COMPARATIVE PERFORMANCE ANALYSIS OF MOD 303 EVACUATED TUBE AND FLAT PLATE SOLAR THERMAL COLLECTORS

by

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ABSTRACT

Comparative Performance Analysis of Mod 303 Evacuated Tube and Flat Plate Solar Thermal Collectors

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The Comparative Solar Project, a pilot study installed on residential building Mod 303 at The Evergreen State College, delivers hot water and radiant heat to eight student residents. The project consists of two solar thermal collectors of comparable production capacities: an Apricus AP-30 evacuated tube collector and a Caleffi NAS10410 flat plate collector. This research evaluates the performance of each collector to determine the effectiveness of solar thermal hot water and radiant heat on campus. Temperature of the heat transfer fluid inside the Apricus AP-30 was measured every ten minutes for one year, from May, 2014 to May, 2015, while data collection began full time on the Caleffi NAS10410 in September after the system became fully operational. These measurements were analyzed to determine which collector provided the most hot water throughout the year and how each functioned at the specific site. The analysis revealed that the Caleffi flat plate collector was capable of reaching much higher temperatures than the Apricus AP-30. In September, 2014, the Caleffi circulated hot water approximately 90% of the time while the Apricus circulated hot water for only 43% of the recorded hours. The Apricus outperformed the Caleffi only during November and December, when low temperatures and limited solar radiation severely affected heat production. System maintenance took place during January and February, 2015, and no data collection occurred until March. Throughout the data collection period, the flat plate collector suffered several issues, such as stagnation, faulty sensor readings and system component failure, all of which influenced the certainty of the results. A lack of available data limited any further analysis and led to the conclusion that a comprehensive monitoring system must be installed in order to fully understand how solar thermal hot water can help The Evergreen State College achieve its carbon neutrality goals.

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INTRODUCTION

Carbon Neutrality by 2020

In 2007, Thomas L. Purce, then President of The Evergreen State College, signed the American College and University Presidents Climate Commitment (ACUPCC), which set in motion the campus-wide pursuit of carbon neutrality. The ACUPCC strives to unite higher education institutions with the common goal of "exercising leadership by modeling ways to minimize global warming emissions, and by providing the knowledge and the educated graduates to achieve climate neutrality". In 2009, as part of this commitment, The Evergreen State College published a climate action plan: *Carbon Neutrality by 2020*. This plan was submitted to the ACUPCC as "an articulation of the strategies, tactics, and resources required to achieve carbon neutrality by 2020".

The Evergreen Carbon Neutrality report laid out a detailed framework with "annual targets for progress in specific GHG categories and spells out specific mitigation strategies within those categories". The criteria and strategies for reducing greenhouse gas emissions include:

- Any action must be consistent with the mission and values of the college,
- It should demonstrate financial efficiencies,
- It should have a reasonable ease of implementation,
- It should be achievable,
- It should advance social, ecological, and economic sustainability,
- Our plan should demonstrate flexibility and resilience to future changes.

Recommended strategies:

- Energy efficiency and conservation,
- On-site renewable energy production,
- Commuting efficiencies and transportation alternatives,
- Waste stream management, including purchasing and food management processes, and
- Building and grounds infrastructure and practices.

Strategic approaches:

- Technical innovations,
- Increasing individual mindfulness and engagement with carbon neutral habits, and
- Institutional policy and procedural changes.

As part of the ACUPCC, The Evergreen State College develops annual greenhouse gas emissions inventories. An original projection of greenhouse gas emissions and targets from 2005-2020 was included in the climate action plan (see Figure 1). The data for 2005-2008 are actual values while the numbers for years following that are projections.

