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The Integration of Heat Resources in a Solar Thermal-Heat Pump Hydronic System

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THE INTEGRATION OF HEAT RESOURCES IN A SOLAR THERMAL-HEAT PUMP HYDRONIC SYSTEM

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This research is dedicated to my family and very close friends who have always supported me no matter what I chose to do. I would not be where I am without you.

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ABSTRACT

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According to the U.S. Department of Energy, roughly 41% of the energy consumed in the U.S. is used the power buildings. Within that number, almost half is used to heat or cool the building. Current technologies allow for consistent thermal management, but most utilize energy harvested from fossil fuels or convert electricity back into thermal energy. Background literature shows that the utilization of alternative heat resources such as heat pumps and solar thermal collectors can greatly reduce the energy used for heat delivery while producing adequate heating performance. A combined hydronic system using a bank of solar thermal collectors in parallel with a heat pump was designed and installed to feed various loads. After commissioning the system, it was run for 17 days during the end of the winter season to ascertain the performance of the solar collectors and the heat pump as heat sources. The heat pump supplied 65% of the thermal energy while the solar thermal collectors provided 35% of the thermal energy. Overall, the system reached a total energy factor of 1.95. The results show that the system performs better than an electric-based or fuel burning system, but improvements can be made through controls optimization and operating the system year-round.

CHAPTER 1. INTRODUCTION

All over the globe, people and industry consume massive quantities of energy to power their homes and offices, travel across the world, and operate factories that produce billions of dollars of goods. Fossil fuels, nuclear, and renewables are the fuel sources that satiate the global thirst for energy. Globally, fossil fuels provide almost 82% of the total energy supply, while nuclear provides approximately 5%. Renewable sources that include solar, wind, geothermal, and others provide only 1% of the world's supply, while the rest is provided by hydro and biomass fuel. Figure 1.1 shows this graphically. The total energy consumption presented is the equivalent of nearly 66 trillion barrels of oil (International Energy Agency, 2014a, p. 6). Almost 87% of the world's global energy supply is a finite resource.

At the same time, populations are growing and countries are continuously trying to advance themselves through economic, social, and infrastructure development. This development requires a key resource: energy. A healthy energy supply drives growth and promotes unfettered progress in all sectors. Buildings, which are encompassed by infrastructure, are of great importance from the perspective of energy usage.

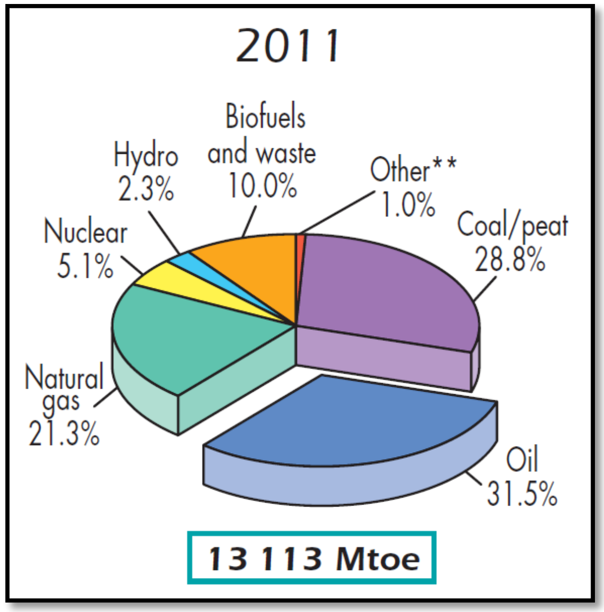

Figure 1.1: Global Energy Supply. Reprinted from *Key World Energy Statistics 2013*, International Energy Agency, 2014, retrieved from http://www.iea.org/publications/freepublications/publication/key-world-energy-statistics-2013.html. Reprinted with permission.

1.1 Problem Statement

A large portion of the energy consumed by the U.S. goes towards buildings, more specifically the heating and cooling of these buildings. Heating, ventilation and air conditioning (HVAC) systems are the systems that control and maintain comfort in buildings through heating and cooling. Energy use by commercial and residential buildings equated to 41% of overall energy usage in the U.S. Homes and offices must be conditioned in some sense, whether through heating, cooling, or most likely a combination of both. In the commercial sector, it takes 39% of the energy consumed in buildings to operate the HVAC. In residential buildings, 48% of the energy consumed is used for HVAC operation (U.S. Dept. of Energy, 2012). The main goal of the HVAC system in any building is to maintain a comfortable space in which occupants are satisfied. Stated in the ASHRAE standard for thermal environmental conditions, 80% or more must find the environment thermally acceptable (*ANSI/ASHRAE 55.2013*, 2013, p. 2*).* The main focus being on occupant comfort combined with low energy prices has been a driving factor behind the lack of efficiency in HVAC systems.

Heating is almost always the largest consumer of energy in commercial and residential buildings. Typically, natural gas or electricity provides the energy to power the source of heating, along with fuel oil and biomass being less common. Power generation by the burning of fossil fuels along with the use of radioactive materials requires multiple energy changes, for instance from chemical the heat to electrical and produces large amounts of byproducts which are harmful to the environment. There has been little incentive to increase efficiency, yet the rising costs of energy and predictions of resource scarcity are causing a change in this perception. New technological developments which can be applied to existing heat sources such as solar thermal and heat pumps have been developed enough to where they have become a viable option for heat generation many climates.

1.2 Research Question

Can the multiple heat sources in a heat pump assisted solar thermal hydronic system be controlled to meet the performance expectations of a traditional hydronic heating system?

1.3 Significance of Problem

In commercial buildings, the heating is typically supplied by an air handling unit (AHU) which uses either a steam/hot water heating coil or an electric coil to provide heat. These AHUs serve multiple areas and are often run continuously throughout the day and night to maintain comfort in the buildings. The continuous operation is inefficient and wastes resources. In the residential sector, heating is mainly supplied by air treatment through a furnace, hot water or steam powered radiant heating, or electric heat.

The generation of heat for energy harvests more than two-thirds of the total amount from the burning of fossil fuels, either through a boiler steam/hydronic system or indirectly through the generation of electricity in large power plants (International Energy Agency, 2014b). These power plants produce greenhouse emissions that pollute the atmosphere. In 2014, the U.S. produced a total of 2,043 million metric tons of carbon dioxide as a byproduct of electricity generation (U.S. Energy Information Administration, 2015). Local power generation for heat production has the same effect of pollution on a smaller scale.

Large power plants are being targeted by the Environmental Protection Agency (EPA) with a recent Clean Power Plan Proposed Rule that stated "Nationwide, by 2030, this rule would achieve CO_2 emission reductions from the power sector of approximately 30 percent from CO_2 emission levels in 2005" (Environmental Protection Agency, 2014, p. 4). Stated in the plan benefits (Fact Sheet, 2014): "The science shows that climate change is already posing risks to our health and our economy" (p. 1). The rule is designed to protect the health of citizens and the climate while driving technological advancements to keep American energy companies competitive. The need for this new EPA ruling also is validated by a recent report released by the World Meteorological Organization (Warrick, 2014), which shows that CO_2 levels in the atmosphere are at their highest point since data started being collected and are rising at higher rates than ever before. To put into perspective the impact the EPA mandate can make, the annual energy use of the U.S. is disproportionately high in relation to its population. In a study from 2005 conducted by British Petroleum, the U.S. consumed around 24% of the world's total annual supply of energy, while only containing 4.6% of the world's population (Stewart, 2008). The reduction of the U.S. greenhouse gasses would certainly help global greenhouse gas production.

Along with the EPA mandate and climate reports, building codes are focusing even more on efficiency and renewable energy. ASHRAE 189.1 is the green building standard that is most often cited. It states "*Building project* design shall show allocated space and pathways for future installation of on-site renewable energy systems and associated infrastructure" (ANSI/ASHRAE/USGBC/IES Standard 189.1-2014, 2014, pp. 22). Other standards such as the International Energy Conservation Code are also frequently adopted.

These evolving building codes along with the push for emissions reductions, more efficient power systems, and the eventual necessary shift from fossil fuels are main drivers in the development of alternative systems that can produce heat and power. The technical advancements noted in the EPA report include the development of alternative energy systems, such as the one studied in the research. The use of solar to provide thermal heating has long been investigated and has shown promise. The use of heat pumps has been common for decades to supply heating in homes and other settings. The combination of these heat sources provides a system that can be robust enough to handle a real demand load while harvesting the power of the sun and minimizing the amount of fossil fueled electricity required.

1.4 Statement of Purpose

The purpose of this research is to ascertain the contributions of the solar thermal and the heat pump resources in a combined hybrid hydronic heating system and observe the relationship between the two heat sources. A subsequent necessity of the research is to successfully integrate the heat pump with the solar thermal hydronic system so that the combined system will reliably operate. A solar assisted heat pump hydronic system was designed and built to facilitate the research. Appendix A shows the full scope of work that was completed. This system effectively allows for a large reduction in energy usage because the solar panels provide a significant portion of thermal energy without any direct cost to the user other than the electricity used to drive the pumps and valves for the system control. The heat pump is also able to provide energy at a higher efficiency compared to conventional methods. The research was conducted in tandem with another colleague who focused on the pumping systems in the hydronic system. The pumping efficiencies along with the primary and secondary pumping loops were investigated to ascertain the performance of the pumps and related components (Krockenberger, 2015).

For this research, the heat pump is operated in a stand-alone manner, allowing it to control itself as it would in a normal setting of a heat pump hot water heater. The interaction of the operation of the solar resource with the heat pump operation and the integrated storage tank are the variables of the most interest. A control design that meets the heating requirements while keeping within the control design parameters is a necessity for the integrity of the research. The energy that the system saves will reduce the electricity that is produced by the burning of fossil fuels.

1.5 Assumptions

The assumptions of this research are as follows:

- The temperature of heat pump supply air will remain constant
- Weather patterns will follow historical trends

1.6 Limitations

The limitations of this research include:

- The thermal storage tank is possibly under-sized.
- The heat pump is located in a conditioned space
- Use of existing solar thermal collectors
- Heat pump hot water heater is used as a packaged system

The system utilizes existing components of the solar thermal array, which was used in its current state. The storage tank is a commercially available unit combined with a heat pump that was not modified in any way for the purpose of research.

1.7 Delimitations

The delimitations of this research include:

- The integration and interaction of the heat pump and solar thermal panels will be the main focus, not the whole system or the pumping system.
- The data will be collected during a 17 day period.

- The control algorithm will not be tested in all weather conditions or seasons.

1.8 Definitions

AHU – (Air Handling Unit) "These units have a fan, a heating and cooling coil, and a compressor if chilled water is not available for cooling. Multizone units are arranged so that each air outlet has separate controls for individual space heating or cooling requirements. Large central systems distribute either warm or cold conditioned air through duct systems and use separate terminal equipment such as mixing boxes, reheat coils, or variable-volume controls to control the temperature to satisfy each space" (*2012 ASHRAE handbook*, p. 11.11 2012*).*

ASHRAE – American Society of Heating, Refrigeration, and Air Conditioning Engineers

BAS – (Building Automation System) "A network of integrated computer components that automatically control a wide range of building operations such as HVAC, security/access control, lighting, energy management, maintenance management, and fire safety control" (Dictionary of Construction, n.d.).

BTU- (British Thermal Unit) "The quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit at a specified temperature (as 39°F)" (Merriam Webster's Online Dictionary, n.d.)

Chiller – "A piece of equipment that utilizes a refrigeration cycle to produce cold (chilled) water for circulation to the desired location or use" (Dictionary of Construction, n.d.).

COP – (Coefficient of Performance) a constant that denotes the efficiency of a refrigerator, expressed as the amount of heat removed from a substance being refrigerated divided by the amount of work necessary to remove the heat. (Coefficient of Performance, n.d.)

Environmental Chamber – A commercial freezer used in the Applied Energy Lab at Purdue University to test various HVAC configurations in and to simulate an insulated area for research purposes.

EPA – (Environmental Protection Agency) "an independent federal agency, created in 1970, that sets and enforces rules andstandards that protect the environment and control pollution" (EPA, 2015).

Heat Pump – An apparatus for heating or cooling (as a building) by transferring heat by mechanical means from or to an external reservoir (as the ground, water, or outside air) (Merriam Webster's Online Dictionary, n.d.)

HVAC – Heating, ventilation, and air conditioning

SEER – (Seasonal Energy Efficiency Ratio) "SEER indicates the relative amount of energy needed to provide a specific cooling output" (DOE, 2012).

VFD – (Variable Frequency Drive) An electronic device that manipulates the output signal to varying hertz to control a piece of equipment, usually a fan or pump. (*2012 ASHRAE handbook*, p.45.12, 2012*)*

1.9 Chapter Summary

This chapter has introduced the specific problem being explored in this thesis. An overview of the research question, significance, purpose has been given along with definitions that have been stated which will be expanded in the literature review. The limitations, delimitations, and assumptions for the research of implementing such a system have been covered. The next chapter provides an overview of more detailed research which exists in relation to this project.

CHAPTER 2. LITERATURE REVIEW

The review of the literature has a three-fold purpose: to discuss prior design of heat pumps and solar thermal systems, to compare similar heat pump solar integrated designs, and finally, to illustrate different control designs that have been used with these types of systems. This approach provides a robust foundation upon which the research of this thesis was built upon. Recommendations to guide the research are also introduced through the review of literature.

2.1 Heat Pump and Solar Thermal Systems

Heating has been one of the most basic concerns of man since the dawn of time. To this day, the most common source of heat is still the most basic: fire. With the perpetual forward march of technology, this source of heat is being contested. Two forms stand out the most: the manipulation of phase change (the heat pump) and the harnessing of the sun (solar thermal). Rising energy costs, advancements in technology, and government incentives are driving the switch to alternative heating sources.

Solar thermal systems have been in development for many decades along with heat pump systems for heating residential buildings. Lloyd and Kerr (2008) did an analysis of commercially available solar thermal systems and heat pump systems for domestic water heating in New Zealand. The measurement of efficiency for both systems was normalized using a coefficient of performance (COP). The efficiency of a typical electric water heater was stated to be 0.67 COP, which was used as a baseline in this study. It should be noted that the COP recorded is that of the system component, not of the full system itself.

Carrington et al. (as cited in Lloyd & Kerr, 2008) conducted multiple tests in a laboratory environment with heat pumps that produced COPs peaking at 2.95. When the same group installed the systems around New Zealand and measured their performance in-situ, the COP of the heat pumps dropped significantly, ranging from 1.06-1.7. This is still using a baseline COP of 0.67. The understanding is that poor installation and the lack of insulation on pre-existing storage tanks was partially to blame for the drop in performance.

Various other researchers' work was compared to the work done earlier by Lloyd and Kerr. Morrison, Anderson, and Behnia (2003) produced a COP of 2.3 for a heat pump in the laboratory based on climatic conditions in Sydney, Australia. Different locations of the condenser produced different COP results, with the integrated condenser producing the highest value of 2.3. Lloyd himself (2008) verified this COP calculation by field testing at an Aboriginal settlement. The increase of the available solar insolation may have produced more favorable results than if the system had been used in a different environment. A lower COP of 1.64 as found for a Floridian installation by Merrigan and Parker (Lloyd & Kerr, 2008).

Lloyd and Kerr also investigated solar thermal system research. Researchers Prud'homme and Gillet, Andersen, and Knudsen (as cited in Lloyd & Kerr, 2008) all had contributing material in the form of solar thermal laboratory or field testing. The consensus between Prud'homme and Gillet and Knudsen was that a COP between 1.5 and 1.7 could be achieved in the field. These systems used flat plate collectors. Knudsen (as cited in Lloyd & Kerr, 2008) measured a large sample of laboratory COPs as 1.9, but in the field the results were a COP of around 1.7. A significant amount of variability was found in many of these studies that took place in the field, attributed to the wide variance of usage by the residential end user.

The Department of Energy (DOE)'s Building Technology Office conducted research more closely related to the research to be done in this thesis. Backman, German, Dakin, and Springer (2013) reported on the design, implementation, and testing of two heat pump systems used for radiant delivery in high efficiency houses in the American southwest. Data was collected for a one year period. Both systems employ an air to water heat pump, a circulation pump, radiant floor circuits, and a fan coil. The fan coil provides air circulation for heating and cooling. A secondary function of the fan coil is to control condensation of the concrete slab used for radiant heating. The functionality of the fan in this capacity was also investigated. Both houses were modeled in TRNSYS to be able to test the designs in other areas and climates (Backman, German, Dakin, & Springer, 2013).

The first house was called the Cana house. It is a 3,300 ft^2 straw-bale dwelling located in northern California where the climate is hot and dry. The system employed in the house is an air source heat pump that offers heating, cooling and hot water. Normally, heat pumps are tested based on a set DOE testing procedure. Due to the procedure not taking into account the additional load of the domestic water production and the air to water heat pump design, the European standards EN 14511 and EN 15316 for rating EER and COP was used. "The heating efficiencies were tested at outdoor conditions of 45°F and a supply temperature of 95°F." (pp. 7). During this test, the heat pump achieved a COP of 4.37 for heating. Over the entire year of testing the performance of the heat pump in the Cana house was slightly lower at 4.18. The heat pump in the function of domestic water heating had a much lower COP of 1.63. This poor performance was attributed to a lack of adequate heat transfer between the heat pump and hot water storage tank (Backman et al., 2013).

The second house built and tested was the Super Energy Efficient Design (S.E.E.D.) house in Tucson, Arizona. The house is a 2,000 ft^2 dwelling that uses a 13 SEER heat pump dedicated to space heating and cooling, unlike the Cana house. A 30 gallon storage tank is also incorporated to prevent short cycling of the system. Over the course of the testing year, the S.E.E.D. house heat pump had a COP of 3.26 (Backman et al., 2013).

On the comparison of heat pumps to solar thermal systems, Lloyd and Kerr (2008) made the conclusion " that there is not too much difference in performance between solar systems that have a permanently connected electric boost backup and heat pump systems over a wide range of environmental temperatures" (pp. 1). In a solar system that uses a circulation pump, there will be a minute amount of electricity needed.

For the use of a heat pump as a domestic water heater, the relatively low COP of 1.64 in the Cana house concurs with much of Lloyd and Kerr's findings. In this capacity, a much higher temperature must be produced to maintain adequate water supply as compared to a radiant hydronic system. Relegating a heat pump to just hydronic heating duties will provide better performance for the system. Backman et al. (2013) also made note that further research would be required to develop packaged air to water heat pumps, along with zone controls. With these components developed along with increasing familiarity and lower manufacturing costs, the system will be a much more viable option.

Morrison, Anderson, and Behnia (2003, p. 152) found in their modeling of the heat pump system that a heat pump coupled to a solar thermal system was able to provide at least 20-30% savings over a standalone heat pump model. With this information, the combination of solar thermal and heat pumps is the logical evolution of the technology.

2.2 Combined Solar Heat Pump Systems

Combining solar thermal systems with heat pumps is the next step in creating a robust, energy efficient source of hydronic heat. For this type of system, there are two main sub-systems: direct expansion solar assisted heat pumps (DX SAHP) and indirect expansion SAHPs.

2.2.1 Direct SAHP

Direct SAHP systems, also called solar boosted heat pumps, utilize the solar collector as the evaporator for the heat pump cycle in most cases. This means that the heat transfer medium must be some sort of refrigerant to operate in the heat pump cycle. The research this thesis will cover will not be utilizing a direct expansion SAHP system, but there is valuable information in the experimentations.

Li, Wang, Wu, and Xu (2007) conducted an experimental analysis on a DX SAHP to heat domestic water in the climate of Shanghai, China. The system consisted of a 150L tank, a condenser, a hermetic compressor, a thermostatic expansion valve, and 4.2m^2 of unglazed flat plate solar collectors to act as the evaporator in the heat pump cycle. The system used R-22 as a refrigerant. While this particular refrigerant is being phased out in much of the world, it is still abundant in China. A month's worth of data was collected in the spring, from April 4th to April 31st. At its highest performing point, the system achieved a COP of 6.61. At its lowest point in testing, the system only achieved a COP of 3.11. This low performance test was during an evening storm when there was no measureable solar insolation to boost performance. The average COP of the system over the course of the experiment was 5.25. Even with the low point being 3.11, the performance of the system is much better than those recorded by solar thermal or standalone heat pump units. One of the driving factors for increased performance is the amount of solar insolation available. With the higher irradiance, temperatures in the evaporator were higher, and thus the COP was raised (Li et al., 2007).

The tank used for the experiments is a 39.6 gallon tank, slightly smaller than the 50 gallon tank to be used for the research of this thesis. The collector area is also slightly smaller than the 7.7m^2 that will be used for this research as well. The average solar irradiance was 709 W/m^2, which is similar to West Lafayette, IN, where the experiment will take place for this research. While a DX system will not be used, it gives hope that the combination system will perform well.

A series of tests more concerned with the effects of load cycles for a DX system was investigated by researchers in Australia in 2007. Anderson and Morrison (2007) conducted three tests to find the varying COP of the DX SAHP system when it was under varied loads. The system used a storage tank of 270 liters, with an average daytime temperature of 25°C (77°F) and an average solar radiation of 1000 W/m^2. The first test was to heat a full tank of cold water. The COP of the heat pump during this test was over six for daytime and four for nighttime. For the second test, half of the tank was cold water and the other half hot water. The COPs of this test were lower, with four and one half being the daytime COP and three being the night time COP. The final test drew off small amounts of water from the heated tank over the course of a full day. The COP for this test was three in the day and two and one half during the night.

The COP of the heat pump degraded as there was less and less of a temperature differential in the storage tank. This is important since the research to be conducted will most likely draw from a tank that is at least half hot. Although not directly related, it provides a basic idea of the performance degradation that may occur due to different temperatures in the tank. Anderson and Morrison (2007) noted that the temperature stratification of the storage tank had a large impact on the heat pump's performance. A point should be made that due to the use of refrigerant in the solar collectors, ambient heat was able to be collected and utilized. For the system in this research, propylene glycol will be used a low pressures; therefore there won't be able take advantage of the phase change of a typical refrigerant to gain thermal energy.

2.2.2 Indirect SAHP

Overall the DX solar heat pump systems have a higher COP than their standalone components, but there are drawbacks to this type of system, mainly that the heat pump is not decoupled from the solar thermal system. If the two were separate, there could be advantages such as providing heat solely through solar thermal energy, and the heat pump being independent of outdoor temperatures in some cases. Also, there are many configurations of indirect solar thermal heat pump systems that can be tailored to specific needs.

Sterling and Collins (2012) used the TRNSYS software to model an indirect solar thermal heat pump system they dubbed i-SAHP. This model compared the i-SAHP system to a normal solar thermal system and a conventional electric water heater. All of the models were tested with the same load profile: four 15 minute draws at various points during the day. The main domestic water tank is a 350 liter tank and is used in all of the simulations.

The first design is a conventional electric water heater setup. The systems feeds a tank with two heating elements: one at the top of the tank controlled to 55°C (131°F) and one at the bottom controlled to 30°C (86°F). The second design was a solar thermal system that used a heat exchanger to transfer the heat to the hot water tank. There were $4m^2$ of flat plate collectors. The pump for the solar loop was turned on when the leaving temperature of the solar collectors was 5°C (9°F) higher than the bottom tank temperature (Sterling & Collins, 2012).

The design of most interest is the i-SAHP. This system utilizes the solar thermal loop and feeds into a 500L float tank. The fluid in the solar loop is a 50/50 mix of water and glycol, the same that will be used for the research in this thesis. The float tank acts as a large thermal capacitor to feed the heat pump when the temperature coming from the solar panels is below a threshold of 55°C (131°F). At all other times, the heat pump will run. Modeling various inlet temperatures for the float tank and the hot water tank, the i-SAHP reached a COP ranging from two and one half to five. When the temperature is above 55°C (131°F), the heat exchanger that is between the float tank and the hot water tank will be used. Over the course of modeling, it was shown that 58-67% of the heat supplied was done so by the solar thermal loop (Sterling & Collins, 2012).

The results of the modeling show that “the dual tank i-SAHP system used the least amount of energy and gained the most solar energy” (Sterling & Collins, 2012, pp. 15). Due to typically lower float tank temperatures for this system the COP of the heat pump increased and more solar energy was harvested. Also, the heat pump was shown to heat a larger area of the hot water tank compared to the electric heating elements. For total electrical consumption, the electric water heater used 20,070 MJ, the solar thermal system used 8714 MJ, and the i-SAHP used 7387MJ. Sterling and Collins (2012) make a point that the next step for this type of system is to investigate other configurations and experiments must be conducted to gain better knowledge.

A paper that is more in line with the research to be conducted is *Investigation of the Performance of a Combined Solar Thermal Heat Pump Hot Water System* by Panaras, Mathioulakis, and Belessiotis (2013). In this particular paper, the authors have tested a physical apparatus of a combined solar thermal heat pump system and used experimental data to create a model for component and system design. The system was tested according to the European Committee for Standardization (CEN) for domestic hot water heaters (Panaras, Mathioulakis, & Belessiotis, 2013).

The design of the system consisted of two flat plate solar collectors connected to a domestic hot water tank. A heat exchanging coil was inserted into the bottom of the tank to act as an indirect solar thermal loop. A heat pump was connected to a heat exchanger that acted as the condenser for the heat pump and also looped into the domestic storage tank at the top. A set point of 55°C (131°F) was implemented according to CEN testing regulations (Panaras et al., 2013). The heat pump was activated when the tank temperature fell below 52°C (126°F) and disengaged above 55°C (131°F). The solar circulation pump was engaged any time the temperature of the solar collector outlet was above 5°C (9°F) of the temperature of the storage tank (Panaras et al., 2013).

The system was tested in four separate scenarios the gather data to help develop the model. The complete system operation was tested in high radiation and a low radiation scenario, a solar only scenario, and auxiliary only scenario. For the testing of the complete system on a high radiation day, the heat pump reached a COP of 3.59. The heat pump contributed 33% of the heat energy while the solar thermal panels contributed 67% of the heat energy. This was the highest efficiency operation. On a low radiation day, the total system had a solar thermal contribution of 41% and a heat pump contribution of 59%. The COP was 3.04. Two more scenarios were tested. For the solar only test, no COP was recorded. For auxiliary only operation, the heat pump had a COP of 2.89. As can be seen from the tests, the high radiation total system test produced the best COP for the heat pump and the most solar percentage (Panaras et al., 2013).

These results were used to build a model in MATLAB and tested for a period of six months. Using this model, it was shown that the tank temperature and ambient temperature were "critical parameters" for performance (Panaras et al., 2013). When the temperature of the tank was higher, the COP of the heat pump was lower due to the efficiency of the cycle being lowered by the temperature differential of the tank and refrigerant. The ambient temperature directly affects the side of the evaporator of the heat pump cycle. Using a set point of 55°C (131°F) for the tank, there were 70% savings over an electrical or natural gas system using an efficiency of 90%. When the tank set point was raised to 65°C (149°F), the savings dropped to 61%. Based on the findings in this paper, a lower tank temperature set point will be used for this research.

More environmentally progressive systems have also been investigated, specifically heat pumps using CO_2 as the refrigerant. These systems have shown promise in heating applications, and have been investigated in that regard by Deng, Dai, and Wang in an investigation of a solar CO_2 heat pump combi-system (2013). The researchers investigated the performance optimization and feasibility of a system that uses a CO_2 heat pump with solar thermal panels for radiant floor heating and domestic hot water heating. A TRNSYS model was also built to validate the optimization methods used. The system consisted of a heat pump feeding a storage tank indirectly with a solar thermal system connected in a similar fashion. The control for the heat pump was based on the tank temperature. When the temperature of the tank fell below 55°C (131°F), the heat pump engaged. When the outlet of the solar thermal collectors was below the temperature of the bottom of the tank where the solar collectors fed, the solar circulation pump would run. This is a simple control design that was used as a baseline for the optimization (Deng, Dai, & Wang, 2013).

TRNSYS tests were run in the winter months with climate information from Shanghai, China. For initial testing parameters, an existing solar thermal heat pump combi-system was used. The storage tank was 500L, the area of the solar collectors was $30m^2$, and the set point of the heat pump was 60°C (140°F). From this starting point, the researchers found that the normal operating parameters for the heat pump inlet temperature were between 45°C - 65°C (113-149°F) with an ambient temperature of (-5)°C - 5°C (23-41°F). Further operation of the system in TRNSYS showed that the average COP of the heat pump was 2.38 and the average solar fraction of the system was 69%. The average tank temperature was 50.9°C (123°F). The researchers found that the system was not economically viable in China at the moment. To allow this system to be viable, the addition of a solar driven absorption chiller was recommended (Deng et al., 2013).

2.3 Control Designs

All of these systems have similar indications of what the most important parameters are for the control of a heat pump solar thermal system. Ambient temperature, heat pump control set point, tank size, and others. The previous research reviewed here will act as a guideline for the research to be conducted for this thesis.

For the supply temperature from the storage tank, the set point hovered around 50-60°C for the research reviewed. A purely solar powered system may have to increase the set point of the supply temperature due to the transient nature of the solar resource. A high temperature of 60°C (140°F) was used to provide adequate heating for an AHU and corresponding ducting by Mammoli, Vorobieff, Barsun, Burnett, and Fisher (2010) The solar resource can also be taken advantage of the raise this threshold if there is available energy. This can allow the system to provide heating when there is no solar available and without using a heat pump (Sterling & Collins, 2012). Both Sterling and Collins (2012) and Panaras, Mathioulakis, and Belessiotis (2013) had a high limit temperature set point of 55°C (131°F) in the storage tank when using the heat pump. The average tank temperature for the simulation performed by Den, Dai, and Wang (2013) were 51°C (124°F). With tight control algorithms, it may be possible to control to a lower point for leaving tank temperature. Although the system design is different, the water loop heat pump system controls optimized by Lian (2011) show that for a better COP from the set of heat pumps in the system, the air duct temperatures should be lower, which in the case of the research to be conducted is the condenser temperature in the tank.. Thus, if the tank temperature is set lower, the COP of the heat pump will be higher.

Many of the problems of solar thermal systems come from the transient nature of solar thermal energy. The most basic idea is to create a buffer for that transient action, which is a storage tank for this type of system. The drawback of a tank is that the energy will eventually be lost as well through radiation and other methods of energy dispersion. Research done by Ucar and Inalli (2008) found through TRNSYS modeling that an underground tank proved to be the most efficient system for retaining heat from a solar thermal system, saving 15% of energy over an insulated above ground tank. Increasing the size of the tank increased the solar fraction used by the system as well. This is important for divesting the system completely from electrical dependence.

Due to the nature of the research to be conducted, the size of the tank is already set at 50 gallons, but this information will be important for future research. Another way to utilize more available solar energy for commercial buildings is to charge the tank during hours of disuse, such as weekends when a building is not scheduled (Mammoli et al., 2010). Although Mammoli et al.'s system was much larger in scale, this strategy will be utilized in the research to be conducted.

Other research was reviewed related to thermal stratification in the storage tank. Depending on where the heat pump condenser coil and inlet from the solar thermal system is located, this can greatly improve the efficiency of the system. Anderson and Morrison (2008) noted that for their system tank stratification had "a significant effect on heat pump capacity" (pp. 1394), and suggested that the coil of the heat pump condenser be placed at the bottom of the tank to improve performance. The heat pump to be used in the research of this thesis concentrates its coils in the lower portion of the tank. Sterling and Collins (2012) also modeled their system with a stratified thermal storage tank to increase the performance of the heat pump.

2.4 Chapter Summary

Through the reviewed literature, this research was developed to focus on heat pump operation, solar thermal operation, and the subsequent control of the two systems. While heat pump systems can provide stable operation while using less electricity, and solar thermal systems can provide almost power-free operation, and thus the combination of the two were investigated further. This combination of heat pumps and solar thermal systems are proven to show improvement over their separate component systems, but the control of an actual system was explored to provide a stronger knowledge of the practical potential of this type of system. Knowledge gained through the review of literature has assisted to the development of the methodology used in this research.

CHAPTER 3. METHODOLOGY

The basic framing of the research and the motivation behind it was discussed in the introduction, while the foundation on which the research has been based was laid out in the literature review. The main goal of the research was to analyze the workings of the solar thermal heat pump assisted hydronic system and the relationship between the solar resource and the heat pump. The creation a control system that successfully integrated the solar thermal and heat pump heat sources together to provide adequate heating to the system was an additional goal.

The ultimate goal for the Applied Energy Lab (AEL) in regards to this system is to have a fully functioning hybrid hydronic system in place by the end of the research period. Appendix A provides a statement of work that shows the design and construction of the apparatus necessary prior to the conducting of the research. It should be noted that parallel research was being conducted at the same time as this research, with that research focusing on the pumping system. The combined efforts of the two research projects were paramount to the success of the overall end goal of creating a fully operational hydronic system.

3.1 Apparatus Design

Prior to the development of this research, the Applied Energy Lab (AEL) at Purdue University used an antiquated hydronic heating system developed in the late

1980s. The system, seen in Figure 3.1, was built as a training device, with no real concern for energy savings. The system used electric heating elements in large copper storage tanks, along with four individual pumps and very basic control valves.

