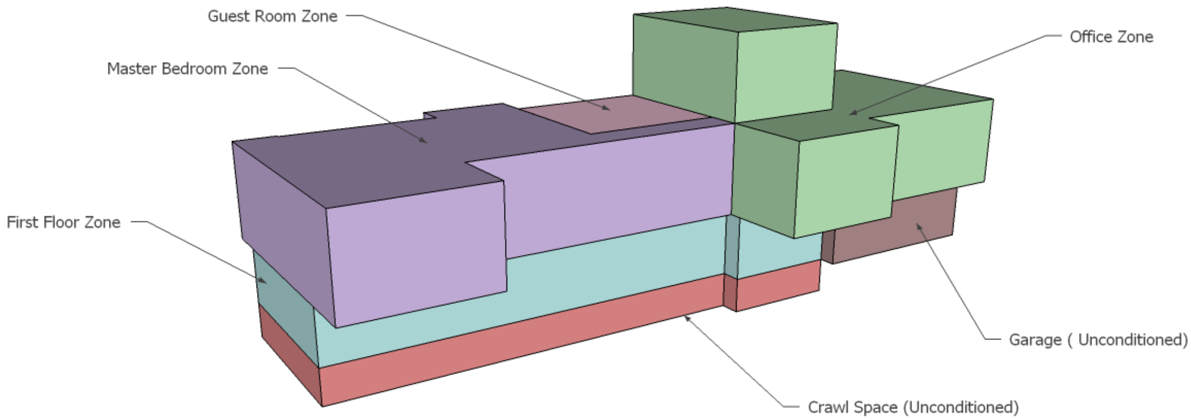

Figure 2. TaC Studios residence HVAC zoning diagram.

Meeting ASHRAE 62.2 ventilation rates introduces another tradeoff choice to builders in the mixed-humid climate zone. Builders want to meet the air flow requirements in the most cost-effective manner, while choosing a system that mitigates the added costs and latent loads that are introduced by ventilation air. Southface has observed that the most prevalent ventilation strategy in the local market is the central fan integrated supply (CFIS). This strategy consists of a ducted outside air intake connected directly to the return plenum of the central HVAC system. The negative pressure of the return pulls ventilation air through the intake and the air is distributed throughout the home using the supply fan and ductwork of the central system. The intake duct includes a mechanical damper equipped with a ventilation timer allowing for variable amounts of outside air to be introduced into the central system. This timer ensures adequate ventilation on mild days when the central system is not calling for heating or cooling by opening the damper and calling on the central fan to run.

Monitoring the additional system run time linked to the CFIS controller will provide further data regarding the energy costs and effectiveness of this ventilation approach. Southface hopes to build upon the past Building America ventilation studies by focusing on the additional fan energy consumption associated with this ventilation strategy.

1.4 Research Questions

The data gathered from this new construction test home will be used to address the following research questions:

- Is the measured energy use for heating and cooling consistent with modeled estimates, given similar ambient weather conditions?
- How does the efficiency of the GSHP compare to AHRI ratings and manufacturer's published data?
- Is "rule of thumb" loop sizing adequate for this application?
- What is the additional fan energy associated with the CFIS ventilation system?

1.5 Scope of Analysis

This report reviews the results of the long-term monitoring effort for this test home. Whole house energy consumption and HVAC energy consumption will be compared to modeled results from BEopt energy modeling software using actual weather conditions. The efficiency and operational characteristics of the home's GSHP will be examined in greater detail, comparing monitored results to manufacturer's data and past research studies. Also, the ability of the home's ventilation system to meet ASHRAE 62.2 ventilation requirements will be determined, as well as the fan energy consumption associated with the system.

2 Research Methods

2.1 Energy Modeling

Southface completed energy simulations and cost tradeoff analysis for this project using the BEopt energy optimization tool, BEoptE+ version 1.1. Several assumptions were made for this analysis based on gaps in the available BEopt inputs. Without an input option to accurately capture the functionality of the home's lighting system, the final design was simulated using the B10 Benchmark lighting package. Similarly, BEoptE+ version 1.1 does not include option for the GSHP or DSH included in this project. In lieu of these options, the most efficient air-source heat pump (ASHP) and electric storage tank options were chosen for the simulation, 18 SEER, 9.2 HSPF and 0.95 EF respectively. This analysis showed a 30.7% whole house source energy savings with respect to the Building America B10 Benchmark (BAB in Figure 3).

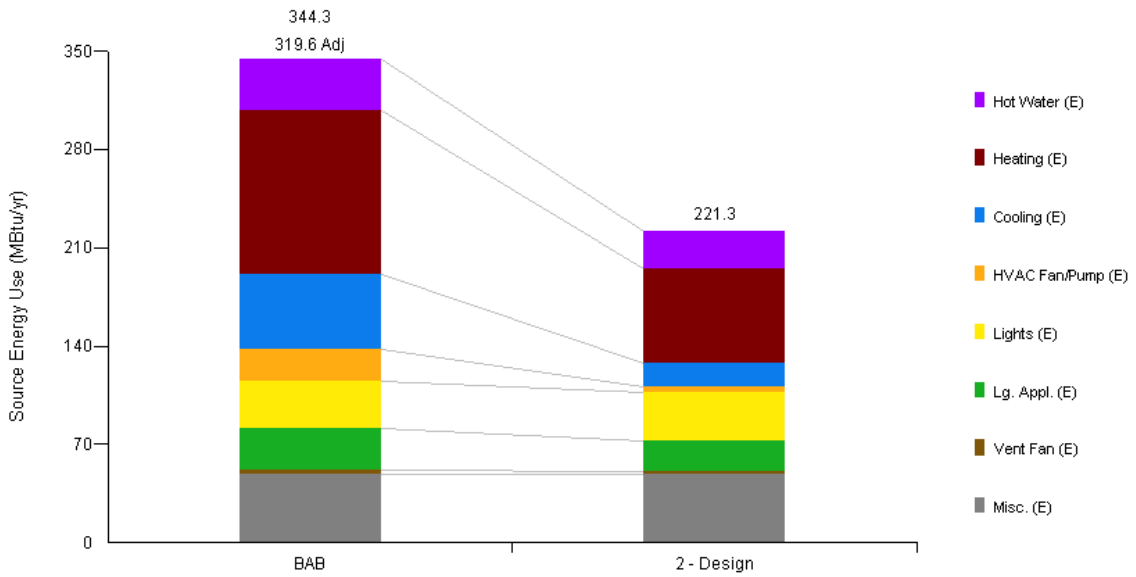

Figure 3. Source energy savings for TaC Studios compared to the B10 Benchmark, BEoptE+ v1.1.

Following the end of construction, Southface completed additional energy modeling using an updated version of BEopt, BEoptE+ version 1.3, which includes options for GSHPs. This analysis showed a drastically different result, a 15.8% whole house source energy savings with respect to the Building America B10 Benchmark. Possible explanations for this discrepancy are discussed later in this report.

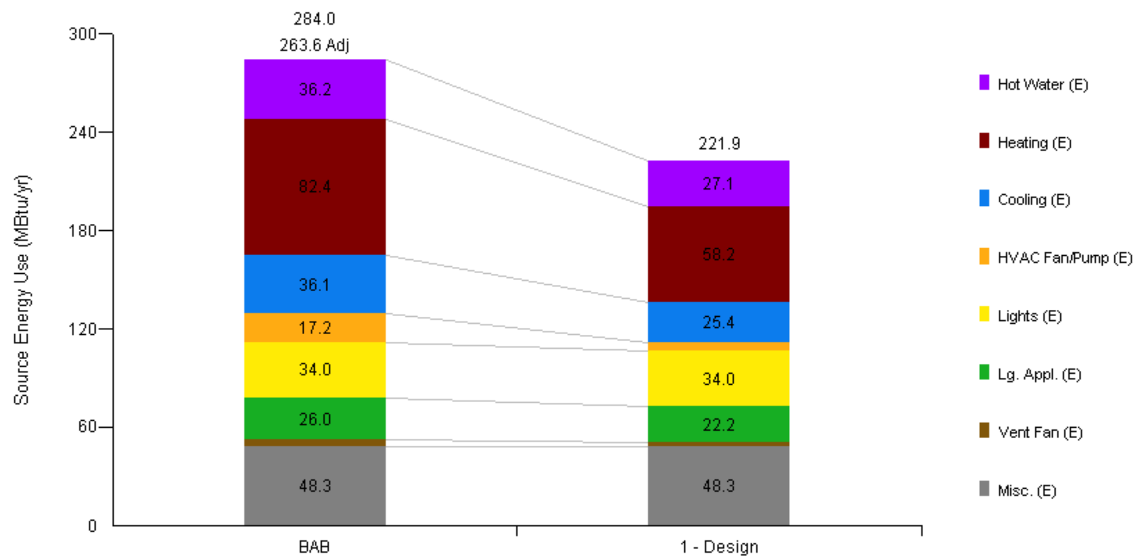

Figure 4. Source energy savings for TaC Studios compared to the B10 Benchmark, BEoptE+ v1.3.

2.2 Data Collection

The technical approach for this research home included short-term testing to verify the whole house infiltration rates and commissioning of the mechanical systems to ensure the system's operation and performance meets design parameters. The long-term monitoring effort collected whole house and end use electric consumption data, as well as measurements necessary to determine efficiency, capacity, and operation characteristics of the GSHP and hot water systems. Table 2 covers a brief description of the test methods employed and purposes.

A monitoring layout for the home is detailed in Appendix A.

Table 2. Test and Monitoring Parameter Description.

