Solar Row Case Study

Results of One Year of Long-Term Monitoring

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Abstract

NREL performed extensive short-term testing and long-term monitoring of a small community of 9 single family attached housing units called Solar Row. This report focuses on four specific research questions that were addressed with results from long-term monitoring data and simulation.

1. What is the estimated annual source energy use of each compared to the Benchmark.
   Average of 67% savings.

2. How does actual monitored energy use compare to that predicted by the simulation?
   Monitored use is significantly less than simulation for 2 of the 3 units. The third unit was similar use to the Benchmark.

3. What is the measured annual energy use for the radiant heating system compared to a standard furnace?
   Simulation showed that the radiant system would save energy; measurements showed that the radiant system used more energy.

4. What fraction of the combined annual hot water and space heating load is met by the solar combi system under both actual operating conditions?
   Average of 25% solar fraction to heat, 69% to hot water.

In addition, monthly energy use plots and other observations are noted for those interested in the Solar Row project in general.

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1 Introduction

Solar Row is a small community of 9 housing units in North Boulder, Colorado, constructed by Wonderland Development. The development faces east and consists of one 5-plex and two duplexes. NREL has performed both short-term testing [6] and long term monitoring of three of the units in the complex. The monitored units were selected to be representative of the community. One is an interior unit, and two end units were selected, see Figure 1.2. The units are mostly similar in energy efficiency features, except that the duplex units were equipped with a forced air HVAC system, while the 5-plex used radiant heating and a minisplit system for cooling. The reason for selecting different HVAC systems was to evaluate each for consideration for another development. Table 1.1 lists out the complete energy specifications of the houses.

This report concentrates measurement and simulation results for one year of occupied use of the units. Weather data plays a significant role in energy use of houses. Simulations were conducted both with Typical Meteorological Year (TMY) data as well as measured weather data from a weather station at the site.

Figure 1.1: Exterior front photo of Solar Row development. Arrow shows north.

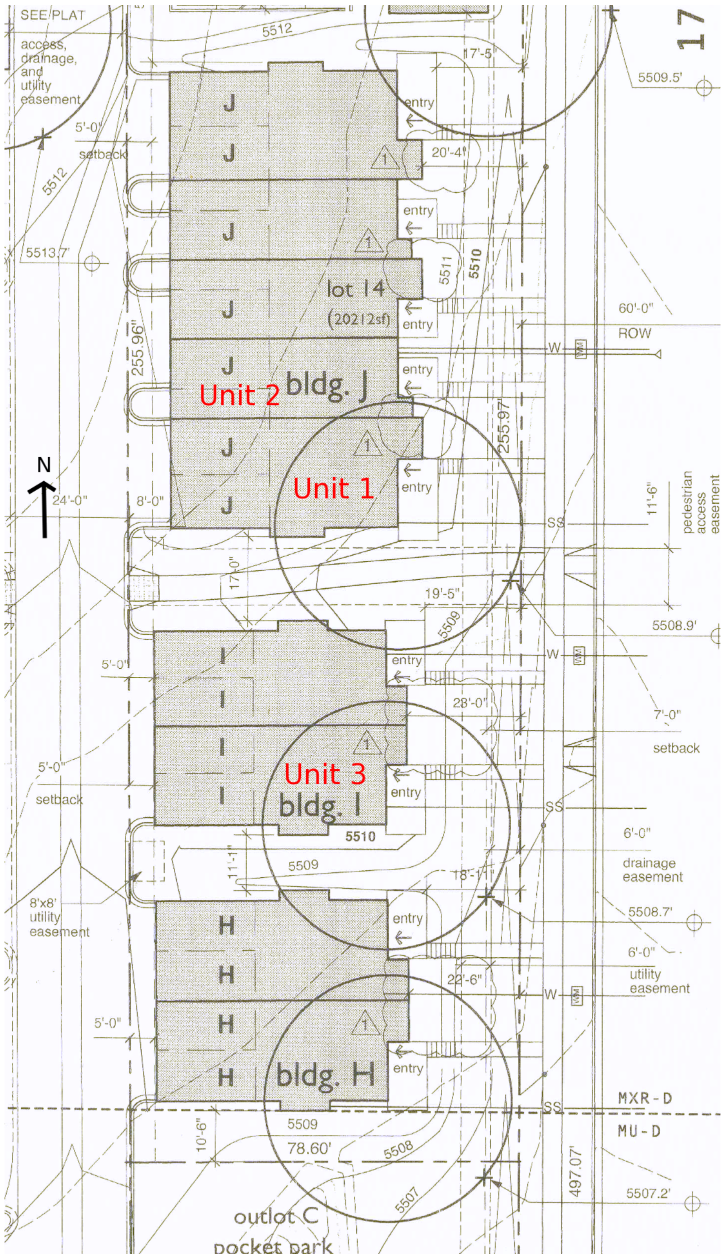


Figure 1.2: Community plan for Solar Row. Three units monitored are labeled in red.

1.1 Research questions

Several questions were developed for research at Solar Row. The questions discussed in this study are listed below.

1. What is the estimated annual source energy use of each compared to the Benchmark.

2. How does actual monitored energy use compare to that predicted by the simulation before and after occupancy? Are major differences (if any) caused by unexpected occupant behavior, building system performance, simulation errors, or a combination?

3. What is the measured annual energy use for the radiant heating system compared to a standard furnace?

4. What fraction of the combined annual hot water and space heating load is met by the solar combi system under actual operating conditions?

Location	Boulder, CO
Conditioned space	Units 1 & 3: 1700 ft^2 finished, 587 ft^2 basement, 2287 ft^2 total conditioned Unit 2: 1258 ft^2 finished, 442 ft^2 basement, 1700 ft^2 total conditioned
Bedrooms	Units 1 & 3: 3 Unit 2: 2
Ceiling	Exterior urethane foam varying from 3" in the center of the building to 0.5" on the north and south ends. 2" of spray urethane inside with an additional R-19 fiberglass batt
Exterior walls	2x6 construction In cavities: approx 3" urethane foam and 2.5" of cellulose with 1" of foam on exterior
Party wall	Double 2x4 construction R-15 fiberglass batts in cavities of both stud walls
Foundation	Poured concrete 2" of foam under slab and 2" foam on interior walls of finished area
Windows	Double glazed, argon filled, low-e, vinyl framed South, East and North windows: U = 0.29-0.31 SHGC = 0.30-0.33 VT = 0.52-0.63 West windows: U = 0.30 0.34 SHGC = 0.22 VT = 0.52
Heating	Units 1 & 2: Munchkin boiler model MC-80 Staple-up radiant floor heating 4 zones one for each floor Solar thermal system can contribute to space heating Unit 3: Forced air system Nu-Air Enerboss air handler with integrated HRV 4 high velocity ducting Solar thermal system can contribute to space heating Single zone
Cooling	Unit 1: Minisplit AC system with three interior units Unit 2: Minisplit AC system with two interior units Unit 3: Central AC
DHW	Units 1 & 2: Solar DHW with boiler used as backup 45-gal Superstor Ultra indirect fired water Unit 3: Condensing storage tank hot water heater
Solar DHW/Space	Combi System 3 Heliodyne Gobi 408 panels,40 degrees tilt, Closed-loop glycol system with external heat exchanger and unpressurized tank with 3 Poly-Iso insulation, foil faced (R- 19) Units 1 & 3: 96 ft^2 collector area 180 gallon tank Unit 2: 64 ft^2 collector area 128 gallon tank
Photovoltaics	3kW DC peak rated system 14 Sunpower SPR-215-BLK-U modules
Ventilation	Units 1 & 2: Two Panasonic Model FV-08VQ3 bathroom exhaust fans operated on timers to achieve ASHRAE 62.2 ventilation levels Unit 3: HRV integrated with Enerboss air handler
Lighting	Mix of incandescent and compact fluorescent lighting
HERS Index [7]	Unit 1: 27 Unit 2: 20 Unit 3: 36

Table 1.1: Energy related specifications

2 Methods

Datalogging equipment was installed in the three units. The dataloggers were set up to collect one-minute, hourly, daily, and monthly data. Primarily the hourly data is used in analysis. The hourly data can be summed and averaged to get daily and monthly data. The one-minute data is primarily used for debugging and specialty purposes. Measurements and their respective sensors are detailed in Table 2.1. System diagrams are shown in Figures 2.1 and 2.2.

Type	**Measurement**	**Sensors involved**
Electrical energy	Whole house	WattNode [1]
	PV	WattNode
	Air Conditioning	WattNode
Thermal energy	Solar collected	Solar tank inlet and outlet temperatures and flow rate
	Solar to DHW	DHW tank inlet/outlet temperatures and flow rate
	Aux to DHW	Boiler outlet/DHW tank inlet temperature and flow rate
	Solar to space heat	Solar tank return/supply temperatures from space heat
	Aux to space heat	Boiler supply and return temperatures to space heat
Temperature	Interior temperature x 4	Thermocouples every floor
	Outdoor temperature	Shielded temperature sensor
	Solar tank temperature	Thermocouples taped to tank surface, top and bottom
Solar radiation	Horizontal	Pyranometer
	PV plane	Pyranometer
Humidity	Outdoor humidity	Humitter
Other	Boiler gas	Gas flow meter
	Hot water use	Water flow meter
	Total water use	Water flow meter

Table 2.1: Summary of measurements and sensors used at Solar Row with results included in this report. Other sensors were installed for other projects not discussed here.