Figure 3.1: Old Hydronic System

The research idea provided the impetus to replace the old electric powered hydronic system with a new design that utilizes the available resources in the AEL and is in line with the prevalent ideas of energy savings and efficiency. The system was broken into two main components: the mechanical system and the controls system. The mechanical system includes the piping, pumps, valves, solar thermal panels, heat pump hot water heater, and supporting mechanical components. The controls system is comprised of the sensors, wiring, control modules, and control interface used to operate and manipulate the system. The a large portion of the new system can be seen in Figure

3.2, which includes the heat pump hot water heater, the beige cabinet that houses the control modules, the secondary pump, and the control valves for the secondary loop branches. The new system allows for more transparency with the individual system components.

Figure 3.2: Mechanical System Layout

The mechanical system for the solar thermal heat pump hydronic system includes multiple components to provide heat to the various loads. The heart of the system is the heat generation, comprised of the heat pump water heater and the solar thermal panels. The supporting systems are the pumps, valves, and heat exchangers used to distribute the heat. A 50/50 mix by volume of propylene glycol is used as the thermal transfer fluid. The even ratio was chosen for its freeze protection properties, allowing the system fluid temperature to drop to negative 28°F before freeze damage would occur. The system piping design is of a primary-secondary loop design and is insulated with half inch thick closed cell EPDM rubber insulation.

Figure 3.3 shows the primary loop for the hydronic system. The glycol mixture is fed through the primary loop pump into five individual branches to the solar collectors to gain thermal energy. After being pumped through the collectors, the glycol mixture is collected and returned from the roof to the laboratory and fed into a plate and frame heat exchanger. The purpose of the heat exchanger is to allow for any excess solar thermal energy to be bled off when it was not needed or when there is a potential for damage to the system. A three-quarter inch ball valve controls the flow of domestic water through the heat exchanger, which is discharged into the building's drain system after cooling the glycol mixture. The glycol mixture is transferred from the heat exchanger to the heat pump hot water heater with an integrated storage tank. Once the glycol mixture is either heated or simply stored in the tank, it then continues from the outlet of the heat pump hot water heater to either the secondary loop or to the primary loop pump where the glycol is circulated back to the roof to gain more thermal energy.

A bypass in the piping controlled by a two way valve was included in the primary loop to allow for the charging of the glycol mixture when there was a low temperature condition. As seen in Figure 3.3, the bypass, labelled KNSSBV, short circuits the primary loop by connecting the loop before the primary loop pump and after the solar thermal collectors. This allows for a path from the primary loop pump, through the solar thermal collectors, and back to the primary loop pump. An expansion tank is placed before the primary loop pump to allow for thermal expansion of the glycol mixture, particularly when the bypass is opened to create the short circuit pre-heat loop.

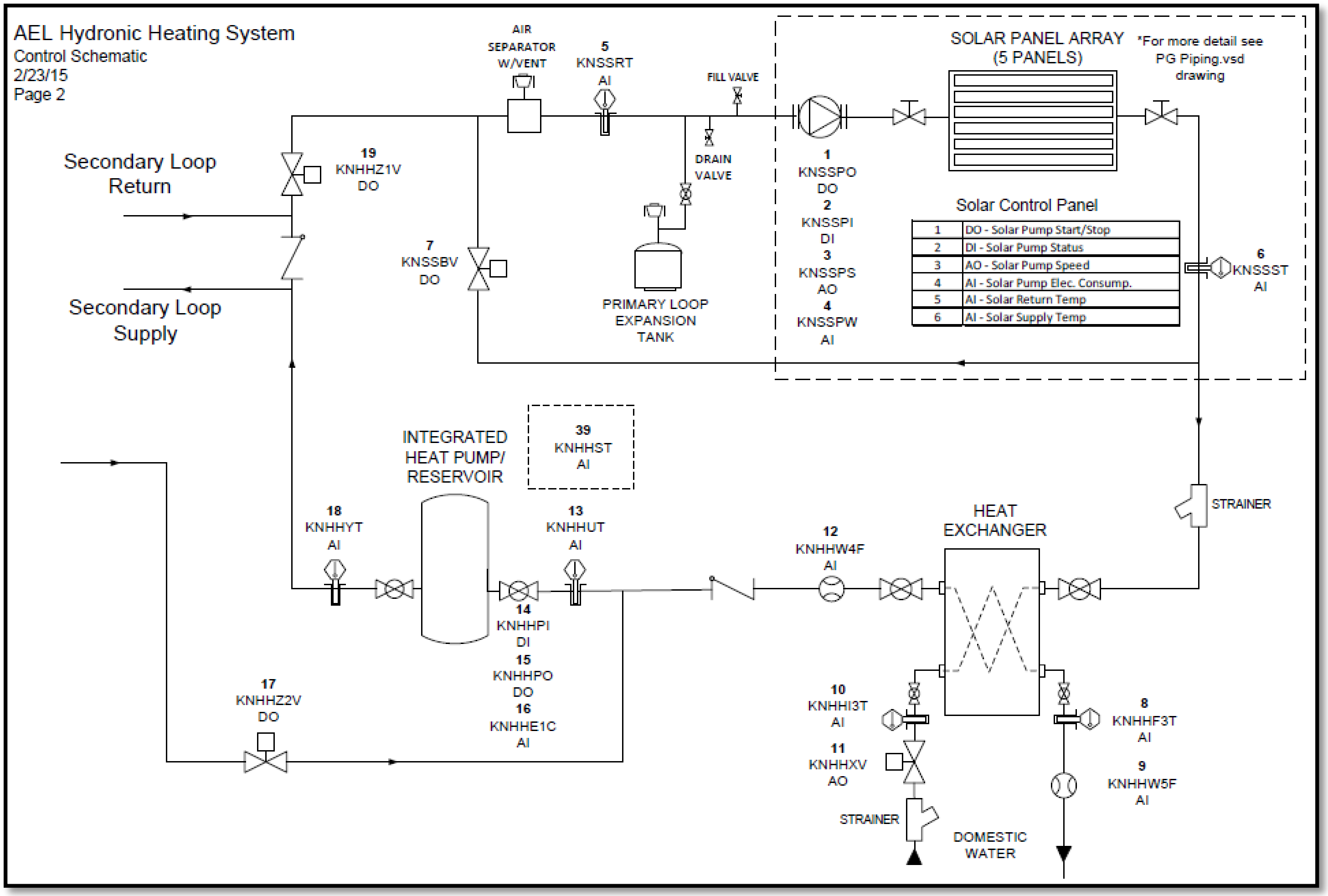

Figure 3.3: Hydronic Heating Primary Loop

Figure 3.4 shows the schematic of the hydronic system's secondary loop. The glycol mixture is distributed to three sources on the secondary loop: two wall radiators contained in an environmental chamber, and a heating coil located in a small commercial air handing unit (AHU) that feed the environmental chamber. Three pressure independent control valves with integrated ultrasonic flow meters control the flow of the fluid through these radiators and the heating coil. Once the fluid flows through the radiators and AHU heating coil, it is collected and fed back either to the primary loop to be circulated through the solar panels or through a bypass, returning to the heat pump hot water heater tank.

The fluid bypass return to the storage tank is controlled with a two way control valve labeled heat pump mode valve (KNHHZ2V), seen in Figure 3.3. The valve is located in a bypass from the return manifold to the hot water heater storage tank inlet. The operation of the valve allows for the secondary loop to act independently from the primary loop, potentially removing the need for the operation of the primary loop pump. A second valve labeled secondary loop bypass valve (KNSSZ1V) located in the primary loop is controlled in tandem with the heat pump mode valve, thus as the heat pump mode valve opens, the secondary loop bypass valve closes. An expansion tank was plumbed into the outlet side of the heat pump hot water heater to allow for expansion of the glycol mixture. The placement of the bypass valves and the expansion tank allows for full operation of the heat pump, secondary pump, and control valves when the secondary loop is isolated.

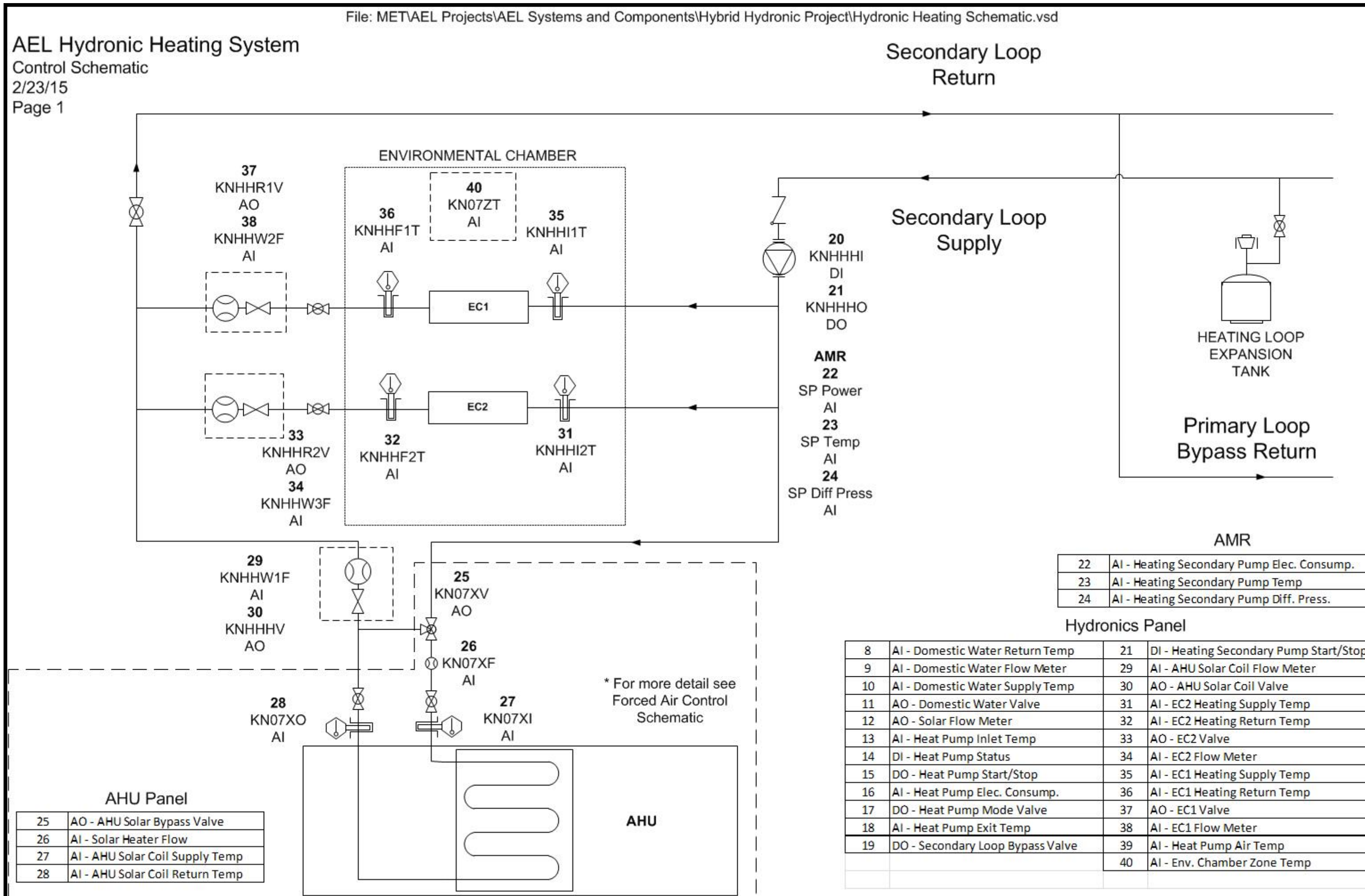

Figure 3.4: Hydronic Heating Secondary Loop

3.1.1 Mechanical System Main Components

There are a total of six solar thermal panels on the roof of the Knoy building seen in Figure 3.5. Five of them are flat plate collectors previously constructed by students. These are the first five collectors starting on the left in Figure 3.5. The sixth solar thermal panel is an evacuated heat pipe array consisting of 21 heat pipes, which is the collector on the far right of Figure 3.5. The heat pipe array is plumbed in parallel with the adjacent flat plate collector. The total area of the collectors is 82.9ft^2. All of the panels are south-facing and angled at 53° to provide better heating performance in the winter from a fixed angle collector. A solar pyranometer was previously installed in the roof and is utilized to measure the solar irradiance.

Figure 3.5: Solar Thermal Panels

A commercially available heat pump hot water heater with a 50 gallon storage tank was chosen for this system. The water tank has two conventional electric heating elements installed in the upper and lower portion, respectively. When the heating set point of the tank was not met by the heat pump alone, the elements are automatically enabled through controls internal to the hot water heater to provide additional heating. Figure 3.6 shows the heat pump hot water heat as it was installed in the AEL. The heated glycol mixture is fed through the top of the tank and piped to the bottom of the tank. The condenser for the heat pump is coiled around the tank, focused mainly on the bottom and center section of the tank. The heat pump is of an air-source design, which collects heat from the air in the laboratory. The AEL is a conditioned space, so a relatively constant supply air temperature of 70°F is available to the heat pump. The space that the heat pump conditions is not the same space that it received air from for the heat pump cycle.

Figure 3.6: Heat Pump Hot Water Heater

The main circulation pump for the secondary loop is a Grundfos Magna 3. The pump features a variable frequency drive, integrated temperature and pressure sensors, and preprogrammed control algorithms to control the flow of the fluid in the system. The pump can also calculate the flow. The control of the secondary and primary loop pumping systems was investigated in another research project.

The AHU has an additional electric heating coil placed after the hydronic heating coil to make up any heating deficiencies. The coil was disabled for this research. The solar heating coil measures 18 inches by 15 inches and is of a two row aluminum design. The AHU itself is scheduled to run for a standard amount of time based on building usage: 6A.M. to 8P.M. This provides the load for the heating coil, thus requiring it to provide heat as necessary when the AHU was operating. The AHU fan provides an average 650 cubic feet per minute of air to the chamber.

The AHU and the radiators condition the environmental chamber which is a large insulated enclosure used for various testing of HVAC configurations and other experiments. The chamber has a footprint of 104 square feet and the interior is eight feet tall. The chamber has a sealed door, with virtually no outside infiltration. The only airflow into the chamber is what is fed to it by the AHU. The chamber itself is highly insulated so as to provide a thermally decoupled test area from the rest of the AEL. The radiators in the chamber are both one and a quarter inch in diameter pipe and are of a simple finned tube design. Radiator EC1 is 29 inches in length, while radiator EC2 is 140 inches in length.

The insulation of the system proved to be a necessary part of the success of the thermal performance of the system. Thermal images were taken prior to insulation and after the installation of the insulation. The reduction in temperatures was on average over 10°F. The increase in temperature allowed for the solar thermal collectors to contribute much more heat to the system than before the installation of the insulation. The thermal images can be seen in Appendix B.

3.1.2 Control System

The heat pump assisted solar thermal hydronic system uses a common building automation system (BAS) from Automated Logic Corporation (ALC). It features multiple control modules and network devices, seen in Figure 3.7, connected to a web based control interface to monitor the system and make changes when needed. The modules have inputs and outputs that are wired to the various sensors and devices in the system allowing them to communicate with the controllers and the web-based graphic interface. More information on the sensors and data collection can be found in Section 3.4.

The hydronic system designed and built for the research utilizes one main control module called a ME812u-LGR. The module has eight outputs and 12 inputs. Connected to this module are two input/output point expanders, called a MEx88u and MEx48u, respectively. In total, 28 inputs and 13 outputs are used. Figure 3.7 shows the panel installation with the three main modules described. A device called an AMR is used to transmit the information available from the secondary loop pump to the BAS via the BACnet open protocol language. This allows for the pump operation data to be transmitted over a single cable and reduces the physically wired point count. Various other ALC modules exist in the AEL that are connected to other systems. A portion of these systems interact with the solar thermal heat pump hydronic system, such as the AHU controls and the combined solar thermal/photovoltaic system. The module diagrams can be seen for the control modules installed for the project in Appendix B.

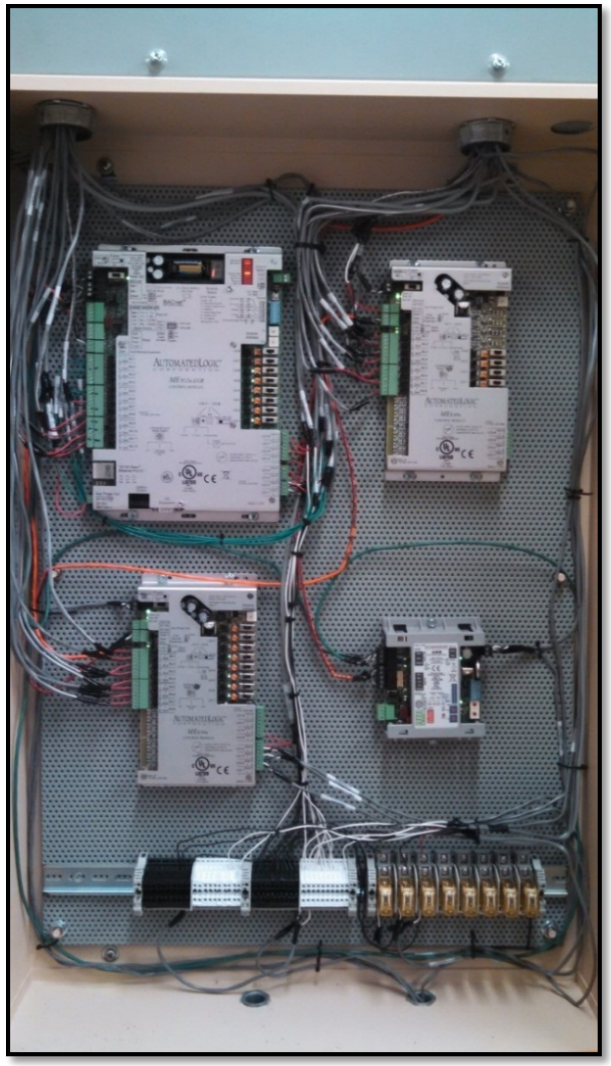

Figure 3.7: ALC Panel Configuration

The BAS has a web-based interface called WebCTRL that provides a central hub for collecting and viewing the various data points from the physically wired control modules and the control code. These data points include temperature sensors, flow meters, and all other sensors, along with the outputs to control the components of the system. Seen in Figure 3.8, the graphic user interface allows the user to monitor and manipulate the control code of the system. A network tree shows all locations and systems visible on the network. Under each of these visible systems is the control code itself. In the control code, alarms, trends, and each individual point property is visible. The logical layout of the software has system inputs on the left, computational logic in the middle, and outputs controlled on the right side. Figure 3.8 shows the input parameters on the left that provide the control for the two output parameters on the right. Software called EIKON Logic Builder was used to create the control code using the inputs and outputs of the system manipulated by a graphic based logic code. The control code can be tested in EIKON Logic Builder and then imported into WebCTRL for use. Any updates made to the code were changed in EIKON Logic Builder and reloaded to the modules themselves.

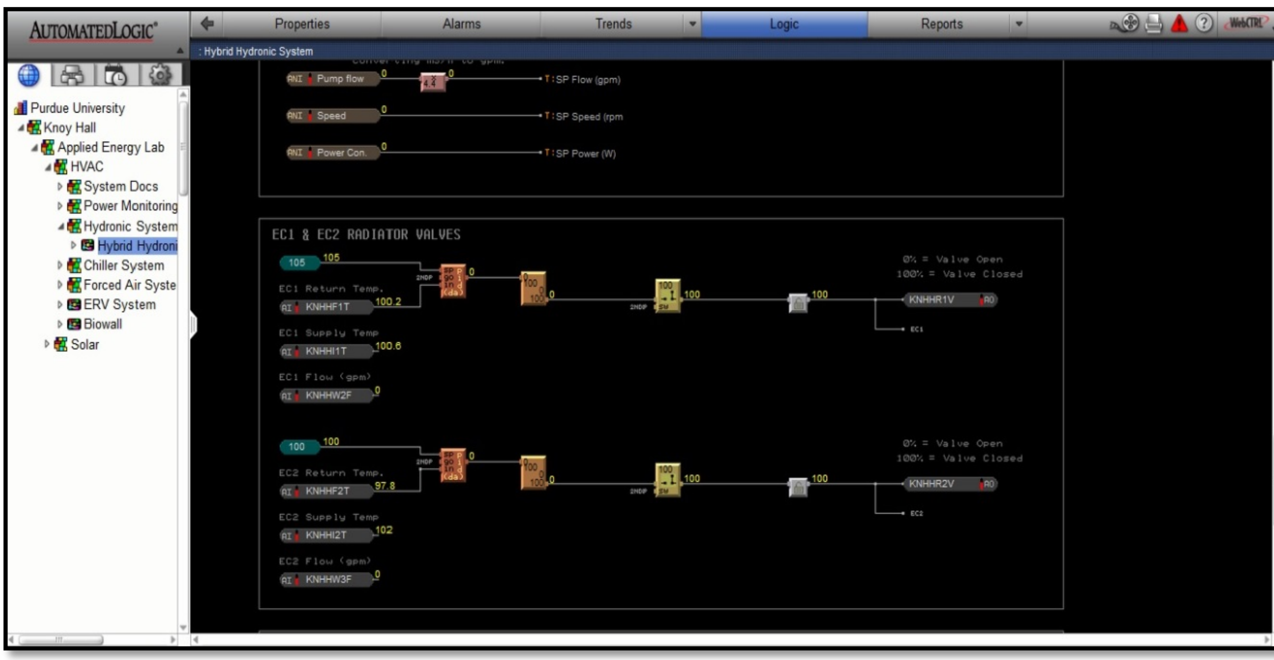

Figure 3.8: WebCTRL Interface

The basic control of the system by the code is laid out in Figure 3.9, which shows the variables that control the components in the system and the resulting modes of operation. The flowchart follows the logic steps used to determine how the system operates.

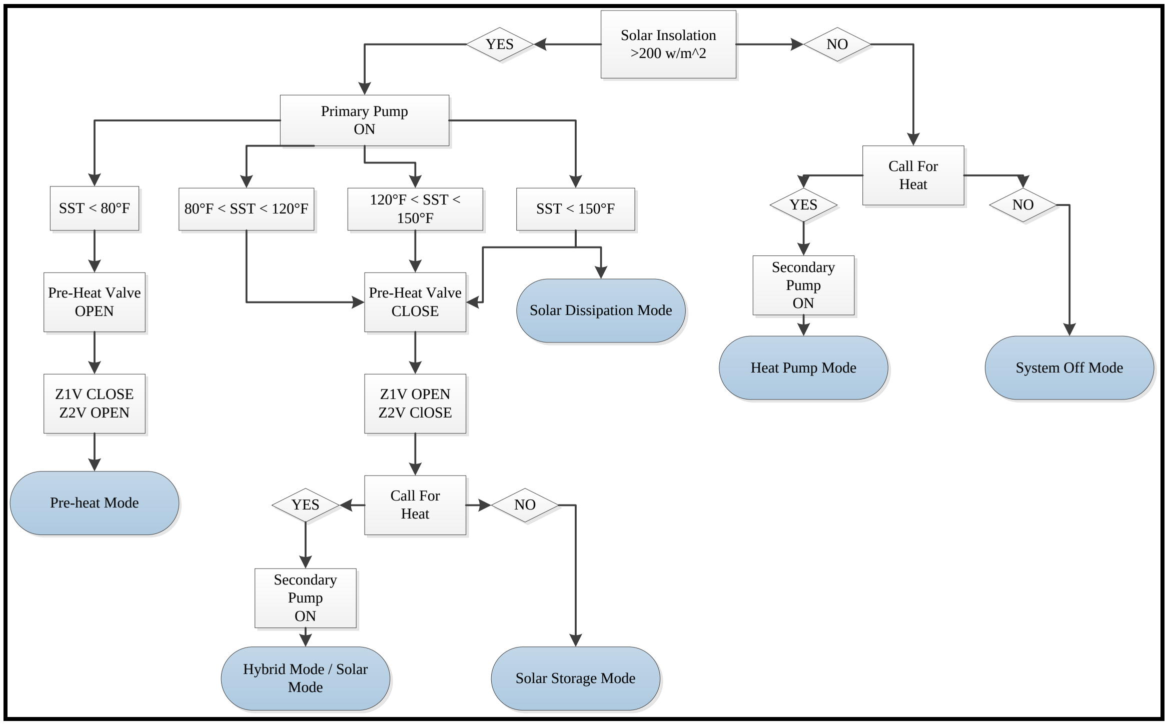

Figure 3.9: Flowchart of Basic System Control

The main independent variables of the system are the amount of solar insolation available, a call for heat, and the solar supply temperature. Solar insolation is the starting point for the flowchart. These variables dictate the control of the primary and secondary pumps, along with the pre-heat valve and zone valves. The modes of operation are highlighted in blue to show the logical path to their operation. For the Hybrid/Solar modes, the two are differentiated by the solar supply temperature (SST in Figure 3.9). Hybrid mode occurs when the SST is greater than 80°F but less than 120°F, while Solar mode occurs under the same basic conditions and the SST is greater than 120°F. The control of the valves is based on the leaving temperature of the loads, and is thus part of the demand side of operation. The call for heat variable is dictated by the demand of the loads, thus including the control from the valves. The full control code that was used during the testing period along with the sequence of operations can be found in Appendix B.

3.1.3 Operational Modes

The solar thermal heat pump hydronic heating system was initially designed to operate in seven distinct different modes:

1. *Solar Pre-heat Mode*[*]*:* The glycol in the solar thermal collectors is pre-heated to increase the temperature entering the storage tank and prevent thermal system shock. In this mode, the pre-heat valve is closed and the primary pump enabled to circulate the glycol mixture through the collectors. When the prescribed temperature set point is reached, the valve opens, sending the heated glycol mixture through the primary loop and to the storage tank.

2. *Heat Pump Mode:* The heating demands are met solely by the heat pump. The heat pump mode valve and secondary loop bypass valve are modulated open and shut, respectively to isolate the secondary loop. The secondary pump and valves operate so as to maintain adequate heating to the three loads.

[*] The solar pre-heat mode and heat pump mode are not completely isolated from one another, as they can be combined to perform their functions simultaneously and separately.

3. *Hybrid Mode:* The solar thermal collectors work in tandem with the heat pump to meet the heating demand. In this mode, the pre-heated glycol is be added to the storage tank to allow for a quicker recovery time of the storage tank temperature if needed.

4. *Solar Mode:* The solar thermal collectors themselves meet 100% of the demand for heat. Solar Mode is the most desirable mode, due to the lowest energy needed to operate the system in this mode. The control code operates as normal, while the heat pump stays dormant due to the storage tank temperature being met by the heated glycol mixture from the solar collectors.

5. *Solar Dissipation Mode:* Any excess solar thermal energy is bled off via a liquid-liquid heat exchanger. This mode is only in operation when in Solar Mode and there is too much heat being produced. The temperature threshold for the mode is based on safety criteria for the mechanical components in the heat pump hot water heater.

6. *Solar Storage Mode:* Thermal energy is stored in the 50 gallon storage tank when there was no call for heating and sufficient solar insolation is available. The primary pump operates and charges the storage tank to the temperature of the heated glycol mixture.

7. *System Off Mode:* There is no demand for heat and the insolation is insufficient, thus both primary and secondary pumps shut off.

3.1.4 Pre-Testing Commissioning Events

An initial system commissioning was completed before the testing began to ensure that the system would function without any major faults that could hinder testing or harm the system. The initial system commissioning checks were done based on a commissioning report that was developed along with specific tests that ensure the proper operation of all components in the system. The commissioning report included tasks such as testing for leaks, confirming valve modulation, and confirming the reaction of the system based on changes made in WebCTRL. The full commissioning report that was conducted can be seen in Appendix C. In addition to the completion of the commissioning report, the two heat sources were tested to ensure that they could produce elevated temperatures in the fluid, thus proving that there were no mechanical impedances that the system's ability to generate heat. A check for heat dissipation was made to ensure the system was operated safely, and errors found in the initial system operation were corrected.

For measuring the performance of the solar thermal panel operation, the system was forced into solar pre-heat mode operation. Figure 3.10 shows the temperature gain of the thick red line from 9:00AM to 11:00AM. A temperature drop around 8:45AM in temperature is the cold glycol on the roof being circulated by the pump through the piping to the sensor location, which is inside the building. The temperature gain begins at 40.5°F and reaches 79.5°F in three hours, a total 39°F gain. The temperature rise over the three hours proves that the solar thermal collectors can gain heat. The solar insolation indicated by the thin blue dotted line also rises at a steady rate in the morning.

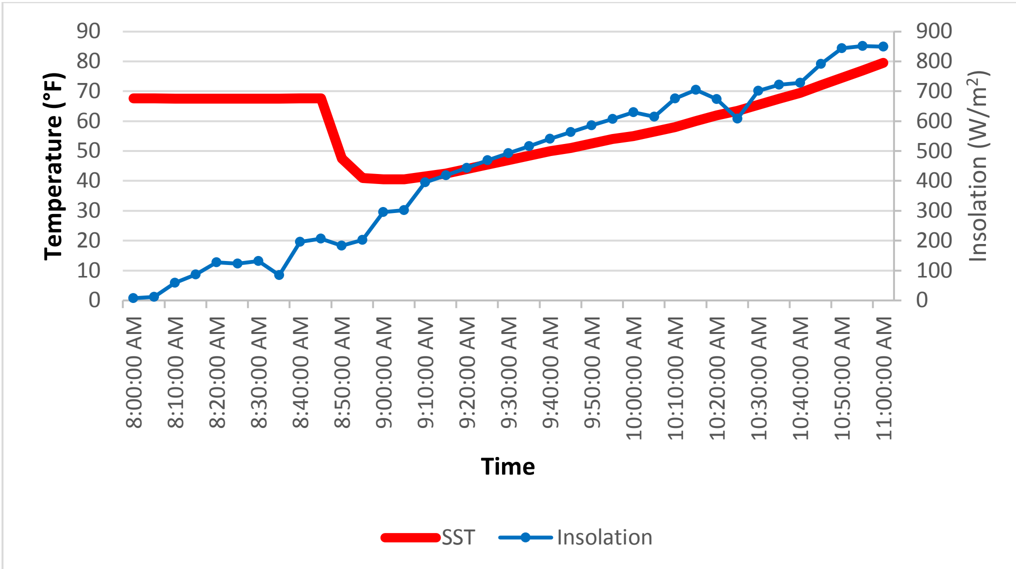

Figure 3.10: Preliminary Solar Collector Operation

For the heat pump test the heat pump was engaged and forced to operate in heat pump mode. A temperature differential between the hot water heater tank outlet and inlet of the heat pump of at least 5°F was required to be maintained for 20 minutes to successfully confirm that there was heat being provided by the heat pump. Figure 3.11 shows the rising outlet temperature of the fluid in blue triangles starting at 8:00AM, and peaking around 115°F before falling off through the afternoon. The outlet temperature of the storage tank is constantly above the inlet or return temperature in red circles from the zones, showing that there is a load in the space. The average temperature differential between the inlet and outlet temperatures is 7.4°F. The heat pump clearly continued to generate heat due to the constant elevation in temperature of the glycol mixture that was leaving the tank versus what was returning from the loads.

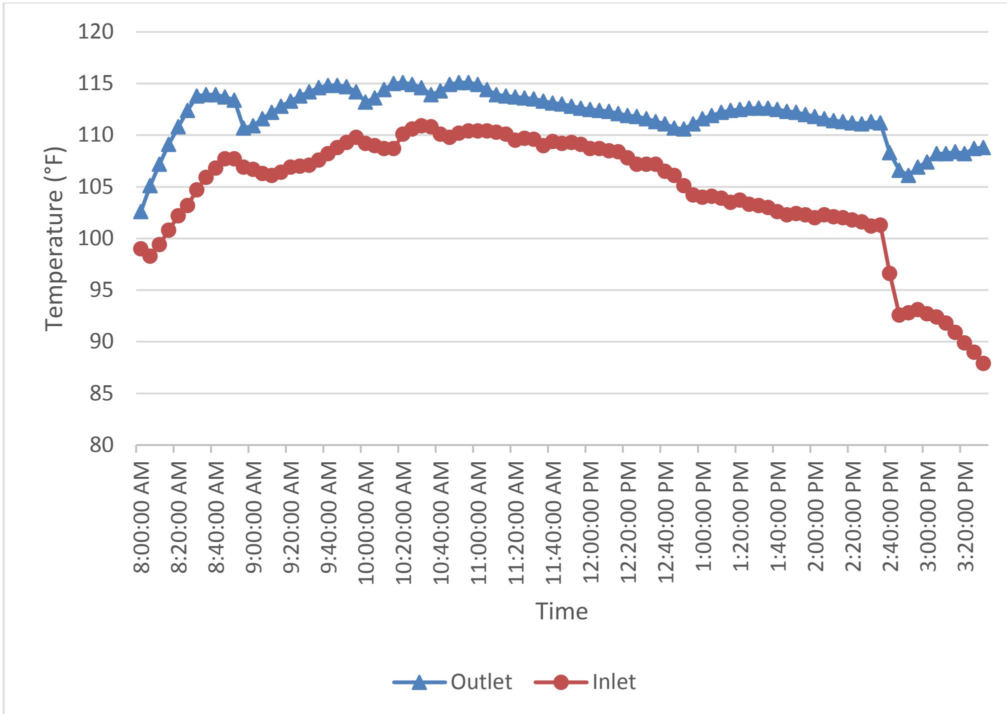

Figure 3.11: Initial Heat Pump Operation Tank Inlet & Outlet Temperatures

Safety for the system is a necessity for reliable operation, and the most important safety function of the system is to prevent the damage of the heat pipes on the roof and the internal components of the heat pump hot water heater. Damage to these components is prevented by maintaining the glycol temperature below 150°F. The heat pump requires this temperature to never be breached to ensure that the manual resettable temperature cut-out devices do not trip. The evacuated heat pipes on the roof will also be damaged if there is no flow through them to remove the heat generated by the phase change of the fluid.