Parameter of Interest	Test Method	Purpose
House infiltration rate	Blower door test and diagnostic evaluation	At construction completion – provide overall infiltration rate and locate remaining major leakage paths
HVAC duct tightness and overall duct system performance	Duct leakage test; Air handler and diffuser flow rates; Room pressure differentials (air handler running, doors closed); total external static pressure	At construction completion – characterize overall air delivery system
Ventilation system performance	Balometer measurements	At construction completion – measure supply ventilation air flow rate and exhaust fan flow rates. Measure house depressurization during exhaust fan operation

Parameter of Interest	Test Method	Purpose
Whole house electric	Power Monitoring	Record whole house electricity use
End use loads	Power Monitoring	Record end use electricity consumption for; Lighting, Home office, Refrigerator, Induction Cooktop, Oven, and Steam Oven Identify demand profiles
Space conditioning and hot water equipment	Power Monitoring, Ground Loop and DHW Conditions Monitoring	Document the operation of the HVAC system relative to interior setpoints and exterior ambient drivers Document the real time efficiency of the HVAC system Document the added run time attributed to the CFIS ventilation system Document the operation of the water heater system relative to resident demand Document the contribution of the DSH to the hot water load
Indoor Environment	Temperature/Relative Humidity (RH) measurements	Analyze the operation of the HVAC system relative to interior and exterior temperature and humidity drives

2.3 Monitoring Period

The long-term monitoring effort began in December 2011 and continues to the present. The installation of this many data points presented challenges that had to be overcome by the Southface research team. Using Modbus-RTU as the communications protocol to the logger allowed for the connection of various recording devices, but the programming of the Trendpoint consumption registers presented issues, as problems with scaling and the bit size of the registers led to the counters resetting. The researchers overcame this issue by calculating consumption from the power draw readings.

The loop temperature measurements posed a greater challenge. Initial measurements showed the change in incoming and outgoing loop temperatures did not return realistic values, with the incoming loop temperatures measured at unusually high levels. The thermocouple calibration was checked and found to be acceptable. After reviewing the newly released Building America Field Test Best Practices website, Southface determined that the loop temperature sensor was not seeing appropriate flow. Longer probes were installed facing directly into the flow of both loops, providing better measurements. Unfortunately, the heating season had passed before reaching this solution, and valid measurements were not available to derive COP performance with water side calculations. An air-side performance value could be determined using the other collected data, but determining correct airflow volume from power readings given the multiple zones of the system presents additional challenges. This report includes analysis of the data collected through this effort focusing on the six-month period from January 15 to July 15, 2012.

Monitoring will continue through early 2013, providing an opportunity to determine water side COP values.

3 Results

3.1 Whole House Energy Use

Given that the home functions as the primary workspace for the owner/architects and features several non-typical end uses loads including a home office, pool, landscape water feature, and other luxury features not accounted for in Building America modeling tools, the monitoring of power consumption at the circuit breaker level was determined to be necessary to validate whole house usage against the modeled results. Usage for appliances not found in a typical residential kitchen (i.e., a steam oven, ice maker, and wine refrigerator) and electric radiant floor heating have been labeled as "luxury" loads. The pumps associated with the pool and a landscape water feature have been labeled as "outside" loads. The home office has also been separately monitored and labeled "home office" load. Figure 5 shows whole house energy consumption for the six-month period from January 15 to July 15, 2012 broken down by end use.

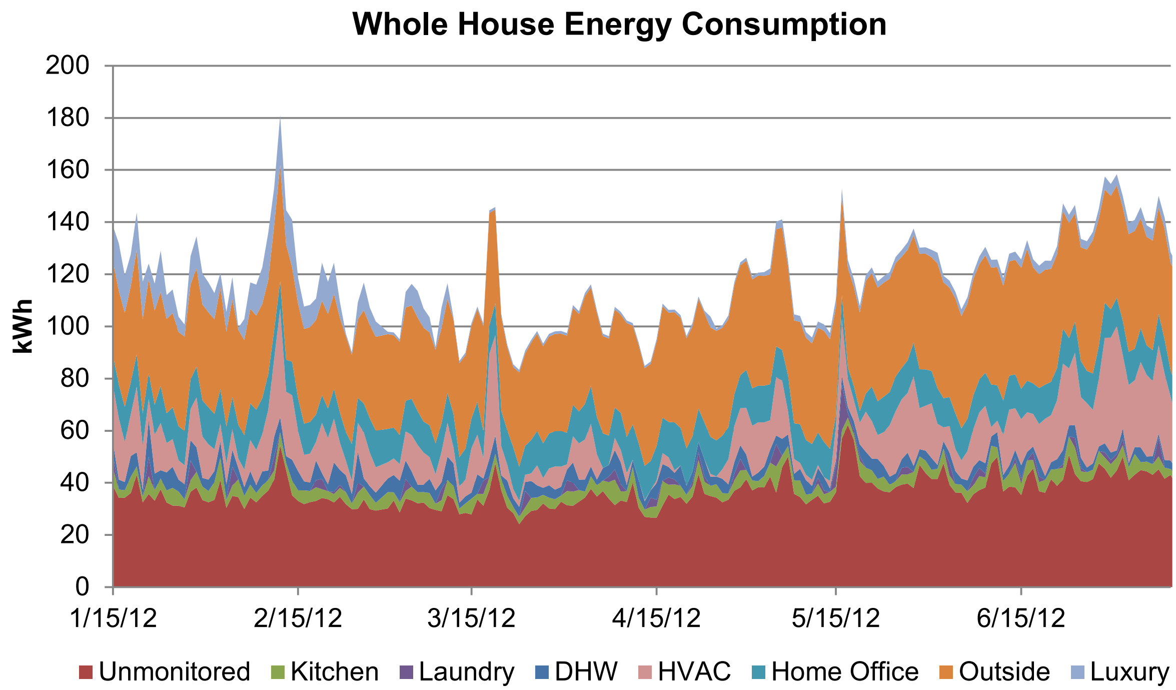

Figure 5. Whole house energy consumption, January 15 to July 15, 2012.

This end-use monitoring brought to light how energy intensive the pool and pond are in relation to the whole house end use, representing approximately 34% of total consumption over the monitoring period. Total consumption for the non-typical loads—luxury, outside, and home office—accounted for 48% of total consumption.

The monitoring data also revealed that all end uses are fairly consistent from month to month except for the HVAC and the luxury loads. While the change in HVAC makes sense based on fluctuations in weather, a closer look at energy consumption for February 2012 in Figure 6, the month with the highest luxury load consumption, shows that the major contributor to this consumption is electric radiant floor heating. In April, this load is less than half the February total, and it goes away completely in May. The other loads in this group stay fairly consistent.

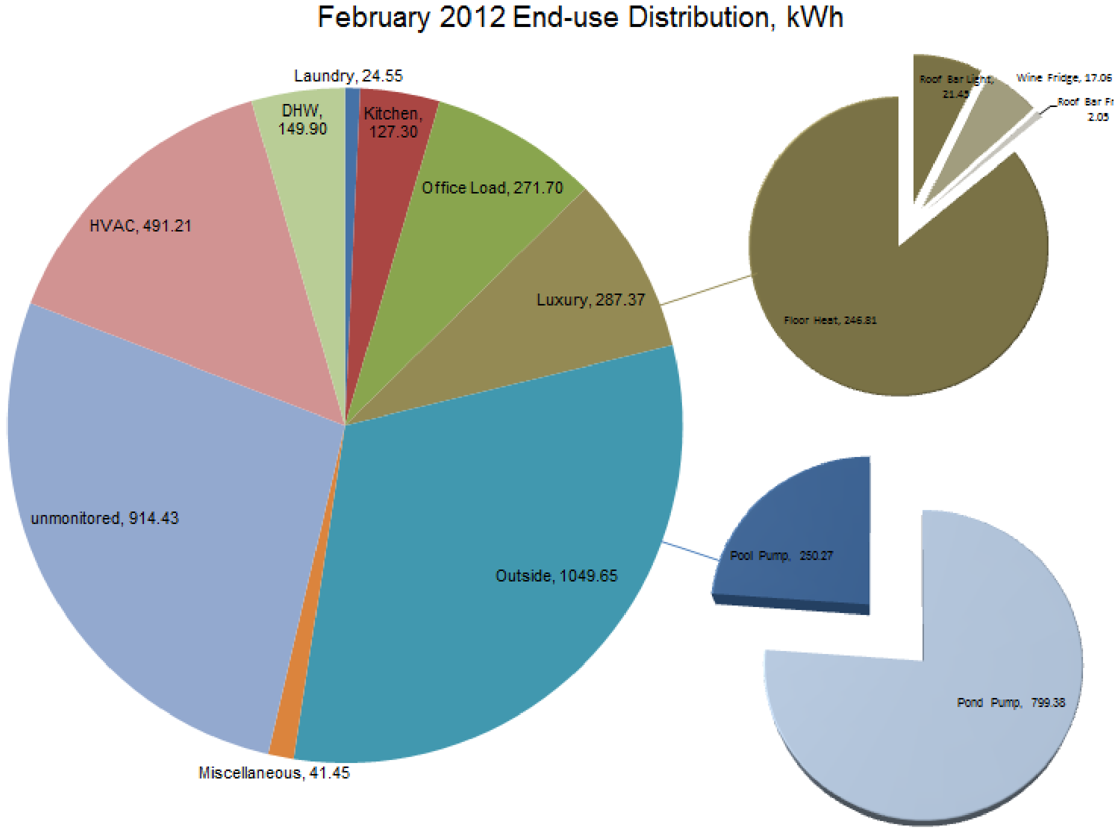

Figure 6. February whole house end-use electric consumption.

The large whole house energy consumption, approximately 3,600 kWh per month over the monitoring period, leads to excessive energy bills in the summer months. The homeowner contacted Southface complaining of a huge jump in electric utility bills in the summer of 2012. Examination of the consumption data did not show a corresponding rise in total consumption, but a closer look at the tiered rate structure used by Georgia Power, Table 3, revealed the cause. A home at this consumption level pays $0.10/kWh in the winter, spring and fall, but that rate jumps to nearly $0.17/kWh in the summer months, with more than half of these rates going to fees, fuel recovery, and taxes.

Table 3. Georgia Power Seasonal Base Rates.