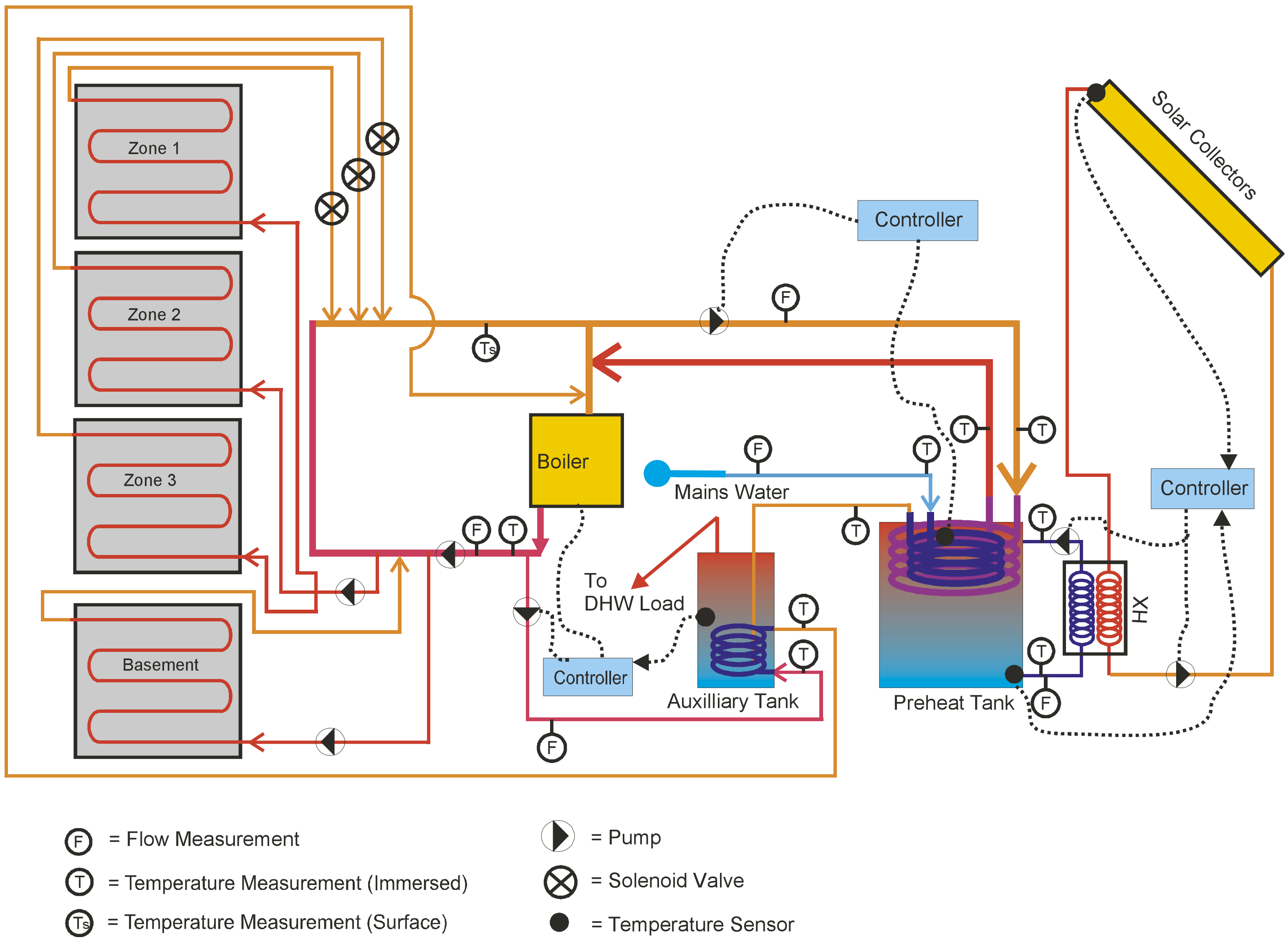


Figure 2.1: System diagram for Units 1 & 2 (the 5-plex).

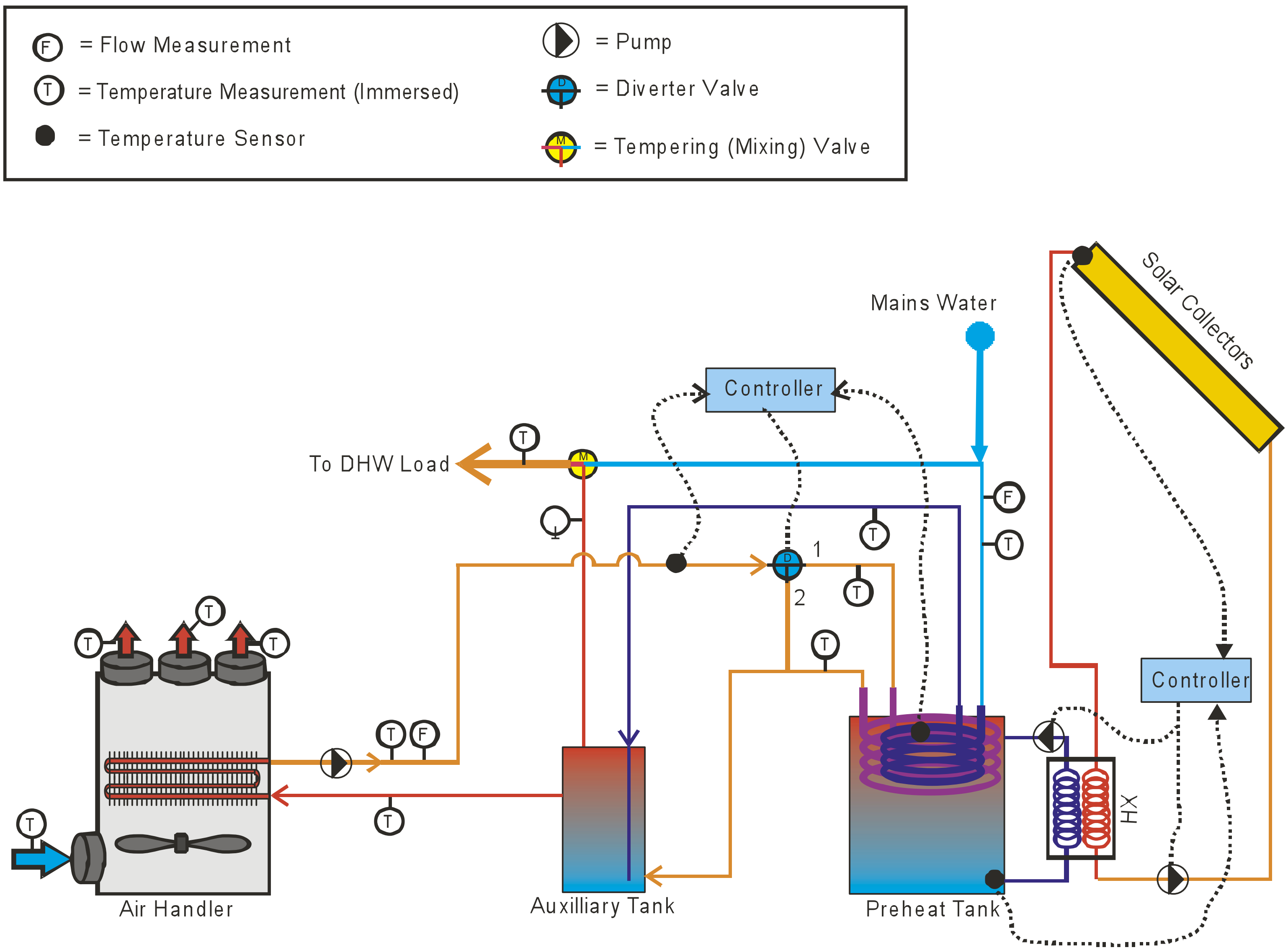


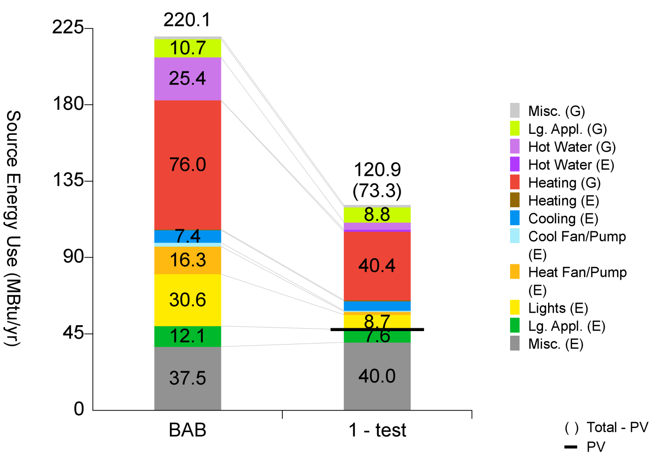
Figure 2.2: System diagram for Unit 3 (the duplexes).

3 Results

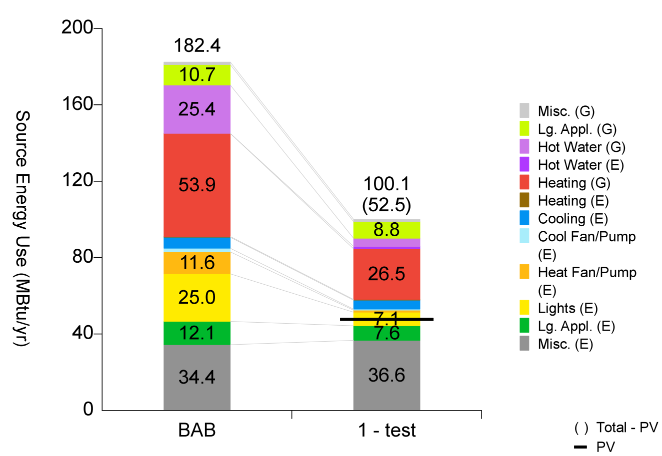
3.1 Estimated source energy savings

Savings relative to the Building America Benchmark [5] were calculated by BEopt [2] simulation (Figure 3.1). The savings numbers are less than would be expected from the assigned HERS Index (Table 1.1). The HERS Indices would correspond to 73%, 80%, and 64% savings for Units 1, 2, and 3 respectively. Since the HERS Index uses a more recent benchmark for the house, which would be a more energy efficient baseline, it would be expected to see lower savings numbers with the HERS than for the Building America Benchmark. Later results will show that the houses used significantly less energy than the BEopt simulation, so it may be that BEopt underestimates savings.

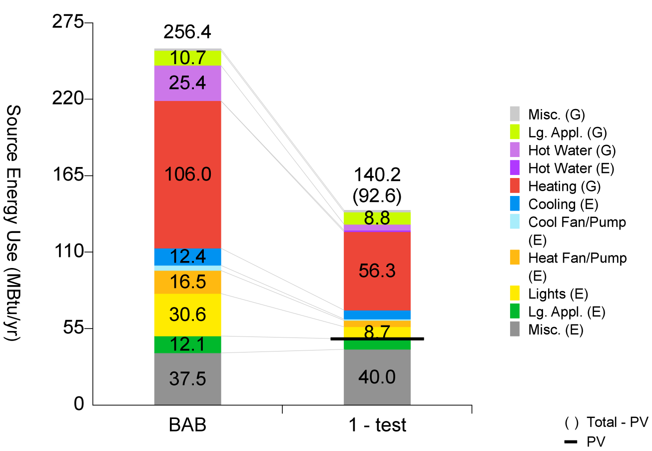
Note that single family attached housing is not currently a simulation option in BEopt, so modifications were made to the program as described in Appendix A. Additionally the Building America Benchmark house was not simulated in a solar neutral way, so these savings percentages have no effect from good or poor solar orientation.



(a) Unit 1: 67% savings



(b) Unit 2: 71% savings



(c) Unit 3: 64% savings

Figure 3.1: Source energy savings relative to the Building America Benchmark (BAB) calculated for the three units. Simulated with Typical Meteorological Year (TMY) data for Boulder, CO.