Historically, the temperature has risen to a point where the heat pipes damaged due to a lack of any flow. To counteract this problem, the primary pump is controlled by the solar insolation, thus if there is greater than 200W/m^2, the pump will run. The temperature is likely to exceed 150°F based on the historical data, in which case the fluid must be tempered to drop below this temperature threshold. To maintain the high limit of the heat pump inlet temperature, a plate and frame heat exchanger is used in conjunction with a domestic water valve to bleed off any excess thermal energy. A basic test of the capabilities was performed to show that the heat could indeed be reduced. The set point for the domestic water valve was lowered from 150°F to 120°F, since 150°F was never reached during the testing period. Figure 3.12 shows the operation of the domestic water valve in blue and the temperature of the fluid entering the storage tank in red. The graph taken from WebCTRL shows the inlet temperature of the storage tank on top and the valve actuation of the domestic water heat exchanger valve on the bottom.

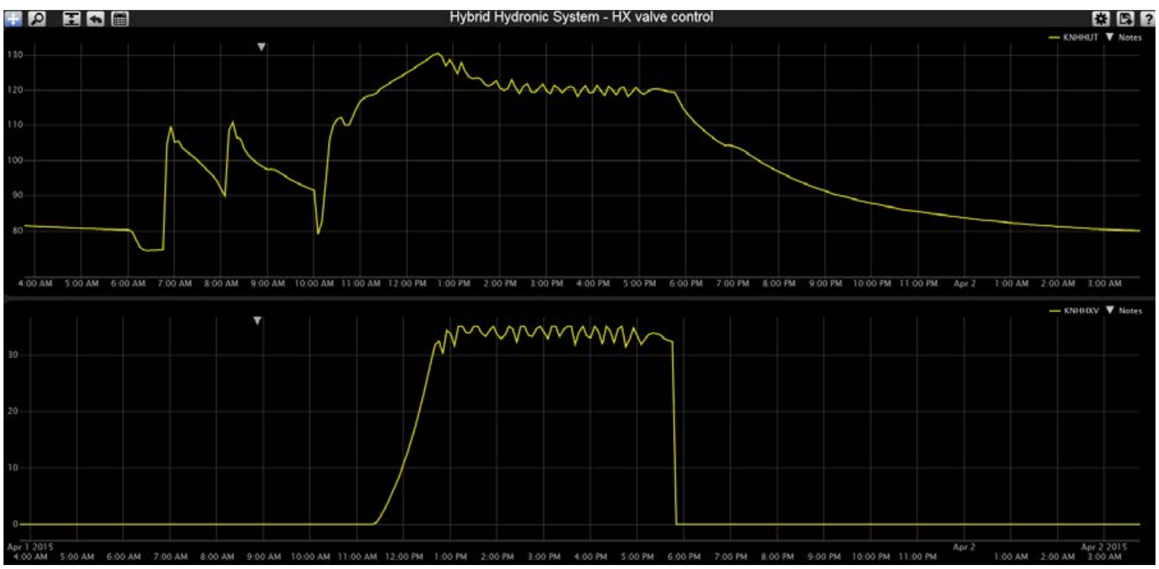

Figure 3.12 Test of Heat Dissipation

Figure 3.12 illustrates that when the inlet temperature to the storage tank reached 120°F, the valve on the heat exchanger opened. The temperature is reduced to the 120°F set point and is maintained until the primary pump is disengaged. The control of the valve was limited as well to prevent flooding in the lab. The test showed that restricting the valve still allowed for proper heat dissipation. The operation of this sub-system will keep the system safe from any thermal overloading.

Three hurdles arose during the commissioning: a discrepancy with flowmeter readings, a faulty power meter, and unwanted glycol infiltration. The ultrasonic flowmeters attached to the pressure independent valves had a discrepancy with the flowmeter in the Grundfos pump. After contacting a representative from both the pump and valve manufacturers, it was learned that the pump flow measurement was a calculated number, not a measured number like the valve flow meters. The pump was also of a slightly larger design than what the system required, thus it was operating towards the bottom of its pump curve. The operation at the lower end of the pump flow capability coupled with the use of the more viscous glycol mixture caused further inaccuracies in the flow calculation. The ultrasonic flow meters integrated in the valves were used for subsequent flow monitoring and data collection. The heat pump hot water heater had an alternating current (AC) watt transducer attached to the electrical leads to measure the voltage and amperage draw by the equipment. The initial installation proved unresponsive to testing, outputting a constant 3.4 volts regardless of the heat pump operation. A defect was found with the product and a new working meter was obtained. The new meter read an average of 521 watts while utilizing just the heat pump, and an average 4041 watts when an electrical element is engaged.

The final check in the initial commissioning phase was to confirm the prevention glycol mixture that was too cold from being introduced into the storage tank. The control of the pre-heat valve was allowing low temperature glycol to be released into the storage tank. The code controlling the pre-heat valve was modified to only allow glycol above a temperature of 80°F to circulate through the primary loop.

With the problem located, the control code was corrected to only allow the valve to open based on temperature of the glycol mixture. Basing the opening and closing of the valve based on the 80°F switch provided a predicable supply temperature that could be maintained throughout the rest of the testing and operation of the system. Figure 3.13 shows that over a four day snapshot the operation of the valve is clearly marked by the solar supply temperature. The areas in blue denote when the valve had a value of one, indicating that it was open and not allowing any fluid into the rest of the primary loop. The orange line is the temperature, where it can be seen that when the temperature reached 80°F, the valve closed, allowing the glycol to flow through the rest of the loop. While the 80°F switch could allow glycol cooler than that already in the storage tank to circulate, a consistent delivery of glycol was more desirable.

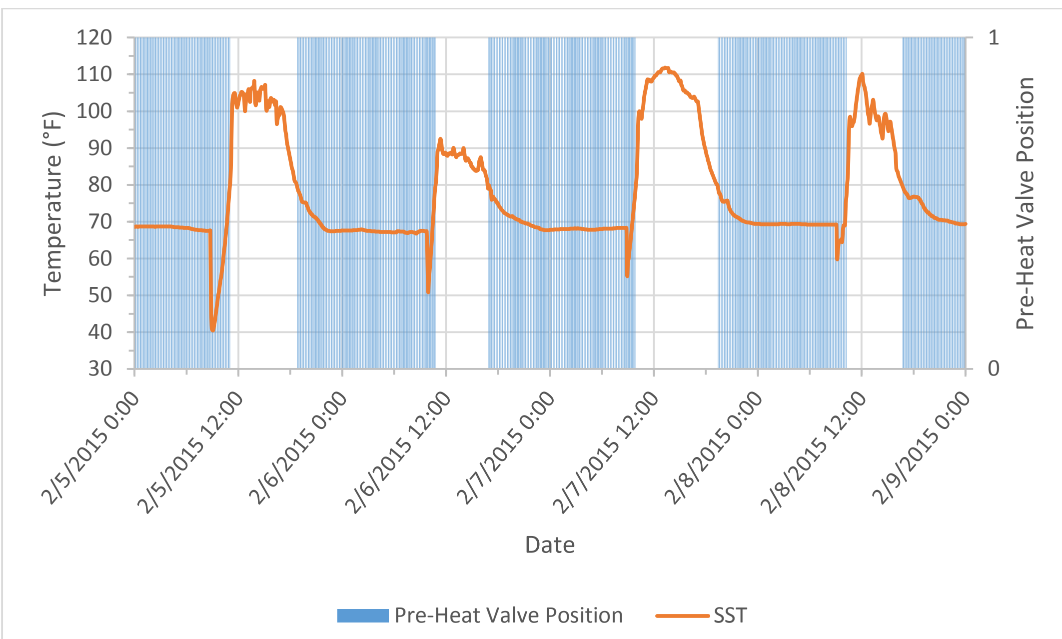

Figure 3.13: Consistent Pre-Heat Valve Operation

3.2 Test Procedures

With the commissioning of the system complete, the tests could be performed without fear of serious mechanical or control failures. Two tests were conducted on the system to determine its performance:

- Operational Performance of the Solar Thermal and the Heat Pump
- Independent Operation Capability

The operational performance of the system was measured over a period of 17 days to determine the operational characteristics of both the solar thermal and heat pump in regards to heat generation, along with the interaction between the two heat sources. The independent operational capability test took place over the period of a week to ascertain the ability of the code to control the system within a set of parameters.

3.2.1 Operational Performance

The operational performance tests were carried out on the system based on a desire to observe the interactions of the two heat sources of the hydronic system and learn how the independent and dependent variables had an effect on their heat production and operation. For these tests, the system was operated as a typical hydronic system using the control code and sequence of operations in Appendix B after the initial system commissioning was completed. The system was monitored using multiple data points to observe the thermal and operational contributions of the solar thermal and heat pump components, along with their interaction with one another. Due to the timeframe and season of testing, it was not possible to observe every mode and its engagement. This phase of testing was conducted for a period of 17 days.

The testing was separated into two segments, each correlating to a heat source. The tests were organized as such:

1) Observe the basic solar thermal operation behaviors.

   The solar thermal panels are paramount to the success of the hydronic system. Their inclusion in the system allows for it to achieve higher levels of efficiency due to low amounts of energy being required to harvest the energy that is available from the sun. The solar collector's performance centers around the temperature of the fluid which is supplied to the storage tank can reach. Independent variables such as the ambient temperature and the available solar insolation affect the collector's ability to heat the fluid, thus they are necessary to observe. To observe the solar thermal operation, the following points relating specifically to the solar thermal portion were recorded for the length of the test to be analyzed:

   - Insolation
   - Ambient Outdoor Temperature
   - Solar Supply Temperature
   - Solar Return Temperature
   - Solar Flowrate
   - Pre-Heat Valve Position
   - Primary Pump Operation
   - Primary Pump Energy Use

2) Observe the heat pump operation behaviors.

   The heat pump performance is dependent on the performance of the solar thermal system since the heat from the solar collectors partially dictates the amount of energy that the heat pump must produce to maintain the supply temperature from the storage tank. The operational performance of the heat pump should be assisted by the solar collectors, not hindered. The relationship between the two heat sources shows how the system operates in the specific climate and timeframe in which it was tested. The following points relating specifically to the heat pump operation and performance were recorded for the length of the test to be analyzed:

- Heat Pump Energy Use
- Heat Pump Activation
- Storage Tank Outlet Temperature
- Storage Tank Inlet Temperature
- Load Flow

3.2.2 Independent Operation Capability

The second test conducted was to allow the system to operate solely on the control code that was enhanced in the previous tests to determine whether or not the system was capable of operating independently for a period of one week. A set of success criteria concerning controls was developed to determine the success of the system's control. No operator intervention took place during this test.

3.3 Measures of Success

There were multiple metrics determined whether or not the two tests outlined in Section 3.2 were successful. The overall goal was to investigate the two heat sources as to how they provide heat to the hydronic system and at the end of the project have the system operate independently. There were specific metrics that had to be met that determined the success of the system in regards to this research.

3.3.1 Operational Performance Success

The first observational test was to observe the various operation parameters of the solar thermal collectors. The success of the test relied on the ability to observe and record the data for the entire 17 day testing period, thus if all the parameters were recorded, the test was a success. Data collected in WebCTRL was able to show any unnatural variations in data, indicating a lack of ability to control the system. The operation of the solar thermal system was framed by weather factors, which impacts the ability to heat the glycol mixture, as well as impacting the relationship with the heat pump to provide heat to the system.

The second observational test of the heat pump hot water heater operation was conducted in tandem to the solar thermal operation test, again for the full 17 day period. The success of the test relied on the ability to observe and record the data. Time intervals and frequency of operation were recorded, along with the temperature profiles of recovery and high usage. The operation of the heat pump is directly influenced by the operation of the solar thermal collectors, and this relationship will be discussed in Chapter 4.

3.3.2 Independent Operation Success

The final measure of success came from the unattended operation of the system. If the system could support its own operation without the intervention of a human for one week, then the test would be a success. This would show that the system can operate at the level of a typical hydronic system controlled by a BAS.

For the independent operation capability test, there are multiple metrics that must be met. Table 3.1 shows the basic criteria that must be met for each individual operation mode. The top row shows the six initial operation modes not including System Off mode while the criteria for the success of those operations are listed in the leftmost column. An “X” indicates that the system must meet the specific criteria.

Table 3.1: *Measures of Success*

	Operation Modes					
Success Criteria	Solar Preheat	Heat Pump	Hybrid	Pure Solar	Solar Storage	Solar Dissipation
Raise glycol ≥80°F in 120 min	X					
Tank exit temp 120±5°F		X	X			
Prevent HP short cycling		X	X			
Prevent HWH electric element engagement		X	X			
Provide useful heat to storage tank					X	
Tank inlet temp <150°F				X	X	X

For the solar preheat mode, the system must run in such a way that the glycol temperature will be increased to the pre-heated temperature of 80 degrees Fahrenheit. The primary loop pump will operate regardless of the ability to reach this target temperature in time due to the need to protect the evacuated heat tube array. The ability to generate heat in a timely manner is necessary in a system that is designed to provide heat, especially one that uses an intermittent source like the sun.

For the Heat Pump and Hybrid modes, the hot water heater tank outlet temperature must be maintained at 120±5°F for the test to be a success, unless the solar supply temperature is above 120°F, which would indicate that the system is operating purely on solar thermal energy. The tank is controlled to 120°F, but the solar contribution could have an effect. During these modes the heat pump must be not short cycled, and the secondary electric heating elements in the heat pump must not engaged. In the case they did engage, it would show that neither the heat pump nor the solar thermal heat sources are able to supply adequate heat during the time the elements are engaged. Short cycling the heat pump is defined as engaging the heat pump and shutting off the heat pump within 20 minutes of each command. These criteria represent the main operation of the system and how it is able to perform.

In Solar and Solar Storage modes, useful heat must be provided to the tank. Useful heat is defined as inputting a higher temperature glycol mixture into the tank than what is currently in the tank. The primary pump will be operated as long as there is sufficient solar insolation to gain as much heat as possible and to prevent the evacuated heat pipes from breaking due to a lack of flow. For these modes the hot water heater tank inlet temperature must stay below 150°F to protect the components of the integrated heat pump itself. The Solar Dissipation mode also must meet the 150°F criteria to protect the heat pump components.

3.4 Data Sources and Collection

The data to monitor and control the system was collected by various sensors monitoring various key parameters. These sensors included temperature sensors, flow meters, solar pyranometer, and power consumption meters. The positions of all the devices and sensors can be seen in Figures 3.1 and 3.2. Specifications for the key sensors are listed below in Table 3.2 to indicate their type and accuracy.

Table 3.2: *Sensor List*

FUNCTION	TYPE	RANGE	ACCURACY
Power Consumption Meter	OSI AC Watt Transducer	5kW max	±0.5% F.S.
Temperature Sensor	BAPI 10K-2 Thermistor	-40-221°F	±0.36°F
	BAPI Averaging 10k-2 Thermistor	-40-221°F	±0.36°F
Flow Meter	Badger XMTR PFT-420	0-25 GPM	±0.5%
Solar Pyranometer	Precision Spectral Pyranometer	0-2800W/m^2	±0.5%

The above sensors are the key sensors that were used to control and monitor the system. All of the data from these sensors was sent from the modules to WebCTRL, where it was collected continuously, 24 hours a day, for the duration of the experiment phases. These data points were trended as necessary within WebCTRL and were exported to Excel for analysis. These data trends were used to map the performance of the system and show whether or not the system could run independently.

For the data analysis, each bulleted point in Section 3.2.1 was imported into Excel. In addition to those points, the secondary pump power use and secondary pump operation were compiled in Excel. Each point was recorded every 15 minutes with the exception of the pre-heat valve position and the insolation which was recorded every 5 minutes. The daily total insolation was integrated from solar pyranometer data collected to give daily solar insolation. The average ambient temperature was recorded once for each day. A total value was calculated for the energy gained by the solar collectors and heat pump, along with the energy used to operate the individual systems. The compilation of this data yielded total system efficiency.

Over the course of the 17 days of data collection for the first test, the daily amount of heat generated by the solar panels was calculated every 15 minutes, tallied daily, and summed for a total at the end of the collection period. The equation for heat gain is normally given as:

$$\dot{Q} = \dot{m} * C_p * \Delta T \qquad \text{(Eq.1)}$$

For the analysis conducted on the hydronic system, a simplified equation was used. The availability of flow rate and temperature data along with the known fluid properties of propylene glycol allowed for a simplified equation based on imperial units to be used. The following equation for the heat gained is arranged as such:

$$Q(\frac{BTU}{hr}) = 425(\frac{BTU}{hr * gpm * °\mathrm{F}}) * flowrate\ (gpm) * \Delta T(°F) \qquad \text{(Eq. 2)}$$

3.5 Threats to Research

There are multiple threats to this research of integrating a solar thermal heat pump system. The main threat to the system's performance is the weather. Due to the nature of the solar thermal panels, they are beholden to the weather, and the climatic conditions during which the tests took place are not optimal for the use of solar energy. Cloud cover paired with a low temperature day could reduce the solar contribution to nothing, forcing the heat pump to work 100% of the time. The inclusion of both heat sources is necessary for the research. Another threat to the research is the lack of control of the AHU as a heat sink. The AHU operates on its own schedule with varying temperatures of air being introduced to the solar heating coil. The environmental chamber radiators do provide a fairly constant load. The uneven load can cause a varying temperature returning to either the storage tank or being supplied to the roof.

3.6 Chapter Summary

The methodology of the tests has now been laid out. The system design and components have been discussed, along with the controls that govern the system's operation and the supporting work done to ensure the system worked properly. The two tests are the operational performance if the heat sources and the independent operation capability. The data collection and methods of analysis were discussed along with the threats to the research.

CHAPTER 4. RESULTS

The methodology of testing the hydronic system has been described and the results of those tests are presented forthwith. The two main tests were conducted simultaneously. The results presented in this section will be analyzed from a system wide perspective in the following chapter. The data and calculations for the results and analyses presented in this chapter are available in Appendix D.

4.1 Operational Performance Results

The operational performance of the system focused on the data collected during the timespan from February 25th to March 13th, a total of 17 days. Solar thermal and heat pump data results are seen below. Discussion and analysis of these heat sources in regards to system efficiency as a whole are in Chapter 5.

4.1.1 Solar Thermal Operation Behaviors

The design of the system is such that the solar thermal collectors should supply a significant portion of the heat for the system. The performance of the collectors is therefore critical to the system as a whole. The various parameters listed in Section 3.2.1 including supply temperature, solar insolation, and outside ambient temperature were monitored and recorded to observe the collector performance and behaviors. Table 4.1 is a summary of the data collected and analyzed for the duration of the testing period. The main parameters of importance are listed across the top and their averages listed below. A corrected average is given for the heat percentage of the solar contribution, along with a total for the amount of heat (BTU) gathered during the test.

Table 4.1: *Basic Solar Thermal Performance Summary*

	Total Solar Q (BTU)	Heat % Solar	Daily Total Insol Time (min)	Time @ 80°F	Time between Pump On & Temp Met (Min)	Total Useful Insol (Wh/m^2)	SST AVG (°F)	Daily Average Ambient Temp (°F)
AVERAGE	14459	31.7	486	10:33	85	5160	108.9	26.1
AVG CORRECTED	22505	49.3						
TOTAL	245798	35.2						

The averages given in the top row represent the daily averages of all the values calculated over the 17 day testing period. For the parameters total time with insolation, time between pump on and temperature met, and total useful insolation, the averages were calculated when there was data available, for instance if there was a day without useful insolation it was not used in the calculation of the average. The solar heat measured in BTUs was calculated by integrating the data given in five minute intervals from the solar pyranometer over the course of a day. The total is the full amount of heat gathered during the test. The time at 80°F is the time when the solar supply temperature reached the threshold of being able to provide useful heat to the system as a whole. Given the information in Table 4.1, it can be seen that the average daily solar heat is significantly lower than the corrected average calculated when there was a positive solar contribution to be made.

The average total useful insolation was 5.16 kWh/m^2/day, which is slightly higher than the average gathered by the National Renewable Energy Lab (NREL). The insolation maps for the timeframe of the testing and the annual insolation is available in Appendix E. The average total time that insolation was available was 452 minutes, or around 7 hours 30 minutes. The data shows that there is useful solar energy coming from the collectors for almost eight hours a day and at an elevated average temperature of around 109°F.

The monitoring of the solar thermal contribution to the system is an important portion of the research, as it is desirable for there to be as much of a contribution as possible. The solar thermal collector input was calculated using Equation 2, with total heat gain over the test period being 245,800 BTU. Overall, the solar thermal collectors contributed 35.2% of the total amount of heat gained over the 17 days. Table 4.1 shows the average of the daily thermal contribution is lower at 31.7%. The lower average number occurred due to 35% of the days being without useful solar heat, but on the days it was available it provided an average of 49.3% of the daily heating. The lower winter temperatures and high cloud cover that results in lower total daily insolation are clearly contributors to poor solar thermal performance. The solar thermal contribution peaked on March 9th at 75.6%, with the highest SST and accompanying insolation and ambient temperature. Given better weather conditions, the system can produce higher solar contributions. The comparison of total contributions is shown in detail in Section 4.1.3.

The average time for the solar supply temperature to reach 80°F, which is the threshold chosen to provide “useable heat”, was analyzed to understand when the solar thermal can be expect to contribute to the system. The time in which the temperature may rise to a useful amount shows how soon the resource may be used. Figure 4.5 shows how often the solar supply temperature was reached in a given 15 minute span. The Y-axis shows the frequency that the threshold temperature was reached during a specific window of time. The X-axis shows the time blocks for the test.

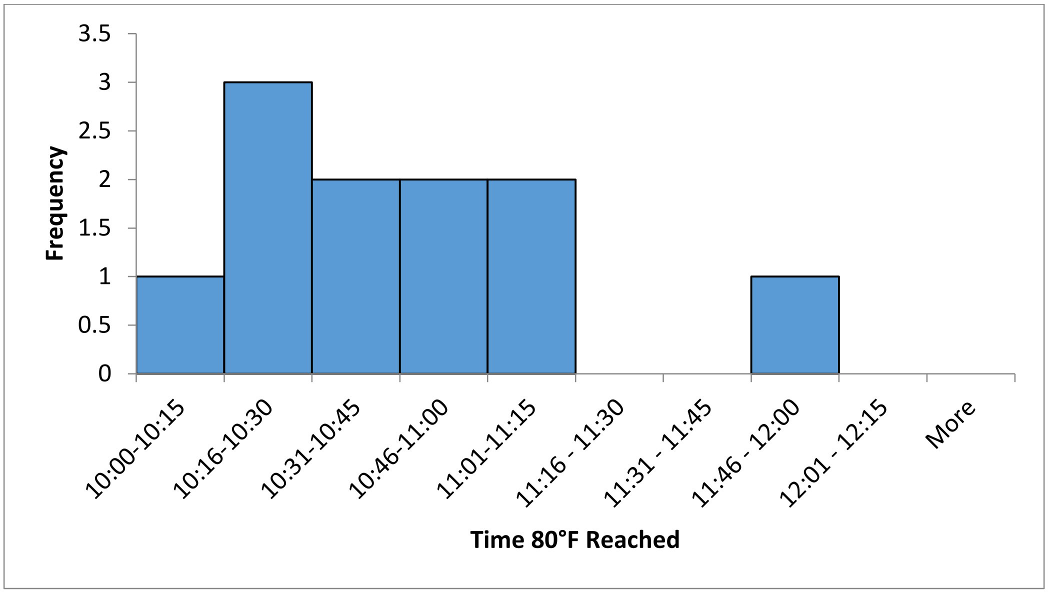

Figure 4.1: Time Useful Solar Temperature Reached

The interval from 10:16 to 10:30 is the most common time to reach the target temperature, with only one outlying time occurring. Only 11 of the 17 days were suitable to gain any solar energy, meaning that there was enough energy to allow the fluid temperature to reach 80°F, thus the potential for a solar thermal contribution during the test was 65% of the time. The time useable solar heat was reached was almost completely within the span of 75 minutes, showing that the system is capable of supplying solar energy between 10:00AM and 11:15AM. The average time to reach the 80°F threshold was 10:33AM, while the median time was 10:30AM.

The time taken from the primary pump operating to the time that the solar supply temperature reaches the useful heat threshold is time when energy must be consumed by the pump yet no solar thermal energy is being added to the system. Figure 4.2 shows the average percentage of time required by the solar thermal system to reach a point of useful contribution. The yellow shows the time with useful contribution, while the blue is the time during which the fluid is being heated. Based on Figure 4.2, 17% of the time during which there is available insolation is used to heat the glycol mixture to 80°F. The requirement for pre-heating the system reduces the total available time for useful insolation to benefit the hydronic system to 83%.

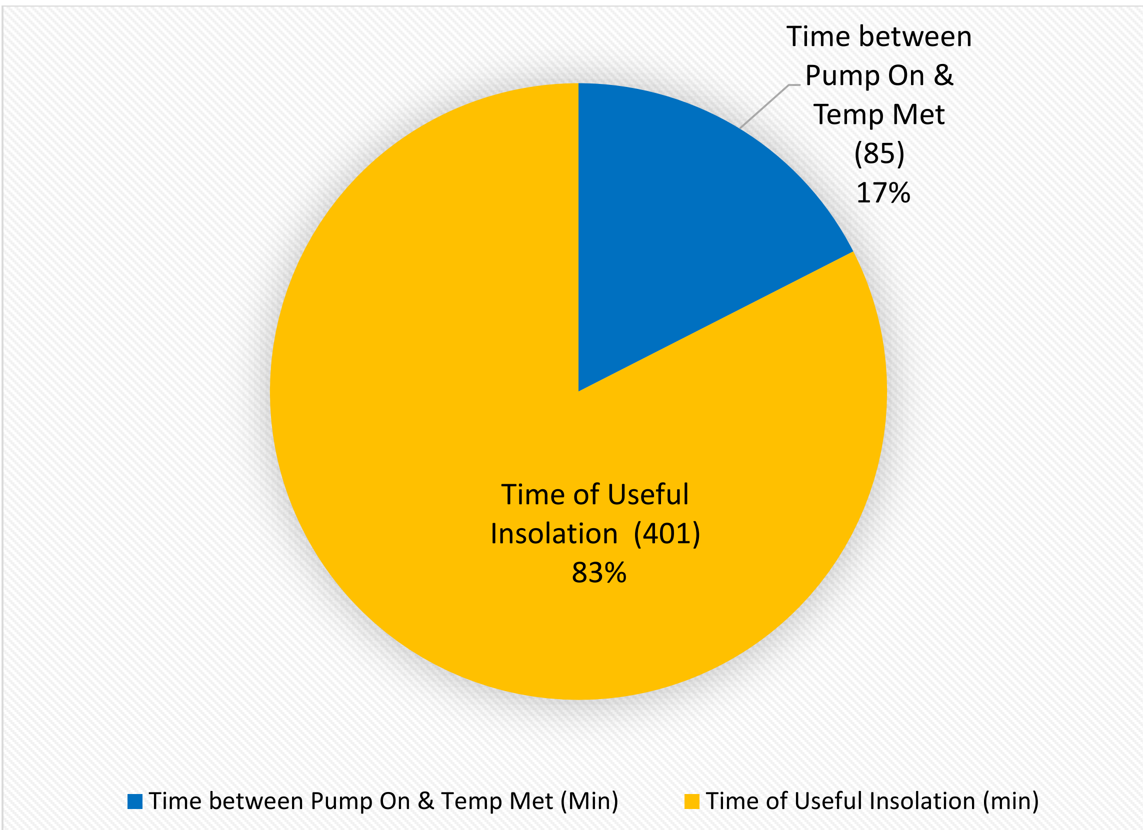

Figure 4.2: Time Breakup of Solar Thermal Operation

When looking at the data collected, it appeared that there is a correlation between the total useful insolation and the solar supply temperature (SST). The highest daily average temperature recorded was 115.4°F, occurring during the day with the fourth highest useful insolation and the highest ambient temperature of those four days with the highest insolation.

The SST average and daily useful insolation parameters are graphed together in Figure 4.3 to show their relationship. On the primary Y-axis is the total daily insolation available that was calculated over the course of a full day. The secondary Y-axis shows the average temperature of the solar supply coming from the roof. The X-axis shows the date that the measurements were taken.

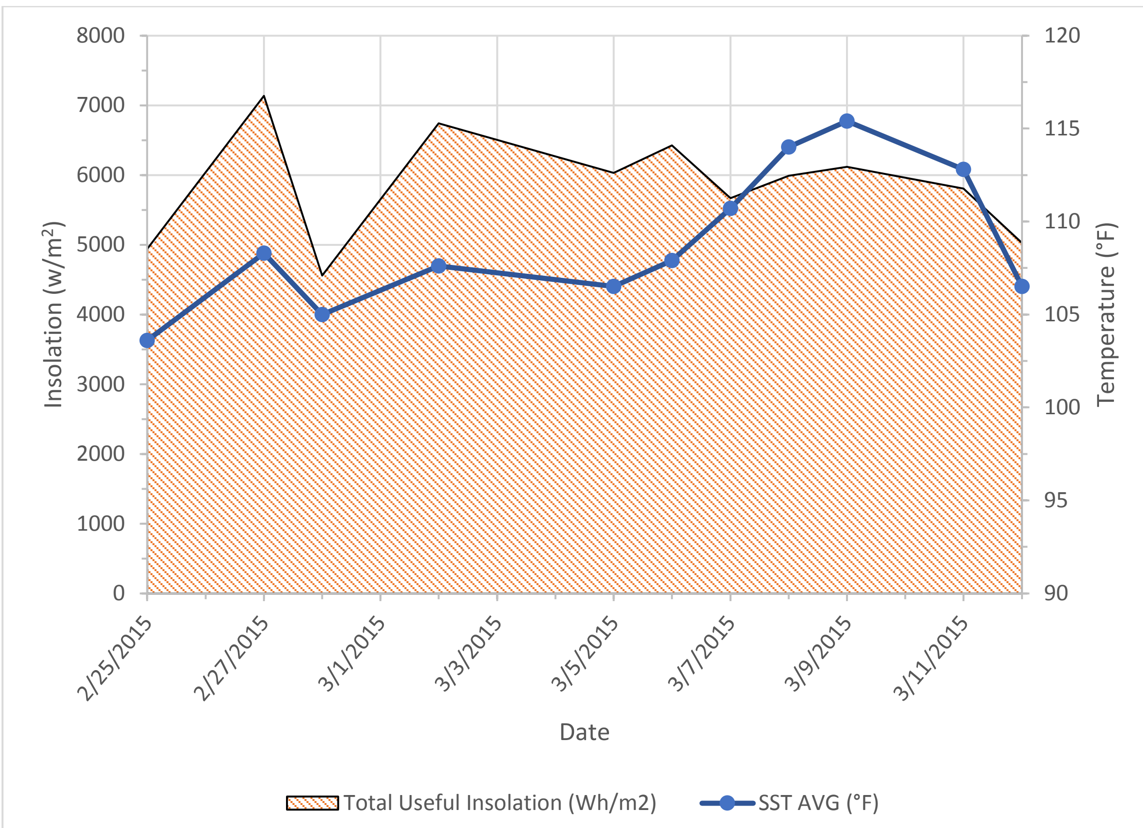

Figure 4.3: Supply Temperature & Insolation Relation

The blue line of the solar supply temperature average appears to track fairly well with the variation of the shaded area of the insolation. The slope direction of both variables matches for every point except for March 7th. The insolation and the ambient outdoor air temperature were both expected to have an effect on the SST. While Figure 4.3 shows a reasonable correlation, there is more information to be learned from calculations.

A correlation certainly exists between the SST, the ambient air temperature, and the total useful insolation for the day. Using Excel's correlation function, the correlation between the SST and the ambient temperature was calculated as a moderate 0.6, and the correlation between SST and the average insolation is only 0.37. To understand the correlation between three variables, the equation below was used to calculate the correlation:

$$R_{z,xy} = \sqrt{\frac{r_{xz}^2 + r_{yz}^2 - 2r_{xz} * r_{yz} * r_{xy}}{1 - r_{xy}^2}} \qquad \text{(Eq. 3)}$$

For Eq.3, z represents the dependent variable of the SST, while x and y are the independent variables of total daily insolation and outdoor ambient temperature. When these are combined, the ambient temperature and the useful insolation yield a strong correlation of 0.7 with the SST. Clearly the more the sun shines, the more energy the collectors are able to capture and transfer to the fluid. This correlation is important to understand the performance of the system over the course of a year.

