EML 5930
Graduate Design Project 1

Final Report

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Abstract

The Off Grid Zero Emissions Building (OGZEB) project is sponsored by the Energy and Sustainability Center at Florida State University. The OGZEB is a 1,064 sq. ft. solar powered building designed as a graduate style flat. The purpose of the OGZEB is to serve as a prototype for testing sustainable technologies. In order for the OGZEB to function as a living laboratory, a full scale data collection system was installed. With this system in place, further testing could ensue which focused on the integration of the solar thermal system with the geothermal heating, ventilation, and air conditioning (HVAC) system in order to improve the efficiency of the HVAC unit during heating cycles. The coefficient of performance (COP) for the geothermal unit without the integrating loop is 2.5 and with the integrating loop is 16. Therefore, this integration was very successful in improving the efficiency of the HVAC unit by significantly decreasing electricity consumption.

Introduction

The market for sustainable technologies has significantly increased with rising concerns of global warming. Significant evidence has shown the drastic increase in carbon dioxide levels within the atmosphere as depicted in Figure 1. There has also been evidence of a well-established relationship between carbon dioxide levels and global temperature due to the greenhouse effect that is shown in Figure 2. The negative impact of increased carbon dioxide levels has created a need for power generation with minimized environmental impact.

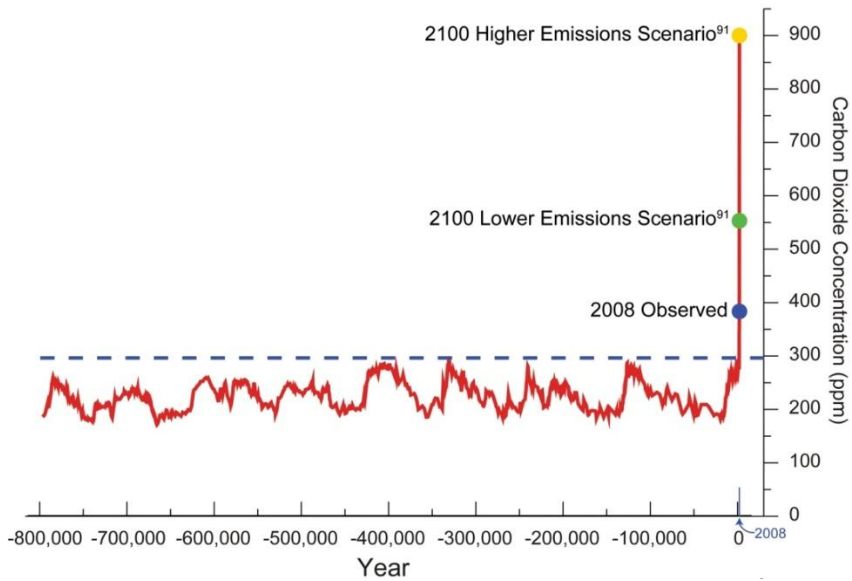

Figure 1: Graph depicting carbon dioxide levels in the atmosphere over the last 800,000 years[1]

[1] http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/full-report/global-climate-change

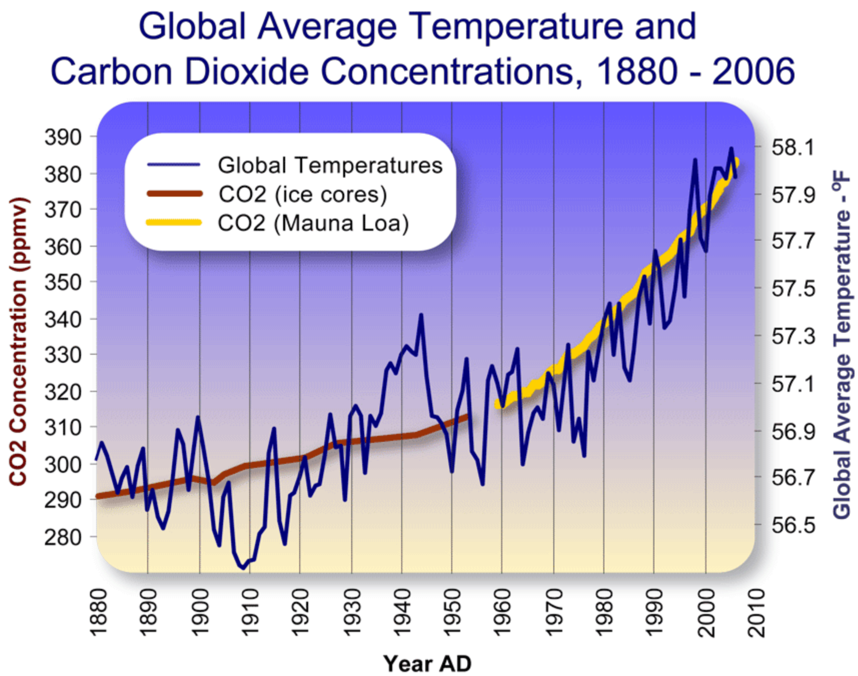

Figure 2: Graph depicting relationship between carbon dioxide concentrations and global temperature[2]

There are also significant concerns about the economic impact of using various sources of energy. Figure 3 shows that the primary source of energy is oil; and with the possibility of oil prices rising over the next few decades as seen in the High Oil Price scenario in Figure 4, there will be a greater demand for a more cost effective source of energy. Sustainable sources are of great interest to the public because they have the potential to satisfy both requirements of being environmentally sustainable and cost effective. In order to reach their full potential, it will be necessary to understand the capabilities and limitations of sustainable technologies. It is this need that inspired the design of the OGZEB to provide the necessary facilities for testing sustainable technologies under real life conditions.

[2] http://www.whrc.org/resources/online_publications/warming_earth/scientific_evidence.htm

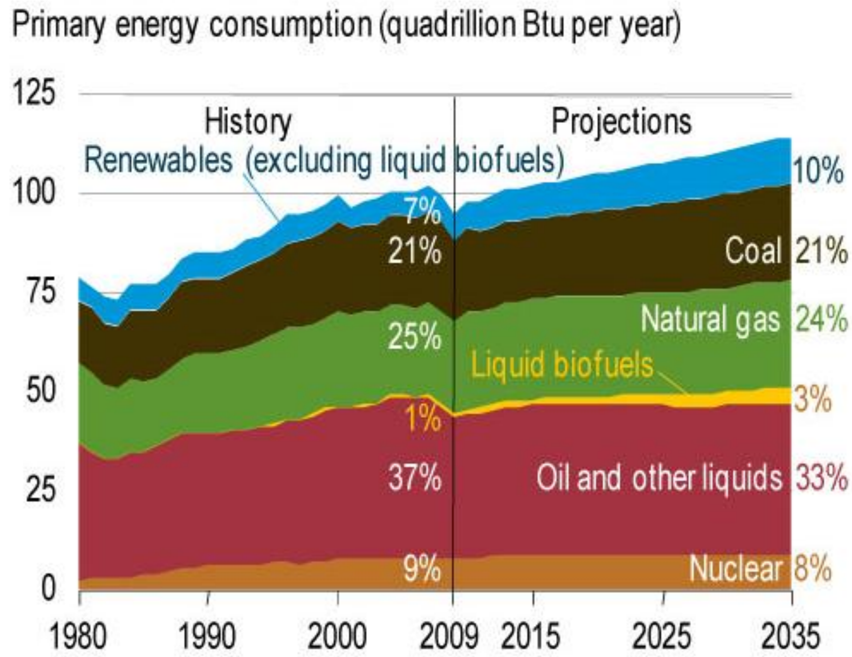

Figure 3: Graph depicting primary energy consumption from 1980 to 2035[3]