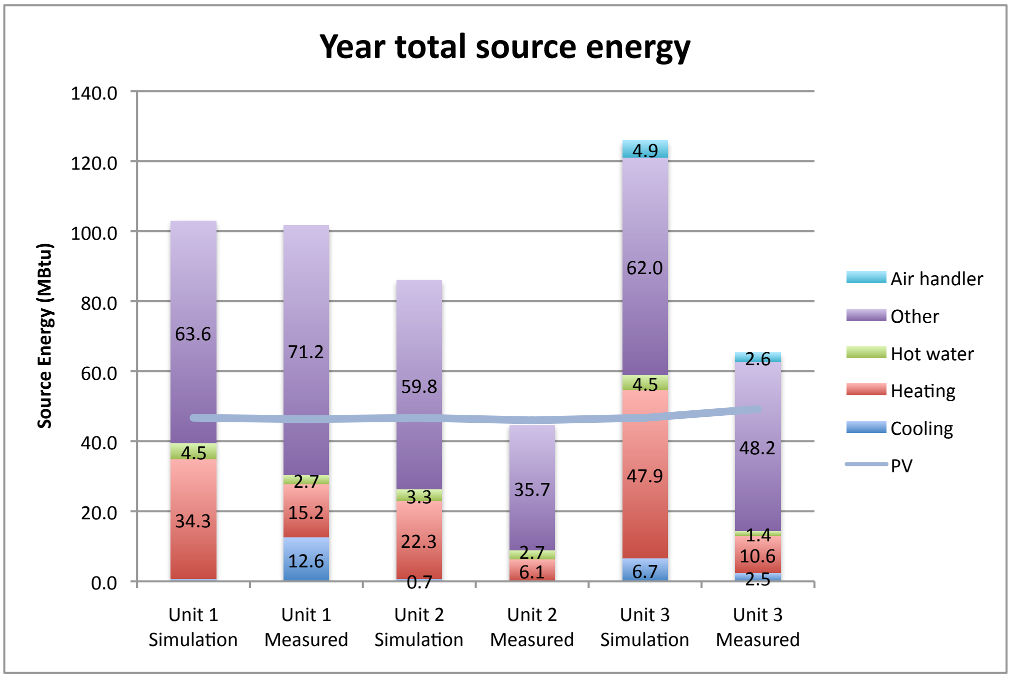


Figure 3.2: Year total source energy use - measurement to simulation comparison.

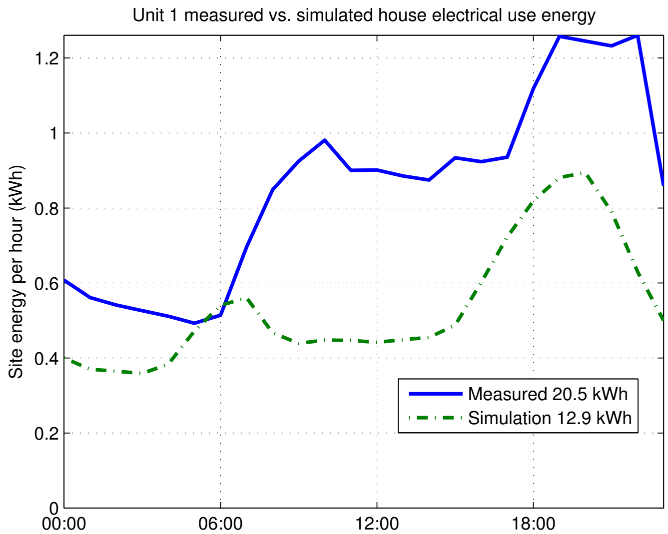
3.2 Monitored energy use compared to simulation

To compare monitored energy use to simulation, a one year weather file was created from the measured data. The weather file was pieced together from January to April of 2009 followed by May through December of 2008. Measured data for outdoor temperature, humidity, and solar insolation were combined with wind and precipitation data from Denver International Airport during the same time period and file was converted from a comma separated file to an EnergyPlus format weather file suitable for BEopt, using the weather file converter available with EnergyPlus [3].

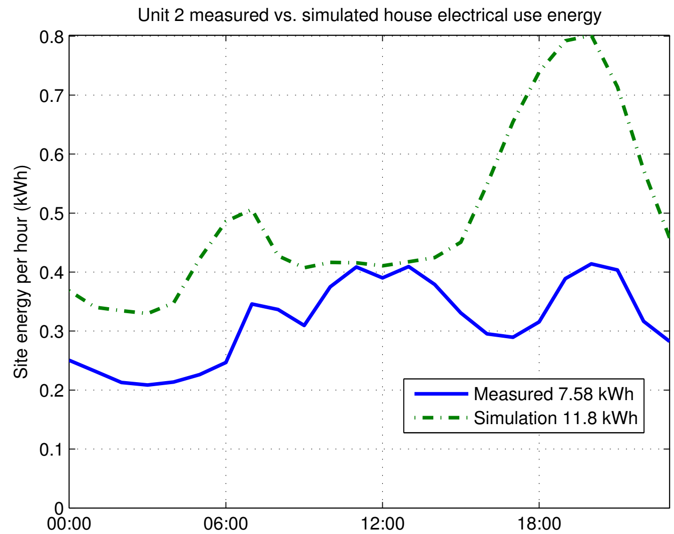
As was mentioned in Section 3.1, two of three units all used less energy than was predicted by simulation. All three units also produced close to or slightly more photovoltaic energy than the simulation predicted. Thus bringing the actual performance of the houses close to net-zero source energy. Complete monthly plots are given in the Appendix B . Figure 3.2 shows the year average predicted energy use compared to the measured.

Much of the energy use discrepancy is explained by occupant preferences. In all three houses, hot water use was significantly less than the Building America Benchmark. Daily average house electricity use was also significantly less than the benchmark. These use discrepancies are displayed via average daily load profiles in Figure 3.3. Hot water use profiles are shown in Figure 3.4.

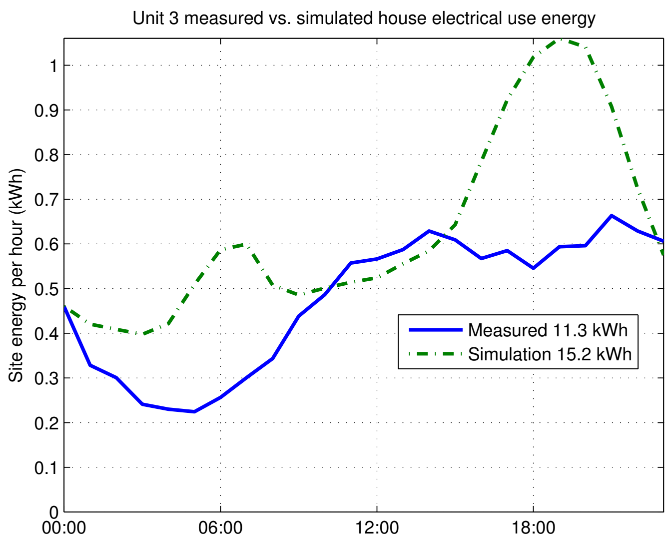
Units 1 and 2 experienced some problems with their PV systems during the one year period, leading to their lower energy productions than optimal. See Appendix C.



(a) Unit 1

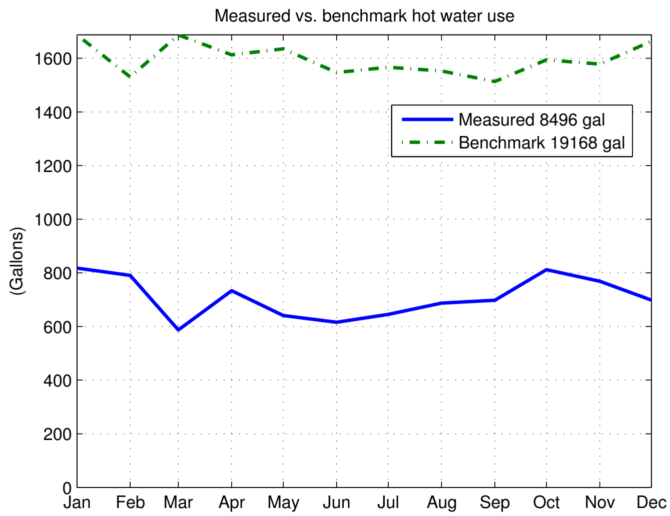


(b) Unit 2

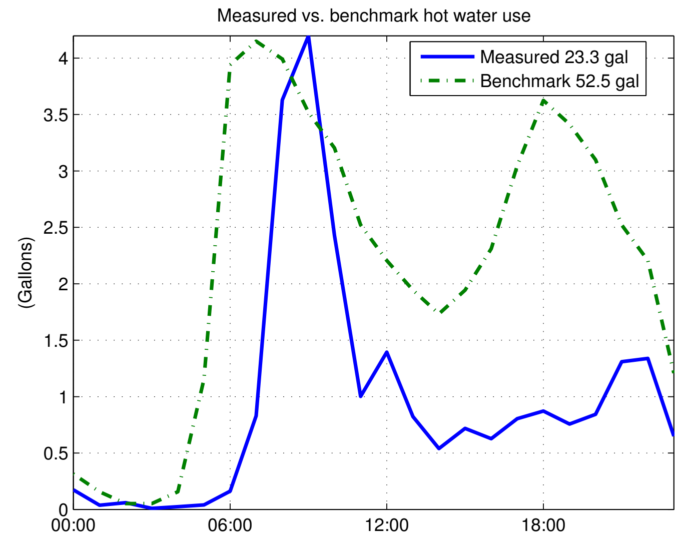


(c) Unit 3

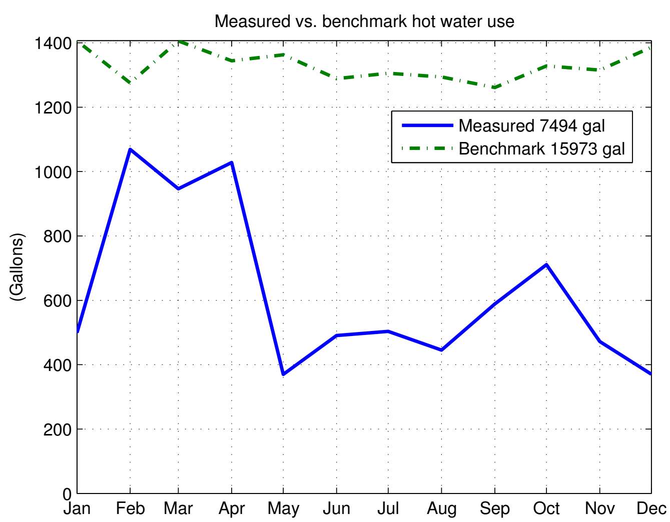
Figure 3.3: Average daily electrical load profile. Unit 1 has higher discretionary electrical use, causing the simulation total energy use to be close to the measured.