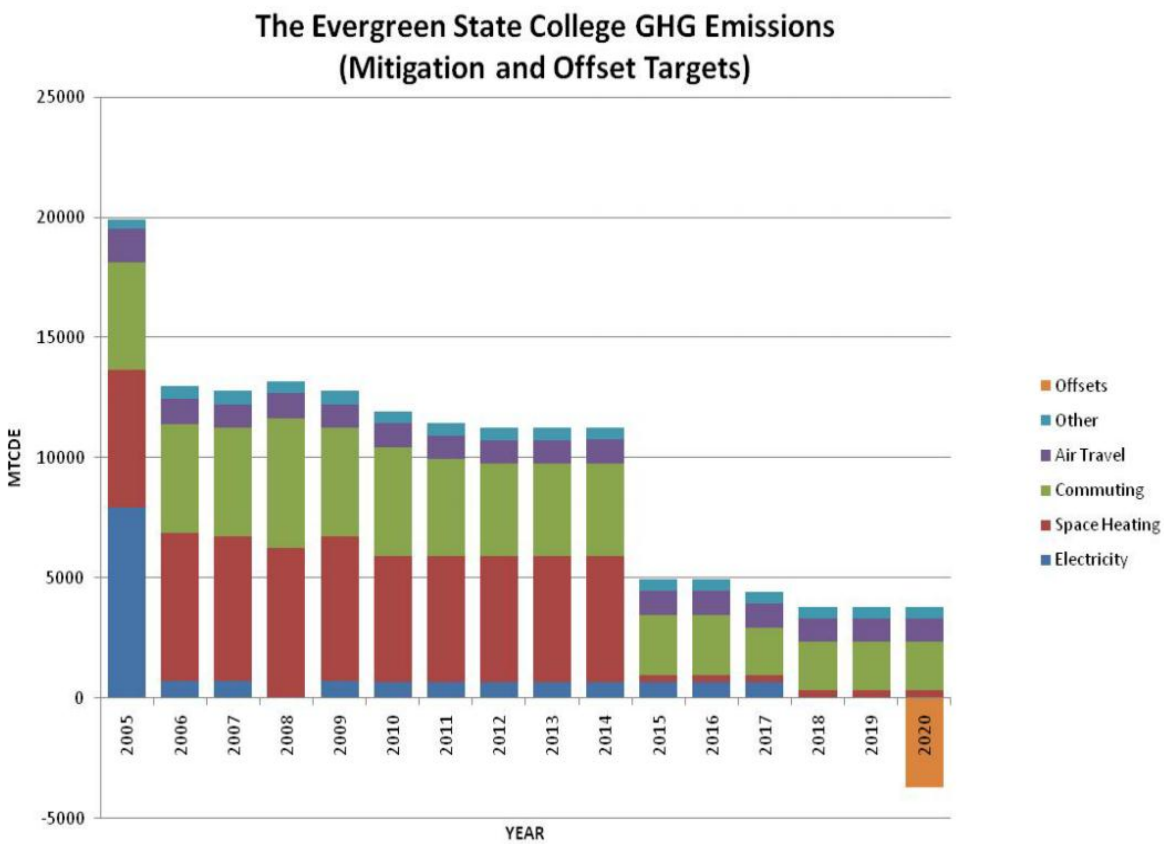

Figure 1: The Evergreen State College GHG Emissions (Mitigation and Offset Targets). 2005-2008 are actual values. 2009-2020 are estimated projections. *Carbon Neutrality by 2020*. The Evergreen State College, 2009. Print.

As evident in Figure 1, electricity, space heating and commuting contributed to a significant amount of Evergreen's greenhouse gas emissions in 2005, approximately 69%

(*Carbon Neutrality by 2020* 18*).* Reducing emissions in these three categories became a priority. Figure 2 below depicts the actual greenhouse gas emissions for 2005-2013. This figure shows a dramatic decrease in electricity use while space heating and commuting continued to contribute to greenhouse gas emissions. Renewable energy certificates purchased by the college are responsible for offsetting greenhouse gas emissions from electricity.