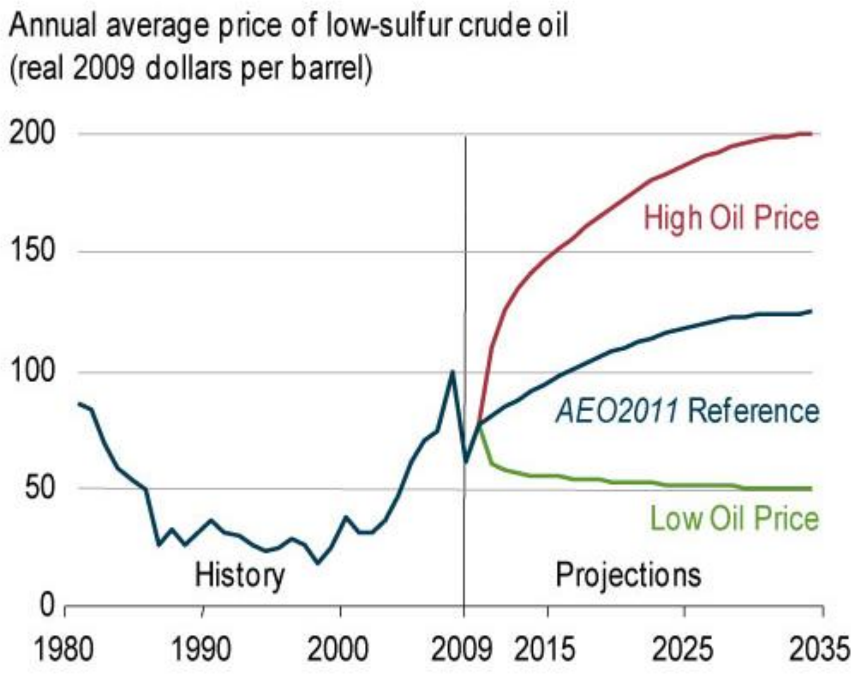

Figure 4: Graph depicting oil price projections through 2035[4]

The OGZEB consists of several different systems that all focus on environmental sustainability and energy conservation. All of the electricity for the building is provided by a 6.9kW photovoltaic (PV) array composed of 30 PV modules while all of the hot water for the building is provided by 120ft^2 of solar

[3] http://www.eia.gov/forecasts/aeo/early_fuel.cfm
[4] http://www.eia.gov/forecasts/aeo/early_prices.cfm

thermal collectors. Figure 5 depicts the south facing roof of the OGZEB showing the PV array and the solar thermal collectors.

Figure 5: South facing roof of OGZEB

Figure 6 shows a front view schematic of the OGZEB displaying all of the main components in the building. These components are located directly underneath the house. The orange and blue lines on the right side of the picture represent hot and cold water, respectively, for the solar thermal system. The solar thermal storage consists of a 250gal water tank maintained at a temperature range of 140°F - 160°F. A heat exchanger located inside this tank receives water from FSU and heats it to provide hot water directly to the building.

The yellow line represents the path of electricity. PV modules produce direct current (DC) electricity which needs to be inverted to alternating current (AC) in order to power the appliances in the building. The energy storage system, however, uses DC electricity; therefore excess electricity is converted back into DC so that it can be stored. The energy storage system is composed of a small battery array, an electrolyzer, hydrogen tanks, and a fuel cell. It was designed to store electricity in the form of hydrogen, represented by the pink line, because there will be no carbon emissions from this process thus promoting the environmentally friendly design of this building. The electrolyzer uses the excess electricity to split water molecules into hydrogen and oxygen. The oxygen is released into the atmosphere while the hydrogen is stored in compressed gas tanks. When the PV array is not providing power to the building, the fuel cell uses the hydrogen, combining it with oxygen taken from the atmosphere, to produce electricity. This is then passed through the small battery array to ensure that the batteries remain charged and continues on to the inverter to provide electricity to the building. The battery array provides charge controlling to this system thus preventing any lag time between energy demand and energy supply. The hydrogen is also used for combustion in the gas stove that has been retrofitted for this clean burning fuel.

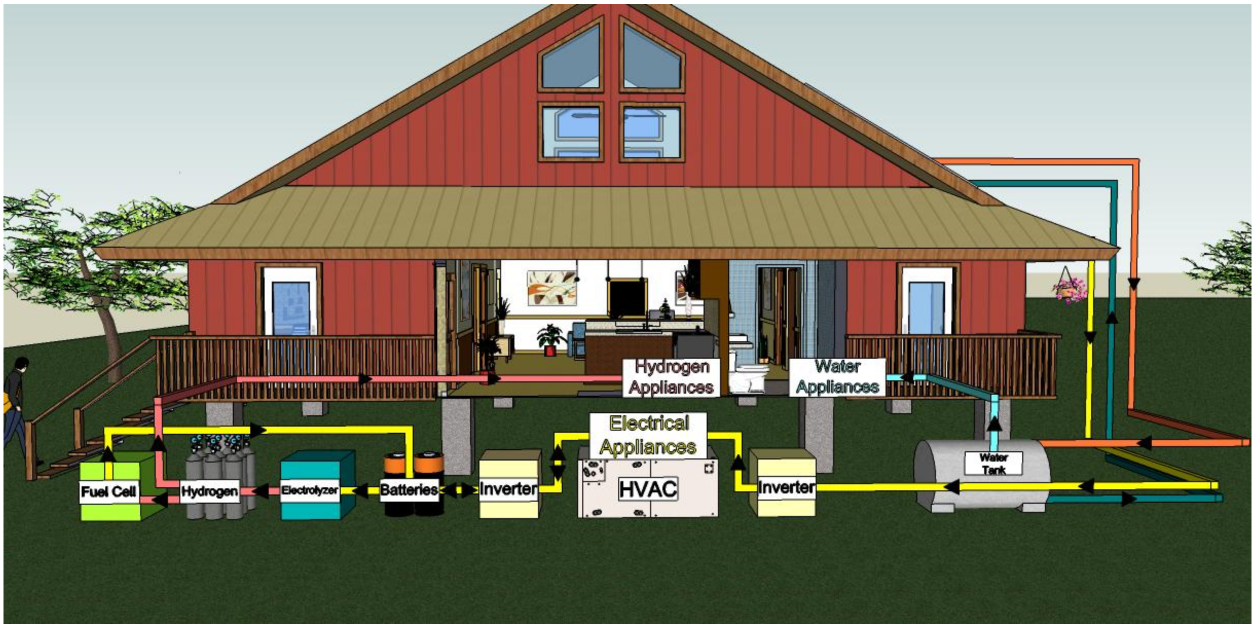

Figure 6: Front view of OGZEB displaying system components

There are several different systems in the OGZEB that can be tested and optimized, however it was decided to focus research on the efficiency of the HVAC unit since HVAC units are one of the most power consuming appliances in a home.[5] The HVAC system at the OGZEB is an Envision Residential geothermal/water source heat pump with piping extending 50 – 80ft underground in order to reach a depth at which the ground temperature remains constant at a value of 70°F.

There are two ways to increase the efficiency of an HVAC unit: increasing heat transfer or decreasing electricity consumption. Previous testing for a senior design project focused on increasing heat transfer while maintaining electrical consumption by connecting the HVAC unit ground loop with the secondary heat exchanger in the solar thermal storage tank. With this setup, it was hypothesized that excess heat from the solar thermal storage could be used to heat water in the ground loop, thus providing a higher temperature working fluid to the vapor compression cycle in the HVAC unit. It was also assumed that during cooling cycles, heat being removed from the air in the building could be used to heat water in the solar thermal system instead of being wasted to the ground. As expected, the COP increased during the heating cycle from 2.5 to approximately 6, however, the integration proved to be ineffective during the cooling cycle because the water in the ground loop was only being heated to 100°F which was not a high enough temperature to transfer heat from the ground loop to the solar thermal system with water at 140°F – 160°F. With this realization, a new design was implemented which focused solely on the heating cycle. Since the solar thermal storage is maintained at such a high temperature, it is possible to bypass the vapor compression cycle completely and allow for direct heat transfer between the water in the integrating loop and the air in the HVAC unit.

Methods

Phase 1:

Since the OGZEB is designed to serve as a prototype for testing sustainable technologies, it is necessary to install a full scale data collection system to monitor the various systems within the building. Siemens provided and implemented the data collection system that is not only designed to test the integration of the solar thermal system with the geothermal HVAC system, but also to provide the ability to test any of the systems in the building for possible future projects. Therefore it was necessary to install

[5] http://www.eia.doe.gov/emeu/reps/enduse/er01_us.html

several different measuring devices capable of collecting data on the electrical systems, heat transfer systems, air quality, hydrogen usage, and solar radiation on the south facing roof.

Analyzing electrical data only requires measuring the amperage since the voltage remains constant therefore ammeters were installed on every circuit in the building. The majority of electrical data is captured at the breaker box since this provides a single location and easy access point to all of the circuits in the building. Table 1 shows the description of the breaker box connections.