A correlation between the solar contribution percentage and the total useful insolation was observed. Between the solar percentage and the insolation is a strong correlation of 0.79, and then a very high correlation of 0.95 between the solar percentage and the daily solar heat collected. These correlations show that when there is a high amount of insolation, the solar percentage will be larger. The percentage will also increase as the total heat collected goes up, which directly relates to the solar supply temperature.

4.1.2 Heat Pump Operation Behaviors

The heat pump is the second source of heat for the hydronic system. Due to the intermittent nature of the solar thermal collectors, the heat pump's constant ability to produce heat makes it an advantageous partner. Using the same sensors and data collected for the solar thermal collectors, the heat pump operation was analyzed to discern its operational behavior within the system. Table 4.2 shows the results of the heat pump operation during the testing.

Table 4.2: *Heat Pump Operation Characteristics*

Total Operation %

	% HP	% OFF	% Elements
Average:	29%	69%	2%

Daily Operational Time (mins)

	HP	OFF	Electric
Average:	389	924	32

Engagement

	Times HP Engaged	Avg Time Length (min)
Average:	6.5	86
Total:	111	

Two obvious questions are how often does the heat pump engage and for how long is it engaged? Over the course of the 17 day testing period, the heat pump was engaged a total of 111 times, equating to a total operational time of 28.9%. Over the course of a day, the average total time the heat pump was enabled was 389 minutes, or around 6 hours 30 minutes. The heat pump engaged an average of 6.5 times for a duration of 86 minutes every day during testing. The heat pump was off a total of 65.8% of the time, with a daily average of 923 minutes, or 15 hours and 23 minutes. The electrical elements were engaged a total of 2.4% during the entire 17 days. Figure 4.4 shows the breakdown of the heat pump hot water heater operation, showing the majority of the time it was turned off due to a satisfaction in temperature and operating a third of the time with either the heat pump engaged or the electrical elements engaged to overcome a temperature deficit.

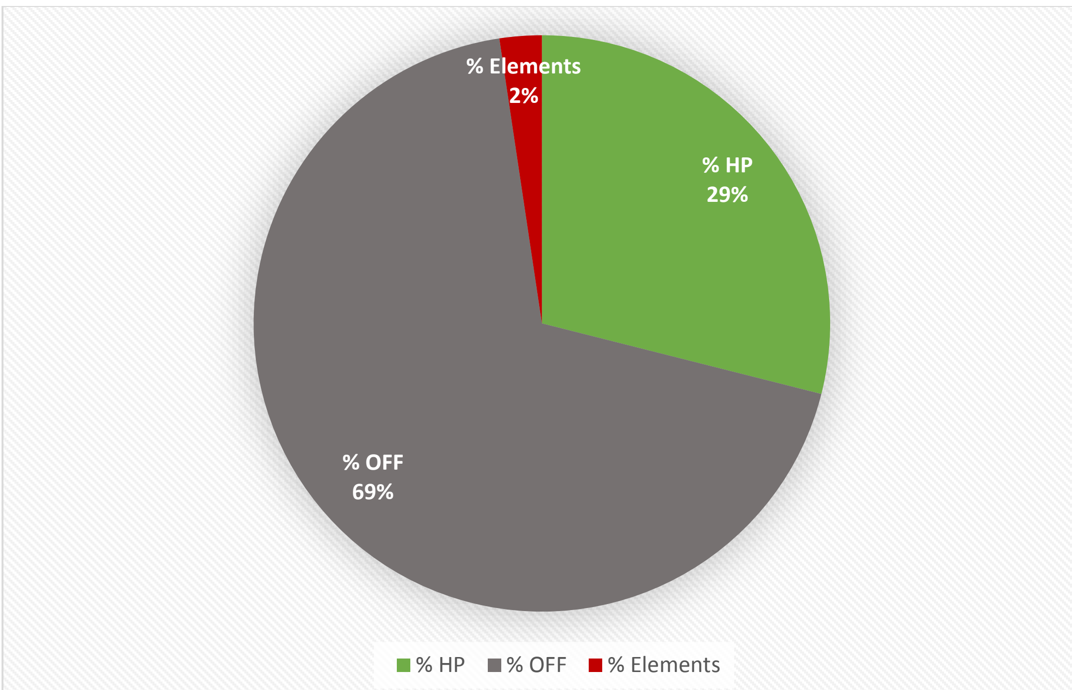

Figure 4.4: Heat Pump Operation Breakdown

During operation, the electrical elements did engage, causing an average draw of 4026 Watts. The average length of engagement was 34 minutes. The electrical elements engaged at least once a day for 12 of the 17 days of testing. The majority of the time, equating to 58.3%, the elements were engaged in the morning at 6:15AM. This specific engagement time may be due to the internal control of the heat pump itself, causing a spike in water temperature based on programming.

4.1.3 Combined Heat Resource Operation Characteristics

In the context of the entire system, the two separate heat resources should complement one another. The solar thermal system was integrated to provide relatively cheap, almost free thermal energy to the system, while the heat pump was integrated to provide a thermal contribution whenever there is a lack of performance from the solar thermal collectors.

Possibly the largest overarching question in regards to the hybrid hydronic system is what the percentages of contributions come from the heat sources. Figure 4.5 shows the simple breakdown of the thermal contributions from the heat pump and the solar collectors.

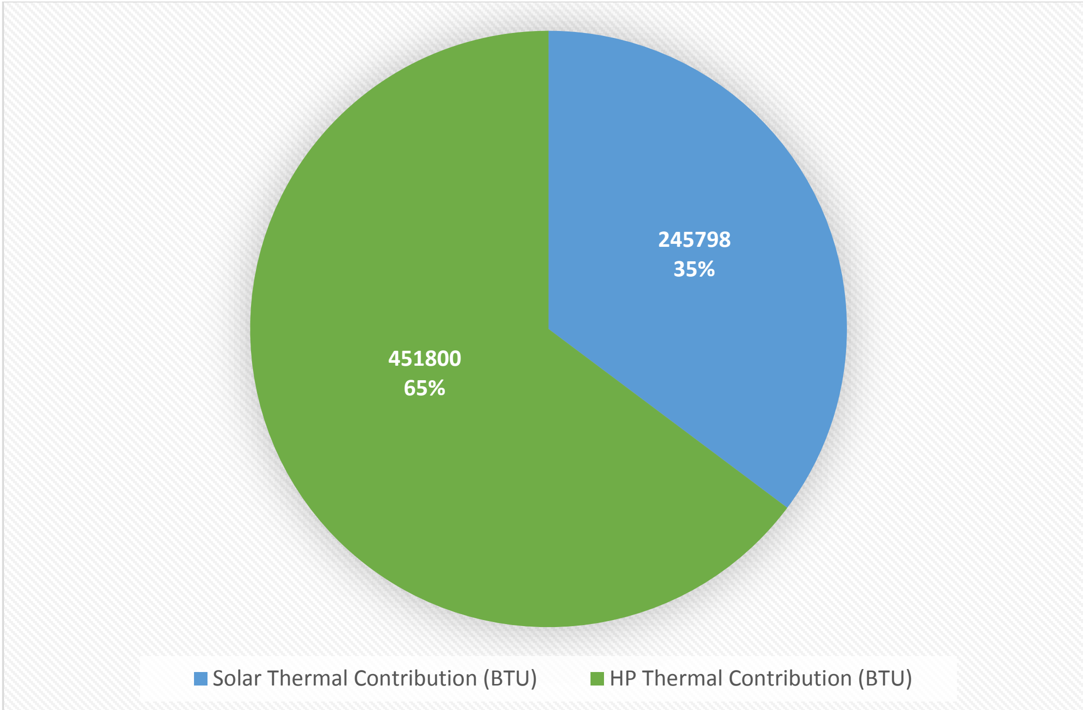

Figure 4.5: Total Thermal Contributions

In total, the system produced 697,598 BTUs, or the equivalent of 204,445 Watthours worth of thermal energy from both the heat pump and the solar collectors. The heat pump is beholden to the performance of the solar thermal portion. When there is no useful energy coming from the collectors, the heat pump must compensate.

A finding was made that during the days that the system is operating with both the solar thermal and heat pump generations, the solar thermal could provide a daily average of almost half the heat required. Figure 4.6 shows the average daily contributions of the heat pump and solar collectors. The inner ring of Figure 4.6 shows the averages over all 17 days of testing, giving the heat pump two thirds of the thermal contribution. The outer ring shows the average of the contribution percentages when there was useful heat provided by the solar collectors, which are the eleven days when the solar supply temperature was above 80°F. When the days with the solar thermal are included, the collectors can almost provide half of the thermal needs.

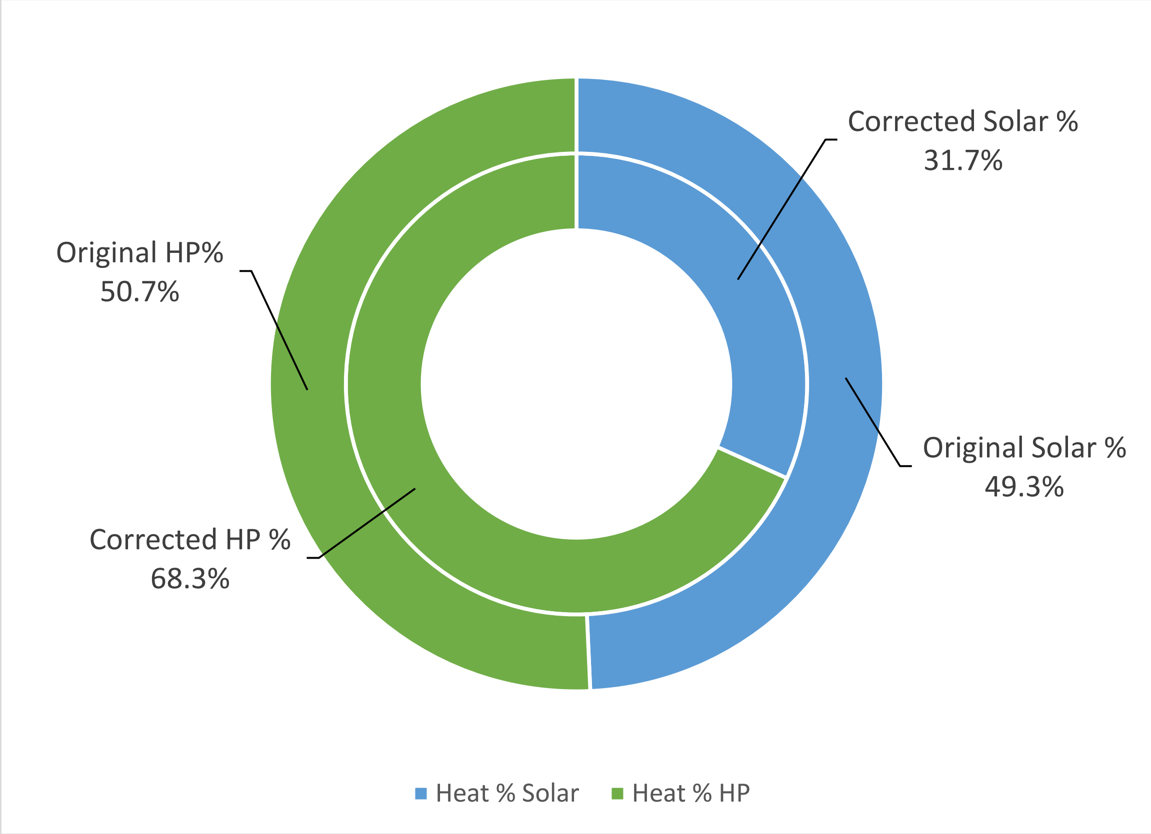

Figure 4.6: Raw and Corrected Average Thermal Contributions

Correlations pertaining to the heat pump were calculated in Excel. The percentage of heat pump thermal contribution has a very strong negative correlation of -0.90 with the SST average temp, meaning that as the supply temperature increases, the amount of heat pump energy decreases. The largest correlation is between the daily solar heat and the percentage of thermal contribution from the heat pump at -0.95.The clear result is that as the insolation and ambient temperature increase, they affect the solar supply temperature. The SST in turn dictates the amount of energy necessary from the heat pump.

4.2 Independent Operation Capability

The final set of tests was to determine whether or not the system could control itself within a determined set of parameters for the seven day period of March 6th to March 12th. The parameters are outlined in Table 3.1 and are centered on the management of the temperatures of both heat sources and the prevention of wasteful operations.

As per Table 3.1, the first criterion to meet is to be able to raise the glycol mixture above 80°F within 120 minutes. Figure 4.7 shows the times to reach 80°F along with the insolation gained during the period of engaging the pump and reaching the temperature set point. The insolation gained before reaching temperature is on the primary Y-axis, the time in minutes is on the secondary Y-axis, and the date of the test is the X-axis. A line is set at the criteria of reaching temperature in 120 minutes. Every day is able to make the temperature within the 120 minute criteria with the average time of meeting temperature being 85 minutes. Plotting the amount of insolation along with the time attempts to show a general relationship between the two variables. Based on both the average operation data and the measured values, the system was able to perform within the criteria.

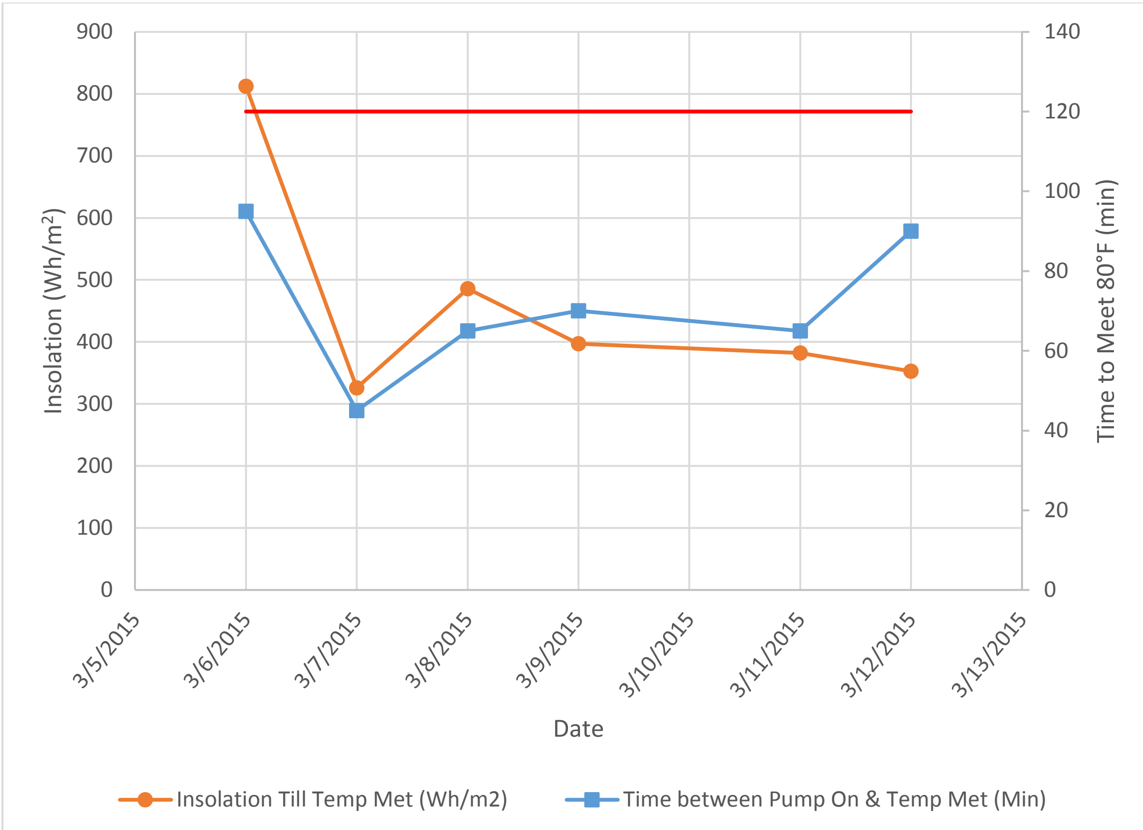

Figure 4.7: Time Satisfaction of Heat Generation

The storage tank temperature was required to remain at a set point of 120 ±5°F while operating in heat pump or hybrid mode. The temperature fluctuated more than expected, and the difficulty with proving the temperature control was attributed to the placement of the temperature sensor used to display the tank temperature. A thermistor was strapped to the outside of the pipe leaving the storage tank. It was shown that this temperature sensor would read on average four degrees Fahrenheit lower than the temperature sensor in the primary pump, which is located in the fluid stream, and thus should theoretically have a more precise reading. The problem lies in that the glycol is only drawn through the piping with the strap on sensor when the primary pump is operating with the pre-heat valve (PHV) shut to allow a full primary loop circuit, or when the PHV is shut and the secondary pump is running to draw fluid out of the tank. These conditions do not reflect with great accuracy what the temperature is at any given point inside the tank.

Figure 4.8 shows the heat pump outlet temperature March 8th and 9th during the testing period. The yellow line indicates the temperature at the outlet of the heat pump. The temperature is at a fairly steady state until around 5:00AM, when it rises sharply. The rise is due to the secondary pump turning on, drawing heated fluid from the tank. During the morning, the temperature fluctuates between 115°F and 97°F. Given that the temperature sensor on the outlet of the storage tank is on average 4°F below the fluid temperature flowing through the pump, the direct temperature fluctuation is assumed to be 119°F to 101°F. The range of 18 degrees is out of the 10°F range for success, thus it fails the test, while the remaining five days operated with similar fluctuations outside of the successful range during heat pump and hybrid mode.

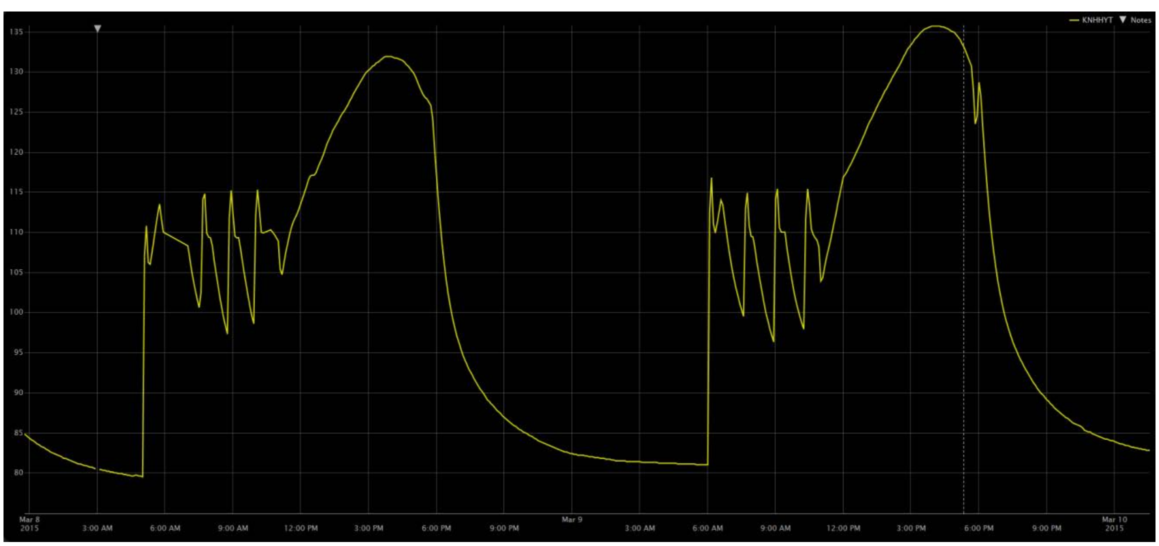

Figure 4.8: Storage Tank Leaving Temperature

March 8th and 9th were the days with the highest percentage of solar thermal contribution, which shows in Figure 4.8. Past noon, the temperature continually rises, as opposed to fluctuating, again caused by the intermittent draw of the secondary pump. The incoming temperature from the solar collectors is flowing enough to overcome the fluctuation and show a constant temperature of the supply leaving the storage tank, thus providing data that is more indicative of the real conditions in the system. Ideally as the weather improves, higher solar temperatures will allow for greater contributions without having to rely on the operation of the heat pump.

The third criterion is the lack of short cycling of the heat pump. Short cycling is defined as engaging the heat pump compressor for a span of less than 20 minutes. During the seven days of the test, the heat pump was cycled two times in a span less than 20 minutes on March 7th and March 11th, thus the goal was not met. Each of these short-cycles occurred around 12:00PM, there was no other commonality to them.

The fourth criterion was to not have to engage the electrical heating elements in the heat pump hot water heater. The system was programmed to allow them to engage if the tank temperature dropped, but the goal was to have them stay dormant throughout the testing period, proving that the solar could supply the necessary heat. As discussed in Section 4.2.2, the elements did engage, with the majority of engagements occurring during the start-up of the hydronic system in the morning hours. It is interesting to note that the elements would engage in the morning around 6:15AM, stay on for 30 to 45 minutes and then reengage around 11:00AM for another 30 to 45 minutes. This occurred during the entire seven day test.

The fifth criterion was to provide useful heat to the storage tank during solar storage mode. When the temperature of the fluid was greater than 80°F, the fluid was directed through the primary loop and into the storage tank. The goal is to have a higher solar supply temperature (SST) than a solar return temperature (SRT), which also indicates the system return temperature when the primary loop is complete. During the seven days of testing, the SST was consistently higher than the SRT. Figure 4.9 shows the constantly positive temperature differential during the times the Solar Storage mode criteria were met, averaging 7.84°F with a maximum of 13.4°F on March 11th. The sharp angles and smooth lines are the times there is no data and the graph is interpolating.

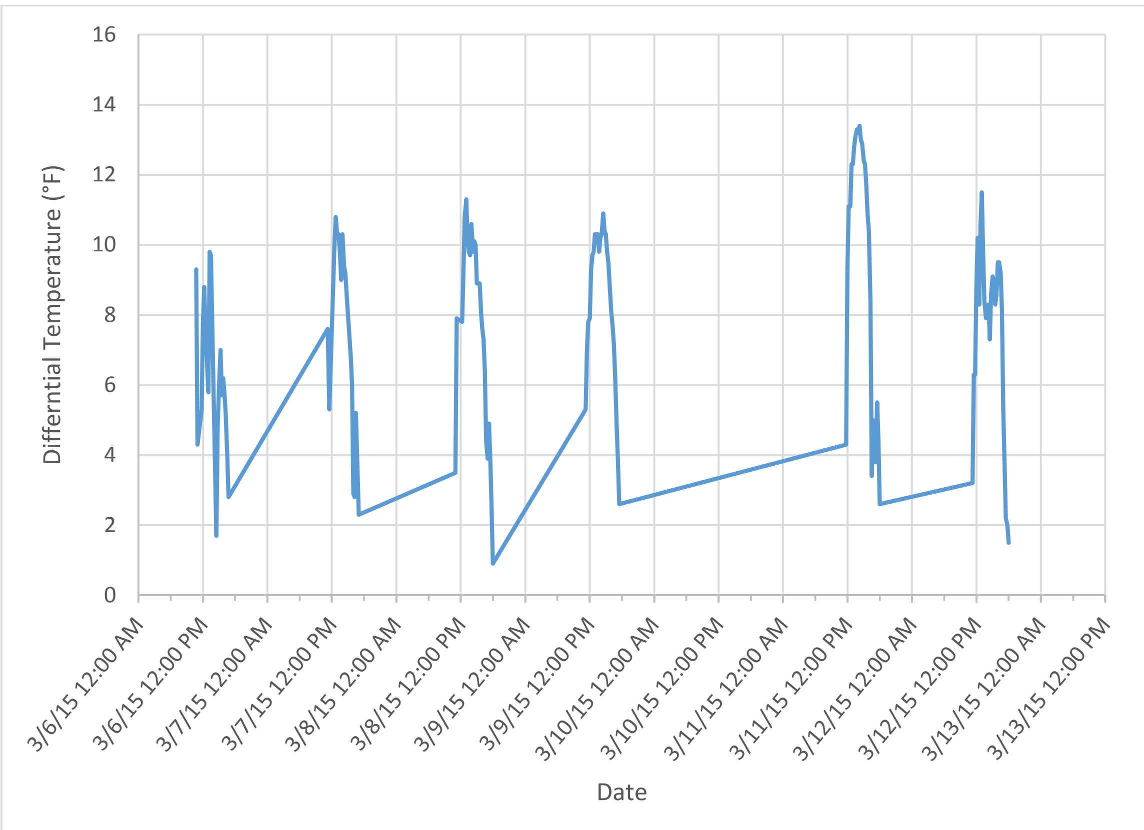

Figure 4.9: Useful Solar Temperature Differential

The final criterion for success that needed to be met was the temperature entering the heat pump hot water heater had to be less than 150°F to protect the mechanical components. The SST was the temperature that dictated the control of the water valve on the heat exchanger placed before the heat pump hot water heater. In the event the SST was greater than 150°F, the water valve would open and lower the temperature of the fluid entering the heat pump to a safe level. During the test and the entire time the data was collected, the SST never reached 150°F. The highest temperature reached was 138.0°F. Based on previous research, the temperature will rise above 150°F during the summer months, necessitating the heat exchanger.

4.3 Chapter Summary

The results presented in this section showcased the operational behavior of the solar thermal heat pump hydronic system. The initial commissioning of the system was discussed, including the few minor difficulties with sensor reliability. Both the solar thermal and heat pump components of the system were discussed and the findings of their operation and relation were presented. The independent operation of the system was monitored and the operation reported, with half the tests considered a success.

CHAPTER 5. ANALYSIS AND CONCLUSIONS

With the hydronic system operating and the performance of the two sources of heat generation documented, the system can be looked at as a whole. Using the data gathered and analyzed in Chapter 4, the efficiencies and modes of the system can be discussed, along with the costs and benefits of this particular hybrid hydronic design. Future work involving the system is outlined at the end.

5.1 Cost Analysis

A system can be as efficient as possible, but if there is no check on costs then it will never be able be a viable option in the real world. The system that has been built in the Applied Energy Lab at Purdue University is a specific, unique design that is difficult to quantify the costs of real world application, yet the benefits of said system in a university environment are numerable.

A basic cost estimate for the system was compiled to give a rough idea of what a comparable system of this magnitude would cost to build. The heat pump assisted solar thermal hydronic system can be broken into three main cost categories: heat generation, delivery system, and monitoring. The heat generation consists of the heat pump hot water heater and the solar thermal panels. The delivery system includes the pumps, valves, piping, insolation, heat exchangers, and all the miscellaneous hardware required to fully install a hydronic heating system. The monitoring section includes the sensors and controls for the system. Table 5.1 shows the cost breakdown along with basic estimates of labor that would be involved to produce a final total cost.

Table 5.1: *Cost Estimate of Hydronic System*

Category	Equipment	Price
Heat Generation	Heat Pump Hot Water Heater	$1,200.00
	Solar Thermal Panels	$5,000.00
Delivery	Pumps	$3,000.00
	Plumbing/misc.	$3,500.00
	Insulation	$500.00
Monitoring	Sensors	$2,000.00
	Controls	$5,000.00
	Installation	$10,000.00
	Total	$30,200.00

Overall, the cost of this system is more than a hydronic system of comparable performance. The return on investment for this type of system is too high to warrant its exact replication in the field. Much of the cost of this system stems from the fact that it is meant for research, and as such includes some of the most advanced equipment for operation and analysis. A reduction in the cost of the system could be brought about by using pumps with less technology, reduce the number of sensors to a minimum for operation, along with reducing the quality of the controllers. Utilizing the reductions listed, a much more economically viable system could be built and installed. As the research that was conducted suggests though, there is potential for this system to work more efficiently than the current architectures.

The true benefit of the hybrid hydronic system is that fact that it is placed in a university setting. Its current location allows it to be used not just for research, but as an educational tool for students who want to learn about emerging technologies in the energy sector. Classes conducted in the Applied Energy Lab regularly employ the equipment to run tests and measure the performance of the systems. From a research perspective, there is much that can be done to improve the system along with using it to supplement other research in the laboratory. These opportunities will be discussed in more detail later. The benefit of having a state of the art hydronic system that will be used for many years to come by students and faculty is truly immeasurable.

5.2 Energy Consumption

A future goal of the Applied Energy Lab is to be a net-zero lab, meaning the power produced by the systems in the lab balances the energy used in the system for education and research purposes. The basic idea of using solar collectors and heat pumps is that they are either inherently more efficient than current fossil fuel methods of heat generation or use a fuel that is so abundant there is no realistic end in sight for its supply.

The performance of the hydronic system is of interest due to the particular employment of two heat sources running in parallel with a glycol mixture while utilizing commercially available components. Combined systems discussed in Chapter 2 have shown COP or energy factor rating ranging from 2.5 to 4. Both COP and energy factor can be used to describe the same basic equation, which is as follows:

$$Energy\ Factor = \frac{Q}{W} \qquad \text{(Eq. 4)}$$

For the equation, Q is the amount of heat generated by both the solar thermal collectors and the heat pump. The work, W, is the work that is used to power all the components of the system, including the primary pump, the secondary pump, and the heat pump hot water heater.

The energy factor of the total system was calculated using the same 17 day data collected for the analysis in Chapter 4. Equation 4 was used for the calculation for the solar thermal heat contribution, producing a total of 245,799 BTUs or 72,036 Watthours. The heat pump energy calculation used the same equation and produced a total amount of 451,800 BTUs or 132,377 Watthours. For the energy factor analysis, Watthours was used for ease of calculations. The combination of the two source's generation yields a total of 204,413 Watthours. To calculate the power consumed by the system, a watt meter was installed on the heat pump hot water heater, the secondary pump was able to communicate power consumption through the building automation system, and the primary pump had a watt meter installed previously. These three sources of power were used to calculate the energy factor. The power supplied to the control panels and the control valves was not included due to an inability to monitor the power. The summation of power used over the course of testing was 104,735 Watthours. Using Equation 4, the total energy factor of the system is 1.95.

With an energy factor of just less than 2, the hybrid hydronic system provides a good starting point for future research. Another positive is that it is still almost twice as efficient as a system using strictly electricity to heat like the old hydronic system that was in the Applied Energy Lab. There are many factors that went into the relatively low energy factor number, with one of the largest being the timeframe of testing. The testing took place during the final weeks of winter in Northern Indiana. Were the testing to take place over the course of a year, it is predicted that the energy factor of the system would rise, especially during the summer months when there will be more solar energy available.

5.3 Mode Analysis

The last focus of the research analysis is that of the modes of operation. At the beginning of the research, a basic set of operational modes were outlined that can be seen in Chapter 3. The seven modes constituted the majority of the system's operation. After the system operated for multiple weeks, it was seen that there was another mode of operation that was not considered during the construction of the research. There were times when the temperature of the fluid in the tank was sufficient to feed the loads, therefore not requiring the heat pump to be engaged along with the secondary pump being on. These conditions coupled with the solar supply temperature being below 120°F showed that the system could circulate and sustain the load. In the instances that this occurred, the primary pump was required to be on, thus the mode described is one where the combination of the heat in the tank and the gains from the solar collectors was sufficient. The mode was named "Tank Storage".

The calculation of the breakdown of the modes was done by using pump operations, heat pump operation and solar supply temperature. By organizing these variables, the modes of operation were calculated. Figure 5.1 is a pie chart that shows the breakdown of the modes during the operation and testing of the system and their contributions to the total operational time.