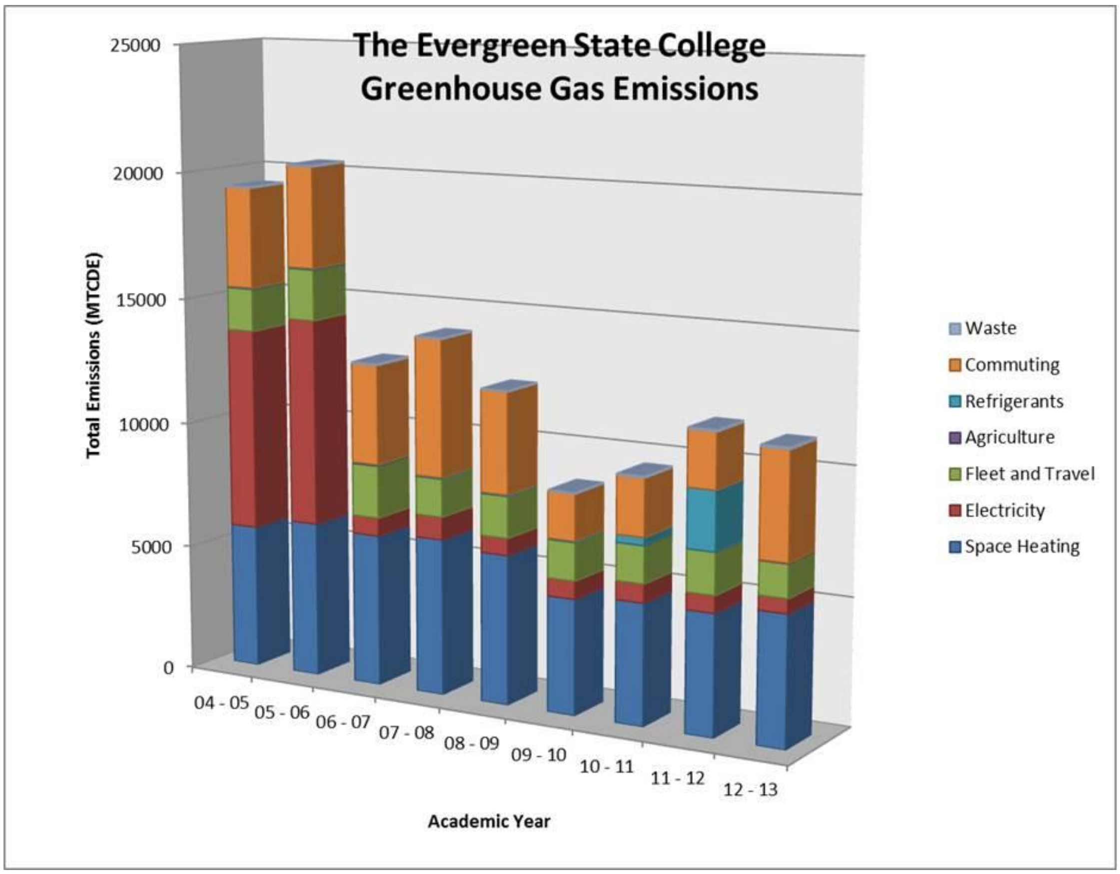

Figure 2: The Evergreen State College Greenhouse Gas Emissions Inventory. "Greenhouse Gas Inventories." *The Evergreen State College*. The Evergreen State College, 2015. Web. 2 July 2015.

Since 2006, Evergreen has been able to claim that 100% of purchased electricity used on campus comes from clean, renewable sources. In 2005, students approved a Clean Energy Initiative to pay $1.00 per credit to pursue campus-wide renewable energy efforts; ninety percent of this fee goes toward buying renewable energy certificates from

Puget Sound Energy and Tacoma Public Utilities to offset use of carbon based energy sources (Clean Energy Initiative).The first renewable energy certificates were purchased in October, 2005, three and a half months into the 2006 fiscal year. As stated in the climate action plan, this is not a permanent solution for greenhouse gas emissions and Evergreen will continue to explore sustainable options and make realistic institutional changes to reduce its carbon footprint. Note that the other 10% of the fee funds on-campus renewable energy projects, such as the Comparative Solar Project, described below.