Table 1: Breaker Box Connection Labels

Breaker Number	Amps	Function
1	20	NW Office LTS
3	20	NE Office LTS
5	20	NW Office REC
7	20	NE Office REC
9	20	Living Room REC
11	20	Bath REC
13	20	Bath LTS
15	20	Kitchen REC
17	20	Kitchen REC
19	20	Fridge
21	20	Range Hood
23	50	Sunny Island
25	50	Sunny Island
27		
29		

Function	Amps	Breaker Number
Data Closet REC	20	2
Data Panel	20	4
Exhaust Fan	20	6
ERV	20	8
Water Heater	20	10
Under House LTS & REC	20	12
Living Room LTS	20	14
A/C	30	16
A/C	30	18
SunPower	30	20
	30	22
SW Room LTS	15	24
SE Room LTS	15	26
SE Room REC	20	28
SW Room REC	20	30

The heat transfer calculations require information about the change in temperature across the inlet and outlet of a heat exchanger as well as the flow rate of the working fluid moving through the heat exchanger. It was also necessary to include ammeters to measure the current usage in the pumps. Figure 7 shows all of the locations where measuring devices were placed. Examples of some of the temperature sensors can be seen in Figure 8 and Figure 9.

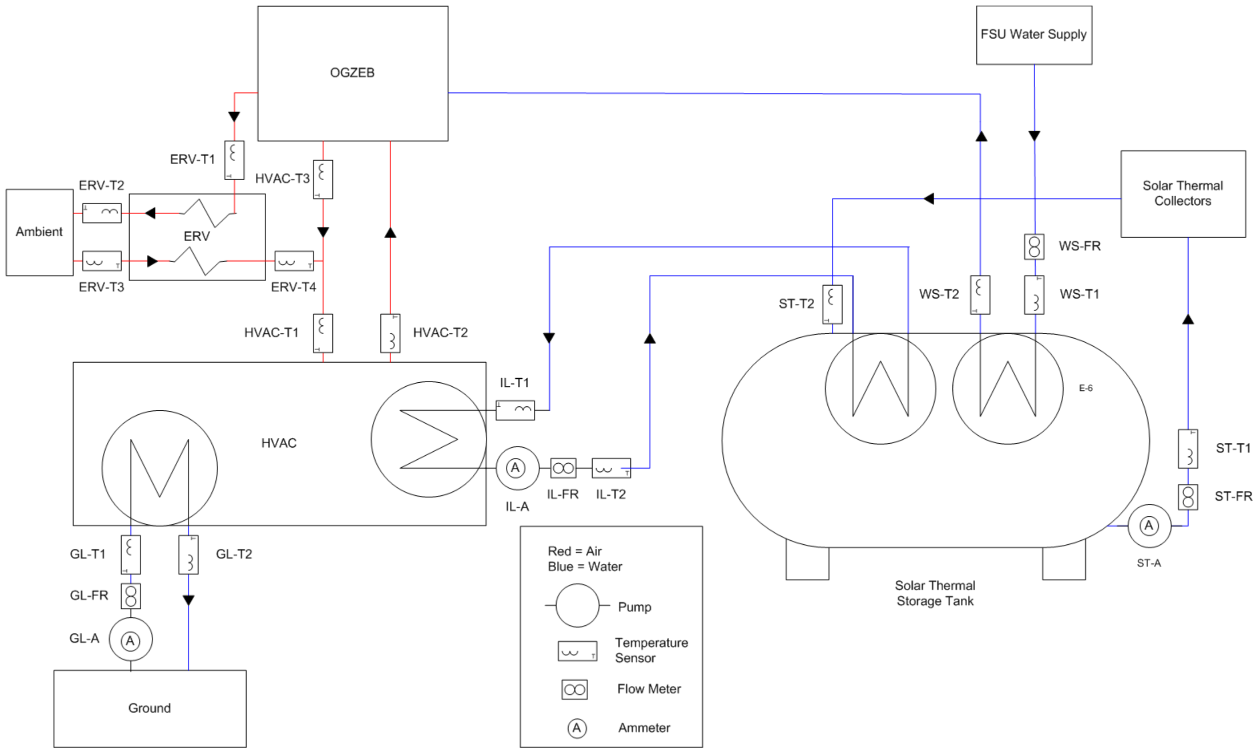

Figure 7: Heat transfer data instrumentation diagram

Figure 8: Wrap around pipe temperature sensors

Figure 9: Duct temperature sensors

Other measuring devices include indoor air quality sensors located in each room of the OGZEB. These measure temperature, humidity, carbon dioxide concentrations, and volatile organic compound (VOC) concentrations and can be seen in Figure 10. An Apogee SP-212 pyranometer was installed on the south facing roof to determine the actual solar radiation reaching the photovoltaic and solar thermal systems. Also, a hydrogen flow meter was installed to measure hydrogen consumption of the stove.

Figure 10: Air quality control sensors

Phase 2:

Integrating the geothermal HVAC system with the solar thermal system will allow indoor air to be heated by the excess heat from the solar thermal system. The integrating loop can be seen in Figure 7. This loop connects a secondary heat exchanger already installed in the solar thermal storage tank with a heat exchanger to be installed in the HVAC air handler. The two main design components of the integrating loop are the heat exchanger to be installed inside the HVAC air handler and the pump. Calculations for the amount of heat transfer that the heat exchanger will need to provide focused on the heat transfer capability of the current HVAC system in order to match this value. The design for most HVAC units assumes that the air in the building is recirculated with very little ambient air entering the indoor environment, thus the inlet temperature of air is estimated at 70°F with a relative humidity of 50%.[6] The outlet temperature of air is typically 100°F during heating cycles. The following equation was used to calculate heat transfer:

Equation 1

$$\dot{Q} = \dot{m} \cdot (h_2 - h_1)$$

where $\dot{Q}$ is the heat transfer, $\dot{m}$ is the mass flow rate, and h is the enthalpy of air. The volumetric flow rate of the air is set by the fan in the HVAC unit at a constant 900ft^3/min (25.5m^3/min). This was converted to a mass flow rate of 0.512kg/s with the following equation where ρ is the density and $\dot{V}$ is the volumetric flow rate:

Equation 2

$$\dot{m} = \rho \cdot \dot{V}$$

Although the density of a fluid is temperature dependent, the temperature intervals under which this system operates do not produce significant changes in density, therefore the density was taken to be the average of the densities at the inlet and outlet temperatures resulting in a value of 1.2kg/m^3. In order to determine the enthalpy of the air at the inlet and outlet conditions, it was necessary to use a psychometric chart as seen in Figure 11. The black arrows show the initial and final enthalpy values.

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[6] Envision Geothermal Heat Pump 2 to 6 tons Specification Catalog