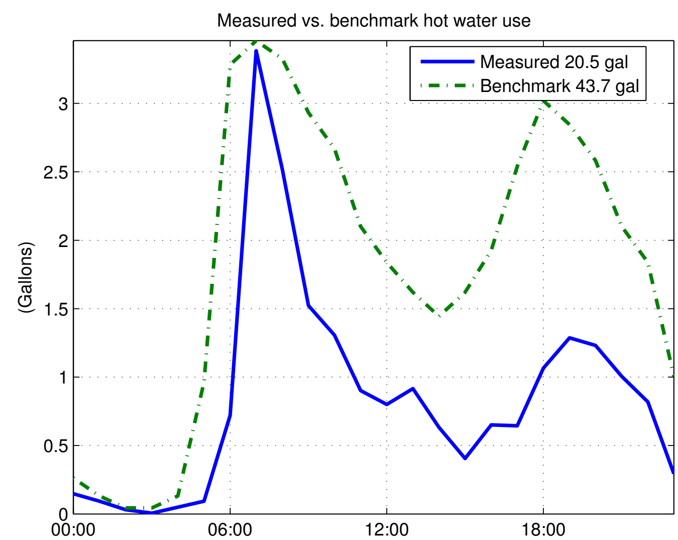
(a) Unit 1 monthly averages



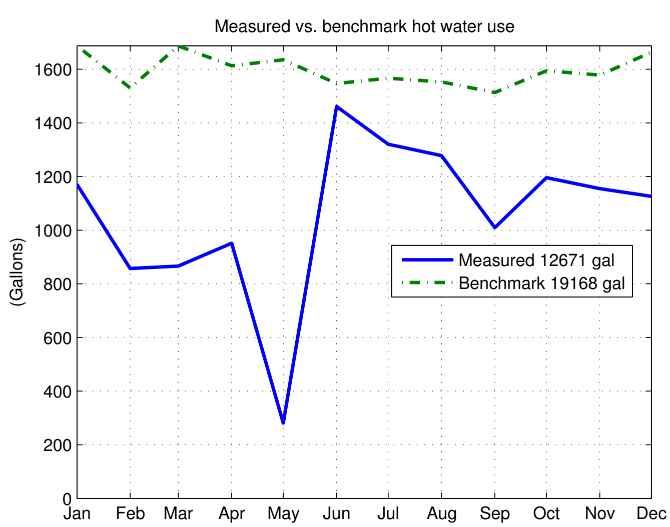
(b) Unit 1 average daily profile



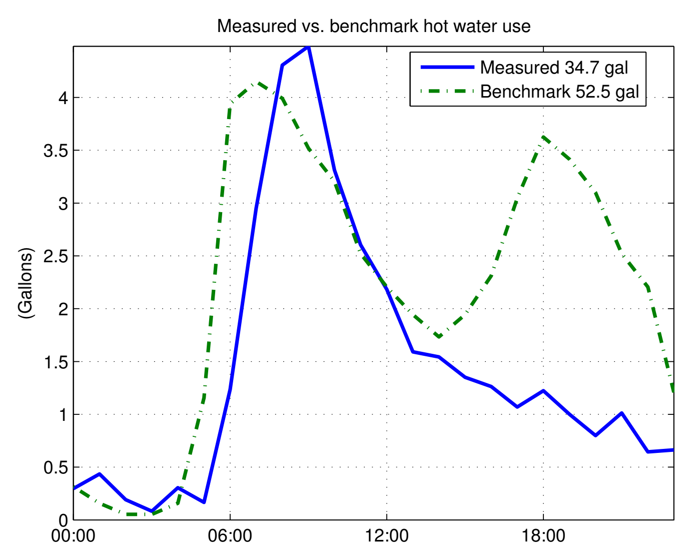
(c) Unit 2 monthly averages



(d) Unit 2 average daily profile



(e) Unit 3 monthly averages



(f) Unit 3 average daily profile

Figure 3.4: Hot water use of the 3 units

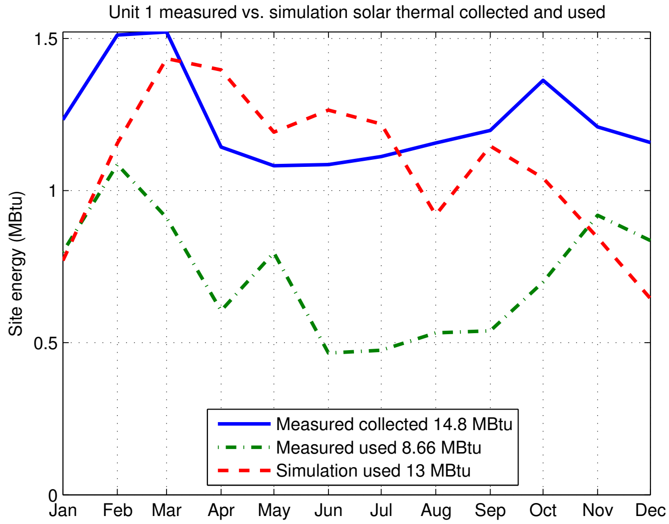
3.3 Radiant heat vs. forced air

Units 1 and 3 were selected to evaluate the energy use of a forced air system compared to a radiant heating system. Both units are the south facing unit of their buildings with similar shading, and they have a similar floor plan. This enabled the experiment of comparing winter heating energy use of each building to compare the two HVAC systems. The radiant unit was simulated with a baseboard hydronic system.

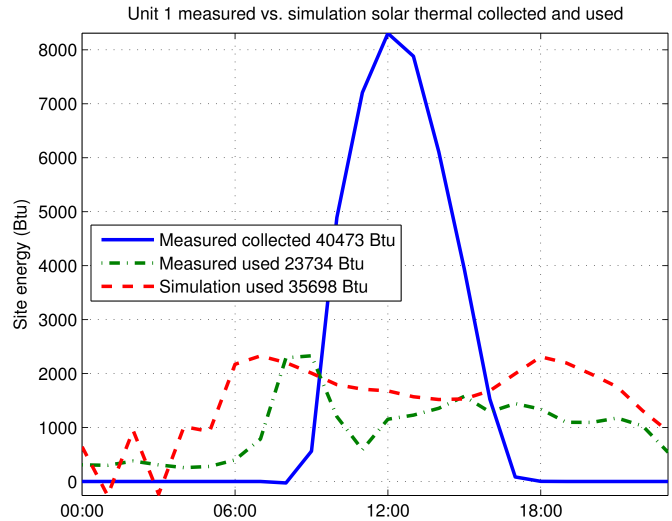
	Unit 1 (radiant)	Unit 3 (forced air)	percent diff
Simulation energy	31.4	43.9	40%
Measured energy	13.9	10.5	-24%
Average indoor temperature Oct-Mar	21.0	19.0	
Heating degree days ^oC	2811	2452	-12.8%
Internal electrical loads	2.8	1.8	

Table 3.1: Simulated and measured energy comparing radiant heating to forced air. Energy numbers in site energy MBtu.

Simulation showed a significant reduction in energy for the radiant heated unit. The measurements however did not confirm this (Table 3.1). Some of the discrepancy is accounted for by a lower average indoor temperature set point in the radiant heated unit. However, the number of degree days - calculated using the measured indoor temperature the measured outdoor temperature - only partially accounts for the higher energy use of the radiant unit.Internal loads also would have affected the heating energy used. However, the radiant heated house had higher electrical use, so it's effect would be in the direction of a larger energy use discrepancy. Whole house natural gas, and ventilation were not measured, which may also have had an effect. This discrepancy was not investigated further.



(a) Monthly averages



(b) Average daily profile

Figure 3.5: Unit 1 solar thermal energy collected and used for space heating or DHW compared to the simulation used solar thermal DHW. Simulation does not calculate collected solar thermal. Use to collection ratio is 59%.

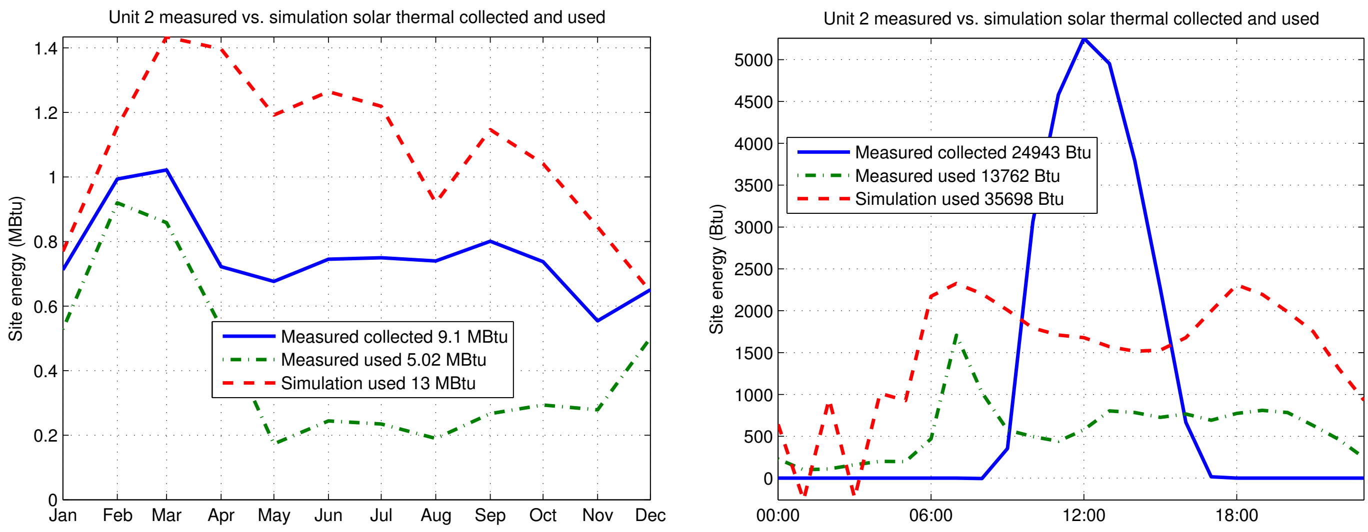
3.4 Combi system and the solar fraction

BEopt simulation does not currently have an input method for solar combi systems. Thus, contribution of the solar combi system to space heat was not simulated in BEopt. Solar thermal contribution to DHW was simulated in BEopt.

Solar thermal energy collected was only measured in Units 1 and 2. Figures 3.5 and 3.6 show the solar thermal energy collected compared to the solar thermal energy used, and also the simulation solar thermal energy used. Reduced hot water use and heating load account for lower measured solar thermal energy used than simulated.