History of the Comparative Solar Project

The Comparative Solar Project is a solar thermal hot water heater pilot study at The Evergreen State College. The Comparative Solar Project initially received funding through a $15,000 grant awarded in the 2010-2011 year by the Clean Energy Committee. Project costs were estimated at $5,000 for equipment and $2,500 for maintenance per collector, totaling $15,000. Established to test the performance and viability of two different types of solar thermal collectors, the project provides hot water and space heating to residential housing unit known as Modular Housing Unit 303 or Mod 303. The grant application listed the specific goals of the Comparative Solar Project as:

- To install two different kinds of solar panels with similar collection capacities for the purpose of comparison,
- To develop relationships between Residential and Dining Sustainability Crew student-employees, faculty, and local companies involved in sustainable design, and
- To foster a conversation between the above mentioned groups in order to develop an academic understanding of the possibilities presented by solar hydronic systems in the Pacific Northwest.

The Comparative Solar Project was designed following The Natural Step's Framework for Strategic Sustainable Development, built around four system conditions for creating a sustainable society. The conditions state that:

> nature is not subject to systematically increasing concentrations of substances extracted from the Earth's crust and produced by society, degradation by physical means and people are not subject to conditions that systematically undermine their capacity to meet their needs" (The Four System Conditions of a Sustainable Society).

The authors of the grant believed that "The Evergreen State College is in violation of the first three requirements due to the methods used to power housing" (Solar Handbook 2). In order to meet all four requirements, Evergreen needed to investigate the many options for renewable and sustainable energy. The Comparative Solar Project aimed to provide a working example of the potential of renewable energy infrastructure in line with the College's continuing efforts to become increasingly sustainable and carbon free. In the 2011-2012 academic year, another grant application was submitted to the Clean Energy Committee requesting $4,000 in funding to install a data collection and monitoring system at Mod 303. The monitoring system would collect a wide variety of data, including values for variables such as total energy generated, pumping energy, tank temperature and system status (Solar Thermal Monitoring System 6). These variables could then be used by students for a variety of analyses that would allow them to develop "a basic understanding of the relationship between weather, climate, and renewable energy generation; to more advanced multivariate analyses when including additional data sources such as solar radiation or information from other campus renewable energy installations or the campus meteorological station" (Solar Thermal Monitoring System 6).

Unfortunately, no funds were awarded and system data collection remained limited to collector temperature only. The lack of a comprehensive monitoring system severely hinders the ability to gain a deep understanding of the value of the system and learning how this technology could potentially contribute to Evergreen's carbon neutrality goals. This thesis evaluates the performance of the flat plate and evacuated tube collectors currently providing hot water and space heating to Mod 303. In the following sections, common systems and components of solar thermal heating will be examined to develop a necessary understanding of the technology which this research and the Comparative Solar Project revolve around. This will lead into an explanation of the methodology chosen for analyzing the performance of each collector as well as the many variables that affect the outcome of this study. A discussion of significant findings will precede the final section of this thesis, which will provide monitoring and data management recommendations for the next year of operation.

SOLAR THERMAL TECHNOLOGY

It is important to this research to understand how solar thermal hot water heating works and the many aspects of this technology. Many types of solar thermal collectors and systems exist, providing varying benefits and drawbacks depending on the site, climate and individual application needs. This section of the thesis will review the basics of solar thermal technology and will describe the system installed on Evergreen's Mod 303.

First, solar thermal is much different than solar photovoltaics. Solar photovoltaic converts solar radiation into electricity while solar thermal heating uses the solar radiation to directly heat a fluid, usually water. Solar radiation is the "rate of energy from the sun being delivered to a surface at any given time" (Irradiance vs. Insolation).