Tier	Usage (kWh)	Winter	Summer	% Increase
1st tier	up to 650	$0.052465	$0.052465	0.0%
2nd tier	next 350	$0.045015	$0.087211	93.7%
3rd tier	over 1000	$0.044190	$0.090126	104.0%

3.2 Energy Modeling Comparison

3.2.1 Comparison of Modeled and Actual Consumption

Before comparing model projections to actual monitored data, Southface updated the energy model using Actual Meteorological Year (AMY) weather data. Table 4 compares the cooling and heating degrees days for the AMY data and the Typical Meteorological Year 3 (TMY3) file used for the initial modeling. TMY3 data sets are a compilation of hourly weather data for a specific geographical location usually based on a 30-year time period (Wilcox & Marion, 2008). This weather profile is then used in building simulations to predict climate specific performance.

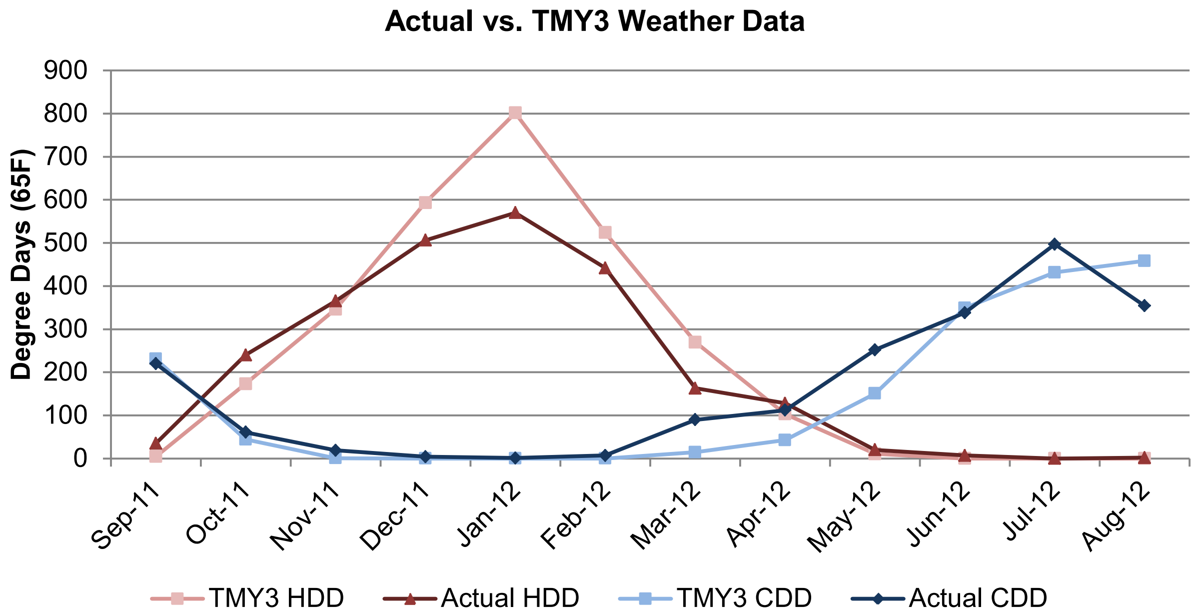

Figure 7. Actual versus TMY3 weather data.

The results summarized in Table 4 show a significantly milder winter heating season and a warmer summer cooling season than is typical for Atlanta. Although TMY3 data should not be used to predict actual weather in any location, it is useful as a possible explanation for large variations in predicted versus actual HVAC energy performance.

Table 4. HDDs and CDDs, Actual Versus TMY3 for Atlanta

	Actual September 2011 to August 2011 Degree Days (reference here)	TMY3 File Degree Days	% Difference of Actual to TMY3
HDDs	2478	2826	-12.3%
CDDs	1955	1722	13.5%

In order to create a valid comparison between the modeled and actual results, Southface individually metered non-typical end uses loads including a home office, pool, koi pond, and other luxury features not accounted for in Building America modeling tools. Removing these end uses from the monitored consumption data allows for a comparison between actual and modeled energy consumption. Figure 8 compares the actual "typical" energy usage to the predicted total energy consumption based on the BEopt model with AMY weather data. It should be noted that removing the non-typical end uses from whole house energy consumption does not remove any internal gains or other effects on the home's HVAC energy use. Measured typical energy use showed 21% greater energy use than weather normalized modeled projections.

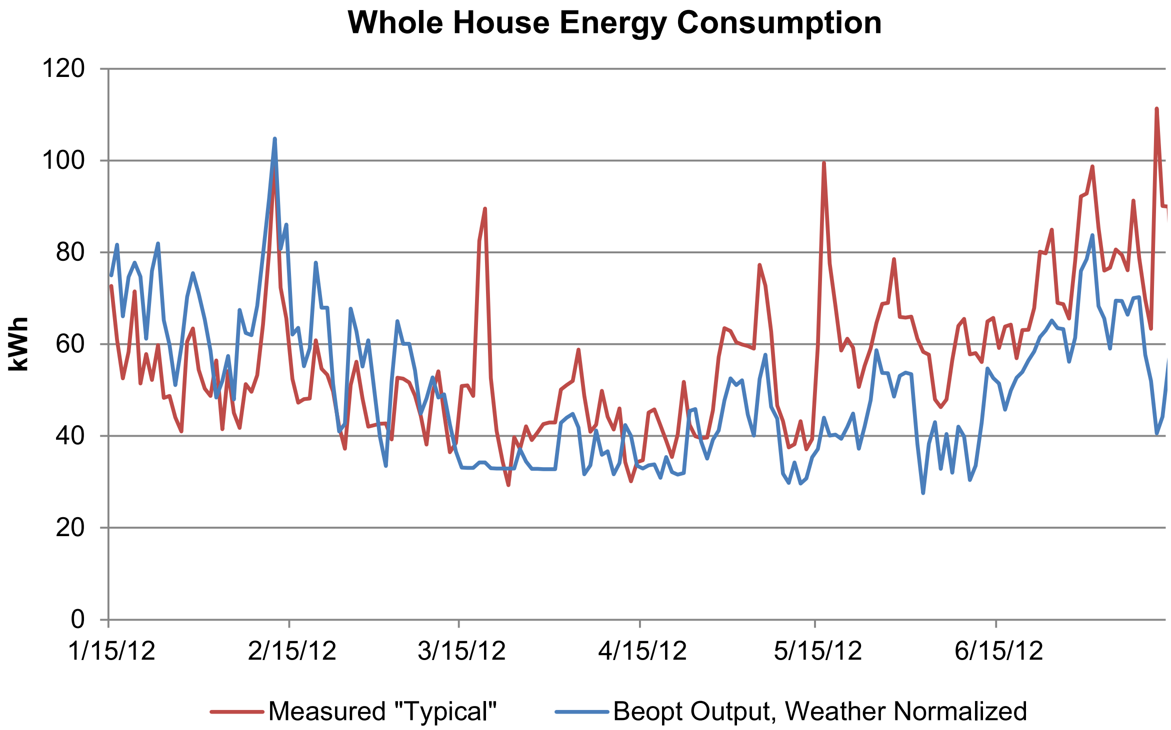

Figure 8. Whole house energy consumption, typical end uses versus modeled outputs.

The data shows excellent agreement for the monitoring period from January 15, to March 15, before unknown, non-weather related increases in the HVAC consumption cause the measured energy consumption to spike. Analyzing the component end use data further, as shown in Figure 9, showed that the HVAC system appeared to be constantly operating for several days at a time in mid-March. Given that the house has a large amount of east-facing glass, these discrepancies may be driven by solar gain. The system run profiles shown in Figure 14 indicate a high frequency of run cycles early in the morning, despite ambient temperatures being below the maintained set-point.

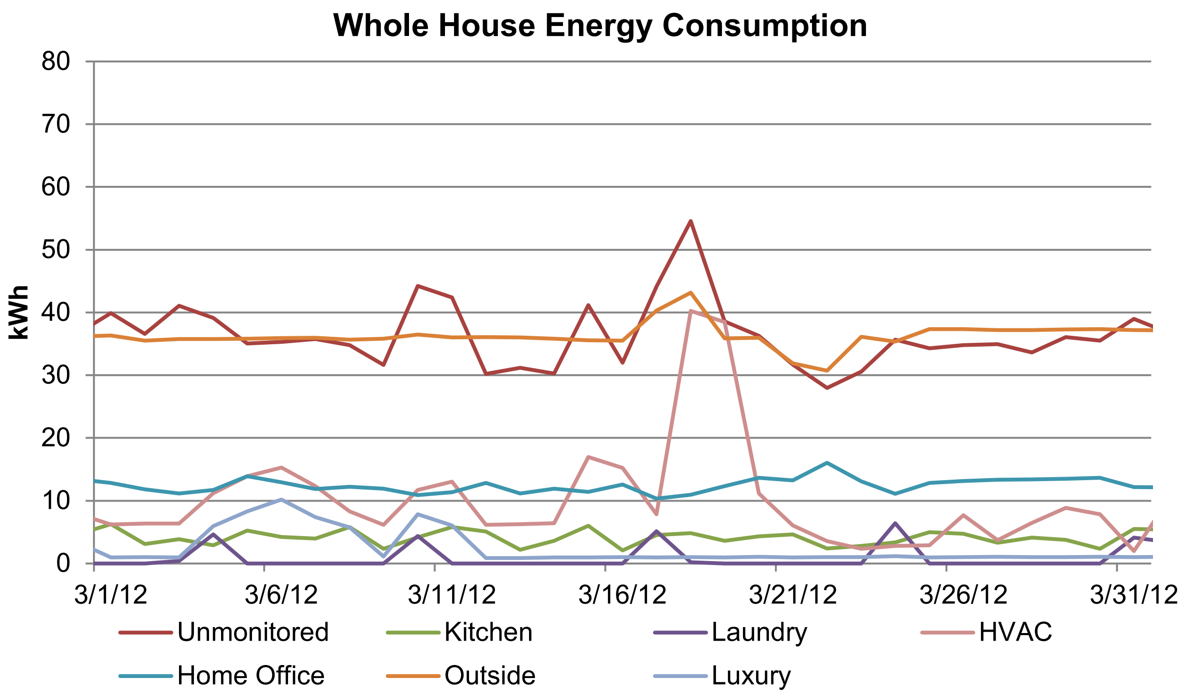

Figure 9. Whole house energy consumption, measured component end uses.