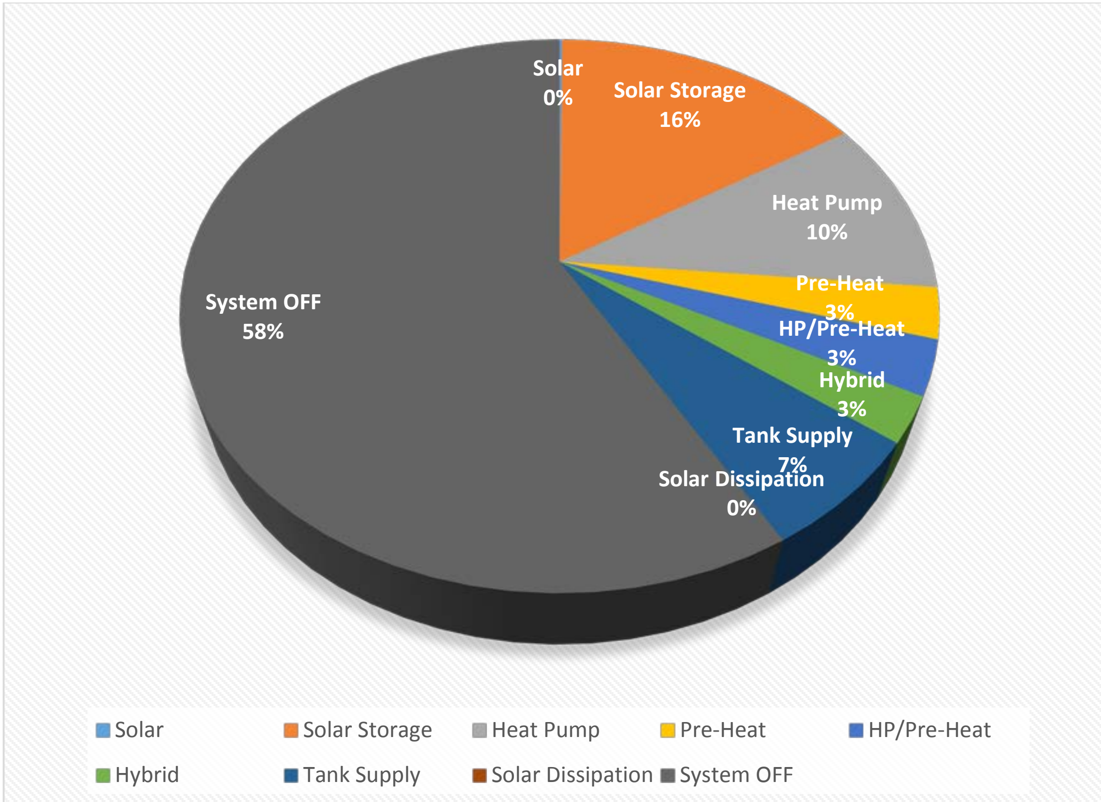

Figure 5.1: Modes of Operation

With the addition of Tank Supply mode, there are a total of seven modes that the system operated in. While being displayed as 0% on the pie chart, Solar mode did occur, albeit only 0.1% of the time. The cause for the low amount of Solar mode is one requirement of it was that there must be a call for heating, and since the system was only calling for heat 23% of the time, it was difficult to match that with the times where there was adequate solar supply. The majority of the solar contribution went to Solar Storage mode. The Solar and Solar Storage Modes can be combined to show the time of complete solar contribution. The combination of these modes yields a 16% operation time. Due to the climatic conditions of late winter causing a decreased ability to produce a temperature in the glycol above the 120°F set point of the heat pump hot water heater, the percentage of time for solar contribution is low. The most usage is seen in the Solar Storage Mode at 15.9%, as the system was satisfied for heat much more often than not. The remaining 0.1% was the time that Solar Mode was engaged.

The Tank Supply mode operated 7% of the time, showing that operating just the two pumps allows the system to maintain during that time period of operation. The Heat Pump mode operated 10% of the time. The small percentage of Hybrid mode shows that the system is either using the solar energy, energy from the heat pump, or the stored energy in the tank. There is very little time when the two systems are working together. The design of running the systems in parallel allows for this split of operation, unlike a combined solar-heat pump powered system which requires the heat pump to be engaged along with the solar component. The majority of the time the system was off.

There was no time that the system operated in Solar Dissipation mode. During the summer this mode will be operated based on previous research and historical observation of the solar thermal collectors. The control of the heat exchanger valve will ultimately control the operation of this mode and will be able to adjust the temperature entering the heat pump hot water heater. In this capacity, the Solar Dissipation mode could also contribute to the development of hot water.

5.4 Future Research Opportunities

The ultimate goal of the research was to create a system that could function on the same level of performance that typical hydronic system could achieve. The observation of behaviors and analysis on the two heat sources in the system conducted by this research establish a solid base for improvement. The system can now be optimized and used for multiple purposes, eventually contributing to a net-zero lab and beyond. Some of the research opportunities include the following:

1. Tank Temperature Setback – One aspect that was not able to be explored during this research was the idea of lowering the tank temperature while still being able to provide adequate heating. By lowering the temperature of the tank, less energy is required to operate the system since it does not have to maintain a higher temperature. The challenge would come with being able to supply enough thermal power during times of high demand when a tank with a lower temperature could not satisfy the draw completely.
2. Heat Pump Control Integration – Currently the heat pump is operated as an autonomous system, allowing for only two user inputs of tank temperature and operational mode setting. Complete vision and control of the heat pump as a system would be extremely beneficial, as the operation of the heat pump could be monitored in much finer detail that what was done in this research. Integrating the controls of the heat pump would be a challenge of network capabilities and communications protocols.
3. Control of Solar Coil in AHU – The solar coil in the AHU was used simply as a load for this research. In the future, the operation of a solar coil in the context of an AHU can be explored. The fairly steady load of a reheat style AHU would allow for experiments to be conducted on supply temperatures, flows, and other parameters of the coil.
4. Hot Water Generation – While currently the system does not produce excess heat, it will as the weather improves. At that point, the possibility for using the heat

exchanger as a means of heating domestic water will be available. The transient nature of solar thermal energy would provide a challenge from a storage perspective. The addition of another storage tank could be applied to provide a thermal capacitor for the heated water produced from the solar thermal collectors. A similar heat source coupling like the one used for this research could be included. Finding a use or load for the hot water would provide another challenge to the research.

All of the suggested research possibilities could contribute to the larger goal of a net-zero laboratory. In conjunction with the solar PV array, the lab can act as a test bed for efficient methods of heating and cooling, along with possible hot water production. The hybrid hydronic system itself will continue to be improved upon, potentially to the point where it is able to operate at the higher levels of efficiency that other researchers have been able to produce with their specific systems. The addition of more efficient solar collectors along with better pumps and a larger storage tank could allow the system to become a leading test apparatus for this design of hydronic systems.

5.5 Chapter Summary

This chapter covered the solar thermal heat pump hydronic system from a broader scale. The basic system costs and benefits, especially in a university environment were discussed, along with the total system efficiency. The modes of operation that were observed during testing were analyzed and future research opportunities were outlined. The goals and aspirations for the hybrid hydronic system were touched upon as well.

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APPENDICES

Appendix A Statement of Work

The following is an outline of the statement of work that has was done to fully design, install, and commission a solar thermal heat pump hydronic system in the Applied Energy Lab (AEL). Table A.1 shows the timeline of work completed for this project. Within the total scope of the project, two theses were produced: one focusing on the integration of the solar thermal and heat pump heat resources, and the other focusing on the pumping system.

Table A.0.1: *Timeline of Hydronic System*

ID	Task Name	Start	Finish
1	Design	10/1/2013	4/30/2014
2	Decommissioning	5/1/2014	5/30/2014
3	Plumbing Installation	6/2/2014	7/30/2014
4	Electrical Installation	7/1/2014	8/15/2014
5	Control Wiring	7/22/2014	9/30/2014
6	Software/Programming	10/1/2014	11/28/2014
7	Commissioning	1/6/2015	2/23/2015
8	Testing	2/25/2015	3/13/2015
9	Analysis of Results	3/13/2015	3/31/2015
10	Documentation of Design & Findings	10/1/2013	4/6/2015

Design

Designing the heat pump assisted solar thermal system started October 2013. This design began as a class project utilizing the graduate students and the students in MET 421, which had very little detail. Once this rough design was produced the design was refined in the spring semester in another course, MET 530. This design withheld much more detail and structure.

Decommissioning

Before installing the newly designed heat pump assisted solar thermal system, the current hydronic system was decommissioned, disassembled and removed from the lab. Decommissioning started the beginning of May and lasted until the end of May. First the glycol/water was removed from the current system and the pipes were drained and disconnected. Next, all power to the hydronic system was disconnected. All the plumbing and electrical that was still being used was temporarily supported, various ways. The last portion of the decommissioning phase was sending the old equipment that was in good shape, but not being used to salvage.

Plumbing Installation

Once the decommissioning phase was finished, the plumbing phase began. This phase started at the beginning of June and continued through the end of July. The plumbing phase started by creating a list of materials to be purchased including pipes, fittings, valves, instruments and pumps. Once the materials were gathered the new components were placed correct locations and proper measurements were taken. The students worked with the zone plumber to properly dry-fit and solder the copper pipes and fittings. The old pipes and pipe routes were used as much as possible to save on material and labor.

Electrical Installation

Electrical installation supplies power to electrical devices for chiller, solar panels, heat pump and low voltage control system. This phase started at the beginning of July through the middle of august. This installation was simultaneously progressing along with the plumbing. This was completed by working very closely with the zone electrician to make sure electrical codes were met.

Control Wiring

The control wiring step consisted of laying out control panels, running conduit and wire to and from the components and the building automation system (BAS). The energy technicians at Purdue were very helpful thought this entire phase. This phase started at the end of July and was completed at the end of September.

Software/Programming

During this phase, the programming for controlling the solar thermal heat pump hydronic system was developed. Along with a sequence being developed, the network for the new hydronic system was established and integrated into the existing WebCTRL system for the AEL. With the networking in place, the sequence was then coded and uploaded into WebCTRL. Testing began after preliminary checks were completed to insure the system is functional.

Commissioning

Commissioning of the system was required prior to testing the system. A commissioning report was developed to ensure that the system components operated as intended and that they system was mechanically sound. The communication with controllers and sensors, modulation of valves, and transfer of data was confirmed. Specific pre-tests were conducted to confirm the correction of abnormalities found in the early testing of the control code.

Testing

Testing took place once a basic program was developed and uploaded to allow the system to operate and the commissioning was completed. The tests outlined in the methodology will take place in the prescribed order. While the testing of the heat pump integration was being conducted, the testing for the pumping system also took place. The main goal of the ultimate project was to fully commission a system, thus both subjects of the theses are required to meet this goal.

Analysis of Results

After the period of testing is complete, the results of the testing can be analyzed. The analysis will look at the electrical consumption, the pressures, the temperatures, and the other parameters that outline the success of the tests set out in the methodology section of this thesis. The results of the tests and subsequent analysis will be able to show what future research the system will benefit from.

Documentation of Design & Findings

Throughout the entire life of the project of the hybrid hydronic system, all events, developments, and designs will be documented. The results of the heat pump solar thermal integration will be compiled and documented in a thesis. In a separate thesis, the pumping system design will be documented and published as well.

Appendix B Sequence of Operations, Control Code, & Drawings

The control code that was used to operate the system is presented in this appendix. The code was broken into a hybrid hydronic code and a solar control code. The control of the air handler was used in the testing but was not modified from previous research. The sequence of operations also included.

Hydronic Heating Sequence of Operations

Solar Pre-heat Mode:

Solar Pre-heat mode will be enabled when the glycol from the solar collectors are less than sufficient (below 80°F), but the solar insolation is above 200W/m^2.This mode will allow the solar portion to gain heat until it is able to contribute.

- The primary pump is operating, circulating fluid to the solar collectors.
- The pre-heat bypass valve is open allowing circulation only through the solar collectors.

Solar Mode:

Solar mode will be enabled when there is a request for heating and there is available solar thermal energy to add to the heat pump water heater tank. Solar supply temperature greater than 80°F.

- Glycol/water is to be circulated through primary loop using the primary pump for solar thermal storage.
- Solar panels are to be the only source of heat.
- Hot water heater is in standby, not adding any additional heat.
- Secondary pump is on.
- Pre-heat valve is closed.
- Primary and secondary loop bypasses modulate to allow flow through the entire system.

- Control Valves will modulate to allow fluid to circulate to the secondary loops based on heating requests.

Solar Dissipation Mode:

Solar dissipation mode will be enabled when the solar supply temperature breaches 150°F. This will allow the heat exchanger to cool the glycol for equipment safety.

- The heat exchanger valve will modulate open when the temperature rises above the set point of 150°F.

Solar Storage Mode:

Solar storage mode is enabled when there is no need for heat in the zone, but solar thermal energy is available. This will allow for thermal storage.

- Primary pump is in operation.
- Bypass valve is closed.
- Hot water heater is in standby.
- Secondary pump is off.

Hybrid Mode:

Hybrid mode will be enabled when there is a request for heating and there is sufficient solar thermal energy, but not enough to do all of the heating responsibilities. This is allow the solar and heat pump to work together to meet the requirements.

- Glycol/water is to be circulated though the primary loop with the primary pump.
- Solar panels will be the primary source of heat and the heat pump will provide additional heating when needed.
- Primary and secondary loop bypasses modulate to allow flow through the entire system.
- Control Valves will modulate to allow fluid to circulate to the secondary loops based on heating requests.
- Secondary pump will be turned on based on heating requests.

Heat pump mode:

Heat pump mode will be engaged when there is insufficient solar thermal energy supply and there is a request for heating.

- Primary pump will be disabled (depending on if pre-heat mode is also in operation).
- Primary and secondary loop bypasses modulate to separate flow through each of the loops.
- Control Valves will modulate to allow fluid to circulate to the secondary loops based on heating requests.
- The secondary pump will be enabled based on heating request

Heat Pump:

The Heat Pump shall operate according to its own internal safeties and controls.

Heat Exchanger

The domestic water valve for the heat exchanger shall open anytime the propylene glycol temperature is more than 150 °F.

The domestic water valve is controlled from the solar supply temperature.

Primary Pump:

The primary pump shall run anytime:

- The solar irradiance is more than $200\frac{w}{m^2}$ AND the primary pump differential pressure is less than 25 psi.
- The primary pump is controlled by Variable Speed Drive (VSD) to maintain a constant flow of 1.2 gpm.

Alarms shall be provided as follows:

- Primary Pump Failure: Commanded on, but the status is off.
- Primary Pump Running in Hand: Commanded off, but the status is on.
- Primary Pump Runtime Exceeded: Status runtime exceeds a user definable limit.

Secondary Pump:

The secondary pump shall run whenever there is a heating request from:

- AHU
- OR Environmental Chamber Radiator 1 (EC1)
- OR Environmental Chamber Radiator 2 (EC2)

AND

- All modulating valves can NOT be closed.

Alarms shall be provided as follows:

- Secondary Pump Failure: Commanded on, but the status is off.
- Secondary Pump Running in Hand: Commanded off, but the status is on.
- Secondary Pump Runtime Exceeded: Status runtime exceeds a user definable limit.

Zone 1 (Solar Heating Coil):

The glycol temperature through the solar reheat coil shall be measured.

The control valve shall modulate open to maintain an air discharge temperature from the unit.

Zone 1 has an adjustable set point defined by the user.

Zone 2 (EC1):

The glycol supply and return temperature through EC1 shall be measured.

The control valve shall modulate open to maintain the minimum hot water return temperature set point.

Zone 2 has an adjustable set point defined by the user.

Zone 3 (EC2):

The glycol supply and return temperature through the EC2 shall be measured.

The control valve shall modulate open to maintain the minimum hot water return temperature set point.

Zone 3 has an adjustable set point defined by the user.

Monitoring:

The following points will be monitored and trended for research and teaching

- Temperature

  The following temperatures shall be monitored:

  - Solar supply temperature
  - Solar return temperature
  - Domestic water supply temperature
  - Domestic water return temperature
  - Heat pump inlet temperature
  - Heat pump exit temperature
  - Secondary pump temperature
  - AHU heating supply temperature
  - AHU heating return temperature
  - AHU discharge temperature
  - Environmental chamber zone temperature
  - EC1 heating supply temperature
  - EC1 heating return temperature
  - EC2 heating supply temperature
  - EC2 heating return temperature

  Alarms shall be provided as follows:

  - High Supply Temperature: If greater than 155°F (adj.)

- Flow

  The following flows shall be monitored

  - Solar flow
  - Solar heating coil flow
  - EC1 heating flow
  - EC2 heating flow
  - Domestic water flow

- Electricity

  The following shall be monitored

  - Primary Pump watts
  - Secondary Pump watts
  - Heat Pump watts

- Run Status

  - Primary pump run status
  - The secondary pump run status

- Energy

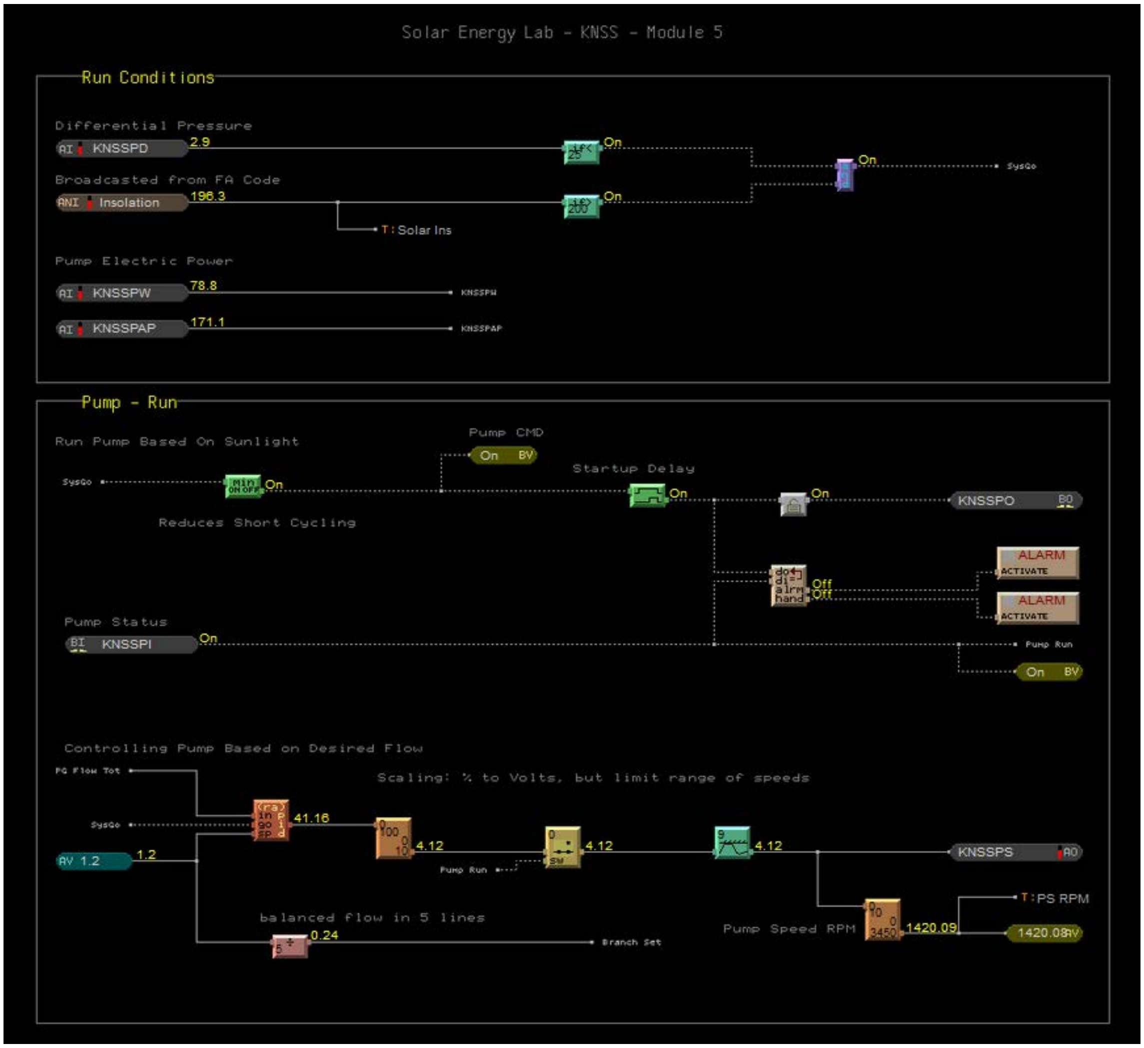
  The total energy of the system shall be computed.

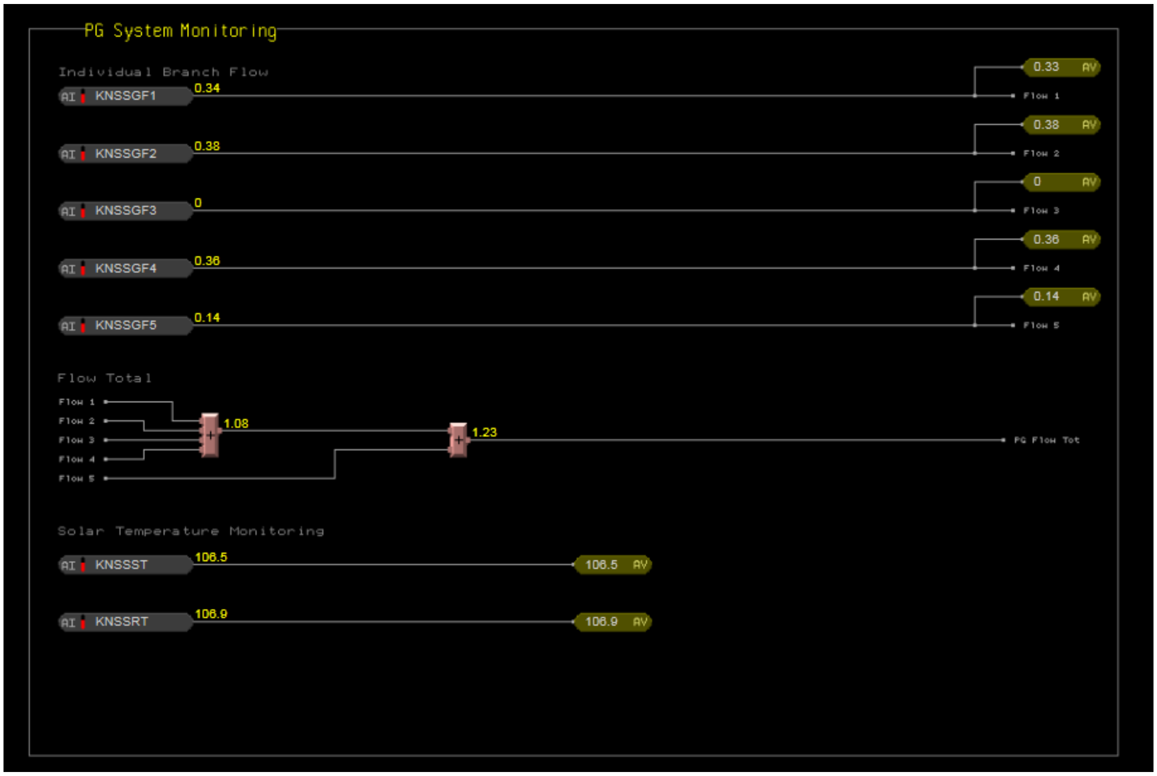
- Pressure

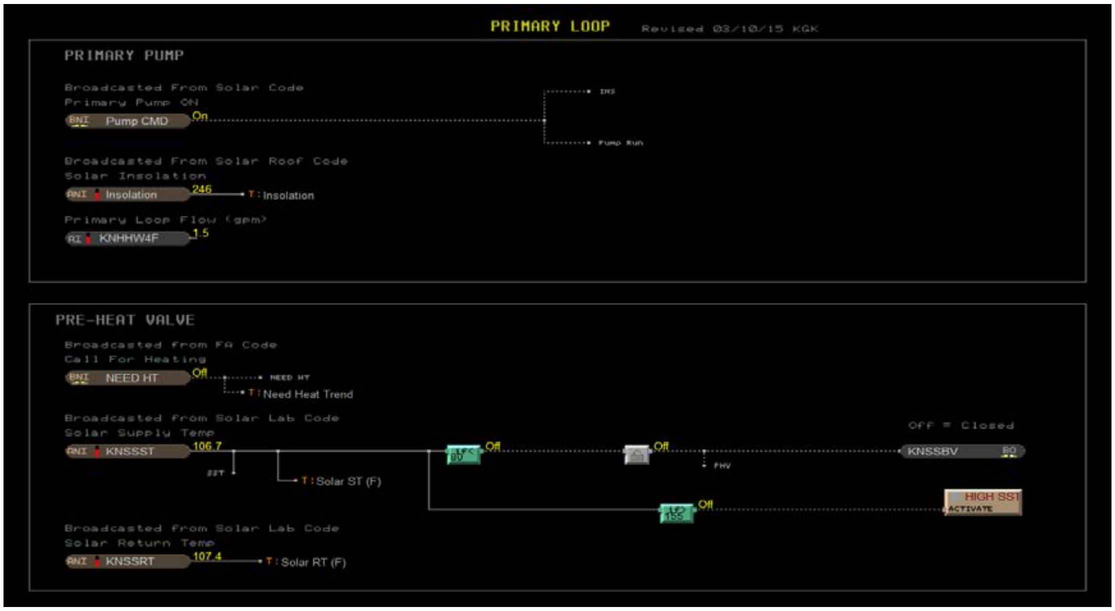
  The following pressure shall be monitored

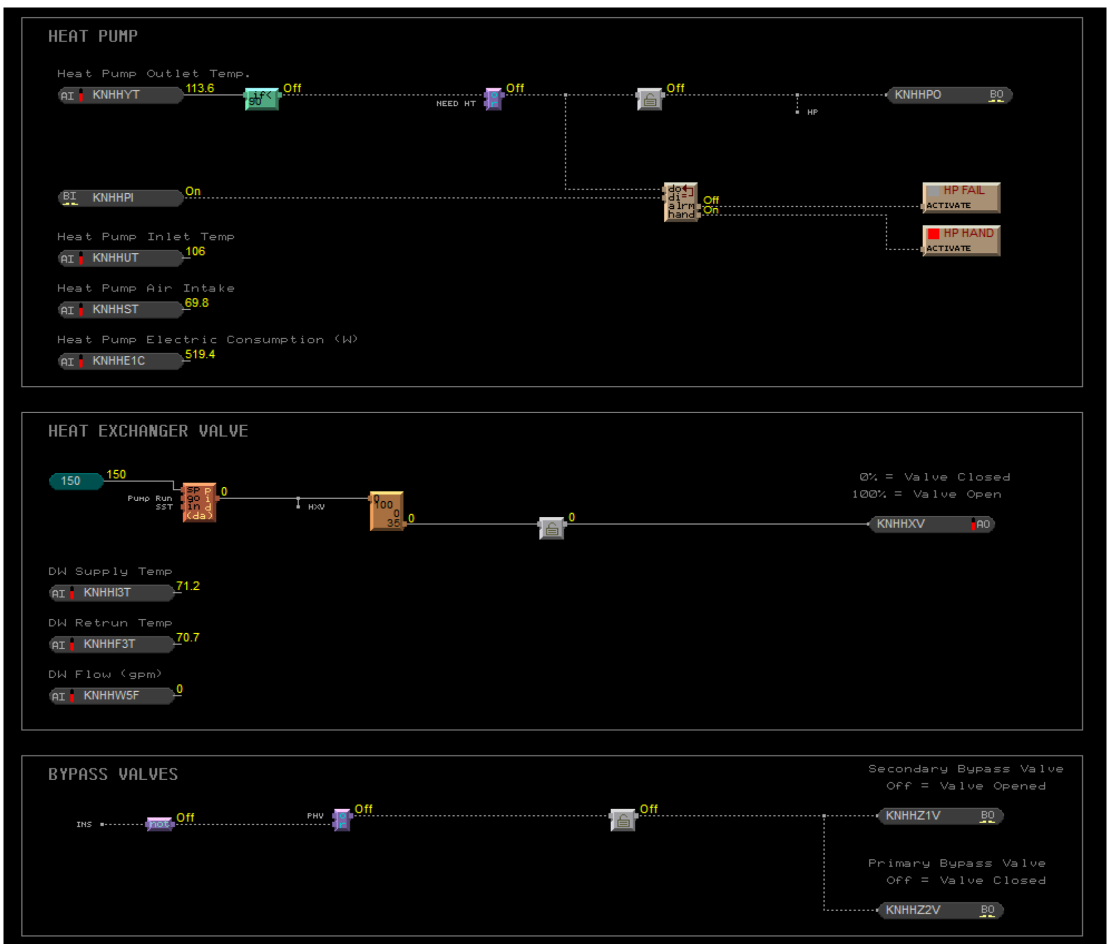
  - Primary Pump differential pressure
  - Secondary Pump differential pressure

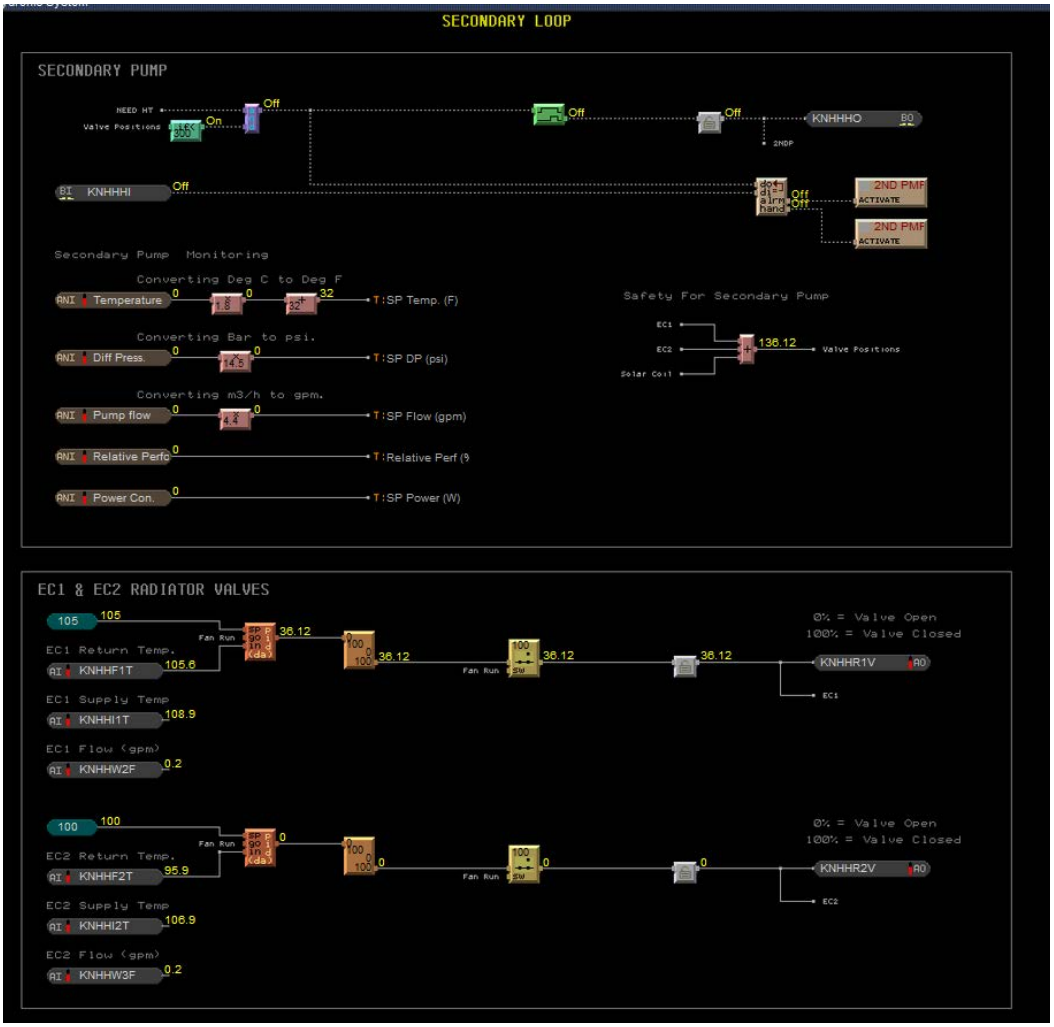
Control Code

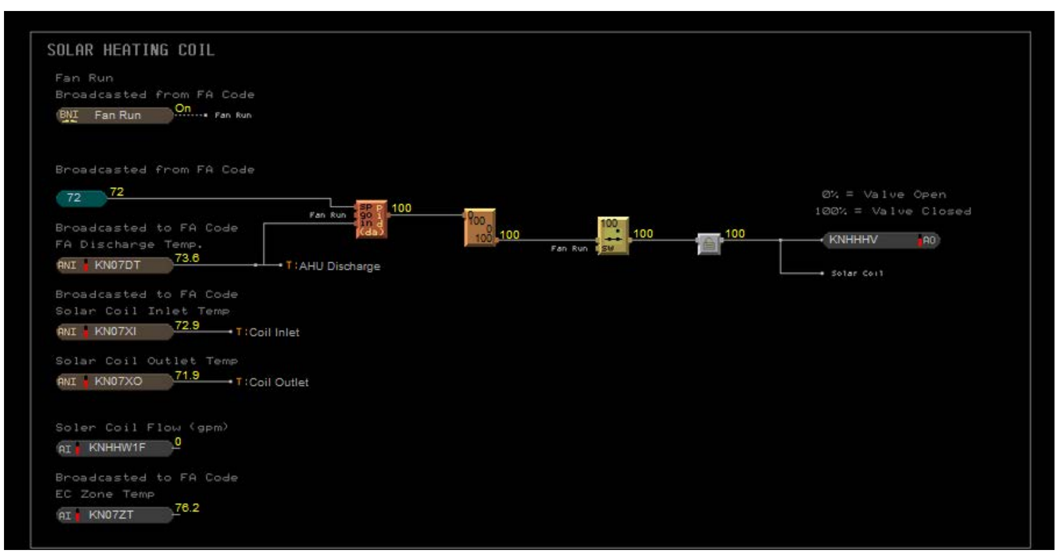


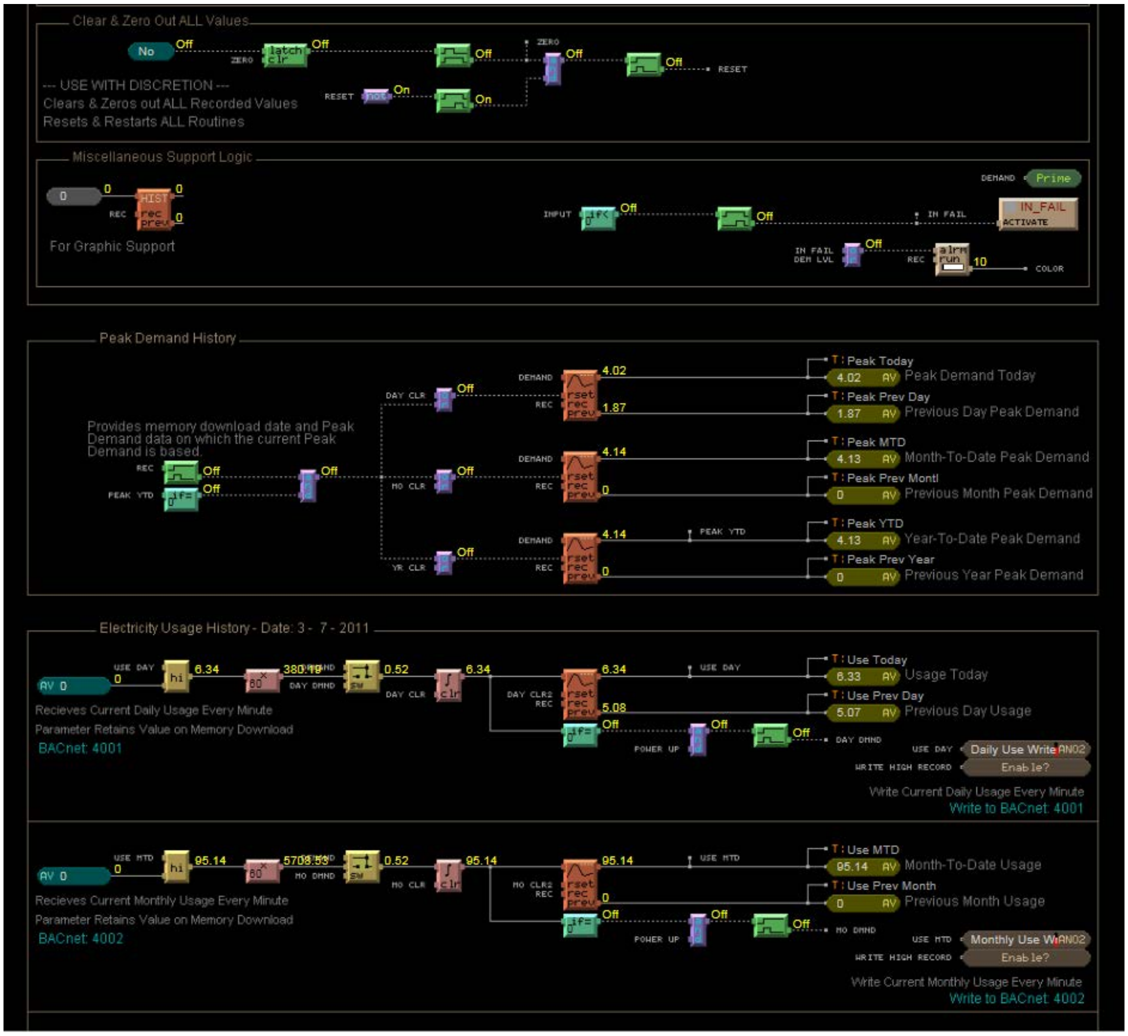

PG System Monitoring
Individual Branch Flow
AI KNSSGF1
0.34
AI KNSSGF2
0.38
AI KNSSGF3
0
AI KNSSGF4
0.36
AI KNSSGF5
0.14
0.33 AV
Flow 1
0.38 AV
Flow 2
0 AV
Flow 3
0.36 AV
Flow 4
0.14 AV
Flow 5
Flow Total
Flow 1
Flow 2
Flow 3
Flow 4
Flow 5
1.08
1.23
PG Flow Tot
Solar Temperature Monitoring
AI KNSSST
106.5
106.5 AV
AI KNSSRT
106.9
106.9 AV