Solar thermal systems, also called collectors, are most commonly used for heating swimming pools, domestic hot water heating, space heating, industrial processes and power production. Collectors generally consist of a frame, absorber, glazing, and insulation (Machine-History.com). They convert solar radiation into thermal energy which can be used immediately or stored for later use--most systems rely on storage tanks to store and exchange heat. Many residential hot water systems, for example, utilize 80-120 gallon hot water tanks while larger applications will utilize specialized, custom storage options (Brehm et al. 6). Furthermore, collectors can be categorized into three separate categories: low-temperature, medium-temperature, and high-temperature, as described below.

Low-temperature collectors provide low-grade heat and are usually unglazed flat plate collectors capable of heating water up to 120° F. This makes them ideal for heating outdoor swimming pools, which is the number one use of solar thermal energy in the United States. Unglazed flat plate collectors can provide up to 80% - 90% of the energy needed to heat a typical residential pool and offer a cost competitive alternative to natural gas and electric water heaters (Basu and Klenck). These collectors are relatively simple and generally cost between $3,000 and $4,000 to purchase and install. Depending on local fuel costs, these systems can pay for themselves within one and a half to seven years (Solar Swimming Pool Heater). The design includes a “black plastic absorber with flow passages, no glass cover; no insulation, and no expensive materials such as aluminum or copper” (Brehm et al. 3). These collectors can effectively use solar thermal energy in warmer climates although they lose efficiency in colder climates.

Medium-temperature collectors provide medium-grade heat between 140° - 180° F and are commonly used for domestic hot water heating and space heating. Medium-temperature collectors may also be used in industrial heating. These collectors have the potential to provide up to 50% of the domestic hot water heating demand in the United States (Solar Thermal: Energy Place). Glazed flat plate collectors (see Figure 3) are the most common medium-temperature collectors. They consist of an insulated, weatherproof box which contains a dark absorber that absorbs solar radiation and transfers thermal energy to a fluid circulating through the panel. Other uses of glazed flat plates include drying crops and heating indoor swimming pools.

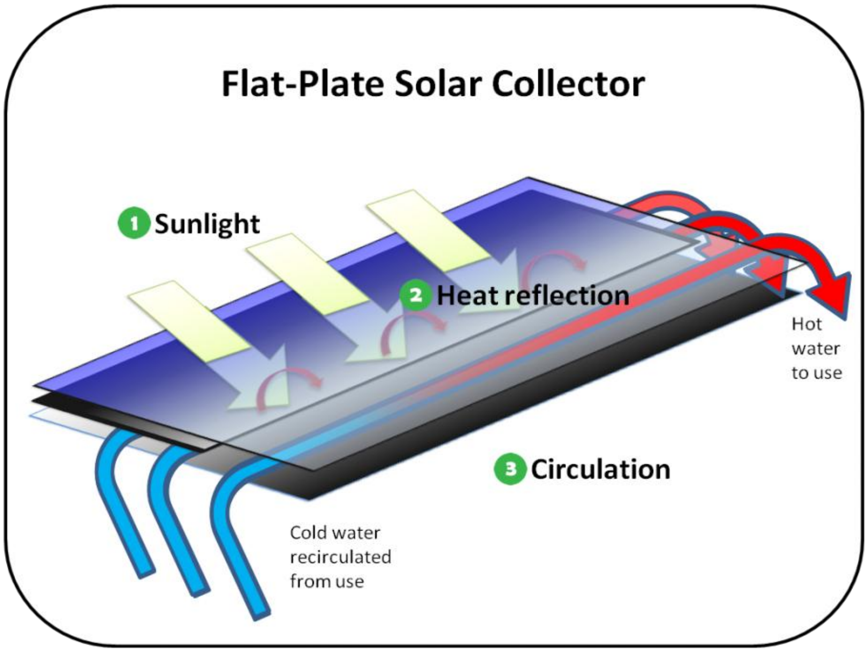

Figure 3: Flat Plate Collector. "Solar Heating and Cooling Technologies." *United States Environmental Protection Agency*. Environmental Protection Agency, 8 May 2015. Web. 11 Aug. 2015.