Figure 10 demonstrates that weather normalizing the BEopt model AMY data inputs shows a stronger correlation to monitored HVAC usage when the actual weather varies significantly from the TMY3 file.

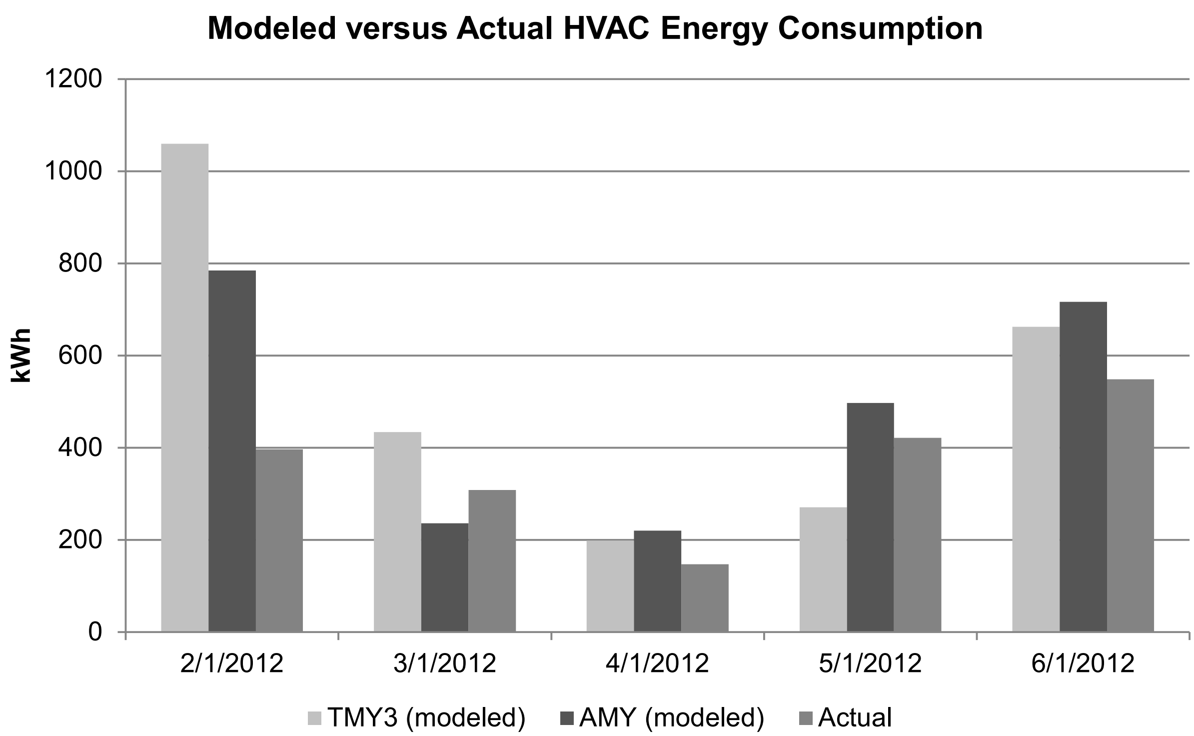

Figure 10. HVAC energy consumption comparison between TMY3, AMY, and actual usage.

3.2.2 Comparison of BEopt 1.1 and 1.3 Outputs

As previously discussed, differences in the outputs of BEopt v.1.1 and v.1.3 drastically reduced the projected source energy savings for this home. The BEopt development team at NREL related that this decrease from 30.7% to 15.8% source energy savings can be traced to changes in the natural ventilation rates, HVAC sizing procedure, and dehumidification loads used by the program.

The initial optimization analysis for TaC Studios was conducted in BEopt v.1.1, an early software release. This version did not have the capability to model GSHPs, a critical energy saving component of the TaC Studios design. As a result, the initial optimization analysis substituted the highest efficiency library input ASHP (18 SEER, 9.3 HSPF) to simulate the predicted energy performance of the GSHP. The most current release, BEopt v.1.3, incorporates GSHPs into the options library; therefore, the model was updated to reflect the actual system type. Southface selected a default option, 18.2 EER and 3.7 COP with low-k soil GSHP, instead of creating a custom library because certain installation performance characteristics were not known, such as loop pipe diameters, grout type, and on-site soil conductivity. Southface conservatively assumed low soil conductivity and standard grout.

Figure 11 shows the results, a 3.6% increase in total source energy use, of the comparison between the GSHP and high efficiency ASHP.

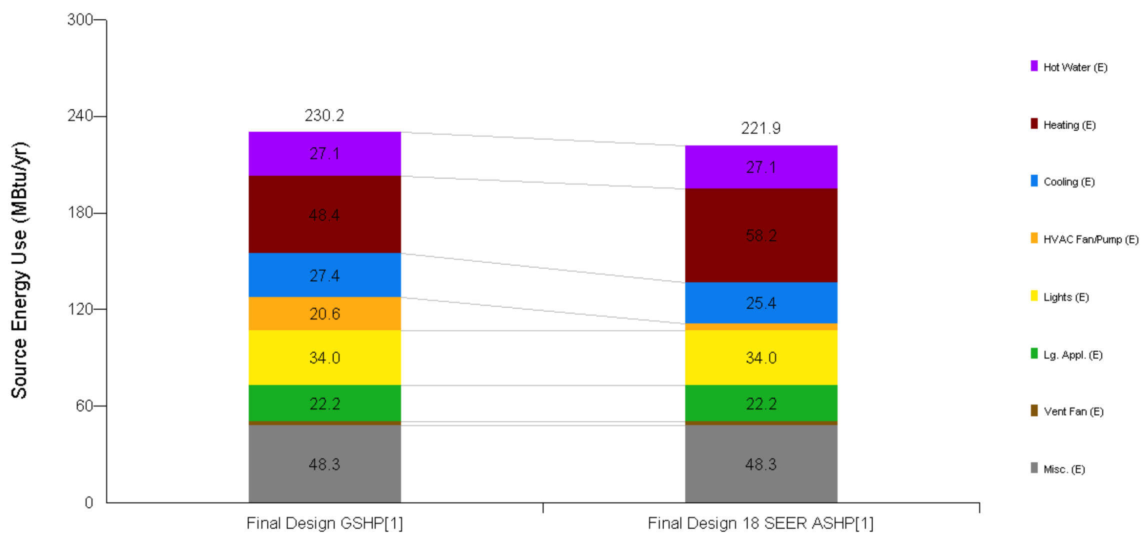

Figure 11. Comparison between GSHP and high efficiency ASHP.

The GSHP option shows lower heating energy use and marginally higher cooling energy use than the ASHP; however, the reductions do not offset the increased pump energy required to operate the GSHP.

3.3 Ground Source Heat Pump

The primary research focus for this study was the evaluation of the home's GSHP and comparing in-field performance against rated efficiency values and the results of previous studies. Southface has found that homeowners and builders select GSHP systems due to perceived increased efficiency and the lack of exposed external equipment outside the home, improving aesthetics and reducing noise. The question becomes whether the efficiency and additional aesthetic and comfort factors associated with these systems offsets their higher initial installation cost. Similar to a conventional air-source heat pump, this cost is a factor of the air handler and associated ducting and controls, as well as the costs for installing the heat exchange loop. For the TaC Studios residence, the loop is a series of five vertical bore wells. The monitoring effort measures overall system power use, electric use for individual system components (compressor, fan, loop pump and DSH pump), loop flow, and temperatures for the ground loop and the DSH. Air temperature and humidity in the supply, return and outside air ducts are also monitored.

The data points are used to calculate system efficiencies for heating and cooling using the following formulas.

Heating Coefficient of Performance:

$$COP = \frac{useful\ heating\ energy}{net\ energy\ input} = \frac{Q_h + (W_{fan} + W_{comp} + W_{DHW,pump}) \times 3.413\ \ Btu/Wh}{(W_{comp} + W_{fan} + W_{pump} + W_{DHW,pump}) \times 3.413\ \ Btu/Wh} \quad \textbf{(1)}$$

where:

COP	= coefficient of performance of the complete system [dimensionless]
Q_h	= useful heat extracted from loop [Btu]
W_{comp}	= energy consumed by the compressor [Wh]
W_{fan}	= energy consumed by the fan [Wh]
W_{pump}	= energy consumed by the loop pump [Wh]
$W_{DHW,pump}$	= energy consumed by DSH pump [Wh]

Heat extracted from the ground loop:

$$Q_h = \left(\Delta T_{T_{in} - T_{out}} \times \dot{V} \times C_p \times \rho \right) \quad \textbf{(2)}$$

where:

$\Delta T_{T_{in} - T_{out}}$	= T_{in} minus T_{out} (°F)
$\dot{V}$	= volumetric loop flow rate [ft3/hr]
C_p	= specific heat of loop fluid [Btu/lbm°F]
ρ	= density of loop fluid [lb/ft3]

Cooling Energy Efficiency Ratio

$$EER = \frac{\text{useful cooling energy}}{\text{net energy input}} = \frac{Q_c + Q_{DSH} - \left(W_{fan} + W_{comp}\right) \times 3.413 \ \text{Btu/Wh}}{(W_{comp} + W_{fan} + W_{pump} + W_{DSH,pump})} \quad \textbf{(3)}$$

where:

EER	= energy efficiency ratio [Btu/Wh]
Q_c	= heat dumped to loop [Btu]
QDSH	*= heat transferred to DWH by desuperheater [Btu]*
Wcomp	*= energy consumed by the compressor [Wh]*
Wfan	*= energy consumed by the fan [Wh]*
Wpump	*= energy consumed by the loop pump [Wh]*
WDSH,pump	*= energy consumed by the desuperheater pump [Wh]*

As noted earlier, there were issues in obtaining accurate loop temperatures during the heating season that made the calculation of COP impossible. Cooling performance measurements showed that the system is performing below the rated and manufacturer's published efficiencies; see Figure 12. From previous research, this discrepancy is to be expected given that the rated conditions do not account for pump energy or increased static pressure from a full duct system (Puttagunta, Aldrich, Owens, & Mantha, 2010). Looking at one week of data with a broad range of temperature conditions reveals a slight increase in the difference between rated and actual performance as the loop temperatures decrease. The overall average EER for this period is 14.3 at an average loop temp of 77.5ºF. These results indicate a 20% reduction from the rated efficiency and are consistent with a similar study (Puttagunta and Shapiro, 2012), which found a 23% lower measured efficiency from the rated performance.