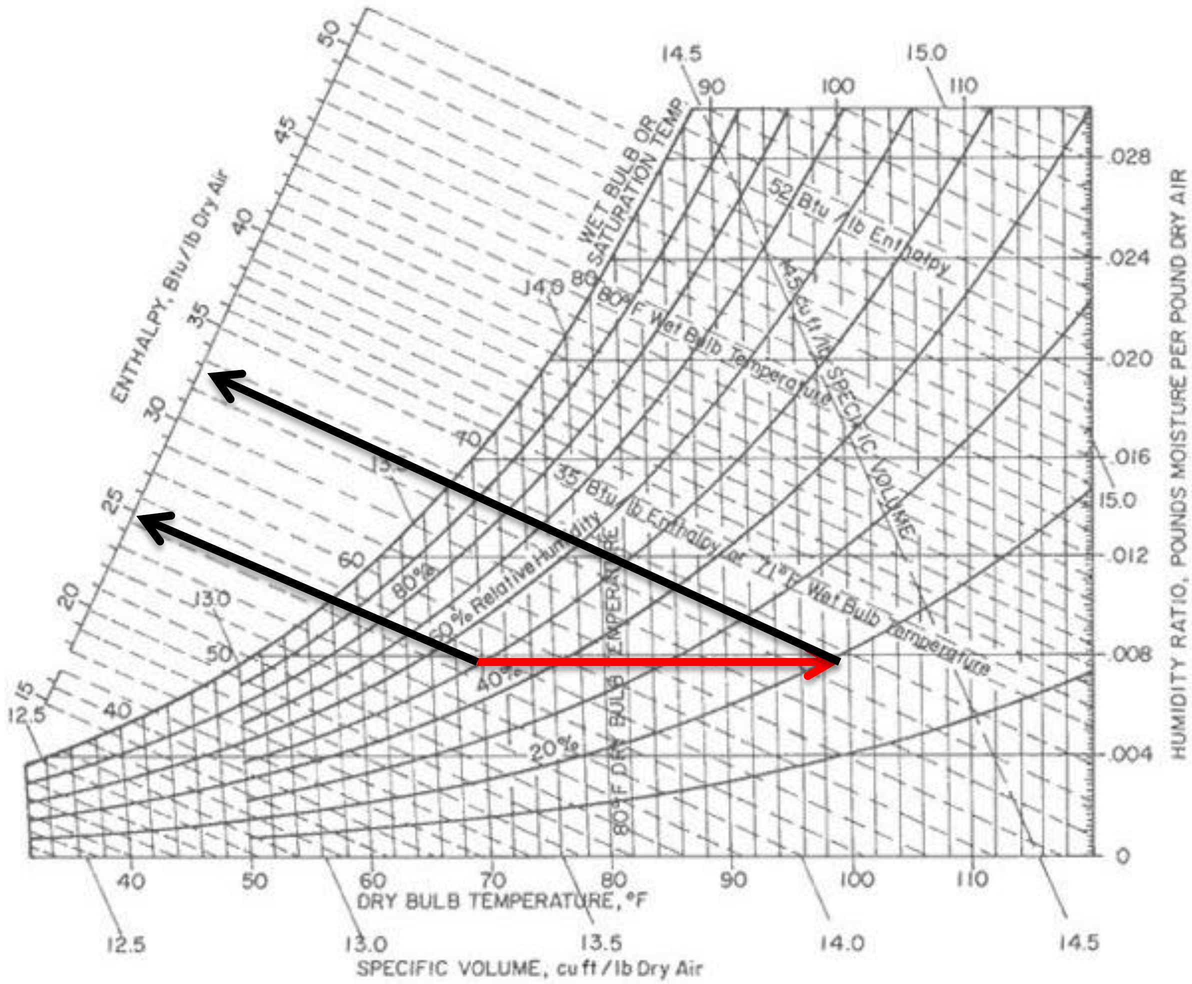

Figure 11: Psychometric chart for air[7]

Performing the calculation for Equation 1 showed that the total heat transfer required is 33,440BTU/hr. With these results, all of the heat exchanger parameters were now defined and are given below, thus a heat exchanger selection could be made.

Heat Exchanger Parameters:

- Air Flow Rate: 900 ft^3/min
- Water Flow Rate: 5 gal/min
- Inlet Air Temperature: 70°F
- Exit Air Temperature: 100°F
- Inlet Water Temperature: 160°F
- Heat Capacity: 33,440 BTU/hr
- Dimensions : 2in x 18 in x 35 in

Super Radiator Coils donated the heat exchanger pictured below in Figures 12, 13, and 14 which is valued at $641. This tube and fin heat exchanger will be able to satisfy all of the parameters listed above.

[7] http://images.brighthub.com/BB/3/BB3CDE0157B3B7F49BB4F2D44CFB90C655CCBBAB_large.jpg

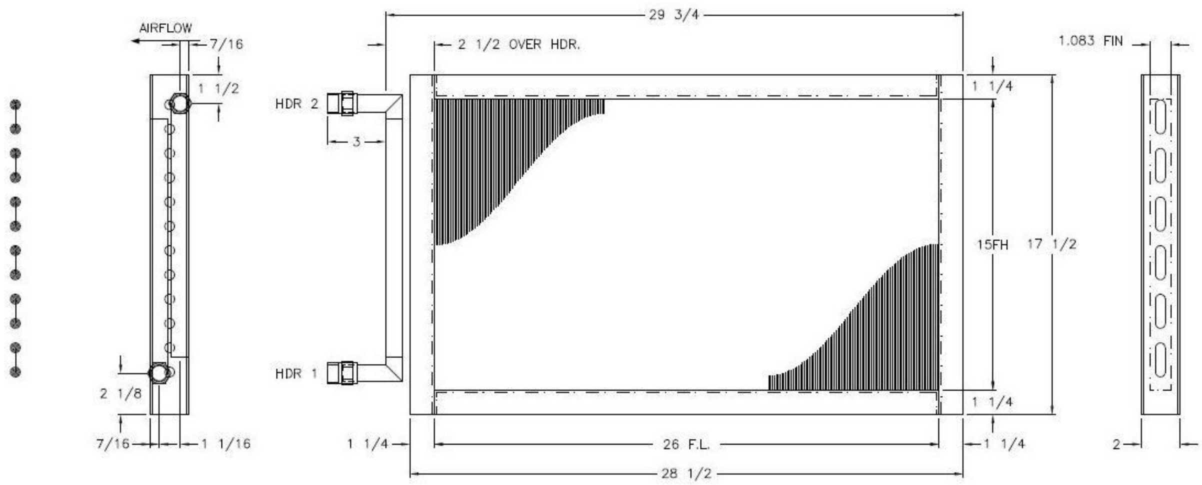

Figure 12: Heat exchanger drawing

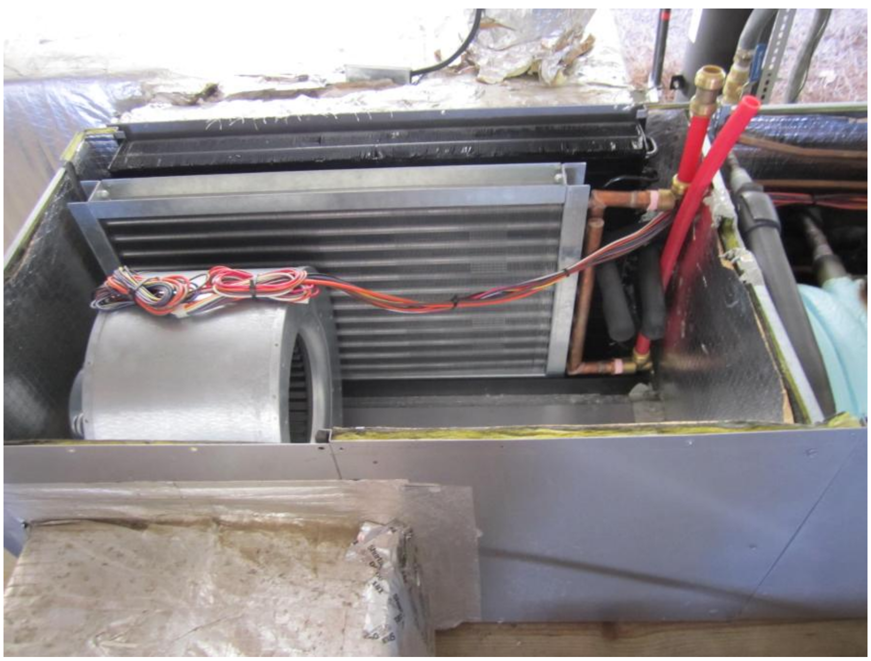

Figure 13: Front view of heat exchanger

Figure 14: Side view of heat exchanger

With the heat exchanger selection complete, it was necessary to determine the size of the pump. The modified Bernoulli equation, Equation 3, was used to analyze the pressure changes in the piping system. It is extremely important to select a pump that can overcome the pressure losses of the system in order to prevent cavitation in the pump.

Equation 3

$$P_1 + \frac{V_1^{\,2} \cdot \rho}{2} + z_1 \cdot \rho \cdot g = P_2 + \frac{V_2^{\,2} \cdot \rho}{2} + z_2 \cdot \rho \cdot g + \sum \frac{f \cdot L}{D_h} \cdot \frac{V_2^{\,2} \cdot \rho}{2} + \sum K \cdot \frac{V_2^{\,2} \cdot \rho}{2} + \Delta P_{HX1} + \Delta P_{HX2}$$

In this equation, the subscript 1 indicates inlet conditions while the subscript 2 indicates outlet conditions. The inlet conditions are considered at the entrance of the pump. The height at the inlet of the pump, z_1, serves as a reference point and was set to the value of zero. The outlet height, z_2, was considered at the highest point in the system, located 5ft above the inlet of the pump, resulting in a pressure change of 2.126psi. In closed loop systems, such as this integrating loop, the pressure exerted by the downward flow pushes against the pressure of the upward flow thus balancing out the system. However this principle could not be used to analyze the size of this pump because this pump will be used to initially fill the system, therefore during the initial filling of the system, there will be no downward force of fluid to counteract the weight of fluid moving upward which is why the outlet conditions are considered at the highest point in the system. This ensures that the pump can properly fill the system, but once operating continuously, the pump need only overcome the pressure losses due to friction. Since the flow rate is constant at 5gpm, the velocity is assumed to be constant throughout the system at a value of 4.689ft/s as determined by Equation 2 where the density of water is 985kg/m^3. This density value is the average value of the densities at the inlet and outlet temperatures of the heat exchanger. As with the heat transfer calculations for air, the calculations for water can be assumed to have a constant density value since the system does not undergo significant changes in temperature and pressure, thus the changes in density are negligible.