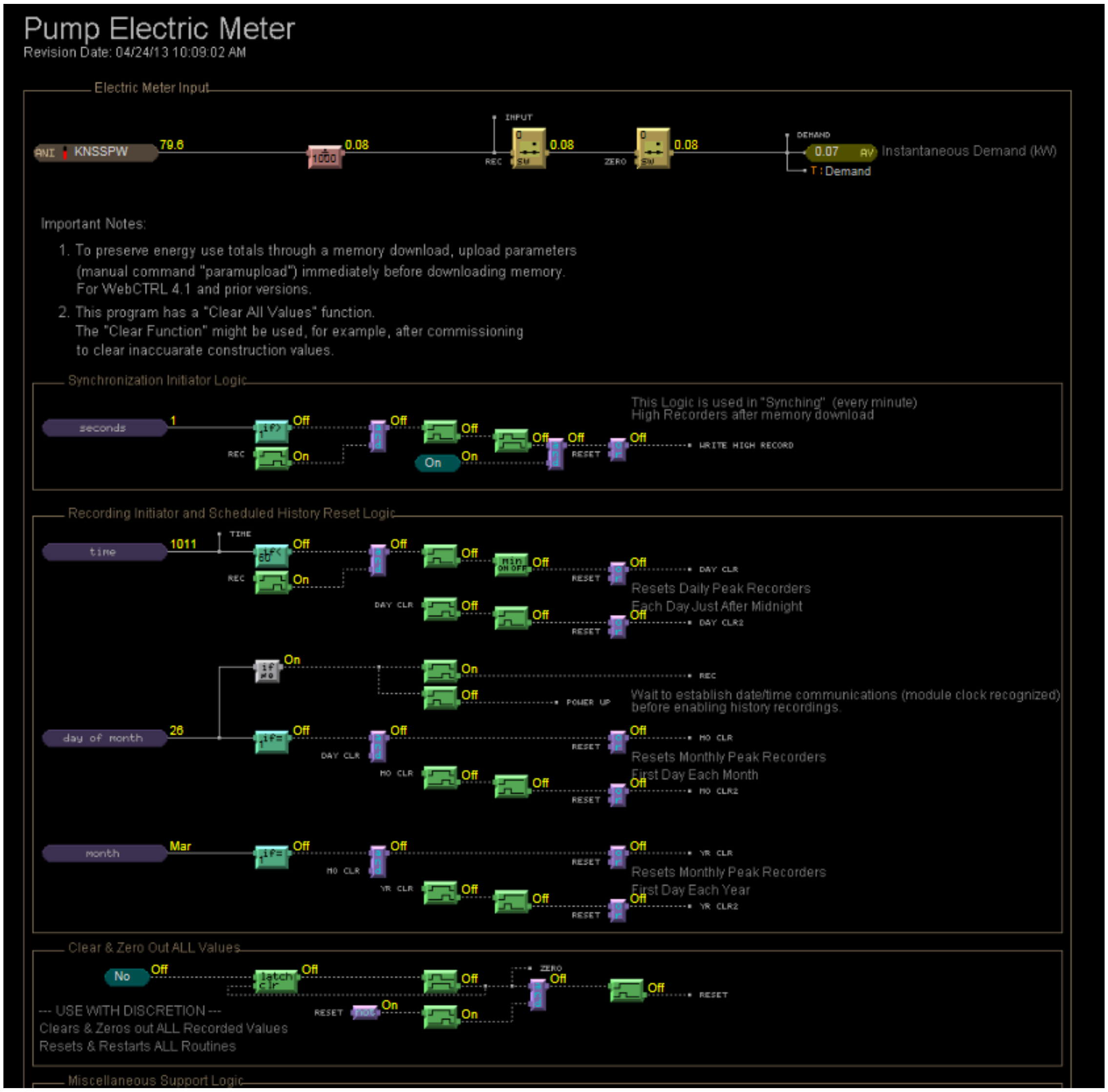

PRIMARY LOOP
Revised 03/10/15 KGK
PRIMARY PUMP
Broadcasted From Solar Code
Primary Pump ON
Pump CMD
On
Insolation
Broadcasted From Solar Roof Code
Solar Insolation
246
T: Insolation
Primary Loop Flow (gpm)
KNHHW4F
1.5
PRE-HEAT VALVE
Broadcasted from FA Code
Call For Heating
NEED HT
Off
T: Need Heat Trend
Broadcasted From Solar Lab Code
Solar Supply Temp
KNSSST
106.7
T: Solar ST (F)
Off = Closed
KNSSBV
HIGH SST
ACTIVATE
Broadcasted From Solar Lab Code
Solar Return Temp
KNSSRT
107.4
T: Solar RT (F)

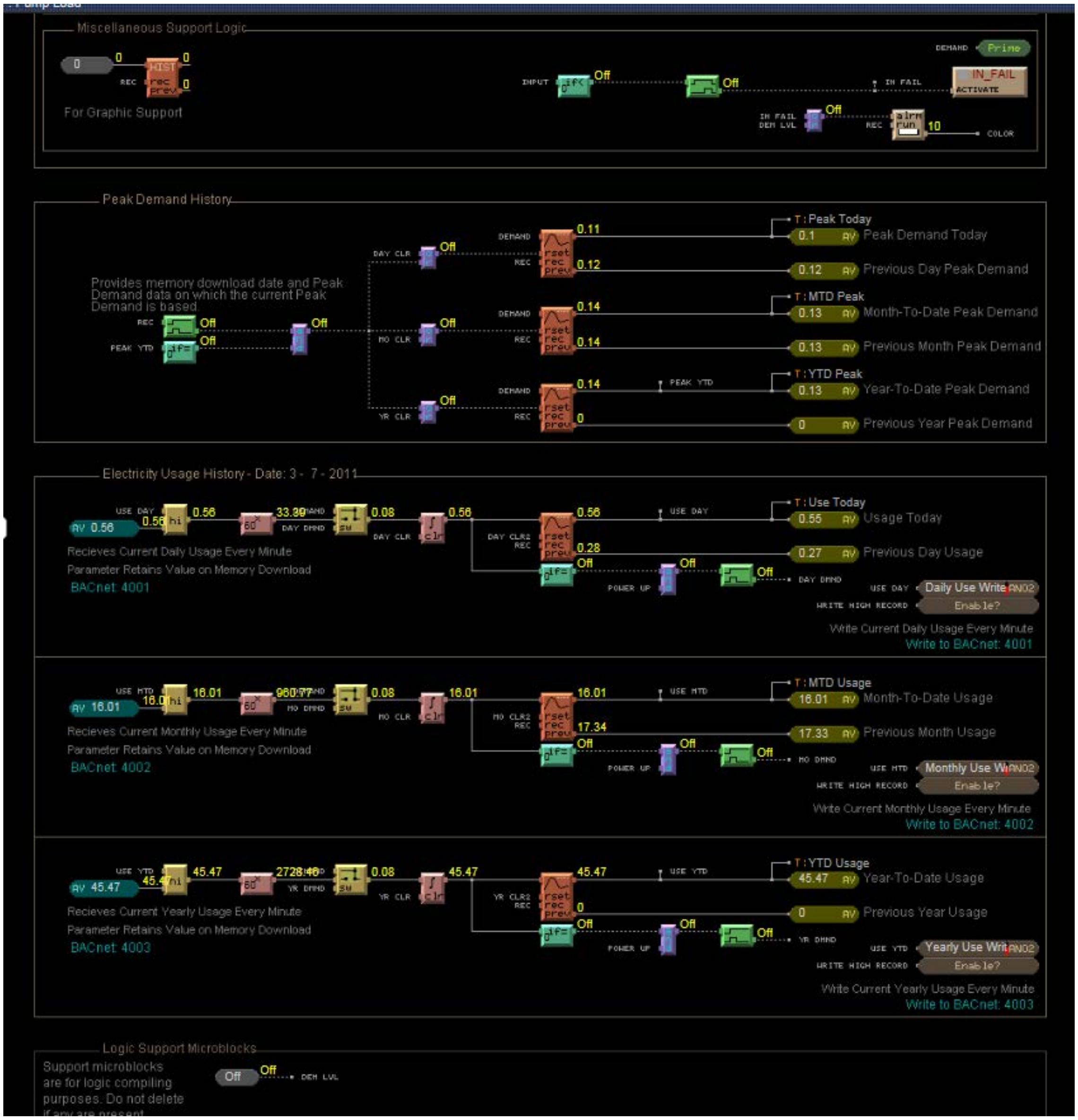

HEAT PUMP
Heat Pump Outlet Temp.
KNHHYT
113.6
Off
NEED HT
KNHHPO
KNHHPI
On
HP FAIL
ACTIVATE
HP HAND
ACTIVATE
Heat Pump Inlet Temp
KNHHUT
106
Heat Pump Air Intake
KNHHST
69.8
Heat Pump Electric Consumption (W)
KNHHE1C
519.4
HEAT EXCHANGER VALVE
150
0% = Valve Closed
100% = Valve Open
KNHHXV
DW Supply Temp
KNHHI3T
71.2
DW Retrun Temp
KNHHF3T
70.7
DW Flow (gpm)
KNHHW5F
0
BYPASS VALVES
Secondary Bypass Valve
Off = Valve Opened
KNHHZ1V
Primary Bypass Valve
Off = Valve Closed
KNHHZ2V

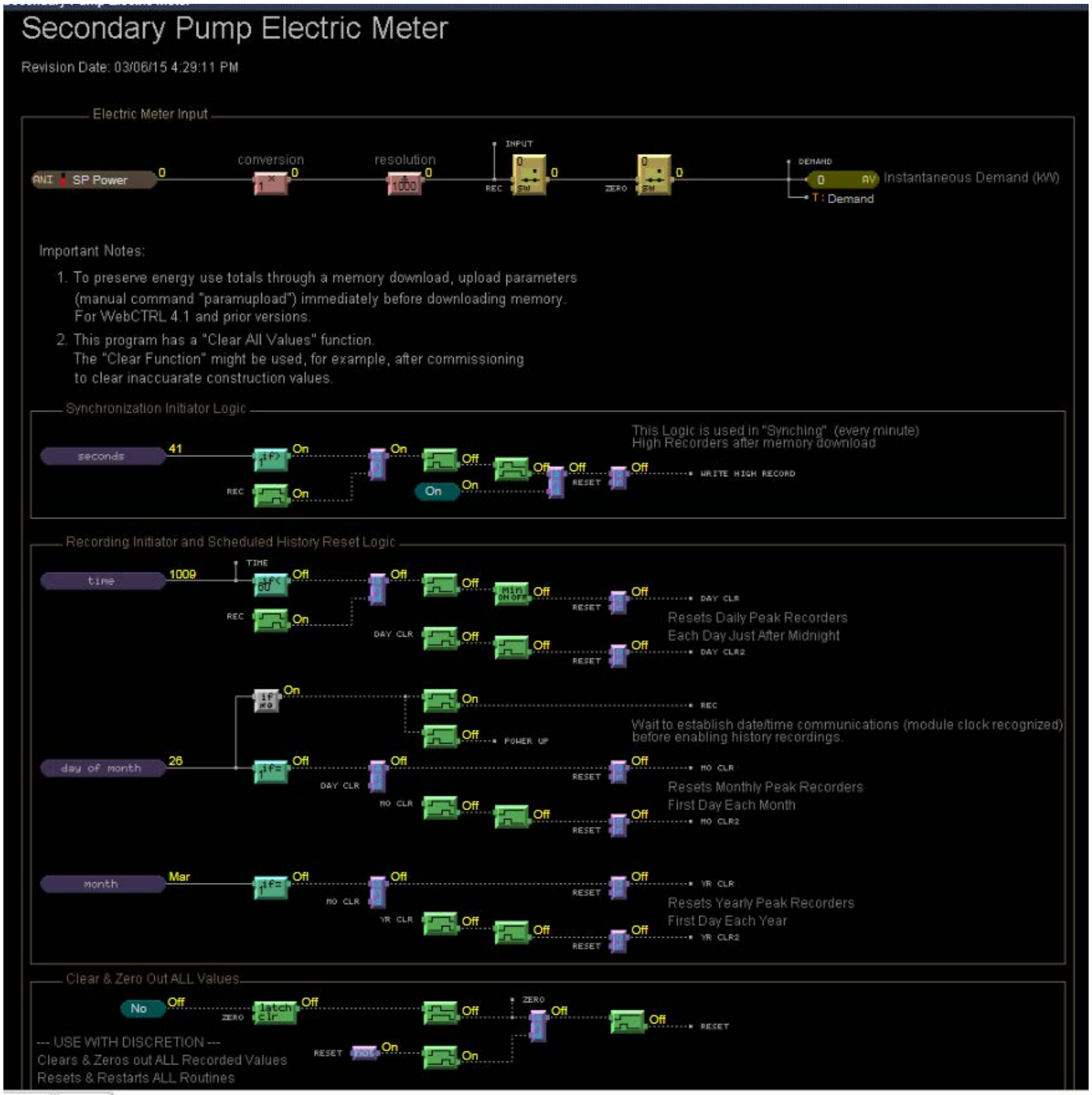

SECONDARY LOOP
SECONDARY PUMP
NEED HT
Valve Positions
On
Off
KNHHHO
2NDP
BI KNHHHI
2ND PMP ACTIVATE
2ND PMP ACTIVATE
Secondary Pump Monitoring
Converting Deg C to Deg F
ANI Temperature
T:SP Temp. (F)
Converting Bar to psi.
ANI Diff Press.
T:SP DP (psi)
Converting m3/h to gpm.
ANI Pump flow
T:SP Flow (gpm)
ANI Relative Perfo
T:Relative Perf
ANI Power Con.
T:SP Power (W)
Safety For Secondary Pump
EC1
EC2
Solar Coil
136.12
Valve Positions
EC1 & EC2 RADIATOR VALVES
0% = Valve Open
100% = Valve Closed
105
EC1 Return Temp.
AI KNHHF1T
105.6
Fan Run
36.12
KNHHR1V
EC1 Supply Temp
AI KNHHI1T
108.9
EC1 Flow (gpm)
AI KNHHW2F
0.2
0% = Valve Open
100% = Valve Closed
100
EC2 Return Temp.
AI KNHHF2T
95.9
KNHHR2V
EC2 Supply Temp
AI KNHHI2T
106.9
EC2 Flow (gpm)
AI KNHHW3F
0.2


SOLAR HEATING COIL
Fan Run
Broadcasted from FA Code
BNI Fan Run
On
Broadcasted from FA Code
72
0% = Valve Open
100% = Valve Closed
Broadcasted to FA Code
FA Discharge Temp.
ANI KN07DT
73.6
T:AHU Discharge
Fan Run
100
KNHHHV
Solar Coil
Broadcasted to FA Code
Solar Coil Inlet Temp
ANI KN07XI
72.9
T:Coil Inlet
Solar Coil Outlet Temp
ANI KN07XO
71.9
T:Coil Outlet
Soler Coil Flow (gpm)
AI KNHHW1F
0
Broadcasted to FA Code
EC Zone Temp
AI KN07ZT
76.2

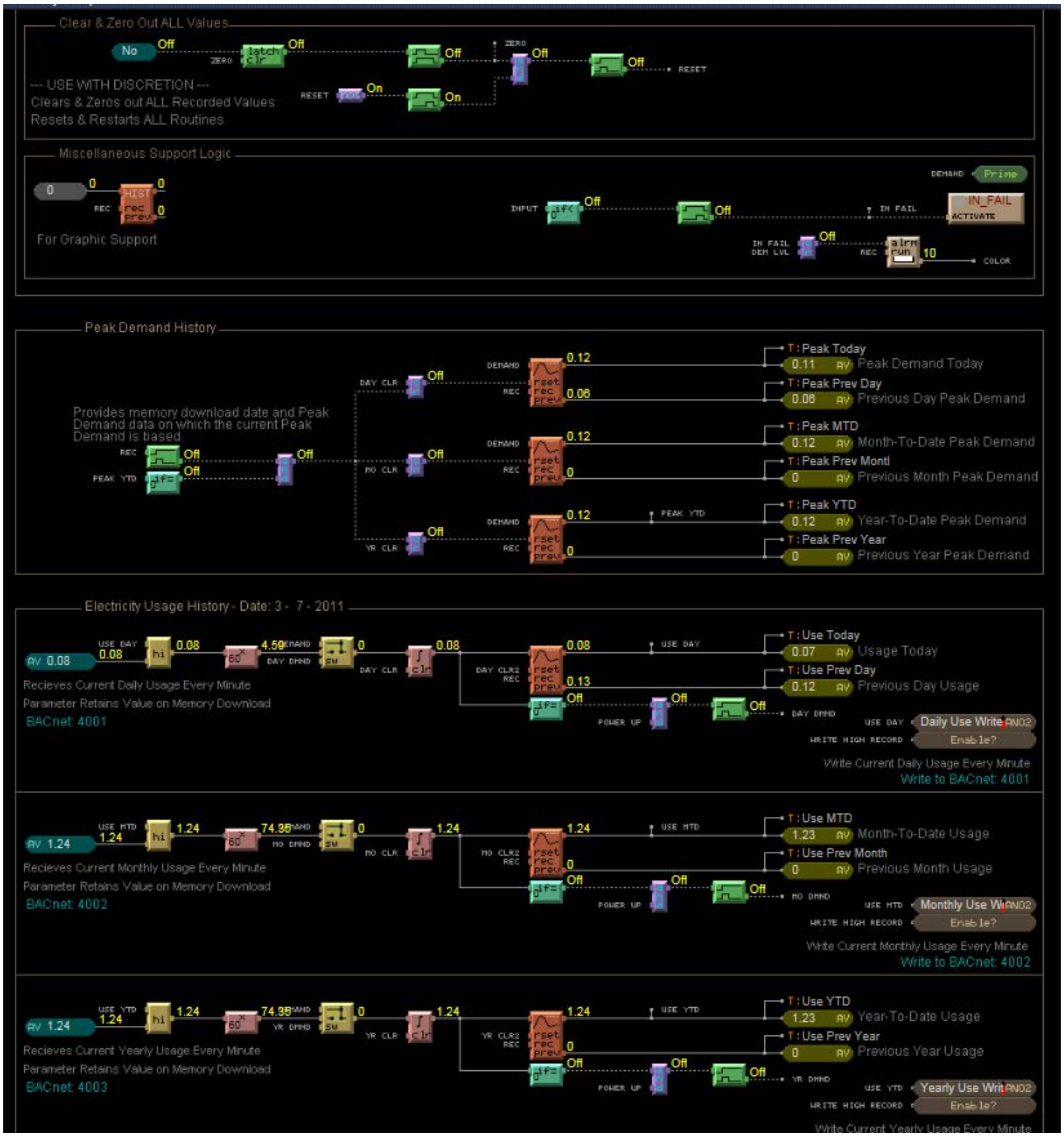

Clear & Zero Out ALL Values
--- USE WITH DISCRETION ---
Clears & Zeros out ALL Recorded Values
Resets & Restarts ALL Routines
Miscellaneous Support Logic
For Graphic Support
Peak Demand History
Provides memory download date and Peak Demand data on which the current Peak Demand is based.
Peak Demand Today
Previous Day Peak Demand
Month-To-Date Peak Demand
Previous Month Peak Demand
Year-To-Date Peak Demand
Previous Year Peak Demand
Electricity Usage History - Date: 3 - 7 - 2011
Recieves Current Daily Usage Every Minute
Parameter Retains Value on Memory Download
BACnet 4001
Usage Today
Previous Day Usage
Write Current Daily Usage Every Minute
Write to BACnet 4001
Recieves Current Monthly Usage Every Minute
Parameter Retains Value on Memory Download
BACnet 4002
Month-To-Date Usage
Previous Month Usage
Write Current Monthly Usage Every Minute
Write to BACnet 4002


Pump Electric Meter
Revision Date: 04/24/13 10:09:02 AM
Electric Meter Input
KNSSPW
79.6
1000
0.08
INPUT
REC
ZERO
DEMAND
0.07
Instantaneous Demand (kW)
T : Demand
Important Notes:
1. To preserve energy use totals through a memory download, upload parameters (manual command "paramupload") immediately before downloading memory. For WebCTRL 4.1 and prior versions.
2. This program has a "Clear All Values" function. The "Clear Function" might be used, for example, after commissioning to clear inaccuarate construction values.
Synchronization Initiator Logic
seconds
This Logic is used in "Synching" (every minute) High Recorders after memory download
WRITE HIGH RECORD
Recording Initiator and Scheduled History Reset Logic
time
1011
DAY CLR
Resets Daily Peak Recorders
Each Day Just After Midnight
DAY CLR2
REC
POWER UP
Wait to establish date/time communications (module clock recognized) before enabling history recordings.
day of month
26
MO CLR
Resets Monthly Peak Recorders
First Day Each Month
MO CLR2
month
Mar
YR CLR
Resets Monthly Peak Recorders
First Day Each Year
YR CLR2
Clear & Zero Out ALL Values
No
--- USE WITH DISCRETION ---
Clears & Zeros out ALL Recorded Values
Resets & Restarts ALL Routines
RESET
Miscellaneous Support Logic

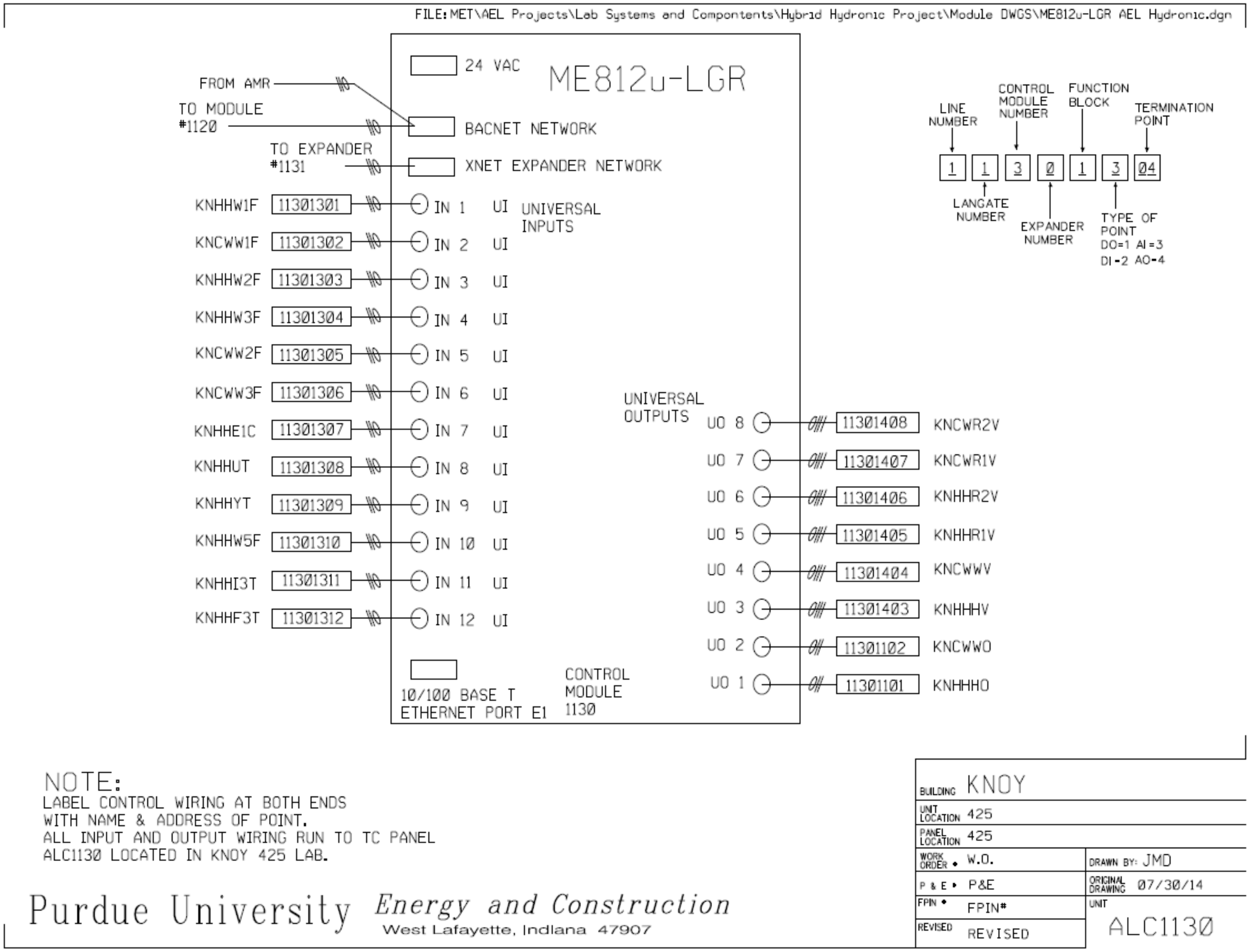

Miscellaneous Support Logic
For Graphic Support
IN_FAIL
ACTIVATE
Prime
Peak Demand History
Provides memory download date and Peak Demand data on which the current Peak Demand is based
T: Peak Today
Peak Demand Today
Previous Day Peak Demand
T: MTD Peak
Month-To-Date Peak Demand
Previous Month Peak Demand
T: YTD Peak
Year-To-Date Peak Demand
Previous Year Peak Demand
Electricity Usage History - Date: 3 - 7 - 2011
Recieves Current Daily Usage Every Minute
Parameter Retains Value on Memory Download
BACnet 4001
T: Use Today
Usage Today
Previous Day Usage
Daily Use Write
Enable?
Write Current Daily Usage Every Minute
Write to BACnet 4001
Recieves Current Monthly Usage Every Minute
Parameter Retains Value on Memory Download
BACnet 4002
T: MTD Usage
Month-To-Date Usage
Previous Month Usage
Enable?
Write Current Monthly Usage Every Minute
Write to BACnet 4002
Recieves Current Yearly Usage Every Minute
Parameter Retains Value on Memory Download
BACnet 4003
T: YTD Usage
Year-To-Date Usage
Previous Year Usage
Enable?
Write Current Yearly Usage Every Minute
Write to BACnet 4003
Logic Support Microblocks
Support microblocks are for logic compiling purposes. Do not delete if any are present