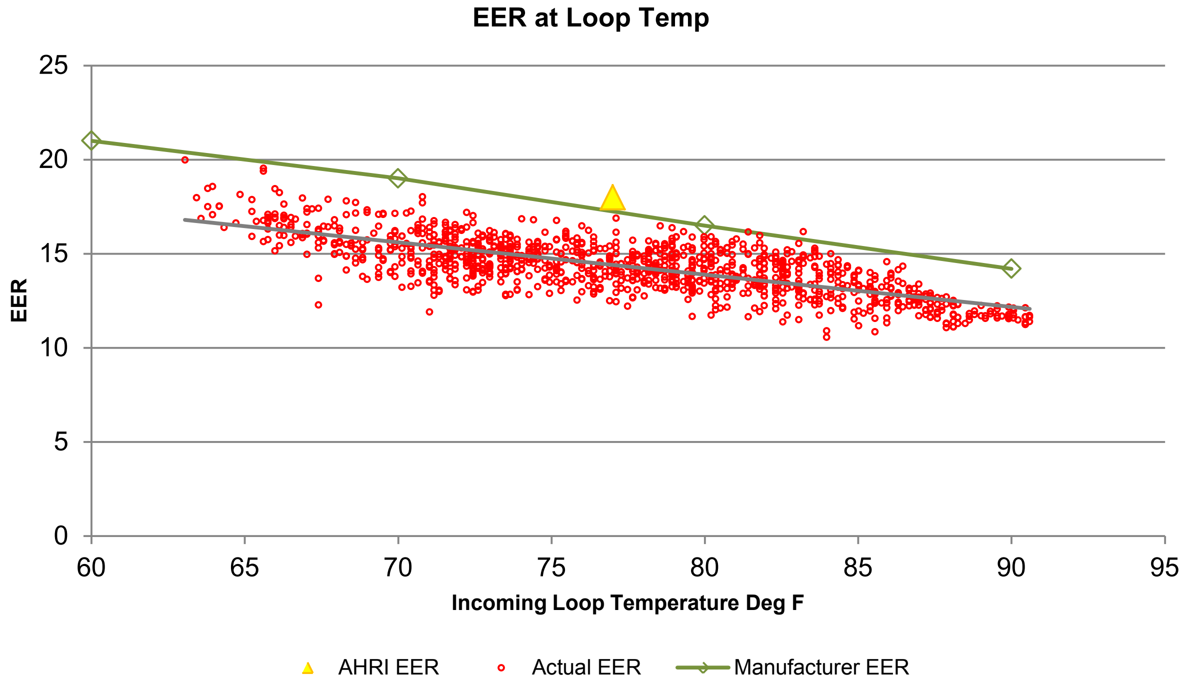

Figure 12. GSHP measured efficiency.

Southface believes inadequate ground loop capacity may be partly responsible for this drop in efficiency, as the incoming loop temps, which are measured after the heat exchange fluid has circulated completely through the loop, show large temperature rises during system run time. The loop temp fluctuations are influenced by the run time of the system (Figure 13). This reduction in performance over time suggests that the loop design could have benefited from a more thorough analysis in the design stage. The vertical bores for this project were based on basic rule of thumb assumptions and no soil analysis was completed. While the cost of this design work is greater, the fact that the loop is essentially a permanent component of the system may make this cost worthwhile. Controlling the thermal envelope and internal gains will have an indirect impact on the overall performance of the system by reducing the amount of time a system runs.

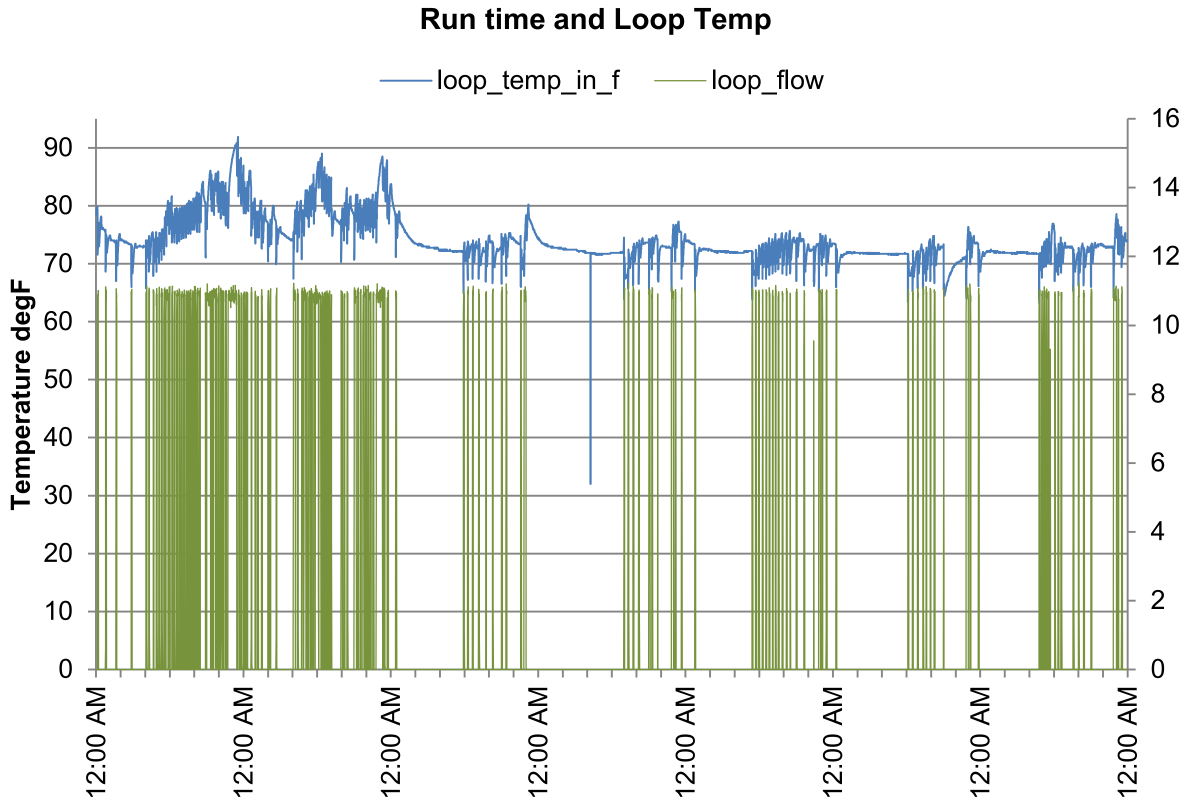

Figure 13. GSHP run time and incoming loop temperatures.

This also points to an issue of system run time, which is influenced by the zoning of the system. Looking at the hottest day of the summer, June 30 (shown in Figure 14), when ambient temperatures greatly exceeded design conditions for a significant portion of the day, it would be expected that a properly sized system would run continuously to keep up with the load, but the system short cycled throughout the day with an average run time of 12 minutes.

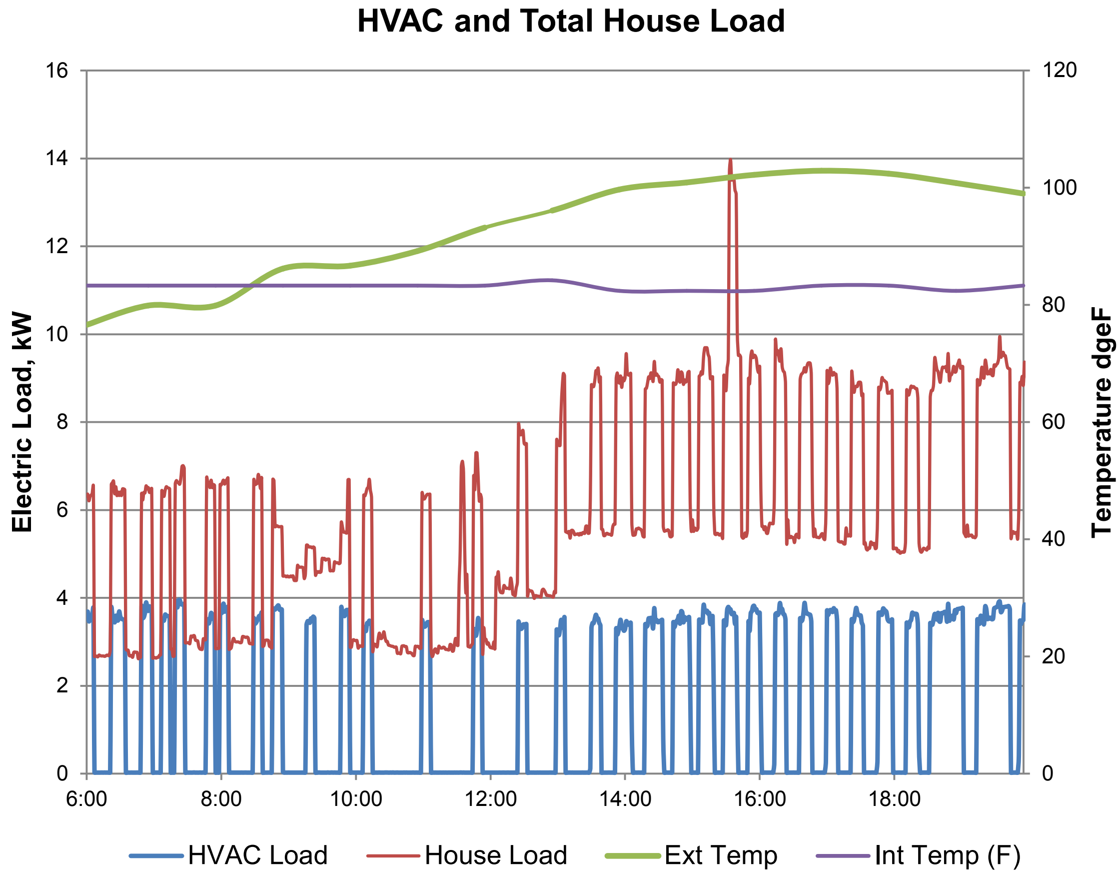

Figure 14. House performance, June 30.