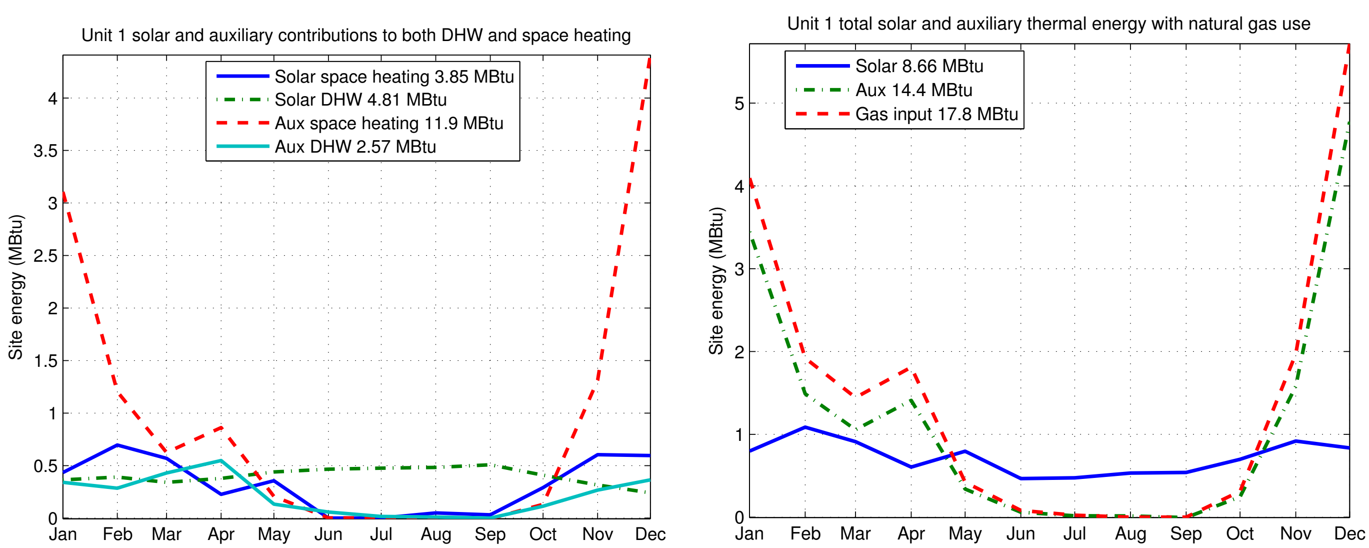
Measurements were taken to investigate the contribution of solar thermal to both space heating and hot water independently. Figures 3.7-3.9 show monthly data, while Table 3.2 shows the yearly sums. In general the contribution of solar thermal was a low percentage of the total space heating load. However, the solar thermal contribution to space heating was at the same level as contribution to DHW for Units 1 and 2.

Last it should be noted that all three units used a separate solar storage tank. Thus, tank loss in the water heater could not be offset by solar thermal unless hot water was used. This issue, combined with low water use in the units lead to lower solar fractions for water heating.



(a) Monthly averages (b) Average daily profile

Figure 3.6: Unit 2 plot same as Figure 3.5. Collection to use ratio is 55%.



(a) (b)

Figure 3.7: Unit 1 measured solar thermal contribution and gas auxiliary backup to both space and water heating. The overall solar fraction is 38% and the overall boiler thermal efficiency is 81%.

	Unit 1	Unit 2	Unit 3
Solar to heat (MBtu)	3.9	2.1	1.8
Aux to heat (MBtu)	11.9	3.7	7.9
Solar fraction	0.25	0.36	0.19
Solar to DHW (MBtu)	4.8	2.9	6.6
Aux to DHW (MBtu)	2.6	2.6	1.3
Solar fraction	0.65	0.53	0.83
Total solar fraction	0.38	0.44	0.48

Table 3.2: Solar thermal contributions to space and water heating.

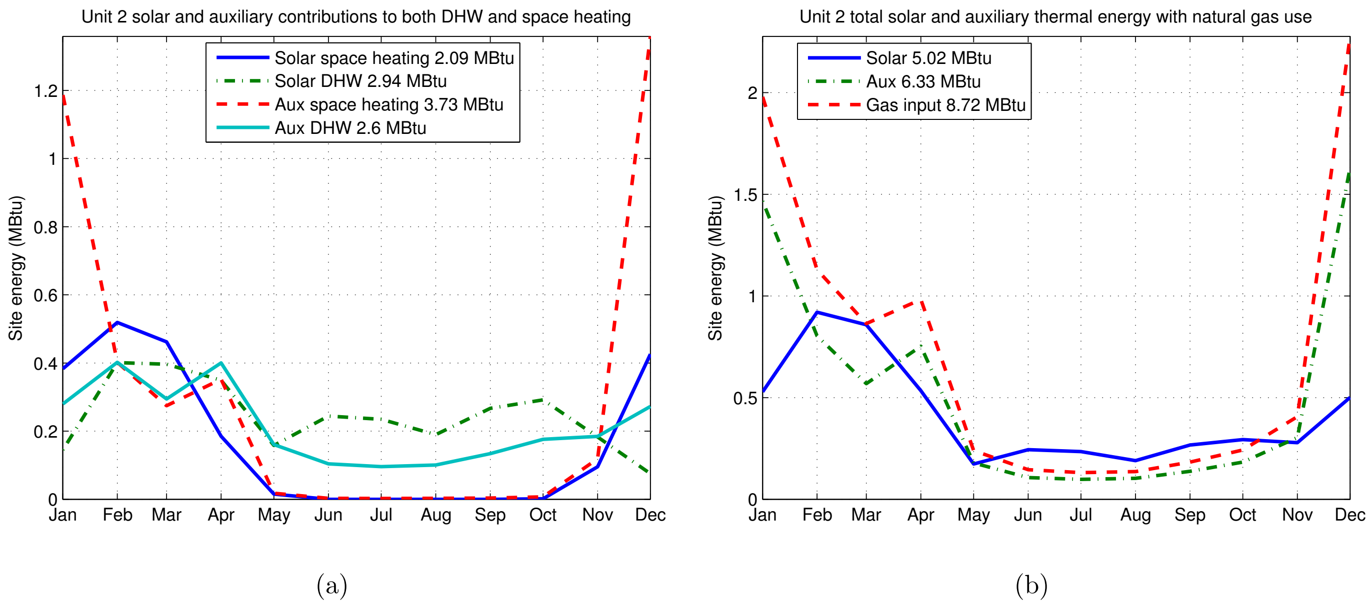


Figure 3.8: Unit 2 measured solar thermal contribution and gas auxiliary backup to both space and water heating. The overall solar fraction is 44% and the overall boiler thermal efficiency is 73%. Solar provides the most significant contribution to space heating in this unit, probably because of the smaller heating load.

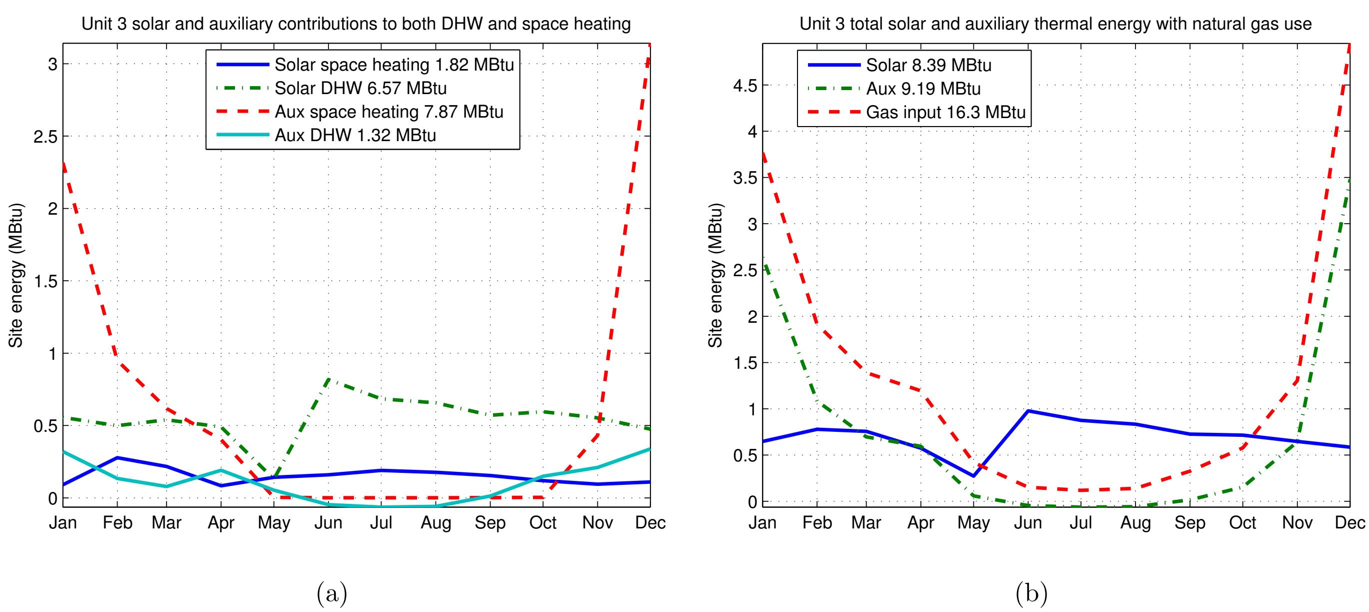


Figure 3.9: Unit 3 measured solar thermal contribution and gas auxiliary backup to both space and water heating. The overall solar fraction is 48% and the overall EF is 57%. In (b), solar is also seen to contribute to space heating during the summer months - this is due to a furnace water cycler, which runs for 4 minutes every 6 hours in order to prevent stagnant water. This wasted thermal energy is about 11% of the total heating load. Additionally, adding heat load during the summer will also cause increased cooling loads.

4 Conclusion

This report only scratched the surface of what is possible with the data coming from Solar Row. Responses to each of the four research questions are:

1. BEopt simulation was used to simulate 67%, 71%, and 64% savings relative to the Building America Benchmark for Units 1-3 respectively for a typical meteorological year.

2. Measured net energy results were less than simulated net energy results. Measured savings (for the measured weather data) were 71%, 103%, and 93% for Units 1-3 respectively. The main explanation is that occupant measured discretionary use was less than simulated benchmark occupant use.

3. Simulation predicted significant savings for radiant heating. Measurements showed that the radiant heated unit used more energy than the forced air unit.

4. BEopt simulation is not currently set up to simulate solar combi systems. Measurements showed that contribution to space heating from the solar combi system was significant, but only 25% of the heating load on average for the three units.

Bibliography

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[2] C. Christensen, R. Anderson, S. Horowitz, A. Courtney, and J. Spencer. Beopt^{TM} software for building energy optimization: Features and capabilities. 2006. http://www.nrel.gov/docs/fy06osti/39929.pdf.