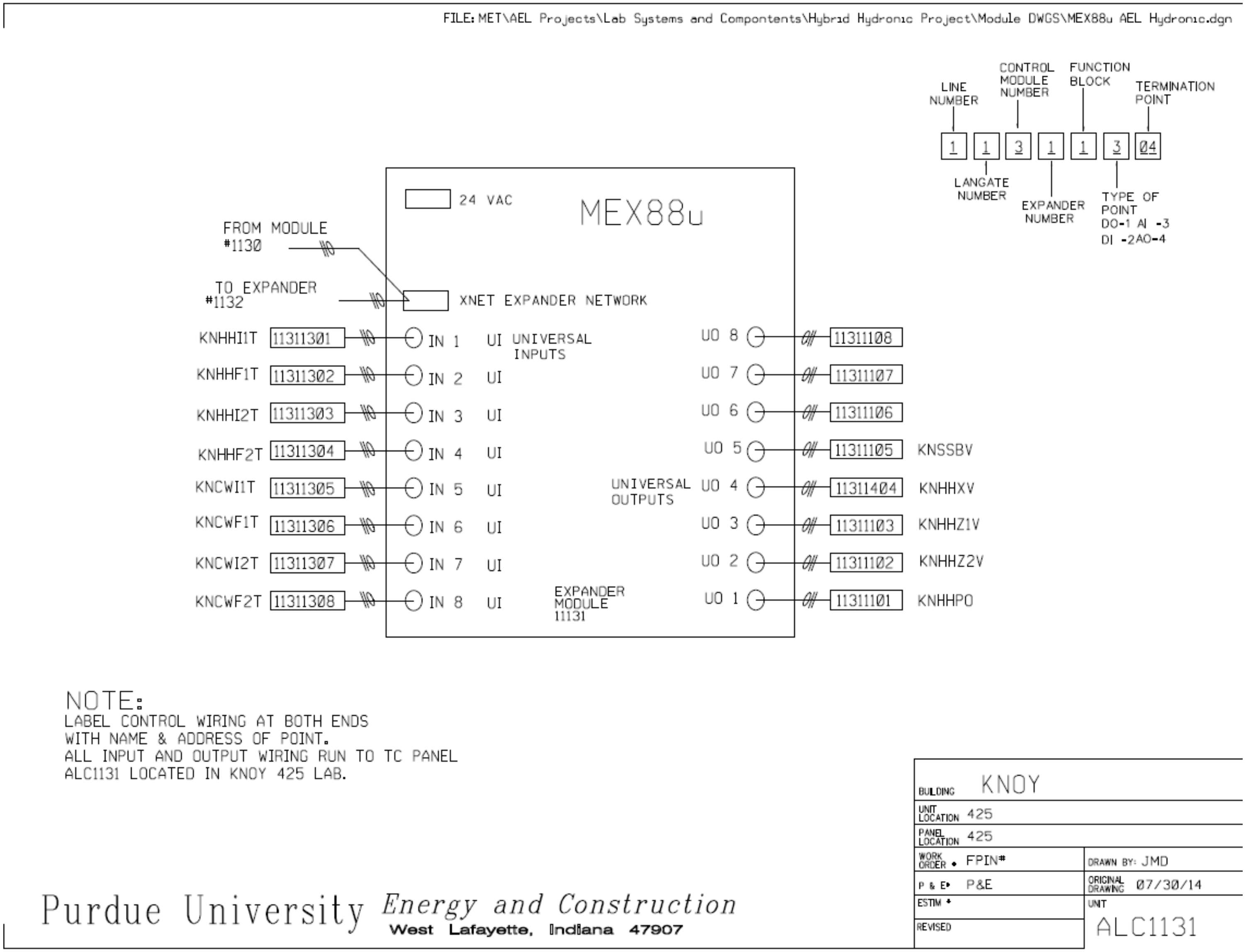


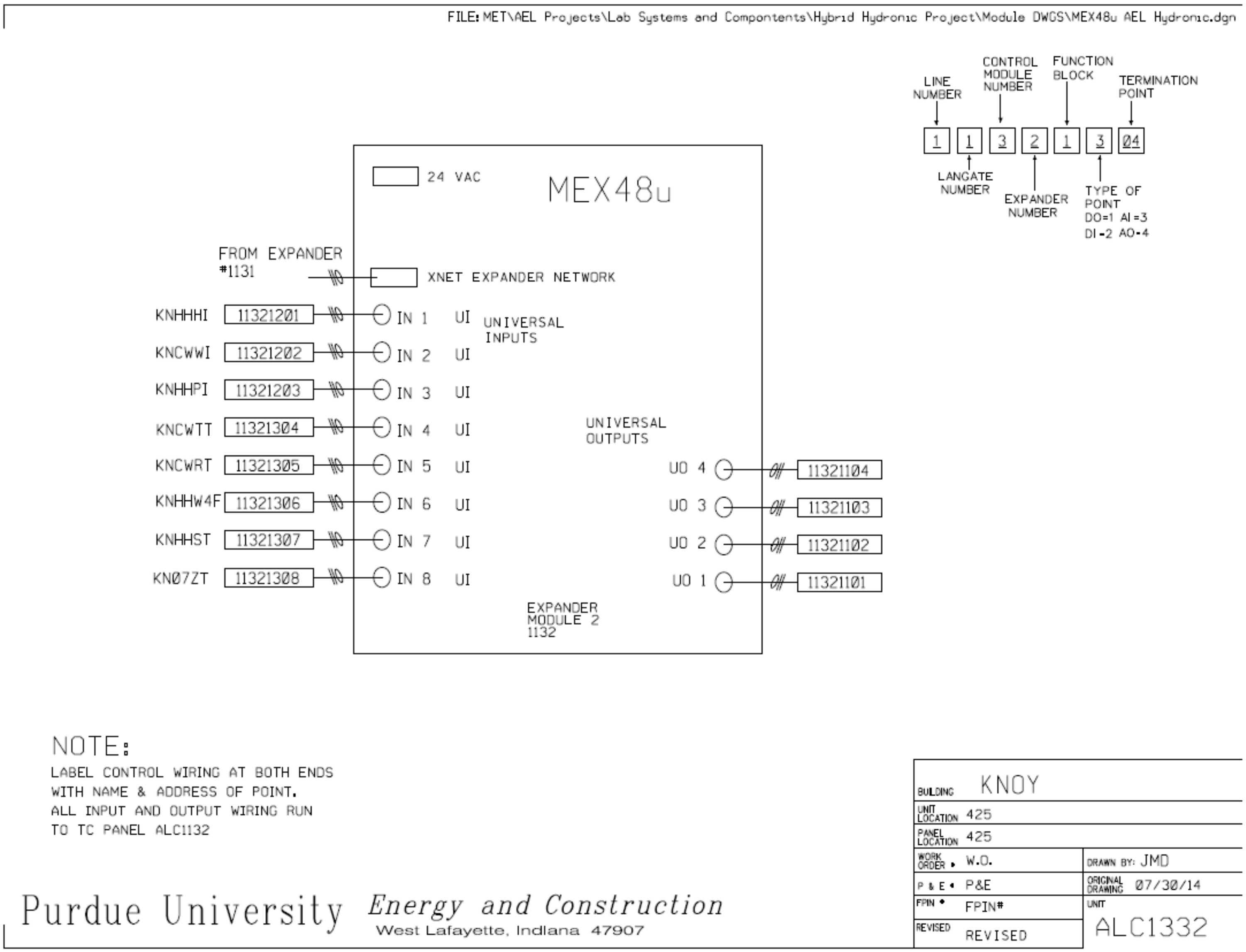
Secondary Pump Electric Meter
Revision Date: 03/06/15 4:29:11 PM
Electric Meter Input
SP Power
conversion
resolution
Instantaneous Demand (kW)
T : Demand
Important Notes:
1. To preserve energy use totals through a memory download, upload parameters (manual command "paramupload") immediately before downloading memory. For WebCTRL 4.1 and prior versions.
2. This program has a "Clear All Values" function. The "Clear Function" might be used, for example, after commissioning to clear inaccuarate construction values.
Synchronization Initiator Logic
This Logic is used in "Synching" (every minute) High Recorders after memory download
Recording Initiator and Scheduled History Reset Logic
Resets Daily Peak Recorders Each Day Just After Midnight
Wait to establish date/time communications (module clock recognized) before enabling history recordings.
Resets Monthly Peak Recorders First Day Each Month
Resets Yearly Peak Recorders First Day Each Year
Clear & Zero Out ALL Values
--- USE WITH DISCRETION ---
Clears & Zeros out ALL Recorded Values
Resets & Restarts ALL Routines


Clear & Zero Out ALL Values
--- USE WITH DISCRETION ---
Clears & Zeros out ALL Recorded Values
Resets & Restarts ALL Routines
Miscellaneous Support Logic
For Graphic Support
Peak Demand History
Provides memory download date and Peak Demand data on which the current Peak Demand is based
T : Peak Today
Peak Demand Today
T : Peak Prev Day
Previous Day Peak Demand
T : Peak MTD
Month-To-Date Peak Demand
T : Peak Prev Montl
Previous Month Peak Demand
T : Peak YTD
Year-To-Date Peak Demand
T : Peak Prev Year
Previous Year Peak Demand
Electricity Usage History - Date: 3 - 7 - 2011
Recieves Current Daily Usage Every Minute
Parameter Retains Value on Memory Download
BACnet: 4001
T : Use Today
Usage Today
T : Use Prev Day
Previous Day Usage
Daily Use Write
Write Current Daily Usage Every Minute
Write to BACnet: 4001
Recieves Current Monthly Usage Every Minute
Parameter Retains Value on Memory Download
BACnet: 4002
T : Use MTD
Month-To-Date Usage
T : Use Prev Month
Previous Month Usage
Write Current Monthly Usage Every Minute
Write to BACnet: 4002
Recieves Current Yearly Usage Every Minute
Parameter Retains Value on Memory Download
BACnet: 4003
T : Use YTD
Year-To-Date Usage
T : Use Prev Year
Previous Year Usage
Write Current Yearly Usage Every Minute

Module Drawings




FILE: MET\AEL Projects\Lab Systems and Compontents\Hybrid Hydronic Project\Module DWGS\MEX88u AEL Hydronic.dgn
LINE NUMBER
CONTROL MODULE NUMBER
FUNCTION BLOCK
TERMINATION POINT
1 1 3 1 1 3 04
LANGATE NUMBER
EXPANDER NUMBER
TYPE OF POINT
DO-1 AI -3
DI -2 AO-4
24 VAC
MEX88u
FROM MODULE #1130
TO EXPANDER #1132
XNET EXPANDER NETWORK
KNHHI1T 11311301 IN 1 UI
UNIVERSAL INPUTS
KNHHF1T 11311302 IN 2 UI
KNHHI2T 11311303 IN 3 UI
KNHHF2T 11311304 IN 4 UI
KNCWI1T 11311305 IN 5 UI
KNCWF1T 11311306 IN 6 UI
KNCWI2T 11311307 IN 7 UI
KNCWF2T 11311308 IN 8 UI
EXPANDER MODULE 11131
UO 8 11311108
UO 7 11311107
UO 6 11311106
UO 5 11311105 KNSSBV
UNIVERSAL OUTPUTS
UO 4 11311404 KNHHXV
UO 3 11311103 KNHHZ1V
UO 2 11311102 KNHHZ2V
UO 1 11311101 KNHHPO
NOTE:
LABEL CONTROL WIRING AT BOTH ENDS
WITH NAME & ADDRESS OF POINT.
ALL INPUT AND OUTPUT WIRING RUN TO TC PANEL
ALC1131 LOCATED IN KNOY 425 LAB.
Purdue University Energy and Construction
West Lafayette, Indiana 47907
BUILDING KNOY
UNIT LOCATION 425
PANEL LOCATION 425
WORK ORDER # FPIN#
DRAWN BY: JMD
P & E# P&E
ORIGINAL DRAWING 07/30/14
ESTIM #
UNIT
REVISED
ALC1131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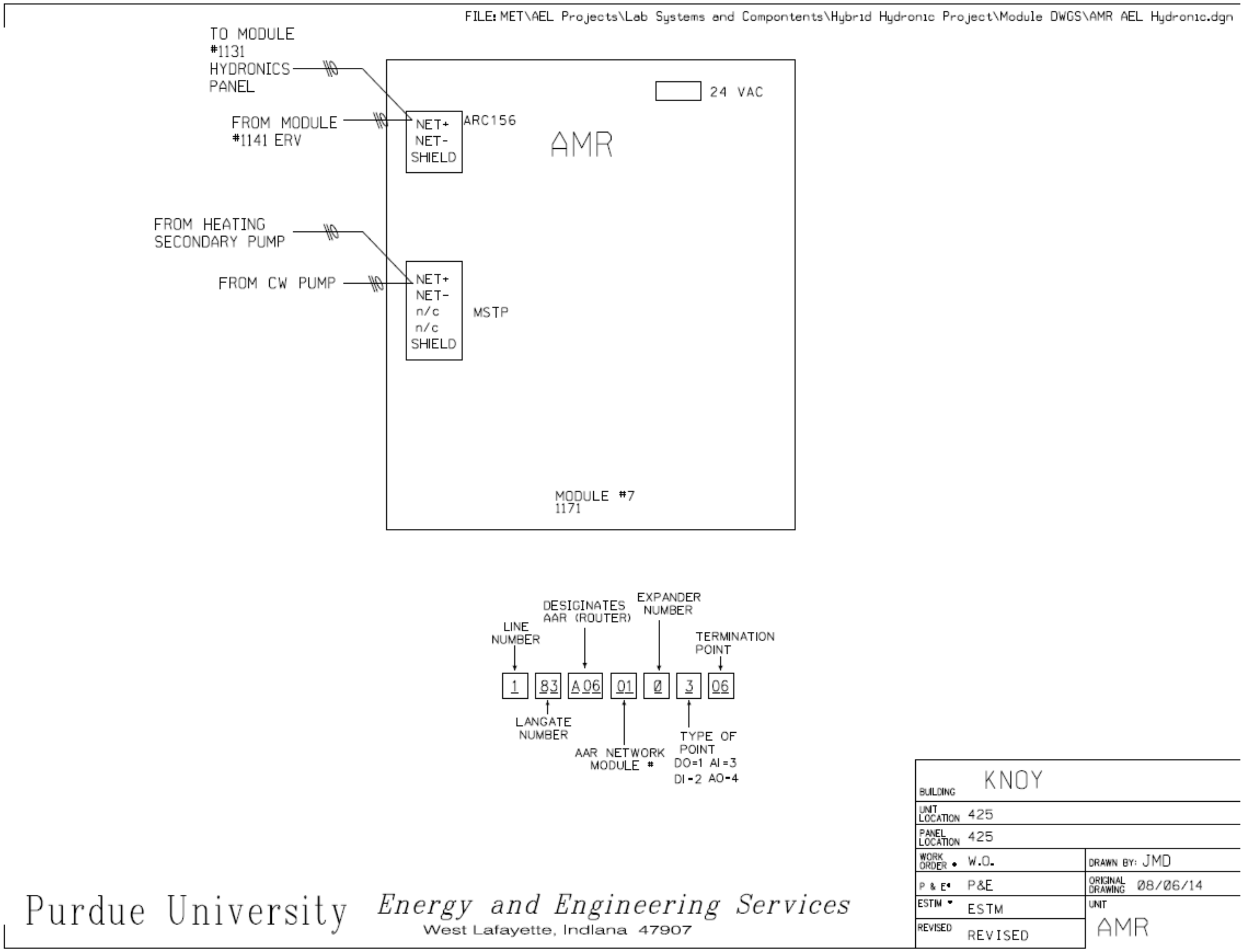
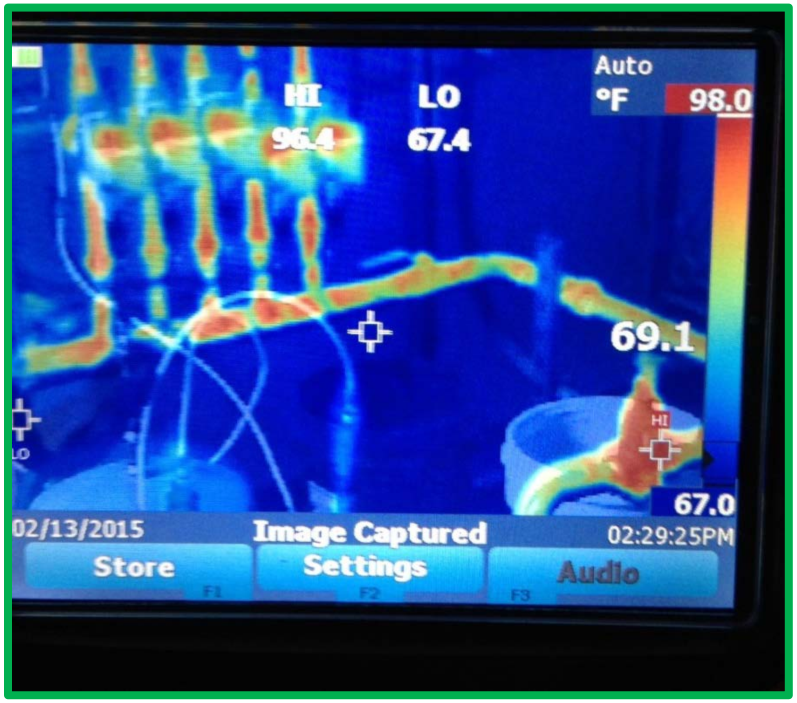
LINE NUMBER
CONTROL MODULE NUMBER
FUNCTION BLOCK
TERMINATION POINT
1 1 3 2 1 3 04
LANGATE NUMBER
EXPANDER NUMBER
TYPE OF POINT
DO=1 AI=3
DI=2 AO=4
24 VAC
MEX48u
FROM EXPANDER #1131
XNET EXPANDER NETWORK
UNIVERSAL INPUTS
KNHHHI 11321201 IN 1 UI
KNCWWI 11321202 IN 2 UI
KNHHPI 11321203 IN 3 UI
KNCWTT 11321304 IN 4 UI
KNCWRT 11321305 IN 5 UI
KNHHW4F 11321306 IN 6 UI
KNHHST 11321307 IN 7 UI
KN07ZT 11321308 IN 8 UI
UNIVERSAL OUTPUTS
UO 4 11321104
UO 3 11321103
UO 2 11321102
UO 1 11321101
EXPANDER MODULE 2
1132
NOTE:
LABEL CONTROL WIRING AT BOTH ENDS
WITH NAME & ADDRESS OF POINT.
ALL INPUT AND OUTPUT WIRING RUN
TO TC PANEL ALC1132
Purdue University
Energy and Construction
West Lafayette, Indiana 47907
BUILDING KNOY
UNIT LOCATION 425
PANEL LOCATION 425
WORK ORDER # W.O.
DRAWN BY: JMD
P & E # P&E
ORIGINAL DRAWING 07/30/14
FPIN # FPIN#
UNIT ALC1332
REVISED REVISED

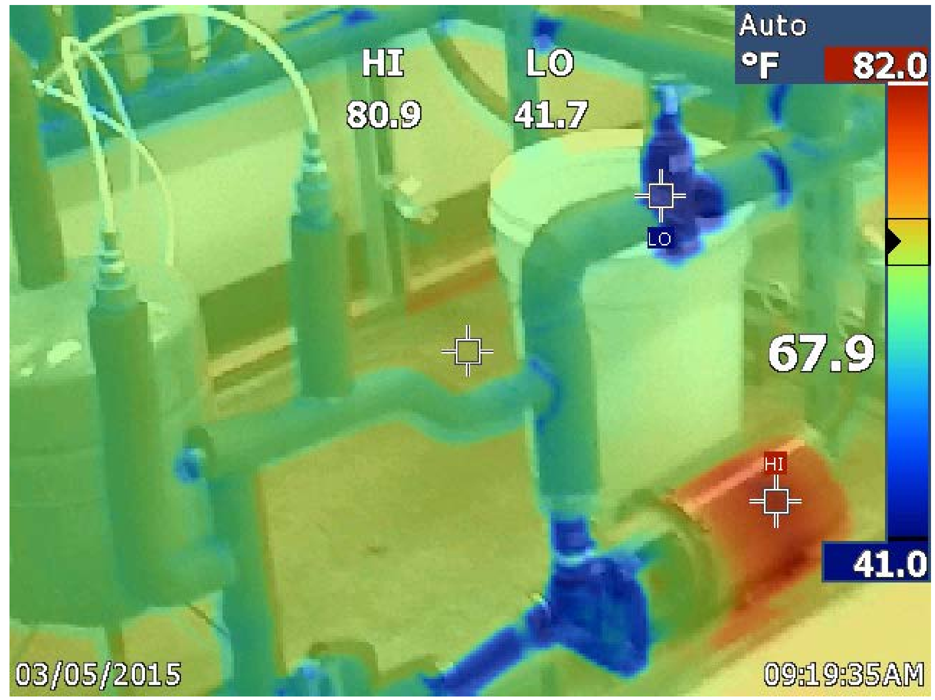

FILE: MET\AEL Projects\Lab Systems and Compontents\Hybrid Hydronic Project\Module DWGS\AMR AEL Hydronic.dgn
TO MODULE
#1131
HYDRONICS
PANEL
FROM MODULE
#1141 ERV
NET+
NET-
SHIELD
ARC156
24 VAC
AMR
FROM HEATING
SECONDARY PUMP
FROM CW PUMP
NET+
NET-
n/c
n/c
SHIELD
MSTP
MODULE #7
1171
LINE
NUMBER
DESIGINATES
AAR (ROUTER)
EXPANDER
NUMBER
TERMINATION
POINT
1
83
A06
01
Ø
3
06
LANGATE
NUMBER
AAR NETWORK
MODULE #
TYPE OF
POINT
DO=1 AI=3
DI=2 AO=4
BUILDING KNOY
UNIT LOCATION 425
PANEL LOCATION 425
WORK ORDER # W.O.
DRAWN BY: JMD
P & E# P&E
ORIGINAL DRAWING Ø8/Ø6/14
ESTM # ESTM
UNIT AMR
REVISED REVISED
Purdue University
Energy and Engineering Services
West Lafayette, Indiana 47907

Insulation Thermal Images

Secondary Loop Piping Insuation Before (left) & After (right)

Primary Pump Insuation Before (left) & After (right)





Appendix C Commissioning Report

Equipment Functional Tests

1.1 Equipment/Systems Project Information Pre-Functional

Equipment/System Name	*Hybrid Hydronic*
Building Name	*Knoy Hall*
Individuals Performing Tests	*M. DeGrove, K. Krockenberger*
Date of Test(s)	*Jan-15*

General Notes
1. This is a generic procedure for various building equipment commissioning, to verify that system components and controls will operate through the BAS, and are in proper working condition to perform functional testing.

2. In all test sections, circle or otherwise highlight any responses that indicate deficiencies (i.e. responses that don't meet the criteria for acceptance). Acceptance requires correction and retest of all deficiencies, report all deficiencies that are noted.
3. This commissioning procedure does not comprehensively address fire and life safety controls.

-

Table 1.1.A. Equipment/System Data-General Data				
PM Equipment #				
Equipment Tag	*Primary Pump/Loop*	*Secondary Pump/Loop*		
Location/Room Number	***425***	***425***		
System Type (Chilled Glycol, Heating Glycol)	*Heating Glycol*	*Heating Glycol*		
Manufacturer	*Burks Pumps*	*Grundfos*		
Table 1.1.B. Exchanger Data				
Heat exchanger Type (Shell & tube, Plate & Frame)	*P&F*	*NA*		
Pump Rated GPM@ft.head	*4.2gpm @ 32ft. Head*	*50gpm @5ft.head*		
Table 1.1.C. Motor / VFD Data				
Motor FLA rated	*1.7/0.75*	*1.61*		
Motor Volts rated	*208-230/460*	*115-230*		
Motor Phase rated	*3*	*1*		
Motor RPM rated	*3450*	*4400*		
Motor HP rated	*1/3*	*1/6*		
VFD Manufacturer	*Magnatech*	*Grundfos*		

VFD Volts rated	*0-230*	*0-230*		
Motor nominal efficiency	*NA*	*NA*		

2.1. Description

(From field inspection. Note under response if the feature as installed differs in any way from the design documents. If an item does not apply, write “NA” for not applicable):

Criteria for Acceptance: Installed characteristics must be in accordance with design intent documentation and/or approved submittals.

Table 2.1.A. Equipment/System Components

Equipment Tag	*Primary Pump/Loop*	*Secondary Pump/Loop*	*0*	*0*

Table 2.1.B. Equipment / Motor and VFD

Equipment labeled?	***Yes***	***Yes***	***Yes No***	***Yes No***
Disconnect labeled?	***Yes***	***Yes***	***Yes No***	***Yes No***
Electrical connections look good?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Contactors in good condition?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***

Table 2.1.C. Valve Control

Equipment Tag	*Primary Pump/Loop*	*Secondary Pump/Loop*	*0*	*0*
Does the pre heat valve open and close?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
Does the chilled glycol valve(s) open and close?	***NA***	***NA***	***Yes No NA***	***Yes No NA***
Does the heating valve(s) open and close?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Does the heat exchanger valve open and close?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
Do the bypass valve(s) open and close?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
Do the bypass valves modulate together?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
Do any valves leak thru?	*No*	*No*		
Do all valves fail in the correct position?	***NA***	***Yes***	***Yes No NA***	***Yes No NA***
Does a common (connecting S & R) exists?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***

Is the pump coupler in good condition?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***

Comments:

3.1. Observation Checklist

Under each unit write an affirmative response ("OK" or "√") if the item is in compliance, a "NA" if the item is not applicable, data when requested, and/or a comment number if the equipment does not satisfy the checklist item. Explain comments in the spaces below the checklists. For tests that require running VAV system fans, and pump motors at full speed, verify that the VAV boxes and control valves on at least one half of the units served by each system are fully open, to avoid over pressurization.

Criteria for Acceptance: All items must be checked as "OK" (or "NA", where relevant) unless other acceptance criteria are noted.

Table 3.1.A. Observation Checklist

Equipment Tag	*Primary Pump/Loop*	*Secondary Pump/Loop*	*0*	*0*
Documentation				
Does the control schematic agree with the field installation?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
General Installation				
Motor rotation correct thru VFD?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Casing condition: cracks, leaks?	*No*	*No*		
Is equipment free of excess noise and vibration?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Thermometers / wells installed per specifications?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Pressure gages / fittings installed per specifications?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Equipment free of visible leaks?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Are sensors in acceptable locations, and installed correctly?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Electrical Controls and Guards				
Motor safeties in place and operable (i.e.Coupler guards)?	***No***	***Yes***	***Yes No NA***	***Yes No NA***
Equipment safeties in place (i.e. relief, pop off valves..)?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***

All control devices, pneumatic tubing and wiring complete?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
HOA switch properly activates and deactivates the unit?	***NA***	***NA***	***Yes No NA***	***Yes No NA***
Table 3.1.A. Observation Checklist (continued)				
Equipment Tag	*Primary Pump/Loop*	*Secondary Pump/Loop*	*0*	*0*
Piping				
Piping properly insulated?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Piping capable of hydrostatically holding 1.5 times the amount of operational pressure.	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Flow direction correct?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Supply glycol temperature.	*56.5*	*98.9*		
Leaving glycol temperature.	*57.4*	*93.8*		
If a relief valve (pop-off, safety, etc.) exists, is it leak free?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
If a PRV exists for maintaining system pressure, does it operate properly?	***Yes***	***NA***	***NA***	***NA***
If applicable, air vents, expansion tanks, air separators installed properly?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Is supply and return piping free of leaks?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Manual valves, unions, or other piping accessories free of leaks or failures?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Variable Frequency Drive (VFD) if applicable				
(VFD) Drive location acceptable not subject to excessive temperature, moisture, dirt?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
(VFD) Programmed accel /decel Time >120sec.?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
(VFD) What is the programmed minimum Hz?	***NA***	***NA***		

(VFD) What is the programmed maximum Hz?	***NA***	***NA***		

Comments:

Solar pump needs a guard around the rotating shaft.

Supply and return temperatures were taken on a cold, gloomy day. The secondary return

Temperatures are an average of all return temperatures for the 3 zones.

Flow meters on the return loops are not functioning properly (reading really high values).

Equipment commissioning / Functional

6.1 Equipment/Systems Project Information General Functional Test

Equipment/System Name *Hybrid Hydronic*

Building Name *Knoy Hall*

Individuals Performing Tests *M. DeGrove, K. Krockenberger*

Date of Test(s) *1/1/2015*

General Notes

1. This is a generic procedure for various building equipment commissioning functional testing, to verify that system components operate as designed with the BAS, as written in the sequence of operation. These are general tests designed for most types of building equipment, critical areas may require a more specific test.

2. In all test sections, circle or otherwise highlight any responses that indicate deficiencies (i.e. responses that don't meet the criteria for acceptance). Acceptance requires correction and retest of all deficiencies, report all deficiencies that are noted.

3. This commissioning Procedure does not comprehensively address fire and life safety controls.

Equipment Tag	*Primary Pump/Loop*	*Secondary Pump/Loop*	*0*	*0*
PM Equipmt #	*0*	*0*	*0*	*0*
Location/Room Number	*425*	*425*	*0*	*0*
6.1.A Functional Test of Pressure Controls				
Is the equipment in automatic control and operating properly?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Decrease the setpoint for flow control of the system being tested.	***OK***	***NA***	***OK NA***	***OK NA***
Did the controls respond to achieve a lower setpoint?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
Increase the setpoint for flow control of the system being tested.	***OK***	***NA***	***OK NA***	***OK NA***

Did the controls respond to achieve a higher setpoint?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
Reset the pressure setpoint, is the unit operating properly?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
6.1.B Functional Test of Temperature Controls				
Is the equipment in automatic control and operating properly?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Increase the setpoint of the glycol temp.	***NA***	***NA***	***OK NA***	***OK NA***
Did the chilled glycol valve(s) close?	***NA***	***NA***	***Yes No NA***	***Yes No NA***
Decrease the setpoint of the glycol temp.	***NA***	***NA***	***OK NA***	***OK NA***
Did the chilled glycol valve(s) open?	***NA***	***NA***	***Yes No NA***	***Yes No NA***
Equipment Tag	*Primary Pump/Loop*	*Secondary Pump/Loop*	*0*	*0*
6.1.B Functional Test of Temperature Controls Cont'd.				
Decrease the setpoint of the heat exchanger.	***OK***	***NA***	***OK NA***	***OK NA***
Did the exchanger valve open?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
Increase the setpoint of the heat exchanger.	***OK***	***NA***	***OK NA***	***OK NA***
Did the exchanger valve close?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
Verify that all setpoints are normal, is the unit operating properly?	***Yes***	***NA***	***Yes No NA***	***Yes No NA***
Increase the setpoint of the glycol temp.	***NA***	***OK***	***OK NA***	***OK NA***
Did the heating glycol valve(s) open?	***NA***	***Yes***	***Yes No NA***	***Yes No NA***
Decrease the setpoint of the glycol temp.	***NA***	***OK***	***OK NA***	***OK NA***
Did the heating glycol valve(s) close?	***NA***	***Yes***	***Yes No NA***	***Yes No NA***
6.1.C. Functional Test of Sequence				
Is the equipment in automatic control and operating properly?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Command insulation above 200 w/m2	***OK***	***NA***	***Yes No NA***	***Yes No NA***
Did the primary pump turn on?	***Yes***	***NA***	***OK NA***	***OK NA***

Return the system to normal, is it operating properly?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Command the solar supply temp below 80F.	***OK***	***NA***	***Yes No NA***	***Yes No NA***
Did the pre heat valve open?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Return the system to normal, is it operating properly?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Command the need heat on and the valve position to less than 300.	***OK***	***OK***	***Yes No NA***	***Yes No NA***
Did the secondary pump turn on?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***
Return the system to normal, is it operating properly?	***Yes***	***Yes***	***Yes No NA***	***Yes No NA***

Comments:

Appendix D Data

Appendix D presents the data that was gathered during the testing period. The raw data is not included due to the large amount not providing any necessary value. The data presented is the main data used for analysis of the system.