The terms ΔP_{HX1} and ΔP_{HX2} indicate the pressure losses in the two heat exchangers in this system. The pressure drop in the Super Radiator Coils heat exchanger, ΔP_{HX1}, is provided in the specifications at a value of 0.607psi. The pressure drop in the solar thermal system heat exchanger, ΔP_{HX2}, was determined to be a value of 2.865psi by analyzing the frictional losses in the heat exchanger, the method of this analysis is further discussed in regards to the entire system. The first step in determining frictional losses is to determine whether the flow is laminar or turbulent based on the Reynolds number.

Equation 4

$$\mathrm{Re} = \frac{V \cdot D}{\upsilon}$$

In Equation 4, *V* is the velocity of the flow, *D* is the inner diameter of the pipe, and ν is the kinematic viscosity. This system is composed of ¾'' PEX piping for its flexibility and ease of installation; the inner diameter for this piping is 0.66''. The average kinematic viscosity of water at the operating temperatures is $6.732\times10^{-4} in^2/s$. This calculation provided a Reynolds number of 5.516×10^4 and since this value is greater than 2300, the flow is defined as turbulent. The Moody plot as seen in Figure 15 will give the friction factor for turbulent flow. All of the piping in this system is smooth therefore the friction factor is determined to be 0.02 producing a pressure drop of 2.829psi due to frictional losses. The last step in solving Equation 3 is to determine the minor losses due to fittings. There are four elbows, two ball valves, two tee joints, and four couplings. The loss factor for each type of fitting is listed in Table 2. The resulting pressure drop due to minor losses is 0.282psi.

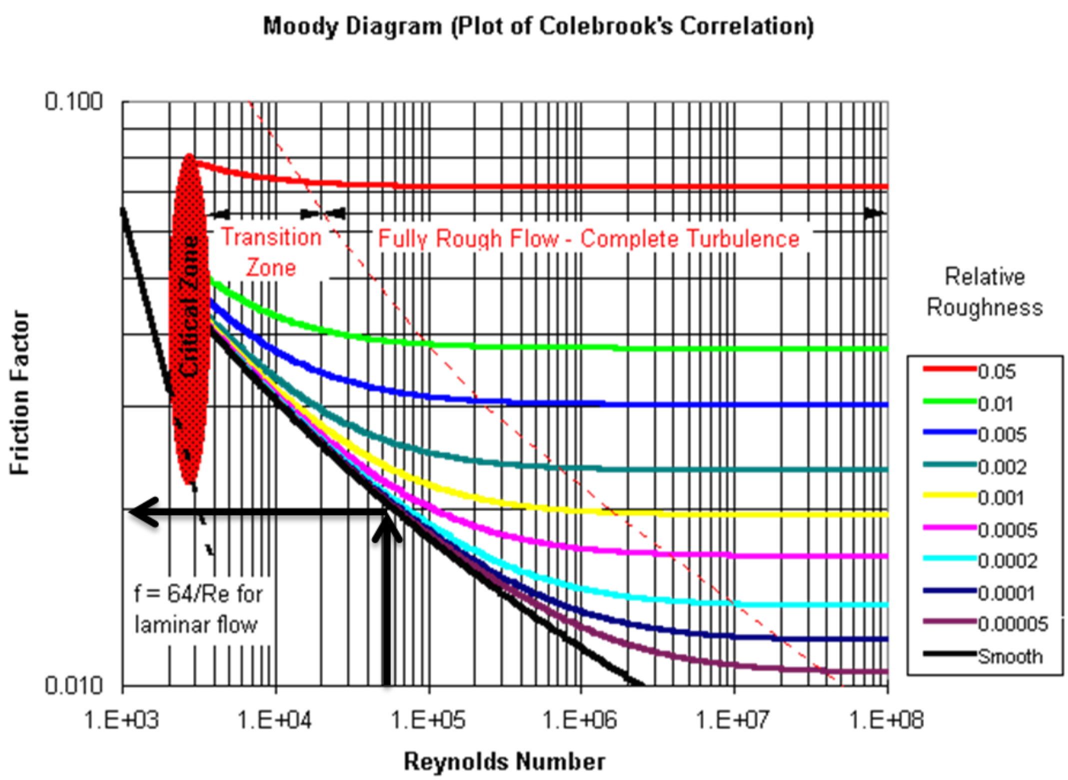

Figure 15: Moody diagram showing friction factor at a given Reynolds number[8]

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[8] http://www.ivt.ntnu.no/imt/courses/tmr4285/moody.gif

Table 2: K factors for various fittings

Loss Coefficient (K)	
Elbow	0.31
Ball valve	0.05
Tee Joint	0.14
Coupling	0.08

Adding all of the pressure losses together revealed a total pressure loss of 8.709psi. This was converted to total head loss of 20.48ft using Equation 5.

Equation 5

$$\Delta H = \frac{\Delta P}{\rho \cdot g}$$

Finally, the pump selection could be performed. It was necessary to look at pump performance charts such as those shown in Figure 16 to see which pump can operate above the calculated parameters with a total head loss of 20.48ft and a flow rate of 5gpm; these pumps are shown in the yellow highlighted region. The 009 Taco series cartridge circulator is the most suitable pump for this system because it is the most cost effective and uses the least electricity. In order to determine more precise conditions at which this system will operate, an iterative method was used to change the flow rate of the pump and then follow through all of the procedures explained above to determine a new head loss at that flow rate. The results seen in Table 3 show that the pump is expected to operate at a flow rate of 5.5gpm with a total head loss of 23.09ft.

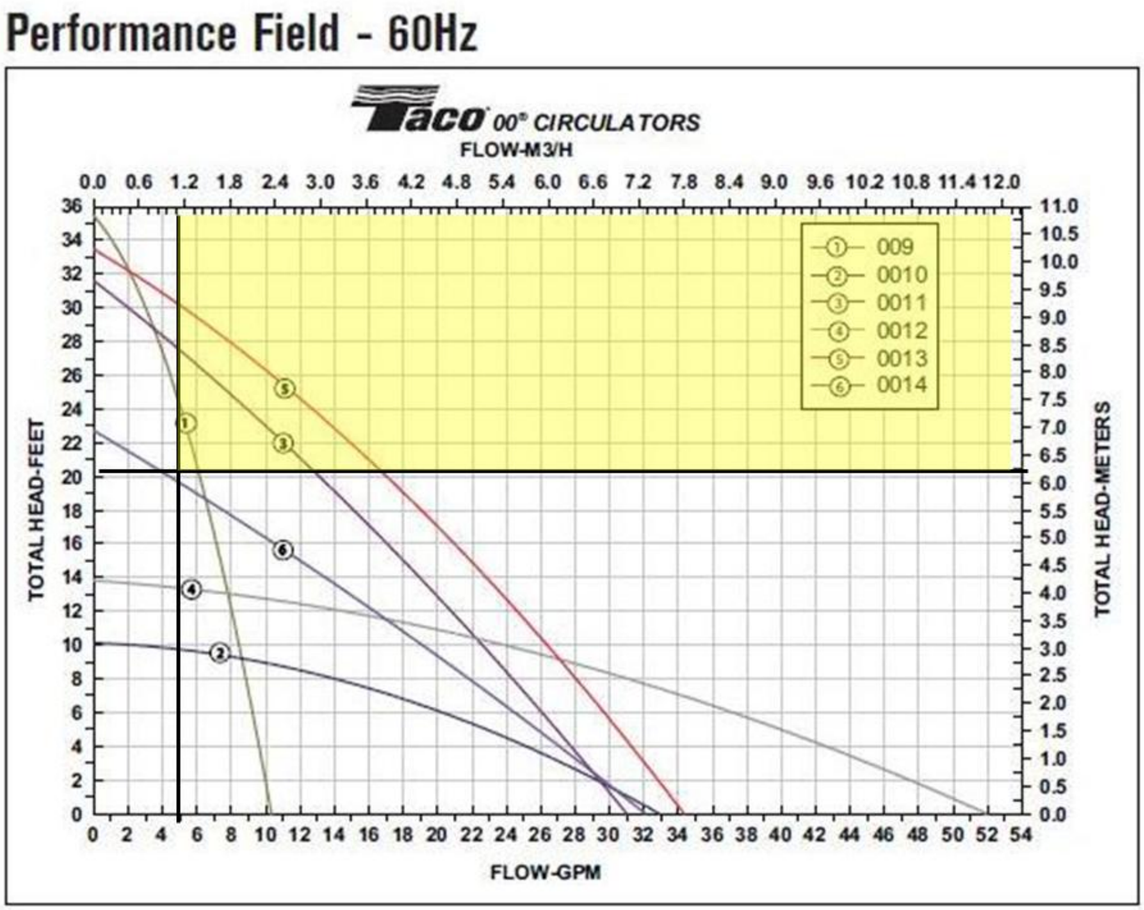

Figure 16: Pump Performance Fields[9]

Table 3: Iterative method to determine actual pump performance

Flow Rate (gpm)	Total Head (ft)
5	20.48
5.1	20.98
5.2	21.50
5.3	22.02
5.4	22.55
5.5	23.09
5.6	23.63

The pump installation can be seen in Figure 17. The pump is strapped to a small reservoir which is used to ensure that the pump stays primed during the initial filling of the system as well as during continuous operation.