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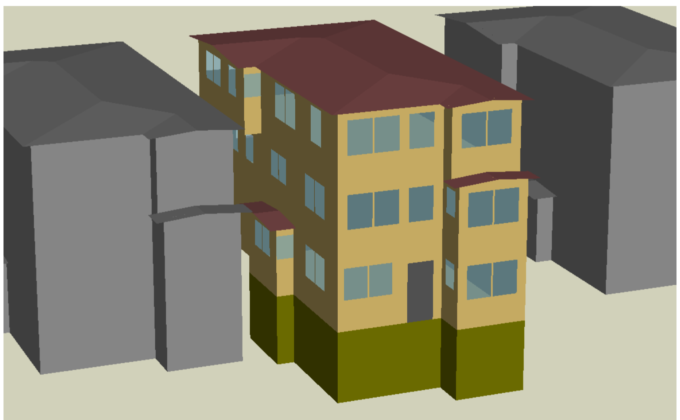
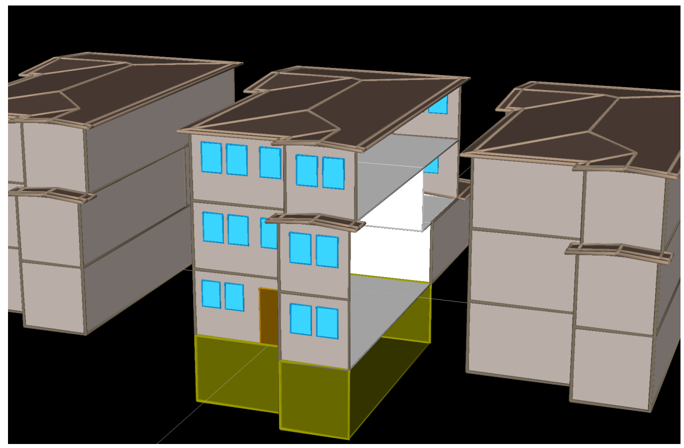
A Simulation inputs



(a) BEopt rendering



(b) eQUEST rendering

Figure A.1: Simulation model used for Unit 3 in BEopt. Neighbors are shown. Actual unit is a duplex. The party wall was simulated as an adiabatic surface, which is accomplished by removing the wall from simulation. The eliminated party wall is shown in (b). In addition, another BEopt modification was made to use a different set of wall U-values for the Benchmark simulation.

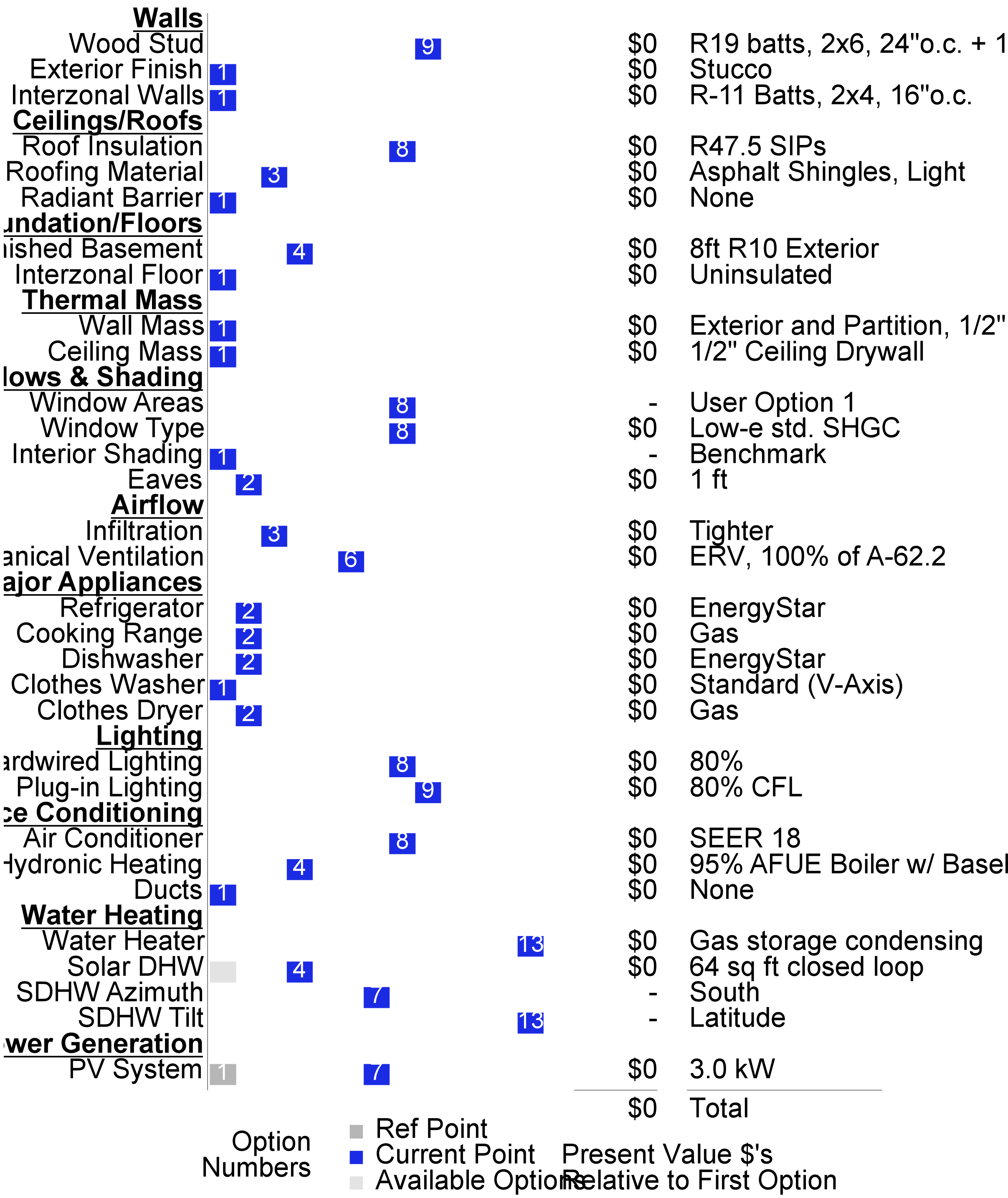


Figure A.2: BEopt 0.9.2 input selection for Units 1 & 2.

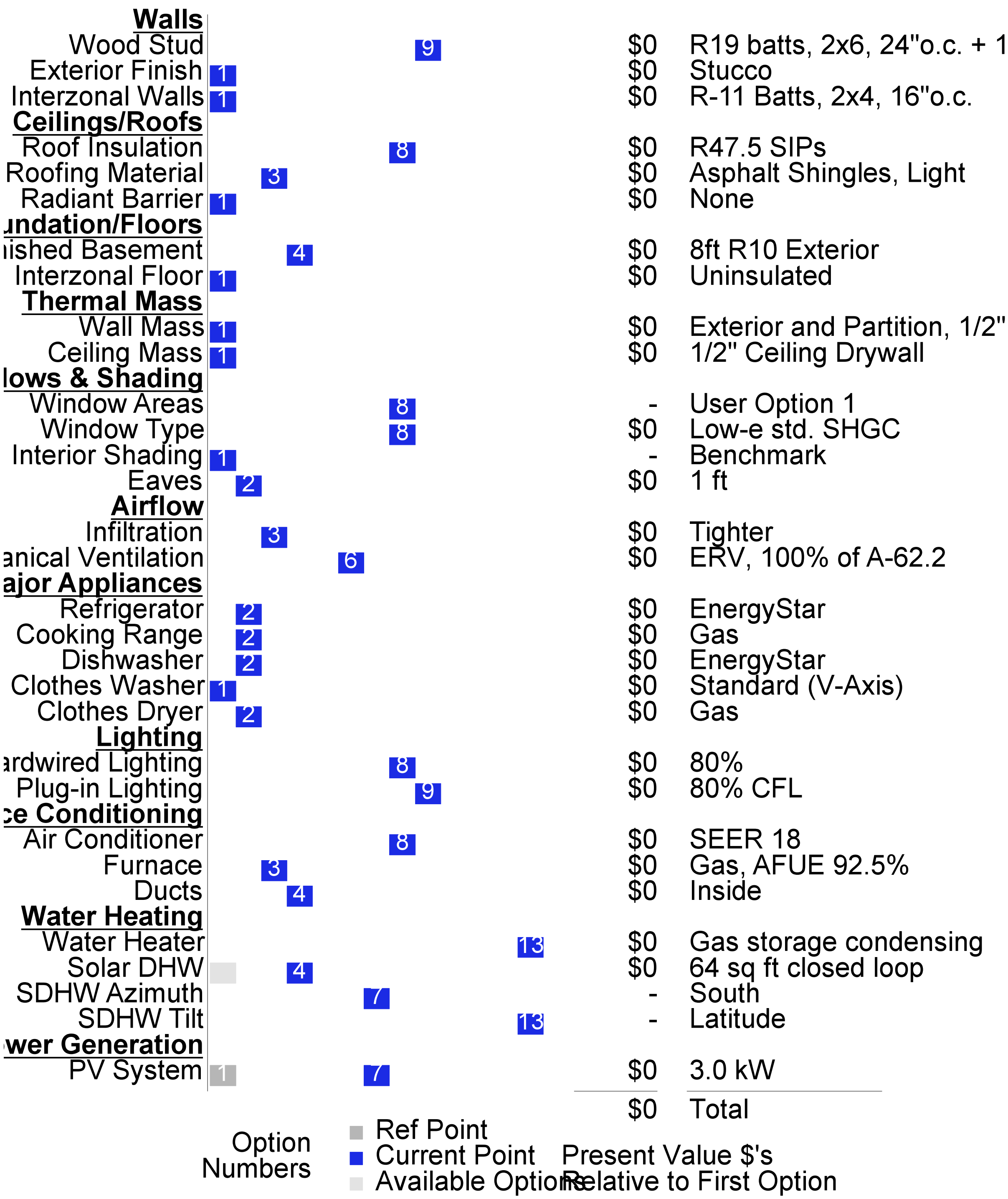


Figure A.3: BEopt 0.9.2 input selection for Unit 3.