TOTAL SYSTEM

Date	Daily Solar Q (BTU)	Daily Solar Q (Wh)	Daily HP Q (BTU)	Daily HP Q (Wh)	Total Q (Wh)
2/25/2015	1365	400	16884	4948	5348
2/26/2015	-1783	-522	46175	13532	13010
2/27/2015	27749	8132	31929	9357	17490
2/28/2015	16482	4830	29975	8785	13615
3/1/2015	-583	-171	47723	13986	13815
3/2/2015	27624	8096	36734	10766	18862
3/3/2015	0	0	35445	10388	10388
3/4/2015	609	178	28221	8271	8449
3/5/2015	19422	5692	22959	6729	12421
3/6/2015	21222	6220	19052	5583	11803
3/7/2015	20862	6114	15339	4495	10609
3/8/2015	27314	8005	12253	3591	11596
3/9/2015	27433	8040	8869	2599	10639
3/10/2015	0	0	16652	4880	4880
3/11/2015	32380	9490	21828	6397	15887
3/12/2015	25702	7533	26471	7758	15290
3/13/2015	0	0	39855	11680	11680
Average	14459	4237	26845	7867	12105
Average with SST>80°F	22505	6596	22027	6455	13051
TOTAL	245798	72036	456364	13374 7	205783

	BTU	WH		
			Total Sol Contrib:	35%
Q Soltotal=	245798.2962	72036.10666	Total HP Contrib:	65%
Q HPtotal=	451800.1209	132377.4354	Total Work of Sys	104735.062 5
Q Systotal	697598.4171	204445.9145	Total System Efficiency	1.95202933 6

SOLAR DATA						
Heat % Solar	Heat % HP	Total Time w/ Insolation (min)	Total Useful Insolation (Wh/m^2)	Total Useful Insolation W/collectors (Wh)	SST AVG (°F)	Daily Average Ambient Temp (°F)
0.07	0.93	470	4938	38023	103.6	21
-0.04	1.04	360	1643	12651		14
0.46	0.54	520	7134	54928	108.3	6
0.35	0.65	400	4559	35107	105	12
-0.01	1.01	0	0	0		21
0.43	0.57	515	6739	51890	107.6	19
0.00	1.00	0	0	0		32
0.02	0.98	165	1010	7775		25
0.46	0.54	485	6028	46417	106.5	10
0.53	0.47	500	6423	49456	107.9	11
0.58	0.42	425	5669	43653	110.7	33
0.69	0.31	505	5988	46104	114	33
0.76	0.24	520	6118	47109	115.4	38
0.00	1.00	0	0	0		42
0.60	0.40	490	5803	44685	112.8	45
0.49	0.51	515	5028	38716	106.5	40
0.0%	1.00	0	0	0		42
31.7%	68.3%	345	3946	30383	108.9	26.12
49.3%	50.7%	486	5857	45099	108.9	24.36

SST HIGH:	138
SRT HIGH:	129

Solar Correlations	
R % Solar vs. Daily Solar Q:	0.95291
R for % Solar vs. Total Insol:	0.8743
R for % Solar vs. Avg SST:	0.8983
R for % Solar vs. Avg OAT:	0.0543
R for % Solar vs. Total Time:	0.8026
R for Daily Solar Q vs. Total Insol:	0.8893
R for Daily Solar Q vs. Avg SST:	0.6851
R for Daily Solar Q vs. Avg OAT:	0.0079
R for Daily Solar Q vs. Total Time:	0.8116
R for Insol vs. SST:	0.3654
R for % Solar in relation to Solar Q & Insol:	0.9547

HEAT PUMP DATA							
Op. % HP	Op. % HP OFF	Op % Electric	Times HP Engage	Avg Engagement Length (min)	Avg Engagement Length elements(min)	Avg Draw (W)	Time of HP elec. Element engagement
89.7%	10.3%	0.0%	2	127.5	0.0	0	0
45.4%	54.6%	0.0%	9	73.3	0.0	0	0
31.6%	66.3%	2.1%	6	80.0	30.0	4045.95	10:45:00 AM
32.3%	65.6%	2.1%	11	45.0	30.0	4074.05	11:45:00 AM
32.3%	65.6%	2.1%	11	45.0	15.0	4006.55	7:15:00 AM
29.2%	70.8%	0.0%	7	60.0	0.0	0	0
28.1%	69.8%	2.1%	9	48.3	30.0	4005.6	9:15:00 AM
34.4%	65.6%	0.0%	8	61.9	0.0	0	0
37.5%	62.5%	0.0%	8	67.5	0.0	0	0
20.8%	74.0%	5.2%	5	213.0	37.5	3975.1	6:15:00 AM
17.7%	77.1%	5.2%	6	185.0	37.5	4065.18	6:15:00 AM
18.5%	78.3%	3.3%	4	75.0	45.0	4095.8	6:15:00 AM
12.5%	85.4%	2.1%	4	52.5	30.0	4008.7	6:15:00 AM
17.7%	80.2%	2.1%	6	47.5	30.0	4006.9	6:15:00 AM
17.7%	79.2%	3.1%	5	60.0	45.0	3985	11:15:00 AM
27.1%	67.7%	5.2%	7	66.4	37.5	3999.2	6:15:00 AM
49.2%	45.8%	5.1%	3	160.0	45.0	4040.87	6:15:00 AM
31.9%	65.8%	2.3%	111	86.4	24.26	2841.70	
					34.38	4025.75	

HP Op Time w/ SST	30.4%
HP Op Time w/o SST	34.5%
Total HP W (Wh):	93044
Total HP Q (Wh):	132377
Total HP Eff:	1.423

HP Correlations	
R % HP vs. Daily HP Q:	0.6319
R for % HP vs. Total Insol:	-0.8743
R for % HP vs. Avg SST:	-0.8983
R for % HP vs. Avg OAT:	-0.0543
R for % HP vs. Total Time:	-0.8026
R for Daily HP Q vs. Total Insol:	-0.5169

R for DailyHP Q vs. Avg SST:	-0.5688
R for Daily HP Q vs. Avg OAT:	-0.3023
R for DailyHP Q vs. Total Time:	-0.4628

SYSTEM MODE

DATE	Solar	Solar Storage	Heat Pump	Pre-Heat	HP/Pre -Heat	Hybrid	Tank Supply	Solar Dissipation	System OFF	Solar Detriment
2/25	0	10	3	0	0	0	1	0	23	4
2/26	0	0	17	14	9	0	7	0	50	9
2/27	0	28	6	0	7	1	0	0	55	1
2/28	0	16	10	4	4	4	5	0	54	4
3/1	0	0	15	1	1	0	12	0	68	1
3/2	0	27	7	3	1	2	3	0	54	2
3/3	0	0	19	0	1	0	14	0	63	0
3/4	0	0	12	6	12	0	15	0	52	4
3/5	0	16	11	2	3	11	5	0	49	1
3/6	1	21	5	2	5	4	6	0	53	2
3/7	1	20	6	1	1	8	6	0	54	2
3/8	0	27	6	2	2	3	1	0	56	3
3/9	0	27	4	4	0	3	2	0	57	4
3/10	0	0	6	2	0	0	4	0	85	2
3/11	0	26	6	3	1	3	6	0	52	0
3/12	0	29	9	2	2	2	7	0	46	3
3/13	0	0	20	0	0	0	6	0	33	0
TOTAL	2	247	162	46	49	41	100	0	904	42
% Time	0.1%	15.9%	10.4%	3.0%	3.2%	2.6%	6.4%	0.0%	58.3%	2.7%

Solar Data

Date	Day of Test	Time @ 80°F	First Time @ 200 W/m^2	Final Time @ 200 W/m^2	Total Time w/ Insolation	Total Time w/ Insolation (min)	Time between Pump On & Temp Met	Time between Pump On & Temp Met (Min)
2/25/2015	1	10:15 AM	9:00 AM	4:50 PM	7:50	470	1:15	75
2/26/2015	2	N/A	11:05 AM	5:05 PM	6:00	360	N/A	0
2/27/2015	3	10:15 AM	8:25 AM	5:05 PM	8:40	520	1:50	110
2/28/2015	4	11:30 AM	9:10 AM	3:50 PM	6:40	400	2:20	140
3/1/2015	5	N/A	N/A	N/A	N/A	N/A	N/A	0
3/2/2015	6	10:00 AM	8:30 AM	5:05 PM	8:35	515	1:30	90
3/3/2015	7	N/A	N/A	N/A	N/A	N/A	N/A	0
3/4/2015	8	N/A	10:55 AM	1:40 PM	2:45	165	N/A	0
3/5/2015	9	10:25 AM	8:55 AM	5:00 PM	8:05	485	1:30	90
3/6/2015	10	10:15 AM	8:40 AM	5:00 PM	8:20	500	1:35	95
3/7/2015	11	10:40 AM	9:55 AM	5:00 PM	7:05	425	0:45	45
3/8/2015	12	10:35 AM	9:30 AM	5:55 PM	8:25	505	1:05	65
3/9/2015	13	10:30 AM	9:20 AM	6:00 PM	8:40	520	1:10	70
3/10/2015	14	N/A	N/A	N/A	N/A	N/A	N/A	0
3/11/2015	15	10:50 AM	9:45 AM	5:55 PM	8:10	490	1:05	65
3/12/2015	16	10:50 AM	9:20 AM	5:55 PM	8:35	515	1:30	90
3/13/2015	17	N/A	N/A	N/A	N/A	N/A	N/A	0
	AVERAGE	10:33 AM	9:08 AM	5:14 PM	8:05	486	1:25	85
	MEDIAN	10:30 AM	9:10 AM	5:05 PM	7:55	490	1:30	90

Time of Useful Insolation (min)	Insolation Till Temp Met (Wh/m²)	Total Useful Insolation (Wh/m²)	SST HIGH (°F)	SST AVG (°F)	Daily Average Ambient Temp (°F)	Daily High Temp (°F)
395	562	4938	116.6	103.6	21	32
360	0	1643	N/A	N/A	14	21
410	881	7134	120.1	108.3	6	16
260	757	4559	119.3	105	12	25
N/A	0	N/A	N/A	N/A	21	26
425	754	6739	120.3	107.6	19	31
N/A	0	N/A	N/A	N/A	32	39
165	0	1010	N/A	N/A	25	33
395	781	6028	122.6	106.5	10	18
405	812	6423	123.6	107.9	11	28
380	326	5669	129.7	110.7	33	43
440	486	5988	134.2	114	33	45
450	397	6118	138	115.4	38	50
N/A	0	N/A	N/A	N/A	42	48
425	382	5803	131.8	112.8	45	59
425	353	5028	118.8	106.5	40	56
N/A	0	N/A	N/A	N/A	42	47
401	590	5160	125.0	108.9	26.1	36.3
410	562	4960	122.6	107.9	26.4	36.5

Correlations

R for Total Time vs. Total Insol:	0.8928
R for total time vs. Avg SST:	0.3324
R for Total Time vs. High SST:	0.6186
R for Total Time vs. Avg OAT:	0.1009
R for Total Time vs. High OAT:	0.2029
R for Total Insol vs. Avg SST:	0.3654
R for Total Insol vs. High SST:	0.2137
R for Total Insol vs Avg OAT:	0.0130
R for Total Insol vs High OAT:	0.1146
R for High SST vs Avg SST:	0.9663
R for High SST vs Avg OAT:	0.6098
R for High SST vs High OAT:	0.5645
R for Avg SST vs Avg OAT:	0.6131
R for Avg SST vs High OAT:	0.5758
R for Avg OAT vs High OAT:	0.9612
R for SST in relation to Insol & OAT	0.7097

insol till T & tot insol	0.79907548
insol till T & sst	-0.508845693
insol till T & OAT	-0.564981908
insol till T/tot insol & OAT	0.9847

SST, SRT & Delta T for Solar

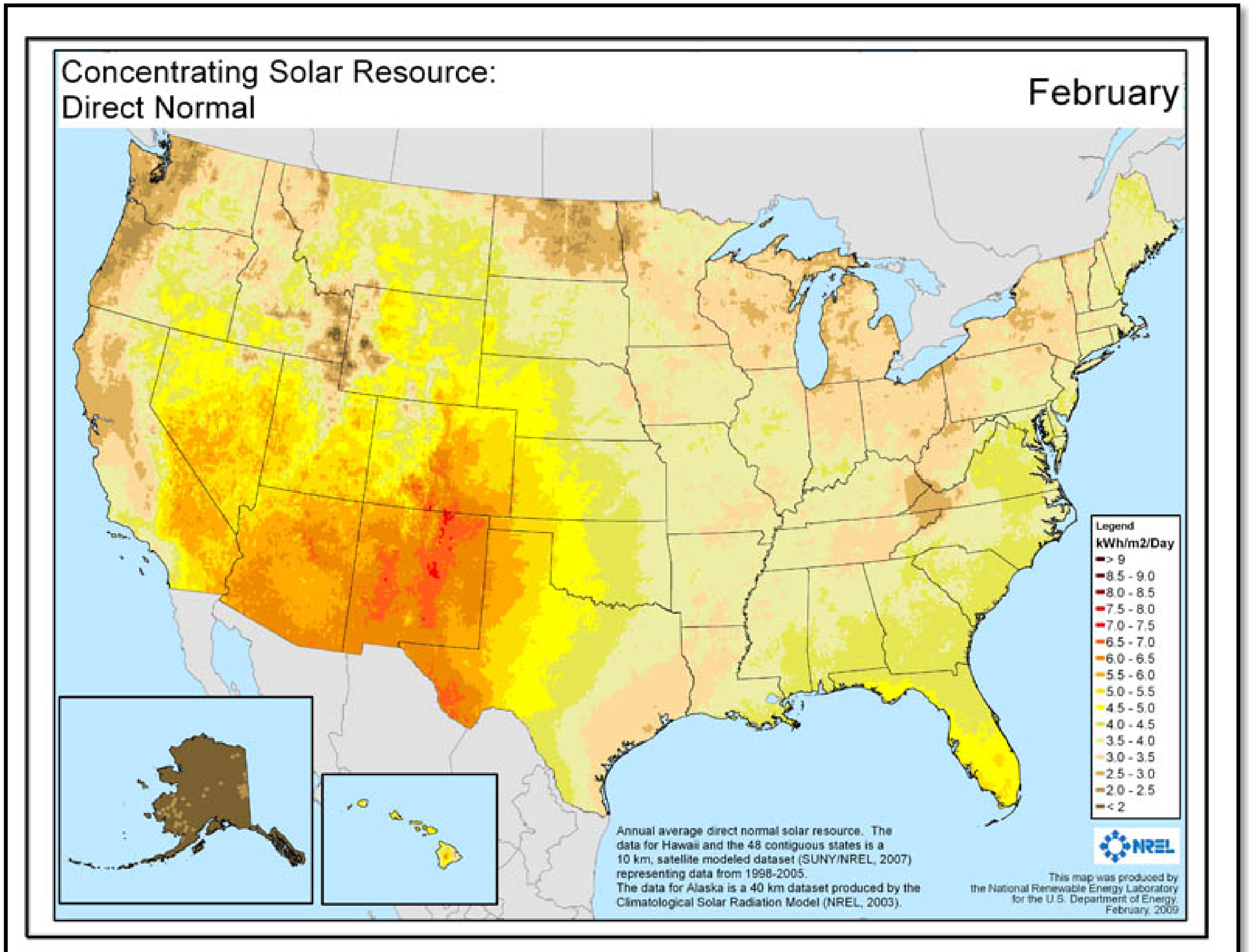
Date	SST	SRT	Delta T	Prim Pump	Sec Pump	Solar Storage Mode
3/6/15 10:45 AM	109.6	100.3	9.3	1	0	Solar Storage
3/6/15 11:00 AM	110.1	105.8	4.3	1	0	Solar Storage
3/6/15 11:45 AM	113.1	107.8	5.3	1	0	Solar Storage
3/6/15 12:00 PM	118.1	110.3	7.8	1	0	Solar Storage
3/6/15 12:15 PM	120.1	111.3	8.8	1	0	Solar Storage
3/6/15 12:30 PM	119.4	111.8	7.6	1	0	Solar Storage
3/6/15 1:00 PM	117.1	111.3	5.8	1	0	Solar Storage
3/6/15 1:15 PM	121.6	111.8	9.8	1	0	Solar Storage
3/6/15 1:30 PM	122.8	113.1	9.7	1	0	Solar Storage
3/6/15 1:45 PM	121.6	113.8	7.8	1	0	Solar Storage
3/6/15 2:30 PM	116	114.3	1.7	1	0	Solar Storage
3/6/15 2:45 PM	116.6	111.8	4.8	1	0	Solar Storage
3/6/15 3:00 PM	117.1	111.2	5.9	1	0	Solar Storage
3/6/15 3:15 PM	118.1	111.1	7	1	0	Solar Storage
3/6/15 3:30 PM	117.2	111.5	5.7	1	0	Solar Storage
3/6/15 3:45 PM	117.7	111.5	6.2	1	0	Solar Storage
3/6/15 4:00 PM	117.2	111.4	5.8	1	0	Solar Storage
3/6/15 4:15 PM	116.6	111.4	5.2	1	0	Solar Storage
3/6/15 4:30 PM	115.1	111.1	4	1	0	Solar Storage
3/6/15 4:45 PM	113.6	110.8	2.8	1	0	Solar Storage
3/7/15 11:15 AM	107.9	100.3	7.6	1	0	Solar Storage
3/7/15 11:30 AM	111.6	106.3	5.3	1	0	Solar Storage
3/7/15 12:30 PM	121.6	111.6	10	1	0	Solar Storage
3/7/15 12:45 PM	123.6	112.8	10.8	1	0	Solar Storage
3/7/15 1:00 PM	124.6	114.4	10.2	1	0	Solar Storage
3/7/15 1:15 PM	126.1	115.8	10.3	1	0	Solar Storage
3/7/15 1:30 PM	126.6	116.8	9.8	1	0	Solar Storage
3/7/15 1:45 PM	127.1	118.1	9	1	0	Solar Storage
3/7/15 2:00 PM	129.1	118.8	10.3	1	0	Solar Storage
3/7/15 2:15 PM	129.3	119.9	9.4	1	0	Solar Storage
3/7/15 2:30 PM	129.6	120.4	9.2	1	0	Solar Storage
3/7/15 2:45 PM	129.7	121.1	8.6	1	0	Solar Storage
3/7/15 3:30 PM	123.6	116.8	6.8	1	0	Solar Storage
3/7/15 3:45 PM	122.1	116.1	6	1	0	Solar Storage
3/7/15 4:00 PM	119.1	116.2	2.9	1	0	Solar Storage
3/7/15 4:15 PM	118.6	115.8	2.8	1	0	Solar Storage

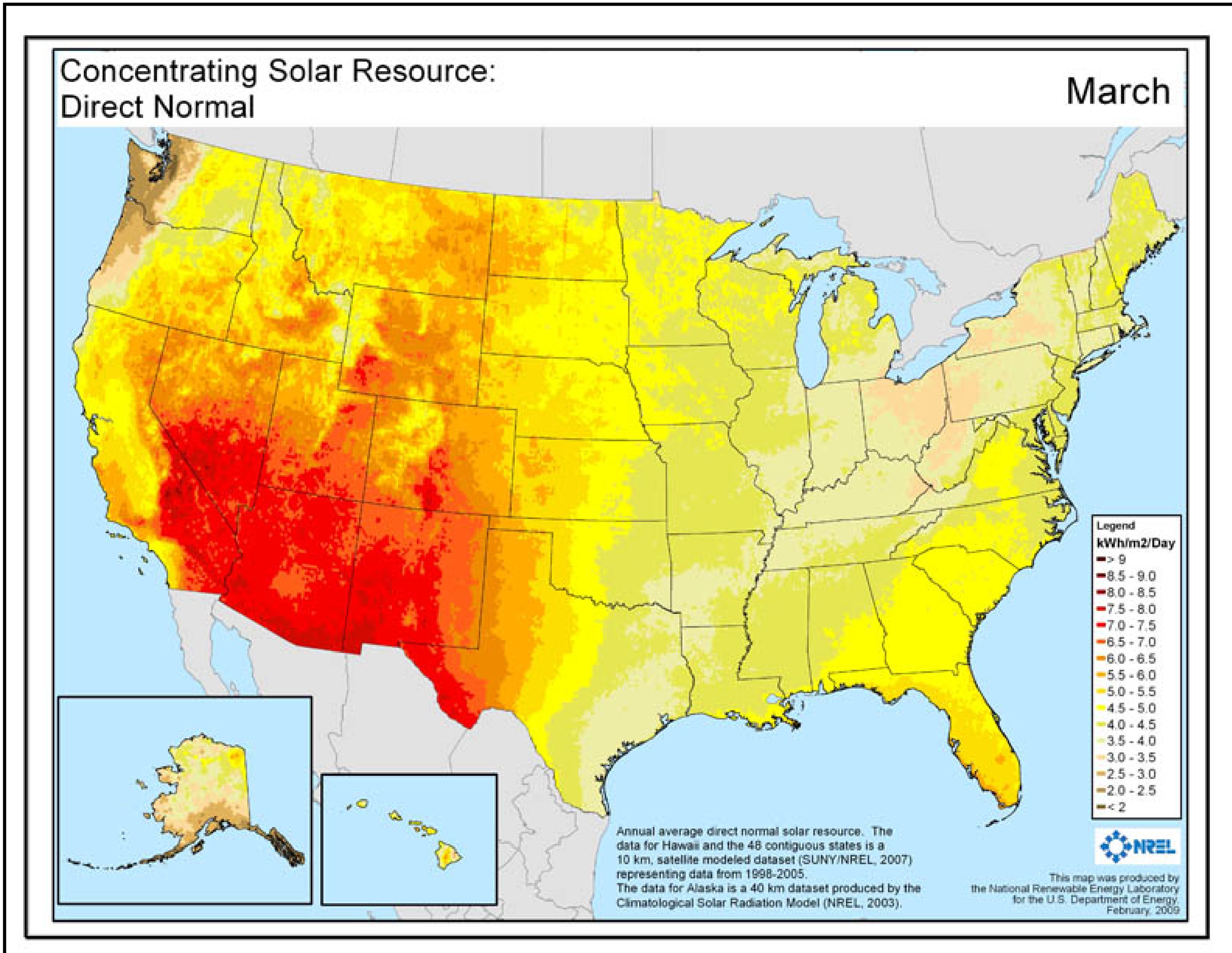
3/7/15 4:30 PM	119.5	114.3	5.2	1	0	Solar Storage
3/7/15 4:45 PM	117.1	113.5	3.6	1	0	Solar Storage
3/7/15 5:00 PM	115.1	112.8	2.3	1	0	Solar Storage
3/8/15 11:00 AM	109.1	105.6	3.5	1	0	Solar Storage
3/8/15 11:15 AM	109.7	101.8	7.9	1	0	Solar Storage
3/8/15 12:15 PM	115.6	107.8	7.8	1	0	Solar Storage
3/8/15 12:30 PM	121.1	111.9	9.2	1	0	Solar Storage
3/8/15 12:45 PM	123.1	112.3	10.8	1	0	Solar Storage
3/8/15 1:00 PM	125.1	113.8	11.3	1	0	Solar Storage
3/8/15 1:15 PM	125.9	115.8	10.1	1	0	Solar Storage
3/8/15 1:30 PM	127.1	117.3	9.8	1	0	Solar Storage
3/8/15 1:45 PM	128.1	118.4	9.7	1	0	Solar Storage
3/8/15 2:00 PM	129.9	119.3	10.6	1	0	Solar Storage
3/8/15 2:15 PM	130.6	120.8	9.8	1	0	Solar Storage
3/8/15 2:30 PM	131.9	121.8	10.1	1	0	Solar Storage
3/8/15 2:45 PM	132.8	122.8	10	1	0	Solar Storage
3/8/15 3:00 PM	132.7	123.8	8.9	1	0	Solar Storage
3/8/15 3:15 PM	133.2	124.3	8.9	1	0	Solar Storage
3/8/15 3:30 PM	133.7	124.8	8.9	1	0	Solar Storage
3/8/15 3:45 PM	133.2	125.1	8.1	1	0	Solar Storage
3/8/15 4:00 PM	132.7	125.1	7.6	1	0	Solar Storage
3/8/15 4:15 PM	132.2	124.9	7.3	1	0	Solar Storage
3/8/15 4:30 PM	131.2	124.8	6.4	1	0	Solar Storage
3/8/15 4:45 PM	128.7	124.3	4.4	1	0	Solar Storage
3/8/15 5:00 PM	127.7	123.8	3.9	1	0	Solar Storage
3/8/15 5:15 PM	127.2	122.3	4.9	1	0	Solar Storage
3/8/15 5:30 PM	125.2	121.3	3.9	1	0	Solar Storage
3/8/15 5:45 PM	123.2	120.7	2.5	1	0	Solar Storage
3/8/15 6:00 PM	118.7	117.8	0.9	1	0	Solar Storage
3/9/15 11:15 AM	108.1	102.8	5.3	1	0	Solar Storage
3/9/15 11:30 AM	112.8	105.8	7	1	0	Solar Storage
3/9/15 11:45 AM	116.6	108.8	7.8	1	0	Solar Storage
3/9/15 12:00 PM	119.7	111.8	7.9	1	0	Solar Storage
3/9/15 12:15 PM	122.1	112.8	9.3	1	0	Solar Storage
3/9/15 12:30 PM	123.8	114.1	9.7	1	0	Solar Storage
3/9/15 12:45 PM	125.6	115.8	9.8	1	0	Solar Storage
3/9/15 1:00 PM	127.6	117.3	10.3	1	0	Solar Storage
3/9/15 1:15 PM	128.6	118.3	10.3	1	0	Solar Storage
3/9/15 1:30 PM	130.2	119.9	10.3	1	0	Solar Storage
3/9/15 1:45 PM	131.1	121.3	9.8	1	0	Solar Storage
3/9/15 2:00 PM	132.6	122.4	10.2	1	0	Solar Storage
3/9/15 2:15 PM	133.6	123.3	10.3	1	0	Solar Storage

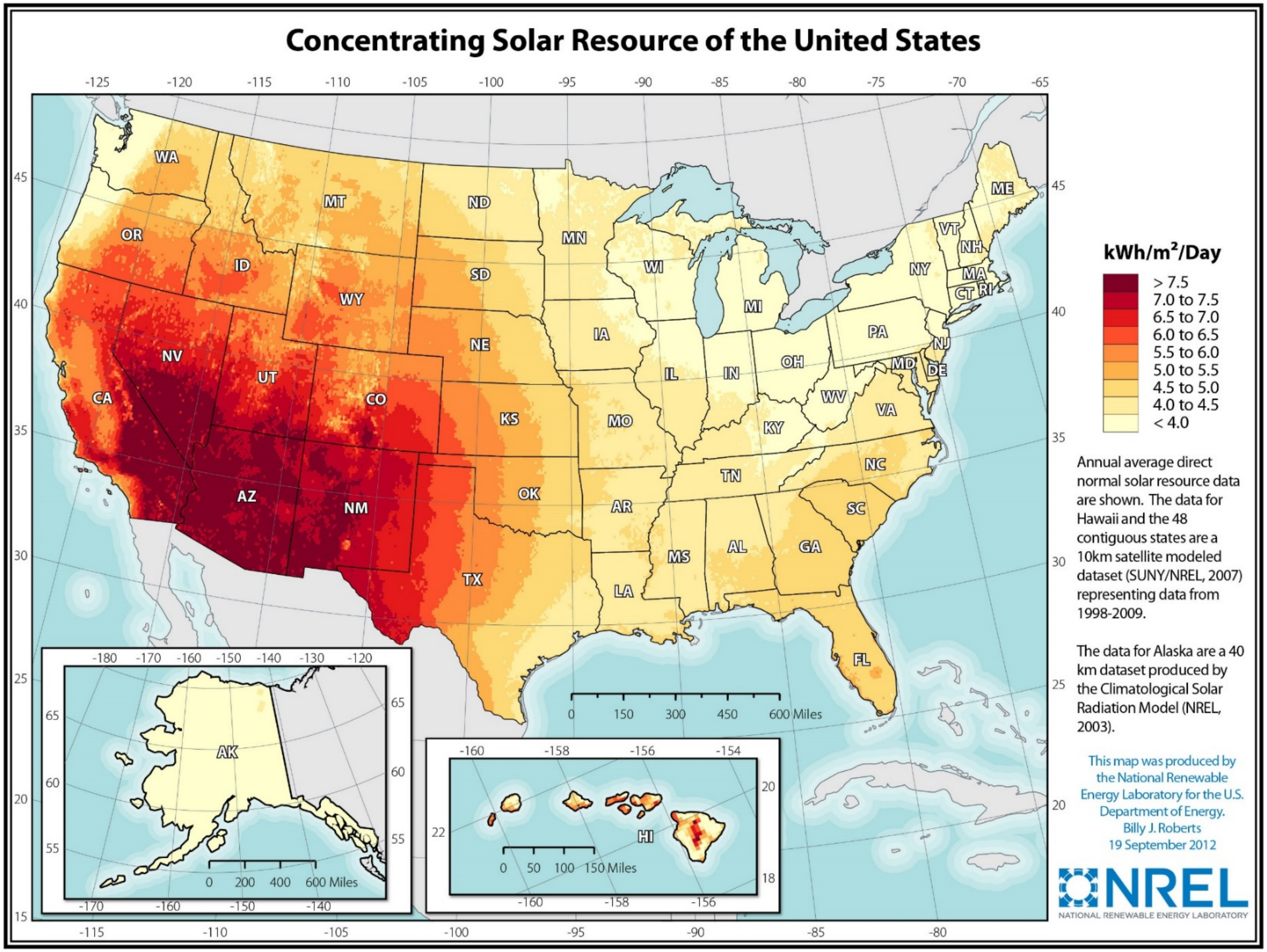
3/9/15 2:30 PM	135.4	124.5	10.9	1	0	Solar Storage
3/9/15 2:45 PM	136.2	125.8	10.4	1	0	Solar Storage
3/9/15 3:00 PM	137.2	126.9	10.3	1	0	Solar Storage
3/9/15 3:15 PM	137.6	127.8	9.8	1	0	Solar Storage
3/9/15 3:30 PM	138	128.5	9.5	1	0	Solar Storage
3/9/15 3:45 PM	137.7	129	8.7	1	0	Solar Storage
3/9/15 4:00 PM	137.3	129.2	8.1	1	0	Solar Storage
3/9/15 4:15 PM	136.9	129.2	7.7	1	0	Solar Storage
3/9/15 4:30 PM	136.2	129	7.2	1	0	Solar Storage
3/9/15 4:45 PM	135.1	128.8	6.3	1	0	Solar Storage
3/9/15 5:00 PM	133.1	128.3	4.8	1	0	Solar Storage
3/9/15 5:15 PM	131.1	127.3	3.8	1	0	Solar Storage
3/9/15 5:30 PM	128.6	126	2.6	1	0	Solar Storage
3/11/15 11:45 AM	110.1	105.8	4.3	1	0	Solar Storage
3/11/15 12:00 PM	116.6	107.3	9.3	1	0	Solar Storage
3/11/15 12:15 PM	118.6	107.5	11.1	1	0	Solar Storage
3/11/15 12:30 PM	119.6	108.5	11.1	1	0	Solar Storage
3/11/15 12:45 PM	121.6	109.3	12.3	1	0	Solar Storage
3/11/15 1:00 PM	122.6	110.3	12.3	1	0	Solar Storage
3/11/15 1:15 PM	124.1	111.3	12.8	1	0	Solar Storage
3/11/15 1:30 PM	125.6	112.5	13.1	1	0	Solar Storage
3/11/15 1:45 PM	126.6	113.3	13.3	1	0	Solar Storage
3/11/15 2:00 PM	128.1	114.9	13.2	1	0	Solar Storage
3/11/15 2:15 PM	129.2	115.8	13.4	1	0	Solar Storage
3/11/15 2:30 PM	130.1	117.1	13	1	0	Solar Storage
3/11/15 2:45 PM	130.7	117.8	12.9	1	0	Solar Storage
3/11/15 3:00 PM	131.2	118.8	12.4	1	0	Solar Storage
3/11/15 3:15 PM	131.6	119.3	12.3	1	0	Solar Storage
3/11/15 3:30 PM	131.7	120	11.7	1	0	Solar Storage
3/11/15 3:45 PM	131.2	120.3	10.9	1	0	Solar Storage
3/11/15 4:00 PM	130.8	120.4	10.4	1	0	Solar Storage
3/11/15 4:15 PM	128.7	120.3	8.4	1	0	Solar Storage
3/11/15 4:30 PM	123.2	119.8	3.4	1	0	Solar Storage
3/11/15 4:45 PM	123.8	118.8	5	1	0	Solar Storage
3/11/15 5:00 PM	120.2	116.2	4	1	0	Solar Storage
3/11/15 5:15 PM	118.6	114.8	3.8	1	0	Solar Storage
3/11/15 5:30 PM	118.3	112.8	5.5	1	0	Solar Storage
3/11/15 5:45 PM	114.7	110.3	4.4	1	0	Solar Storage
3/11/15 6:00 PM	111.1	108.5	2.6	1	0	Solar Storage
3/12/15 11:15 AM	105.5	102.3	3.2	1	0	Solar Storage
3/12/15 11:30 AM	105.6	99.3	6.3	1	0	Solar Storage
3/12/15 11:45 AM	109.6	103.3	6.3	1	0	Solar Storage

3/12/15 12:00 PM	115.1	106.3	8.8	1	0	Solar Storage
3/12/15 12:15 PM	117.1	106.9	10.2	1	0	Solar Storage
3/12/15 12:30 PM	115.1	106.8	8.3	1	0	Solar Storage
3/12/15 12:45 PM	118.1	107.5	10.6	1	0	Solar Storage
3/12/15 1:00 PM	118.8	107.3	11.5	1	0	Solar Storage
3/12/15 1:15 PM	117.1	107.3	9.8	1	0	Solar Storage
3/12/15 1:30 PM	116.1	107.7	8.4	1	0	Solar Storage
3/12/15 1:45 PM	115.1	107.2	7.9	1	0	Solar Storage
3/12/15 2:00 PM	114.9	106.8	8.1	1	0	Solar Storage
3/12/15 2:15 PM	114.6	106.3	8.3	1	0	Solar Storage
3/12/15 2:30 PM	113.6	106.3	7.3	1	0	Solar Storage
3/12/15 2:45 PM	114.6	106	8.6	1	0	Solar Storage
3/12/15 3:00 PM	115.1	106	9.1	1	0	Solar Storage
3/12/15 3:15 PM	115.1	106.3	8.8	1	0	Solar Storage
3/12/15 3:30 PM	114.6	106.3	8.3	1	0	Solar Storage
3/12/15 3:45 PM	115.1	106.5	8.6	1	0	Solar Storage
3/12/15 4:00 PM	116.1	106.6	9.5	1	0	Solar Storage
3/12/15 4:15 PM	116.6	107.1	9.5	1	0	Solar Storage
3/12/15 4:30 PM	116.6	107.4	9.2	1	0	Solar Storage
3/12/15 4:45 PM	115.9	107.8	8.1	1	0	Solar Storage
3/12/15 5:00 PM	113.1	107.8	5.3	1	0	Solar Storage
3/12/15 5:15 PM	111.1	107.3	3.8	1	0	Solar Storage
3/12/15 5:30 PM	108.5	106.3	2.2	1	0	Solar Storage
3/12/15 5:45 PM	107.5	105.5	2	1	0	Solar Storage
3/12/15 6:00 PM	107.3	105.8	1.5	1	0	Solar Storage
MAX:	138	129.2	13.4			
AVG:	122.2421	114.4	7.842069			

Appendix E Insolation Maps




Concentrating Solar Resource:
Direct Normal
March
Legend
kWh/m2/Day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Annual average direct normal solar resource. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.
The data for Alaska is a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).
NREL
This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy. February, 2009


Concentrating Solar Resource of the United States
kWh/m²/Day
> 7.5
7.0 to 7.5
6.5 to 7.0
6.0 to 6.5
5.5 to 6.0
5.0 to 5.5
4.5 to 5.0
4.0 to 4.5
< 4.0
Annual average direct normal solar resource data are shown. The data for Hawaii and the 48 contiguous states are a 10km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2009.
The data for Alaska are a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).
This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy. Billy J. Roberts 19 September 2012
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
0 150 300 450 600 Miles
0 200 400 600 Miles
0 50 100 150 Miles
WA
OR
CA
NV
ID
MT
WY
UT
AZ
CO
NM
ND
SD
NE
KS
OK
TX
MN
IA
MO
AR
LA
WI
IL
MI
IN
OH
KY
TN
MS
AL
GA
FL
SC
NC
VA
WV
PA
NY
VT
NH
ME
MA
CT
RI
NJ
DE
MD
AK
HI