As shown in Figure 2, the house is divided into four distinct zones of varying sizes and orientations. Each zone has a programmable thermostat set to provide conditioning when that zone is most typically occupied; early morning and evening for the main floor, daytime for the office zone and night for the master bedroom. The guest room zone is rarely used and typically not directly conditioned. The system was sized using ACCA Manual J and took into account the increased air sealing and improved glazing values over conventional, code minimum values, but it is not apparent if the zoning was factored in the design. Essentially, a system designed for a 3,500 ft^2 house is being operated to meet loads for significantly smaller areas, which most likely leads to the short cycling indicated in Figure 14. This data also indicated very little difference in power consumption between low and high stage operation. Figure 15 shows the individual component loads from a longer run event that displays a brief period of low stage operation, from 6:00 to 6:03 PM, then full compressor operation with fluctuations in fan speed. From this, it appears that the staging is minimally effective in dealing with part load conditions.

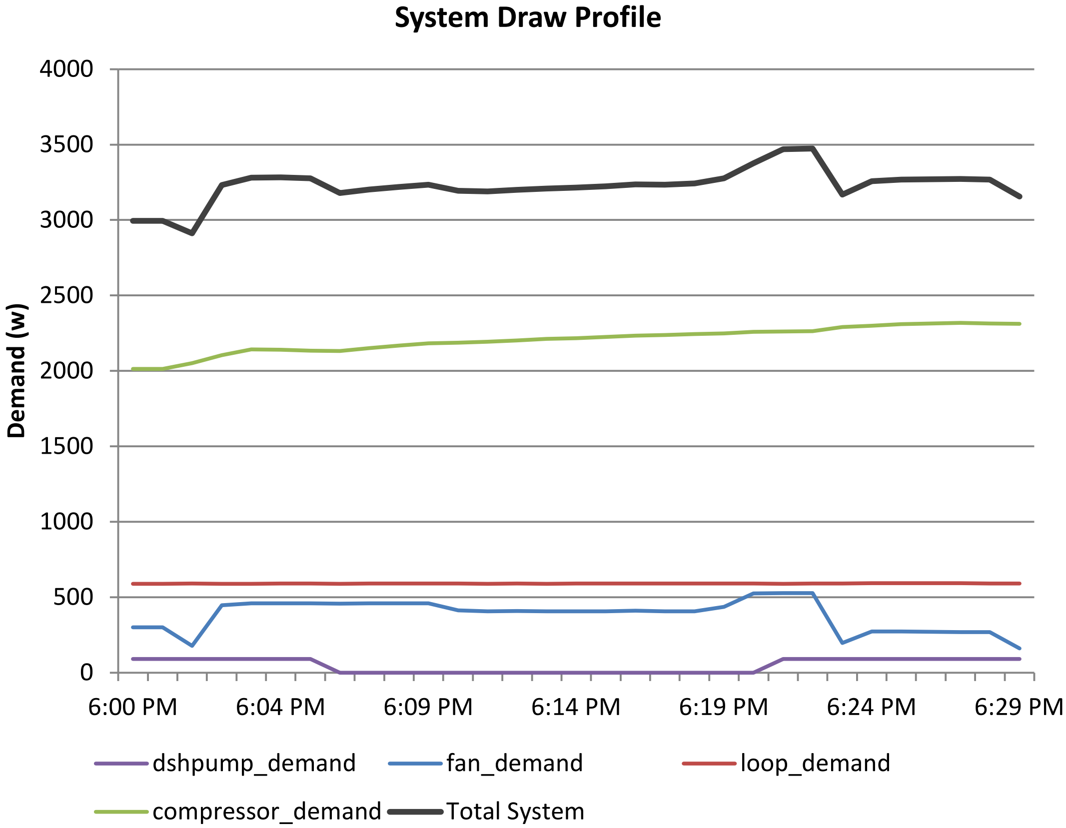

Figure 15. HVAC System draw profile.

3.4 Desuperheater (DSH)

The DSH operation was not initiated until September 2012, after the monitoring period covered in this report. Initial data gathered from early September, shown in Figure 16, suggests that there is an issue in which the operation of the DSH may be lowering the temperature of the water in the water heater tank. It is not clear if this is due to a change in temperature settings by the owner or if the DSH is truly reducing the temperature of the stored hot water. Comparing power draw of the DHW tank element to the tank and DSH loop temperatures suggests that the tank temperature settings have been altered. As monitoring continues, this will be studied further.

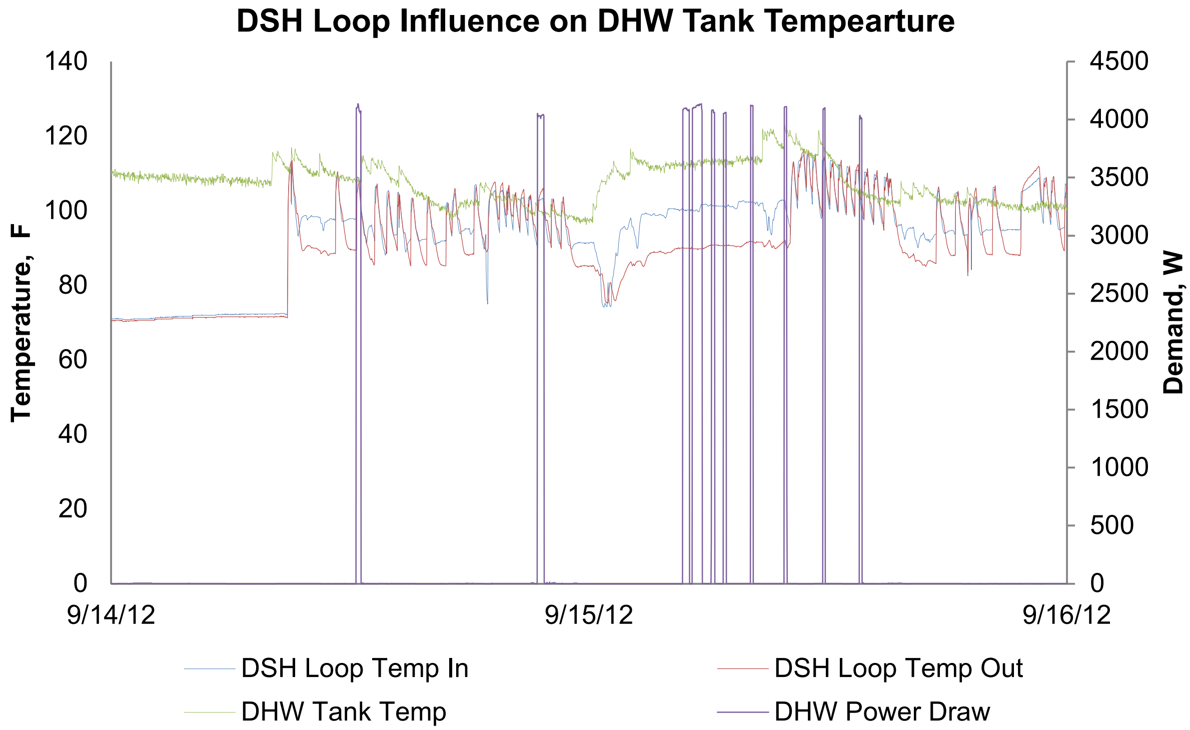

Figure 16. DSH influence on DHW tank temperature.

3.5 Ventilation

Building America has identified the development of ventilation best practices as a critical path milestone on the path towards achieving 50% whole house energy savings (NREL, 2012). Southface has observed that the prevalent strategy used to meet the ventilation flow and controls requirements of ASHRAE Standard 62.2 in the local market is the CFIS, the approach implemented in this test home. In order to evaluate the viability and energy impacts of this system choice, Southface completed system commissioning to ensure the system had adequate flow to meet Standard ASHRAE 62.2 requirements and installed long-term monitoring equipment to track the additional run time and energy consumption of the air handler fan.

The ASHRAE 62.2 ventilation standard sets a minimum continuous ventilation rate based on a home's conditioned floor area and number of bedrooms.

$$Q_{fan} = 0.01A_{floor} + 7.5(N_{br} + 1) \quad \textbf{(4)}$$

where

Q_{fan}	= fan flow rate, cfm
A_{floor}	= floor area, ft^2
N_{br}	= number of bedrooms

For this test home, the continuous ventilation rate would be 66 cfm (3,570 ft^2 of conditioned floor area and three bedrooms). The system commissioning tested the ventilation flow rate as 133 cfm with the air handler operating in fan only mode. ASHRAE Standard 62.2 allows an exception for the effective ventilation rate of an intermittently operating system based on the fan flow rate during the on cycle, the base ventilation rate requirement, ventilation effectiveness, and system fractional on time.

$$Q_f = Q_r/(\varepsilon f) \tag{5}$$

where

Q_f	= fan flow rate during the on-cycle
Q_r	= ventilation air requirement
ε	= ventilation effectiveness
f	= fractional on time, defined as the on-time for one cycle divided by the cycle time

Given the tested ventilation flow rate for this home, the ventilation system could operate with a fractional on-time of 50% and deliver an effective ventilation rate that meets the ventilation standard. The ventilation controller used on this project, the Honeywell Y8150, includes simplified inputs for conditioned floor area, number of bedrooms, and ventilation airflow that were set for the test home and measured flow rate, Figure 17. This control also features a microcontroller, which optimizes ventilation air delivery based on normal HVAC run times (Honeywell International Inc., 2011).