[9] http://www.taco-hvac.com/uploads/FileLibrary/101-032.pdf

Figure 17: Pump installation

Results

Phase 1:

The data collection system implemented by Siemens displays real time data and has also been recording and trending the data necessary for calculating the efficiency of the integrating loop. The completion of this system has now allowed the OGZEB to reach its full potential of serving as a testing facility for sustainable technologies. Screenshots of the data collection system can be seen in Figures 18, 19, and 20.

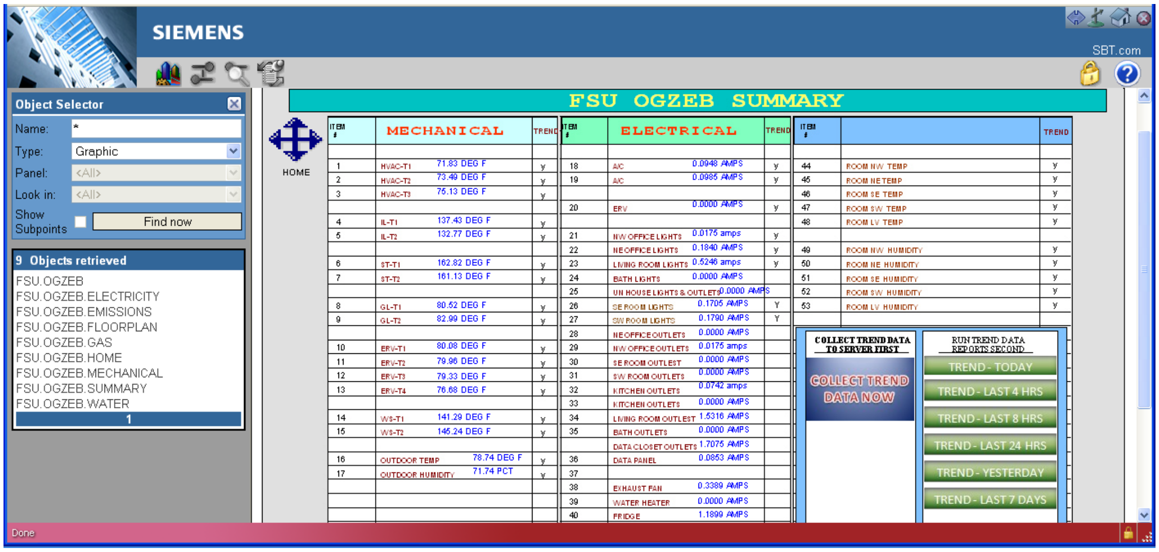

Figure 18: Data being recorded for efficiency calculations

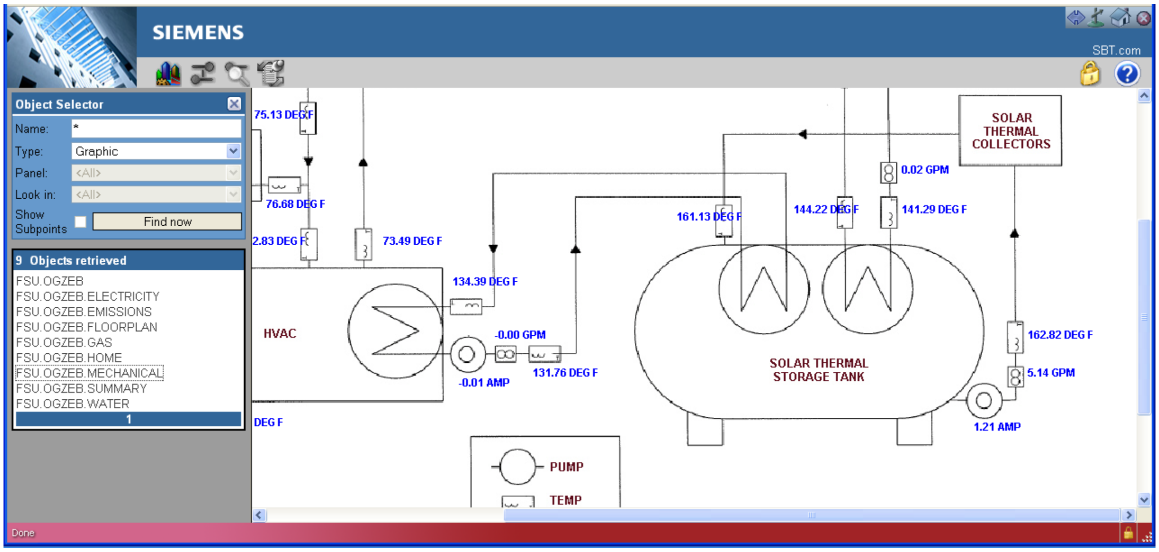

Figure 19: Real time mechanical systems data

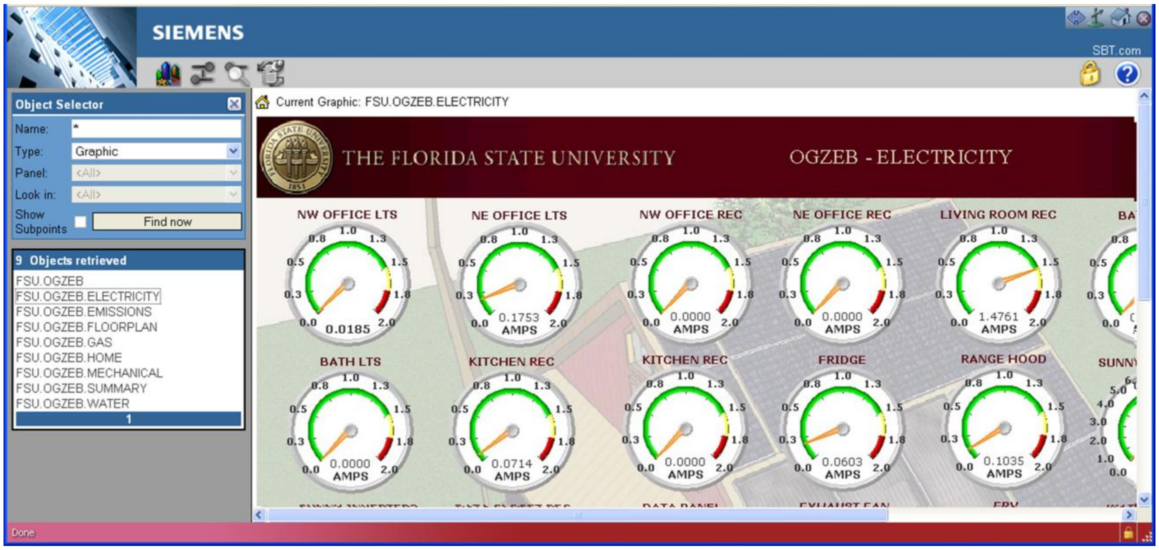

Figure 20: Real time electrical data

Phase 2:

The coefficient of performance calculations are determined by Equation 6. In this equation, $\dot{Q}_H$ is the heat transfer to the air, and P is the power required to produce that heat transfer. The heat transfer is determined by Equation 7 where $\dot{m}$ is the mass flow rate of the air previously defined to be 0.512kg/s, c_p is the constant specific heat defined as 1.005kJ/kg-K, and ΔT is the change in air temperature across the heat exchanger. The amount of power for the HVAC unit operation alone includes the power used for the compressor, HVAC fan, and ground loop pump. The power for the integrating loop includes the integrating loop pump, HVAC fan, and solar thermal pump. These power calculations were determined using Equation 8 where *I* is the current in amps and *V* is the voltage in volts.