B Monthly simulation and measurement results

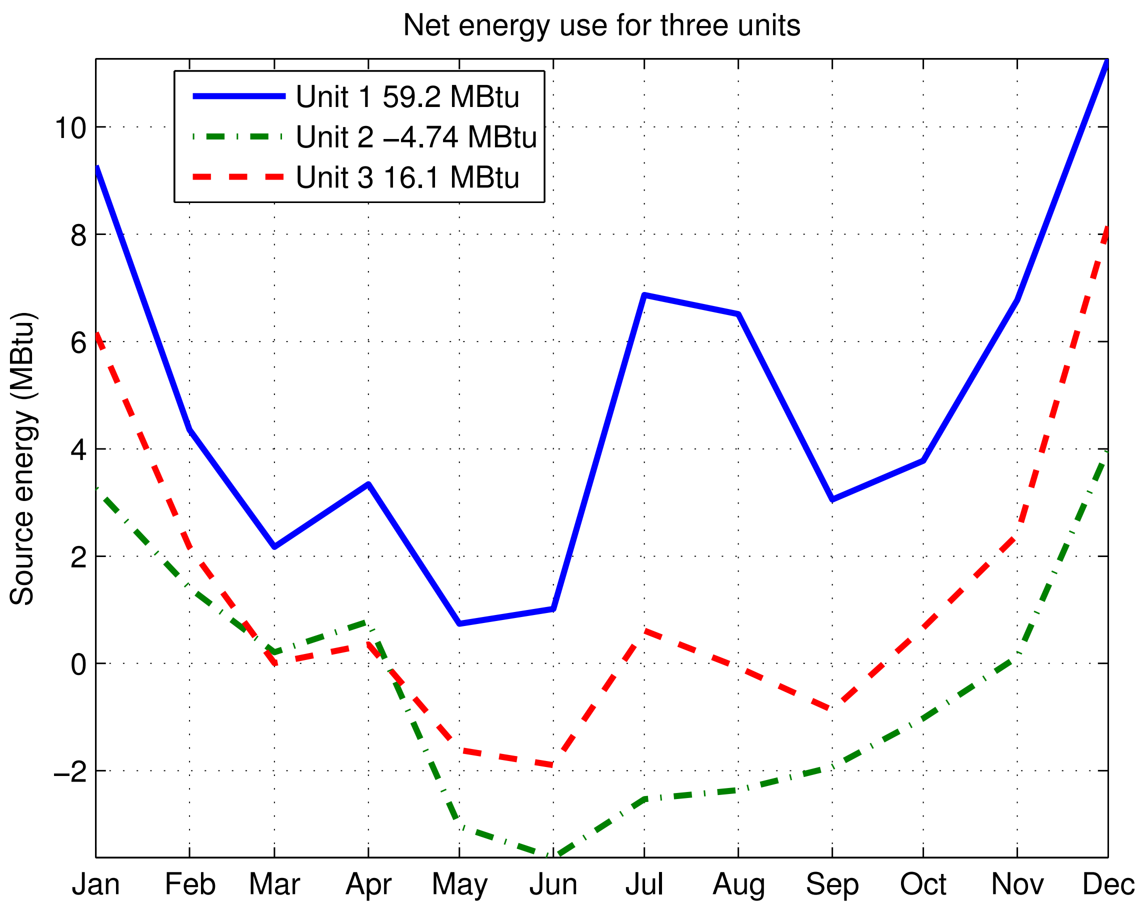


Figure B.1: Net source energy use of the three units. Source energy conversions are 3.365 for electricity, 1.092 for natural gas. Legend shows yearly sum.

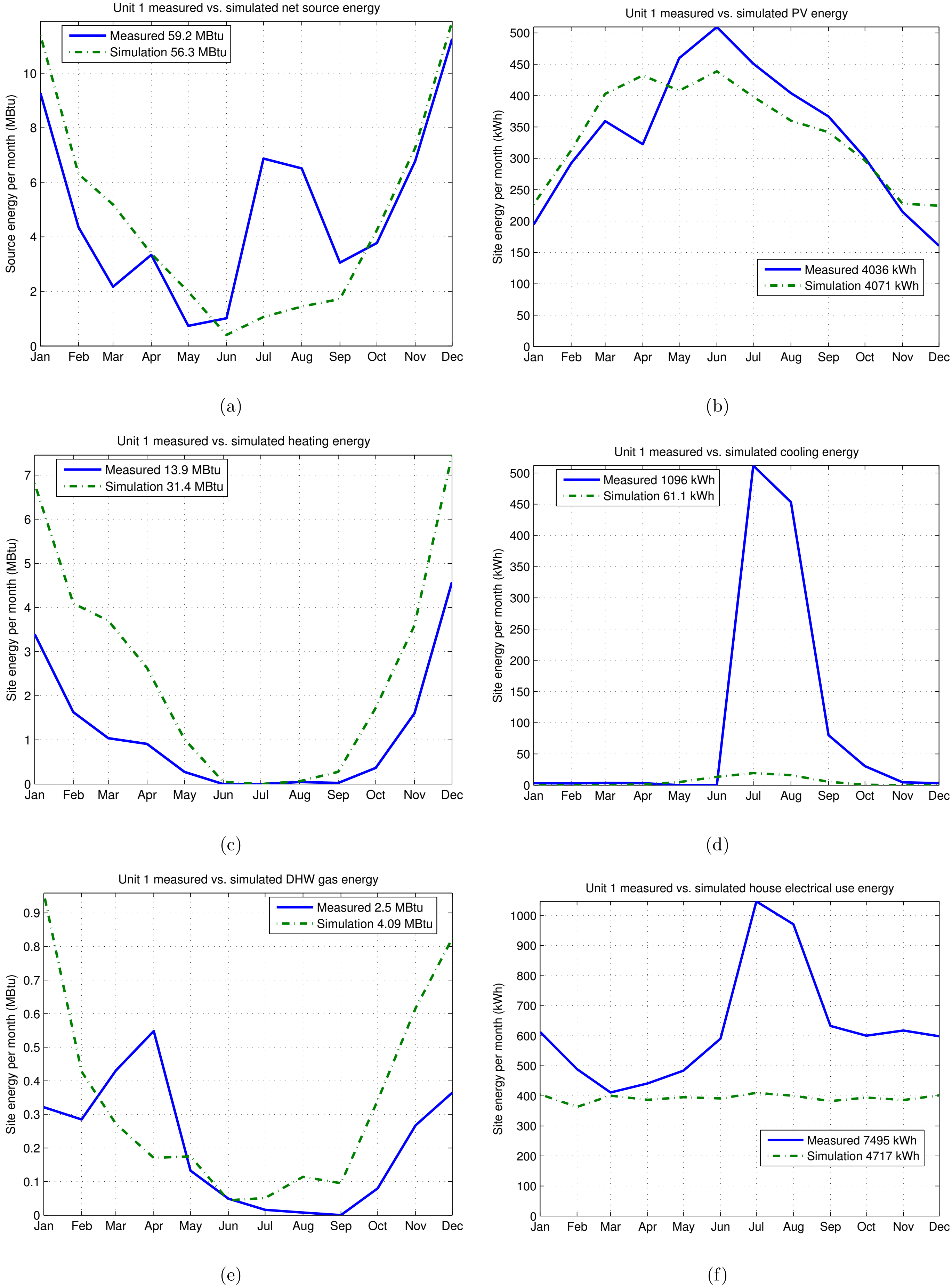
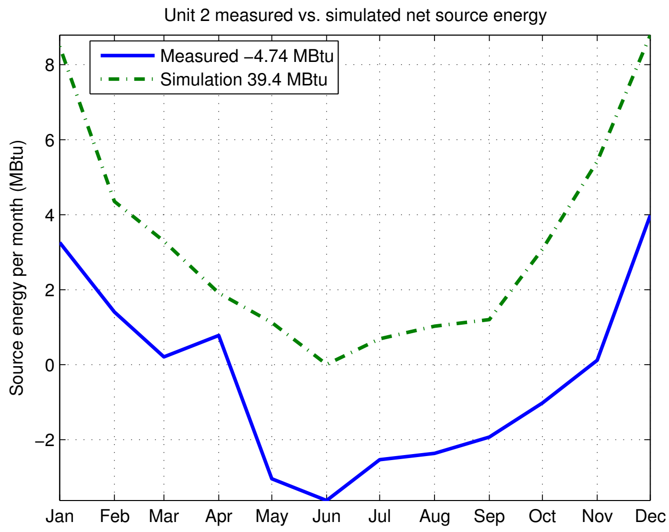


Figure B.2: Unit 1 results



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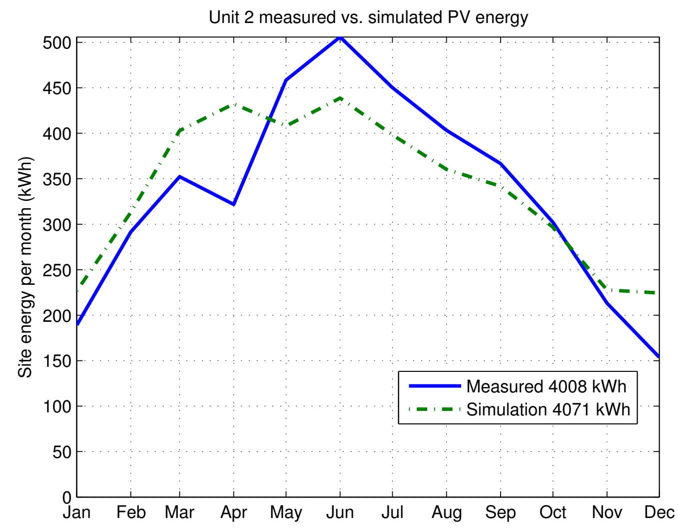

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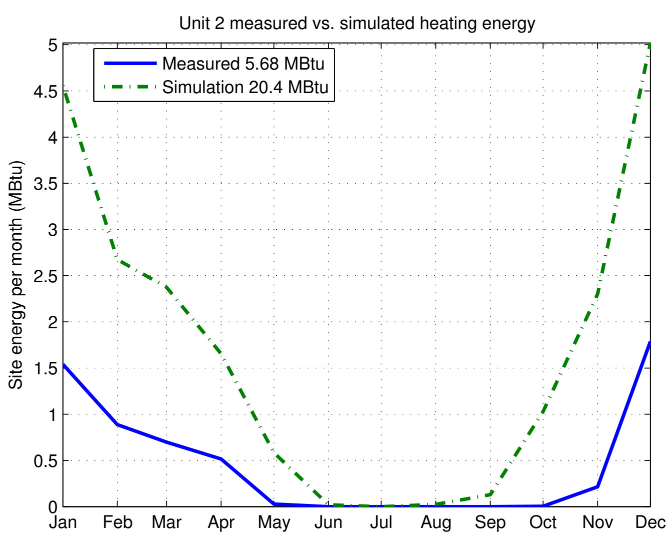

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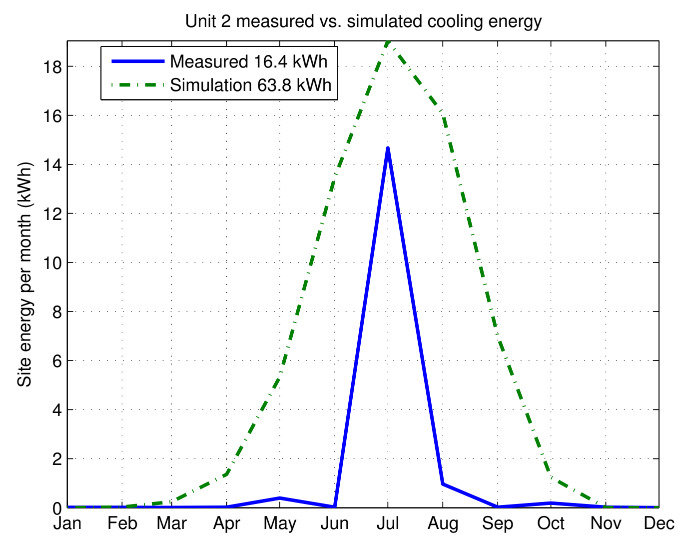