Figure 17. Ventilation control settings.

The energy impact of the system includes the added fan run time necessary to deliver ventilation air, above that of the system run time to meet space conditioning loads. To facilitate this analysis, measurements of air handler fan power draw and ventilation air dry-bulb temperature and relative humidity were collected.

Following system commissioning and the installation of monitoring equipment, the homeowner contacted Southface complaining that the air handler fan ran continuously regardless of system calls for heating or cooling. Consultation with the system installer did not lead to a satisfactory solution, and the homeowner disconnected the controller in March 2012. The fan power draw data, shown in Figure 18, demonstrates the problem with the system.

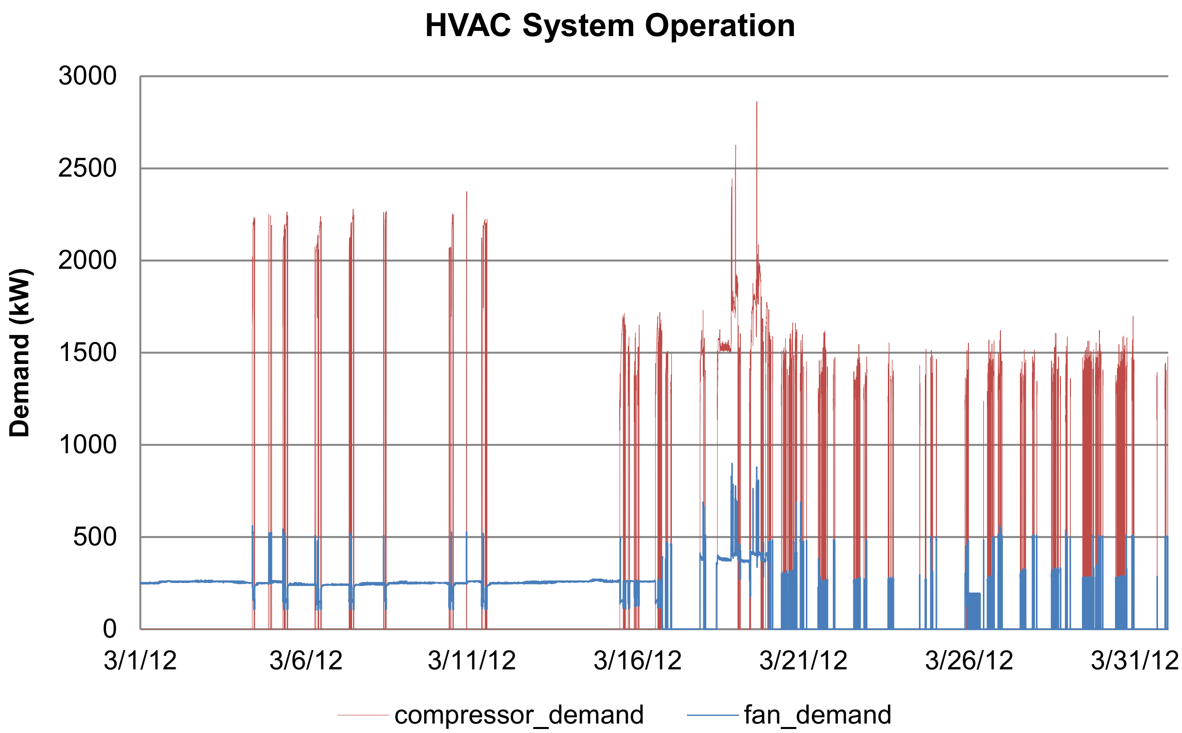

Figure 18. HVAC system operation, March 2012.

Until March 16, when the homeowner turned off the ventilation controller, the air handler fan ran continuously regardless of normal system operation, drawing a constant 290 W. Consultation with Honeywell revealed that improper wiring to the home's zoned thermostats may have caused the problem, but the homeowner was not willing to revisit the ventilation operation and has since left the ventilation controller in the "off" position, relying on windows, natural air exchange, and point source exhaust to provide ventilation to the home. Since this change, the homeowner has not complained of any adverse health or comfort effects.

Despite the installation issues with the ventilation controller, the measured data can still be used to determine the fan energy impact of this ventilation approach if the system had been operating correctly. Reviewing the measured data on a daily basis over the six-month period from January 15 to July 15, 2012, revealed that, except for peak heating and cooling periods, the system fractional run time was below the 50% fractional run time needed to deliver an effective ventilation rate that meets ASHRAE 62.2; see Figure 19.

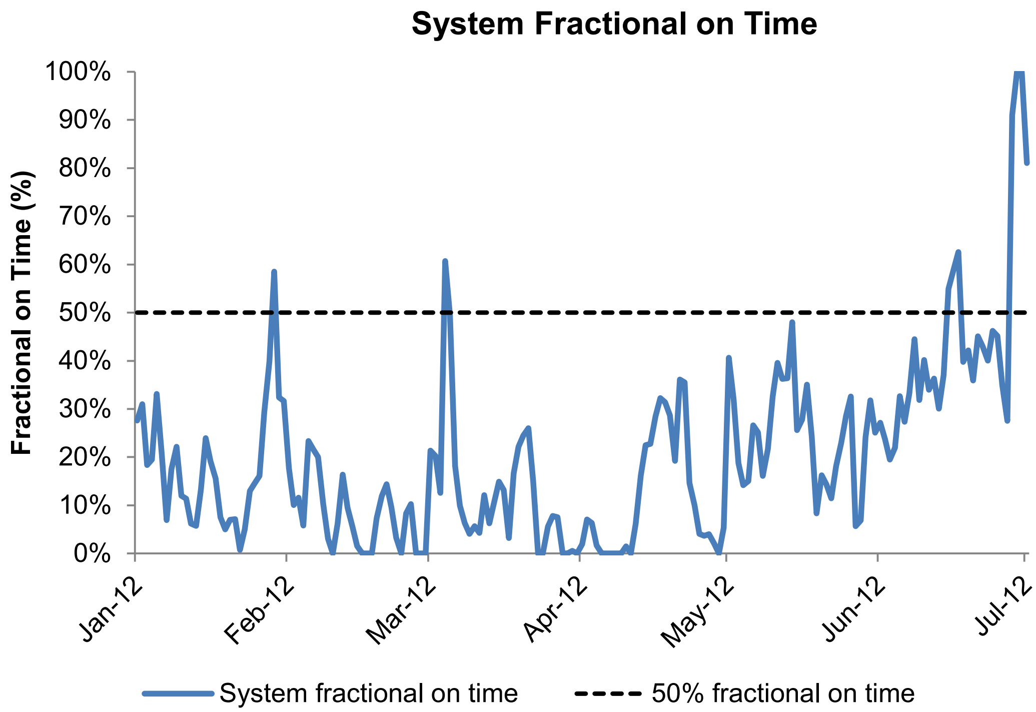

Figure 19. System fractional on time.

In order to deliver the 50% fractional run time needed to meet ASHRAE 62.2, the system would be required to run an additional 1,363 hours. Given the measured fan power draw for the system in fan-only mode, 290 W, this would result in 395 kWh of additional consumption, or roughly 2% of the total house consumption, for this six-month period. Given that this house has high electric usage because it functions as a home office and has high exterior power loads, this percentage would be significantly higher in a typical home.

4 Discussion

Reviewing whole house energy consumption for this home showed the significant additional energy consumption associated with non-typical end use loads including a home office, pool, landscape water feature, and other luxury features not accounted for in Building America modeling tools. While these end uses do not find their way into the typical home, these features are expected for the clientele of the owner architect. Over the six-month monitoring period, these non-typical loads made up 48% of the whole house energy consumption, as shown in Figure 5. Removing these non-typical loads from the monitored whole house energy consumption, the measured results showed 21% greater energy use than modeled projections.

The results of energy modeling analysis and the monitored data gathered from this home reveal some limitations with using current Building America energy modeling tools to project whole house energy consumption. Most residential energy modeling tools, including BEopt, do not allow for the addition of non-typical end uses, so providing a realistic picture of anticipated whole house energy use will be difficult in similar cases where non-typical loads will be present. Southface also found a large shift in the projected savings delivered by different BEopt software versions, BEoptE+ v1.1 and v1.3. These discrepancies were explained by updates to the software's natural ventilation rates, HVAC sizing procedure, and dehumidification loads, but the large reduction in predicted savings reduces confidence in using the software as a tool to help future projects meet Building America savings goals.

Similar to past Building America research on GSHPs, Southface found the in-field cooling efficiency for the home's GSHP to be lower than the AHRI rated performance and manufacturer's published product data, averaging 14.3 EER over the monitoring period compared to a rated efficiency of 18 EER. Adding the ground loop and DSH pump energy into the efficiency calculations accounts for some of this degraded performance, as does the added static pressure from the home's duct system, but other installation issues likely caused additional loss of efficiency. Increased loop temperatures following system run times indicate that the ground loop for the system is likely undersized and that rule of thumb loop sizing did not provide adequate heat exchange for this home. The system zoning also likely contributed to reduced efficiency, as the system often short cycled, running in the high stage to meet the load of a single zone. Additional issues with the installation of the home's ventilation control show that HVAC system design and installation best practices should remain focus areas for Building America.

In answering the question of real versus perceived value for GSHP systems, the research findings do not show an increase in efficiency far above that of traditional air-source systems. Data rated from AHRI for high efficiency ASHPs gives cooling efficiency values ranging from approximately 11 to 14 EER (AHRI, 2013). While the in-field performance for these systems would suffer the same reduction associated with the home's duct system and other factors that are not included in rated conditions, there is no added energy consumption associated with ground loop or DSH pumps. The in-field efficiency measurements from this research do not show a cost-effective argument for the inclusion of GSHPs in the pursuit of increased energy savings; however, these systems do provide additional aesthetic and comfort factors that may be of value to homeowners. If properly sized and controlled, a GSHP may also provide better part load performance and avoid the use of electric supplemental heat in extreme heating conditions associated with traditional ASHP systems.