Equation 6
$$COP = \frac{\dot{Q}_H}{P}$$

Equation 7
$$\dot{Q}_H = \dot{m} \cdot c_p \cdot \Delta T$$

Equation 8
$$P = I \cdot V$$

In order to get an accurate comparison between efficiency values, as many variables as possible were kept constant. All of the blinds in the building were completely closed to prevent sunlight from affecting the indoor air temperature. All of the interior doors were kept open to allow for proper circulation. All unnecessary appliances were turned off and no one entered the building during testing to prevent any heat transfer from appliances or people affecting the results. Also, tests were started with the indoor air temperature at 70°F and ended when the indoor air temperature reached 78°F. However, it is not possible to control any changes in ambient air temperature or other weather features. Therefore, several experiments were performed to validate the findings and ensure that these experiments are repeatable.

Figure 21 shows the COP for the HVAC unit operating alone with a value of 2.5. It is important to note that the COP starts at a very low value and then increases to a steady state value because the startup of the system requires significant power but produces very little heat transfer for the first few minutes of operation. Using the integrating loop as an auxiliary heat source allowed the unit to operate with a COP of approximately 16 as can be seen in Figure 22. This is a significant increase in efficiency due to the large decrease in electricity usage since the integrating loop can provide heat to the air without using the vapor compression cycle. These findings are extremely beneficial and provide the necessary evidence to pursue commercial applications of this type of system.

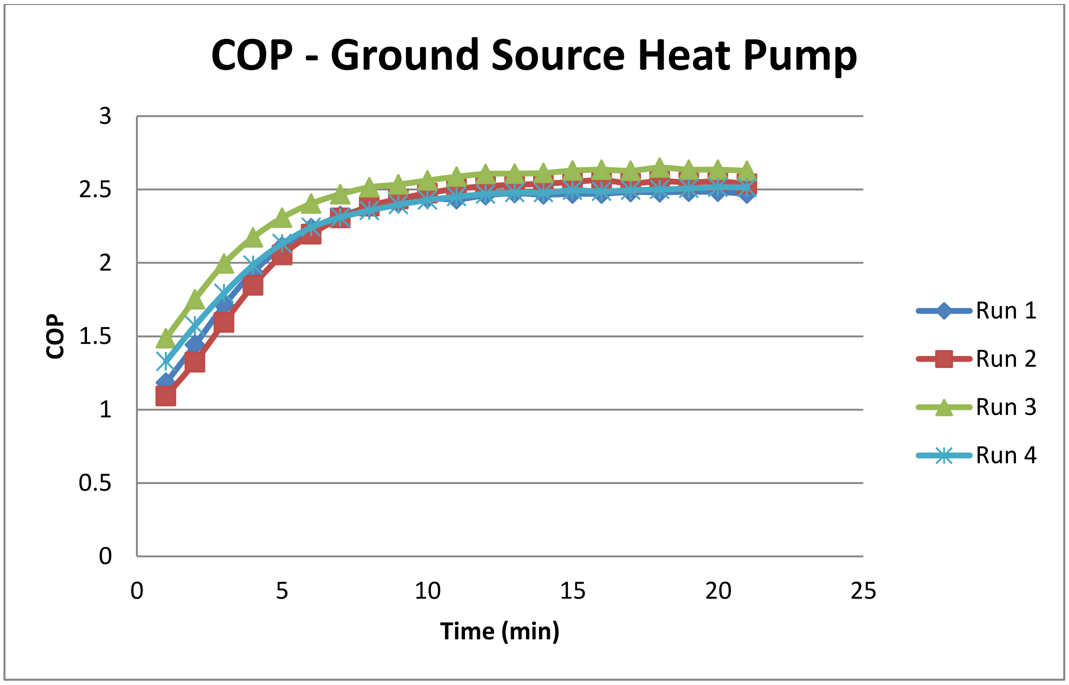

Figure 21: Graph depicting COP data for the HVAC unit operating alone

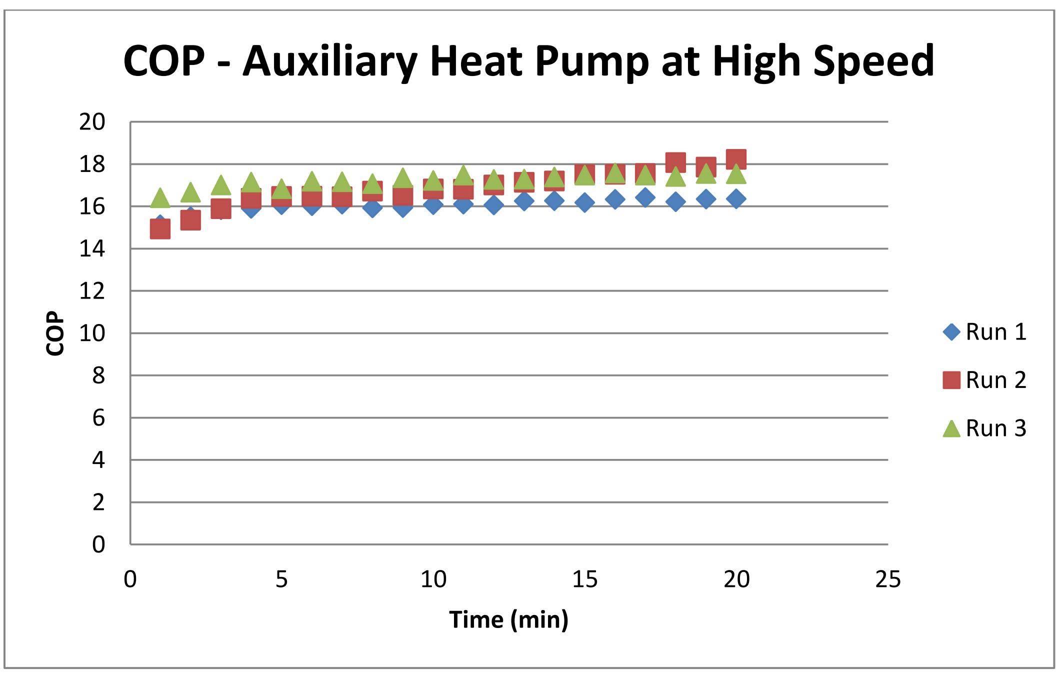

Figure 22: Graph depicting COP data for HVAC unit operating with the integrating loop at high speed

It was also of interest to look at certain variations of the integrating loop. The pump purchased for the integrating loop is a variable speed pump which allowed for testing at a high speed and low speed. At a lower speed, it is expected to have a decreased amount of heat transfer, however it is also expected to have a decreased amount of power consumption. The results seen in Figure 23 show that the COP at a lower pump speed actually decrease to an average value of 14. The decrease in power consumption is not enough to overcome the decrease in heat transfer, therefore it is beneficial to maintain the higher speed flow rate. Another variation included the use of fans. Each of the five rooms in the OGZEB has a fan that was turned on during this set of experiments. The combined power electricity usage of the fans was 115W. The results seen in Figure 24 and Figure 25 showed that the fans did not affect the heat transfer of the unit, therefore they only added to the power consumption. Since the HVAC unit uses 3.5kW of electricity, adding the power used by the fans did not have any significant effects on the COP value. However, the integrating loop operates with 0.6kW of electricity so adding the power consumption of the fans had more of an impact on the efficiency resulting in lower COP values. Therefore, it was determined that the use of the fans during heating cycles with the integrating loop was not beneficial.

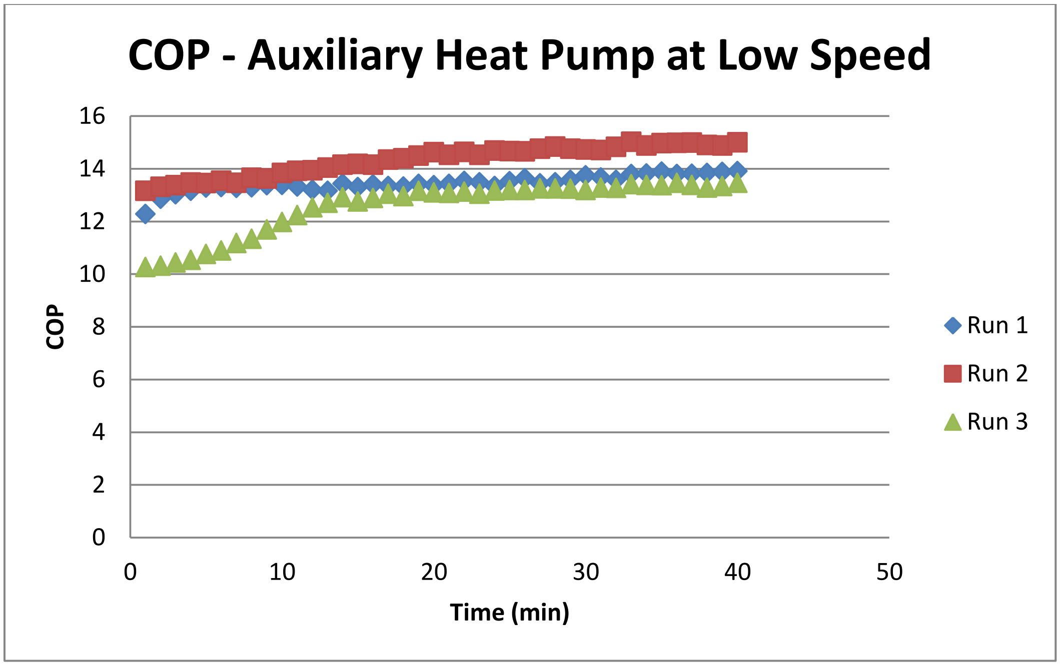

Figure 23: Graph depicting COP data for HVAC unit operating with integrating loop at low speed