Evacuated tube collectors fall into the medium-temperature category as well as the high-temperature category. Evacuated tube collectors are often used in overcast and colder climates. The collector consists of rows of parallel glass tubes. The air between the outer and inner tube is vacuumed out in order to reduce convection and conduction heat loss, which allows evacuated tube collectors to reach higher levels of efficiency than flat plate collectors (see Figure 4). Evacuated tube collectors work better with higher absorber temperatures and low radiation, exhibiting greater efficiency in the morning and afternoon when the sun's angle is 40° - 80° from perpendicular. This feature lets these collectors obtain higher heat output throughout the day (Machine-History.com).

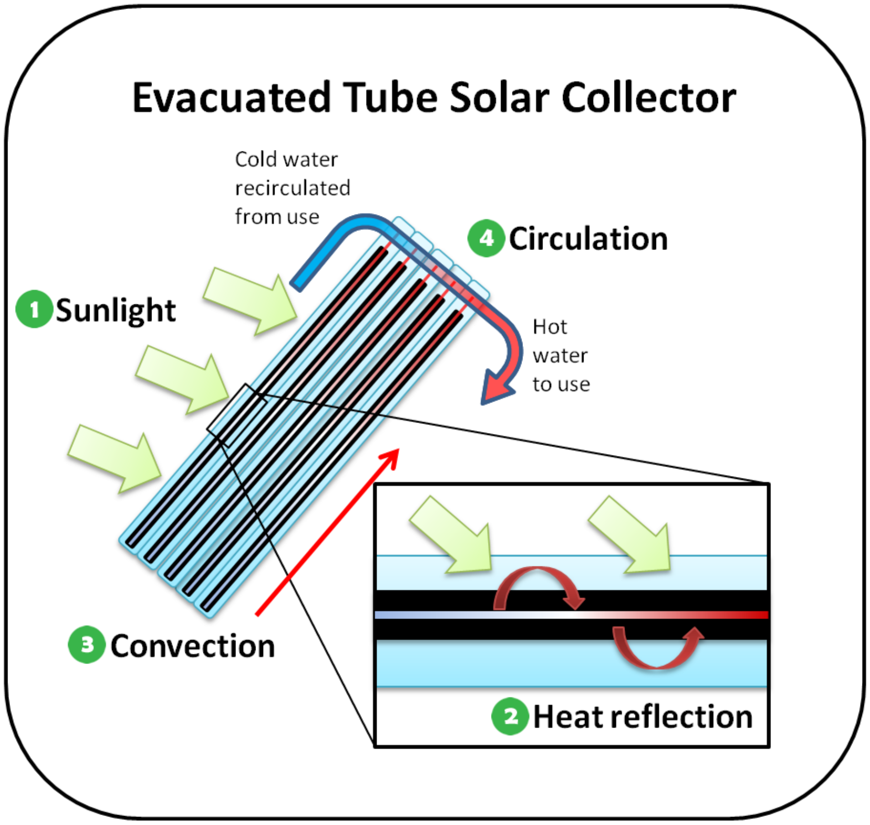

Figure 4: Evacuate Tube Solar Collector. "Solar Heating and Cooling Technologies." *United States Environmental Protection Agency*. Environmental Protection Agency, 8 May 2015. Web. 11 Aug. 2015.

High-temperature collectors heat water above 180° F and are used for industrial processes and electricity generation. Evacuated tube and highly efficient glazed flat plate collectors can fit into this category. However, concentrating solar collectors such as parabolic troughs and dishes are the most effective at reaching high temperatures, and can reach temperatures much higher than 200° F. In a concentrated solar collector system, mirrored dishes or troughs focus the sun's energy on an absorber filled with a heat-transfer liquid or water (see Figure 5). Concentrated collectors are mainly used for power production in regions with high solar radiation resources (Solar Heating and Cooling Technologies).