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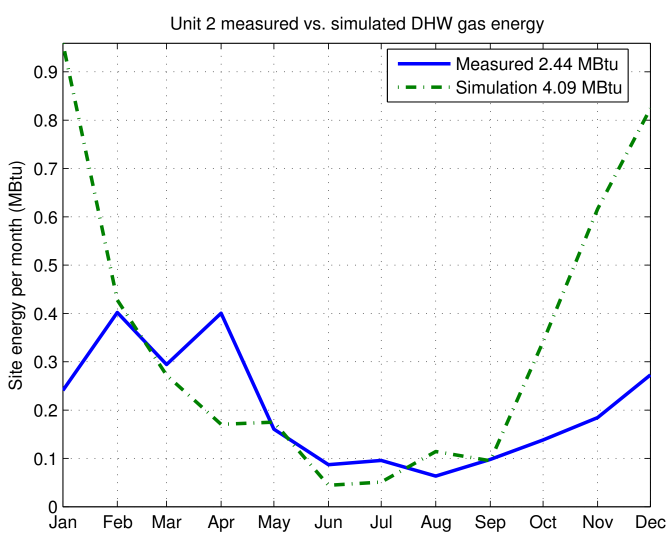
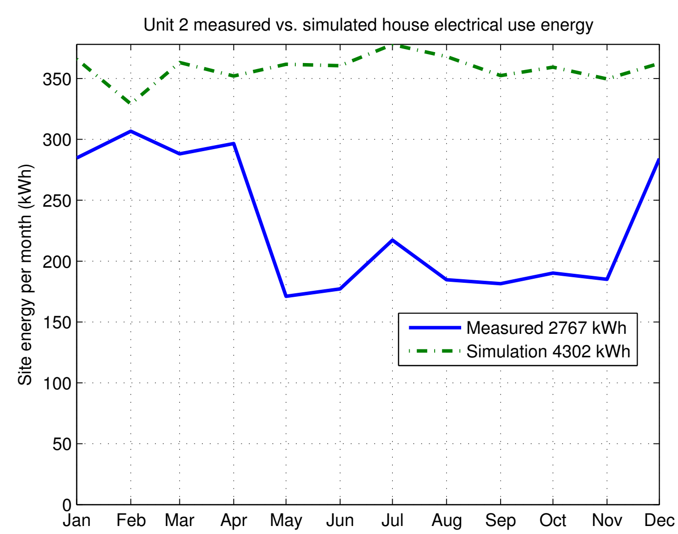


(e)



(f)

Figure B.3: Unit 2 results

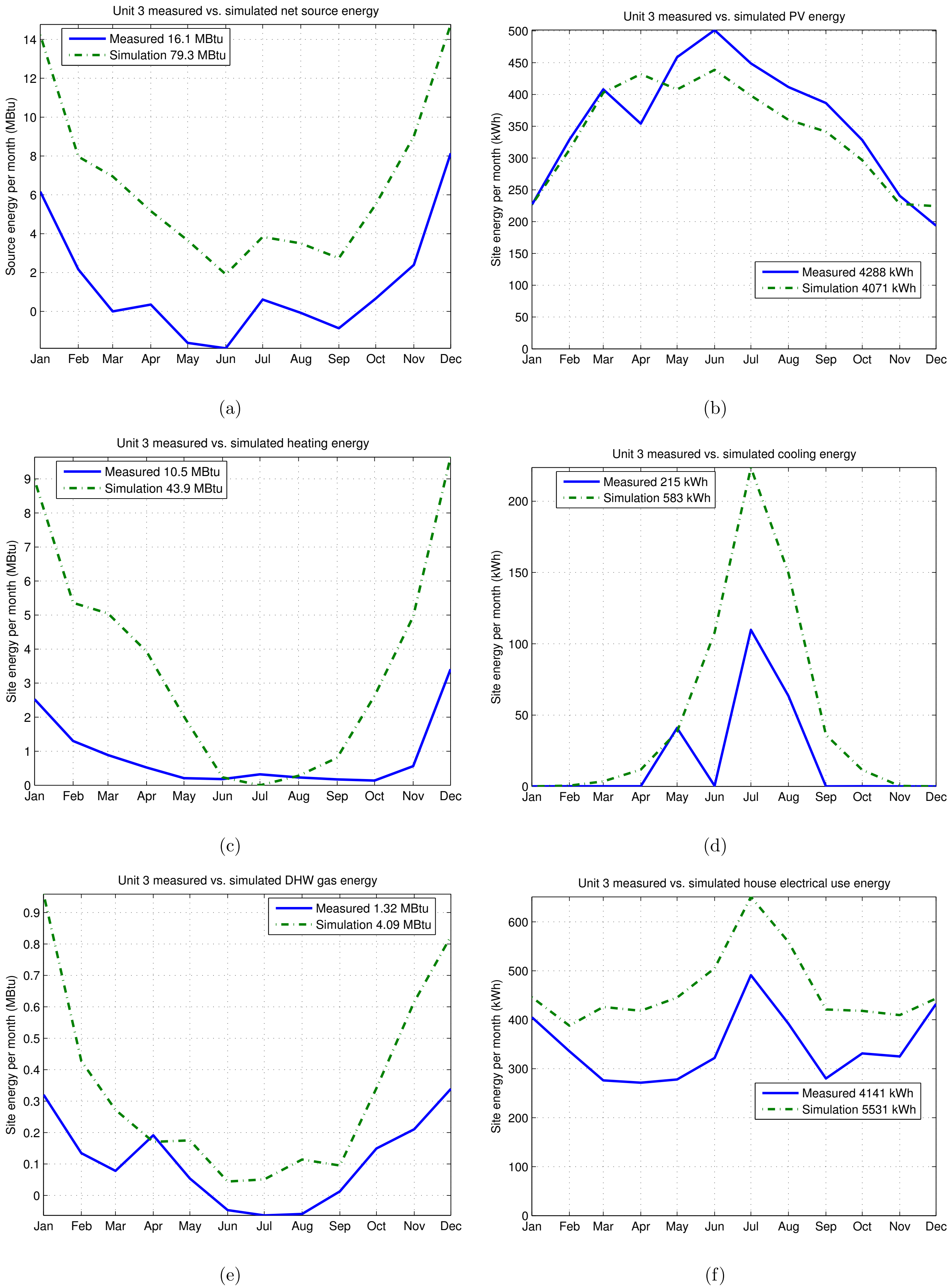
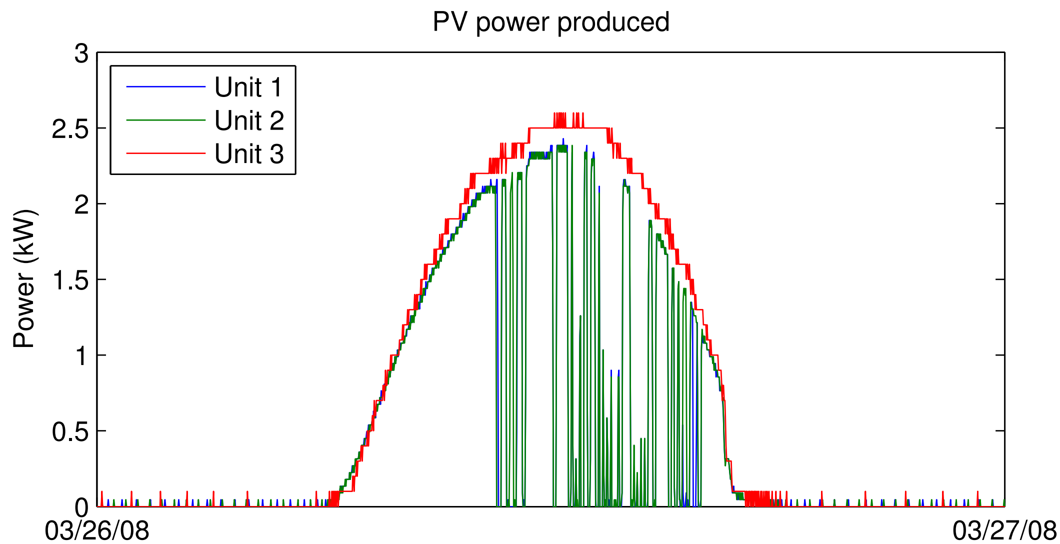


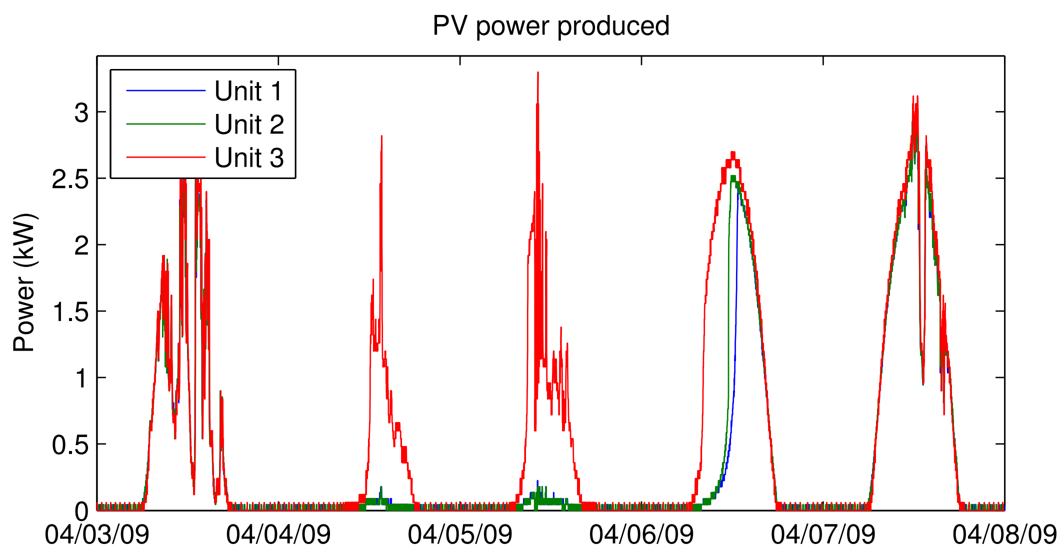
Figure B.4: Unit 3 results

C PV measurements differ from predicted

Figure C.1: Solar array angles measured using Google Sketchup [4] with a 3D axis aligned to the building. The duplex units have a slightly higher solar array angle than the 5-plex units with the exception of the 5-plex array mounted on the sloped roof.



(a) Data collected from the pre-occupied period. Units 1 and 2 had a problem with the system cutting out, and both units would cut out at the same time. Cutting out of Units 1 and 2 stopped in April and the three units stayed in sync for most of the time. Unit 3 has a slightly higher output power due to a higher panel tilt angle (Figure C.1).



(b) During some periods of the year, again Units 1 and 2 exhibited problems. The problems appeared to correct themselves and the units in general would stay well in sync. Shading is mostly ruled out by the surrounding days with normal performance.

Figure C.2: One minute data of PV power produced. Units 1 and 2 have an unexplained problem that causes them to cut out or just not produce power. The way Units 1 and 2 follow each other is intriguing since they are not directly connected to one another. It seems that they must be shutting off due to an interaction with the grid that affects them both. Overall this lead to year average PV measurements being less for Units 1 and 2 than their simulation and Unit 3.