The monitoring effort for this home will continue through early 2013. Southface plans to collect information on GSHP heating efficiency and assist the homeowners with recommendations to reduce whole house energy consumption, particularly from the large loads associated with the home's pool and landscape water feature.

5 Conclusion

This new construction test home provided valuable information on current construction best practices for homes in the mixed humid climate. The information can be used to provide guidance to future Building America industry partners on the path towards achieving 50% whole house energy savings. Following are research questions and answers regarding this home:

- *Is the measured energy use for heating and cooling consistent with modeled estimates, given similar ambient weather conditions?*

Removing non-typical loads from the monitored whole house energy consumption, measured data showed 21% greater energy use than weather normalized modeled projections with a majority of this increase traced to HVAC consumption.

- *How does the efficiency of the GSHP compare to AHRI ratings and manufacturer's published data?*

  The measured in-field cooling efficiency for the home's GSHP was 14.3 EER, a 20% reduction from the rated efficiency. The reduced efficiency can be traced to the addition of ground loop and DSH pump energy to the efficiency calculation and other differences from rated conditions, including a full duct system with higher static pressure. Southface believes inadequate loop sizing and improper controls settings, which caused the unit to short cycle in the high stage, also had an impact on lowering the measured efficiency.

- *Is "rule of thumb" loop sizing adequate for this application?*

  Given the large rise in incoming ground loop temperatures observed during periods of extended run time, Southface does not believe that the home's ground loop, including five 250-ft vertical wells, provides adequate heat exchange. The vertical bores for this project were based on basic rule of thumb assumptions and the rate at which the loop temp increases suggests that the design may have benefitted from more detailed analysis including soil conductivity testing. While the cost of this is greater, the fact that the loop is essentially a permanent component of the system may make this cost worthwhile.

- *What is the additional fan energy associated with the CFIS ventilation system?*

While the ventilation system controls did not function as intended, the monitored data for system run time provided enough information to determine the added fan power associated with this ventilation strategy had the system been controlled properly. In order to deliver the 50% fractional run time needed to meet ASHRAE 62.2, the system would be required to run an additional 1,363 hours. Given the measured fan power draw for the system in fan-only mode, 290 W, this would result in 395 kWh of additional consumption for the six-month monitoring period.

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6 Appendices

Appendix A: Monitoring Diagrams

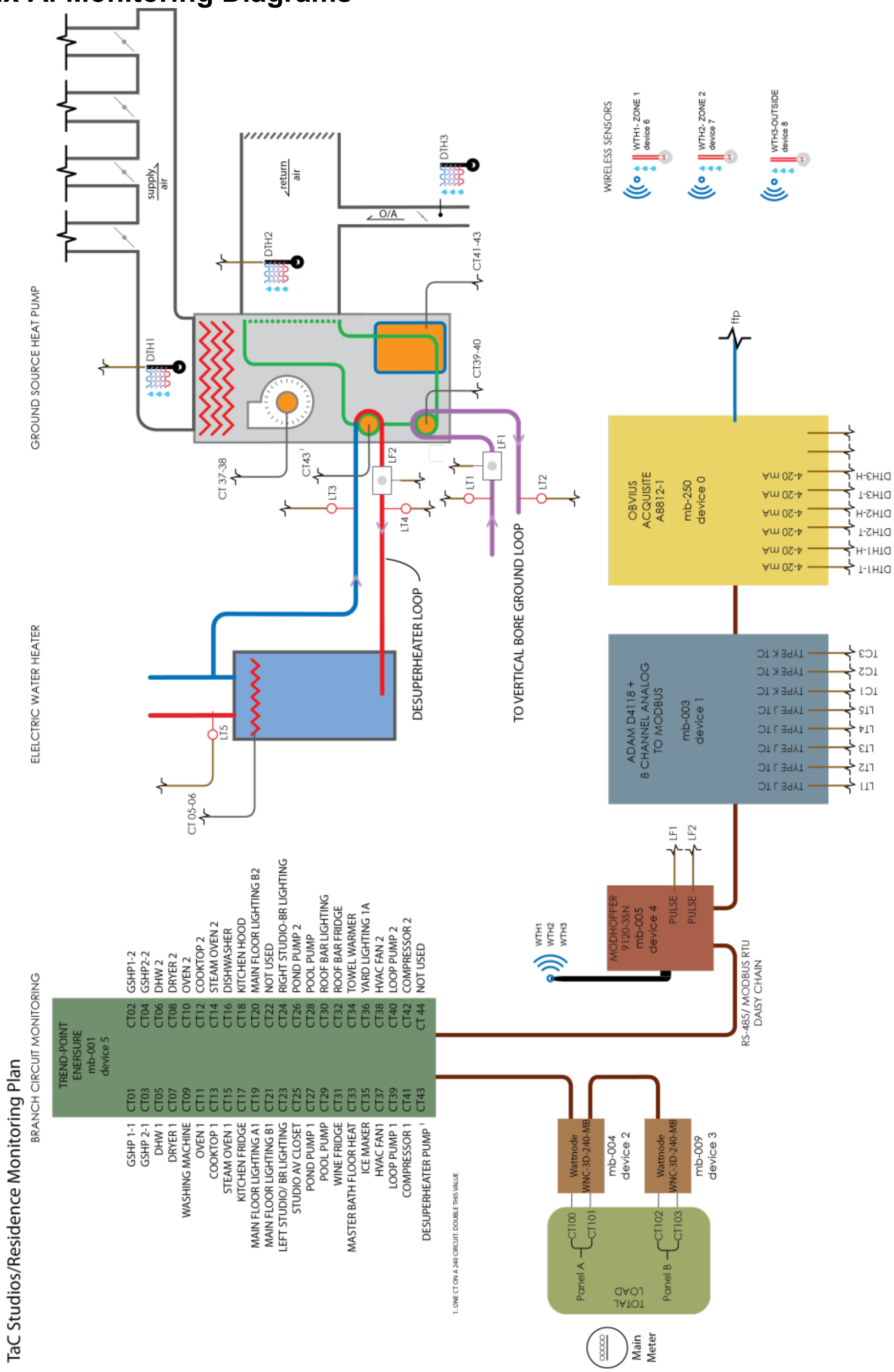

Figure 20. Monitoring diagram.

Table 5. List of Monitoring Equipment.

Measurement	Equipment
Electric energy	Trendpoint Enersure Power Meter
Duct air temperature, humidity	Vaisala HMD40Y
Ground/DSH loop flow	Seametrics SPX-100/SPX-050
Pulse Counter	Obvius Modhopper 9120-3SN
Ground/DSH loop temperature	Omega TC-J-NPT-U-72
Water heater tank temperature	Omega M12JSS-1/4-U-12-B
Thermocouple Data Acquisition	Adam 4118 Thermocouple Input Module
Wireless Sensor Receiver	Obvius Modhopper 9120-3SN
Temperature, Humidity	Point Six Wireless Temperature/Humidity Sensor
Sensor Signal Conversion/Data Recording	Obvius Acquisuite A8812-1

Appendix B: Project Map and Location

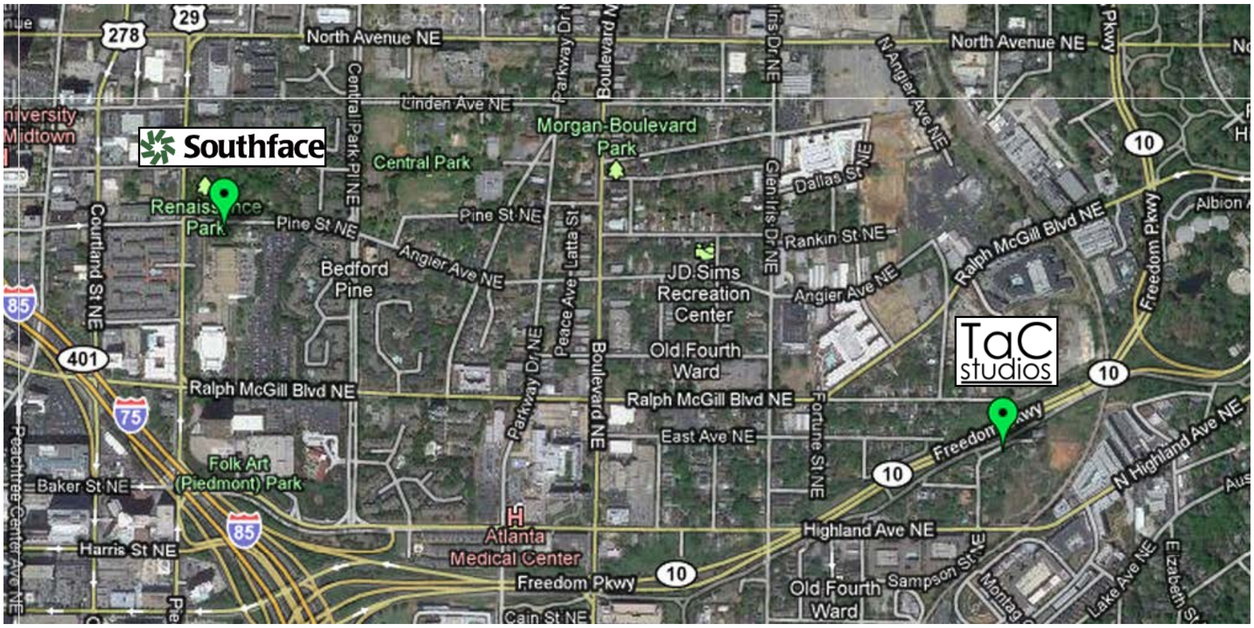

Figure 21. TaC Studios residence location. *Credit:* Map Data © 2012 Google, Sanborn

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