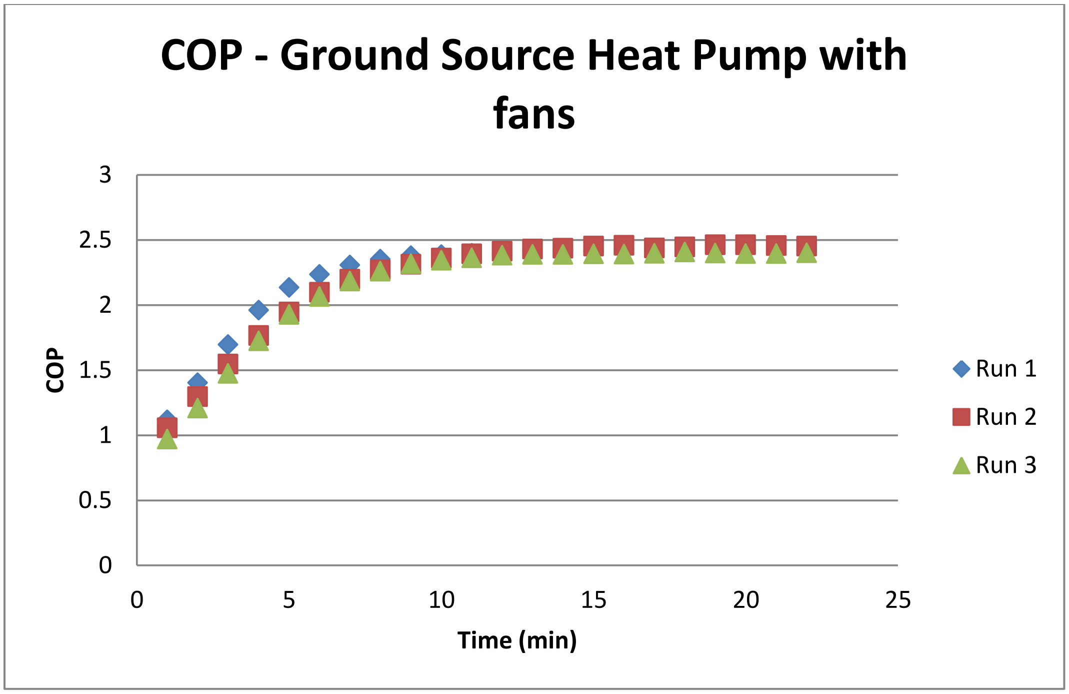

Figure 24: Graph depicting COP data for the HVAC unit operating alone with fans

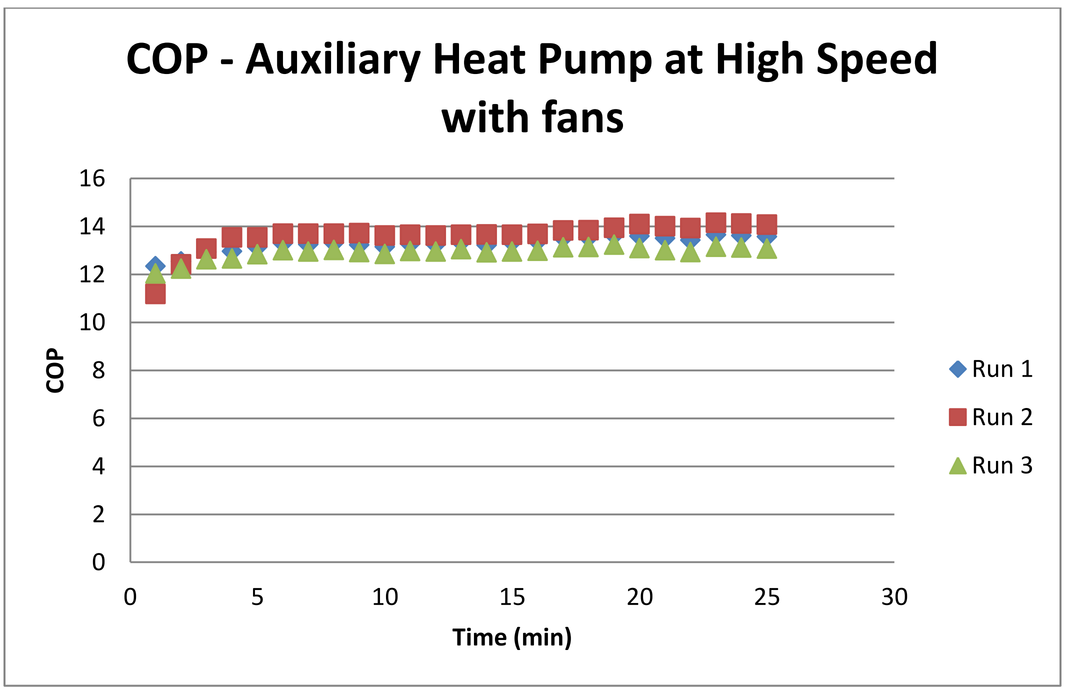

Figure 25: Graph depicting COP data for HVAC unit operating with the integrating loop with fans

It is important to note the instrumental limit of error within the calculations to ensure that any differences in results are not due to variations within the measuring devices. The equation for this calculation can be seen in Equation 9 where Δ symbolizes the error value for that variable. The resulting error for the integrating loop COP was 1.412 or a relative error of 8.7% while the ground source heat pump COP had an error of 0.209 or a relative error of 9.1%. Therefore, the errors in these results are acceptable to find the trends to be accurate.

Equation 9

$$\Delta COP = COP_{avg} \cdot \sqrt{\left(\frac{\Delta \dot{Q}}{\dot{Q}_{avg}}\right)^2 + \left(\frac{\Delta P}{P_{avg}}\right)^2}$$

Conclusions

The implementation of the data collection system was very successful and will allow for testing of various sustainable technologies in the future. This living laboratory can provide the evidence necessary to determine which technologies should be pursued commercially as well as the best way to implement them with current technology.

The results of the efficiency testing show that the integrating loop drastically improves the efficiency of the HVAC unit during heating cycles. The Energy Information Administration estimates that a household consumes 3,524kWh annually for space heating.[10] If the HVAC unit was operating alone, this would require the unit to operate for 1,006hr annually at a rate of 3.5kW. If the integrating loop was used instead, it would only consume 603.6kWh at a rate of 0.6kW. This results in an energy savings of 2920.4kWh annually. This type of energy conservation is particularly beneficial at night to prevent the small battery array in the OGZEB from becoming depleted. Also, reducing electricity consumption will reduce the need for backup power thus conserving hydrogen fuel. This type of energy conservation is exactly what the OGZEB was designed for.

A basic cost analysis of this system was performed assuming an electricity cost of $0.117/kWh[11] in Tallahassee which showed that using the integrating loop instead of the ground source heat pump would save $341.69 annually. The total cost of materials for the integrating loop is $980.95; this results in a payback period of 2.87 years. A solar thermal system has a payback period of 3 to 5 years.[12] Therefore to heat the air in a home with a solar thermal system and subsequent integrating loop will result in a total payback period of 6 to 8 years. Therefore, this type of sustainable design can be very beneficial to the consumer thus proving to be a profitable endeavor. Also, if this were to be pursued commercially, the price of materials would decrease due to bulk purchasing. Overall the data collection system and integrating loop tests proved to be very successful.

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[10] http://www.eia.doe.gov/emeu/reps/enduse/er01_us_tab1.html
[11] http://talgov.com/you/rates.cfm
[12] http://www.sunmaxxsolar.com/sunmaxx-solar-hot-water-payback-period-explanation.php

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