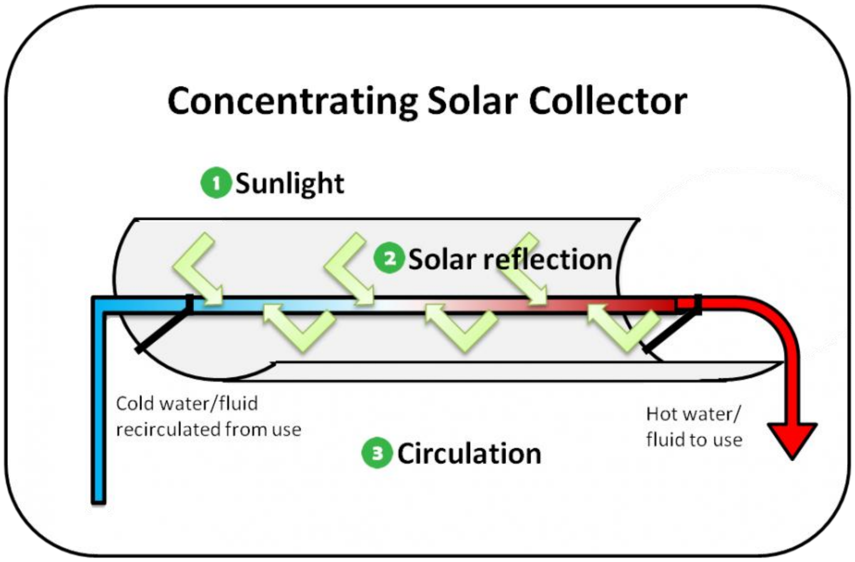

Figure 5: Concentrating Solar Collector. "Solar Heating and Cooling Technologies" *United States Environmental Protection Agency*. Environmental Protection Agency, 8 May 2015. Web. 11 Aug. 2015.

Solar thermal systems can be further categorized into various configuration options: passive and active, direct and indirect. Passive systems do not require pumps or other electrical operating components. In an active system, heat exchange relies on a circulating pump and temperature regulation apparatus. Direct (open loop) systems circulate potable water directly through the system while indirect (closed loop) systems circulate a heat-transfer liquid between the collector and storage tank. Figure 6 compares common characteristics of the different system types.

Solar Hot Water System-Types Compared

System Type	Climate & Description	Advantages	Disadvantages	Installation
Integral Collector Storage (ICS)	Passive: Open loop for mild climates	Simplicity; lowest cost	Poor freeze protection; poor tank insulation	Heavy units; easy to install; can have cosmetic-appearance issues
Thermosyphon	Passive: Open loop for mild climates; closed loop can be used in harsh climates	Simple open loop; tank is insulated	Open loop has poor freeze protection; closed loop needs a heat exchanger; potable water lines to collector subject to freezing	Very heavy systems; easy to install; can have cosmetic-appearance issues
Direct Pump: Direct circulation	Open loop for mild climates only	Simple active system; can be PV powered	Poor freeze protection; freeze valves can give false security	Easy installation; needs electrical source
Drainback: Closed loop, forced circulation	Closed loop for all climates	Simple system when compared to antifreeze systems; limited overheating	Needs a high-head pump and heat exchanger; harder to power with PV	Slope of collectors and piping is critical
Closed-Loop Antifreeze: Forced circulation	Closed loop for all climates	Best freeze protection; easily PV powered	Most complex; can have overheating problems; needs a heat exchanger	Most difficult installation

Figure 6. Solar Hot Water System-Types Compared. Marken, Chuck. "Solar Water Heating Systems Buyer's Guide." *Home Power*. Home Power Inc., June-July 2008. Web. 22 July 2015.

Passive systems work well in warmer climates with little risk of freezing, relying on convection or gravity to circulate water instead of pumps or other electrical components. The water circulated through the collectors is the same water being delivered directly to the user. There are two types of passive systems: thermosyphon (see Figure 7) and integral collector storage (see Figure 8).

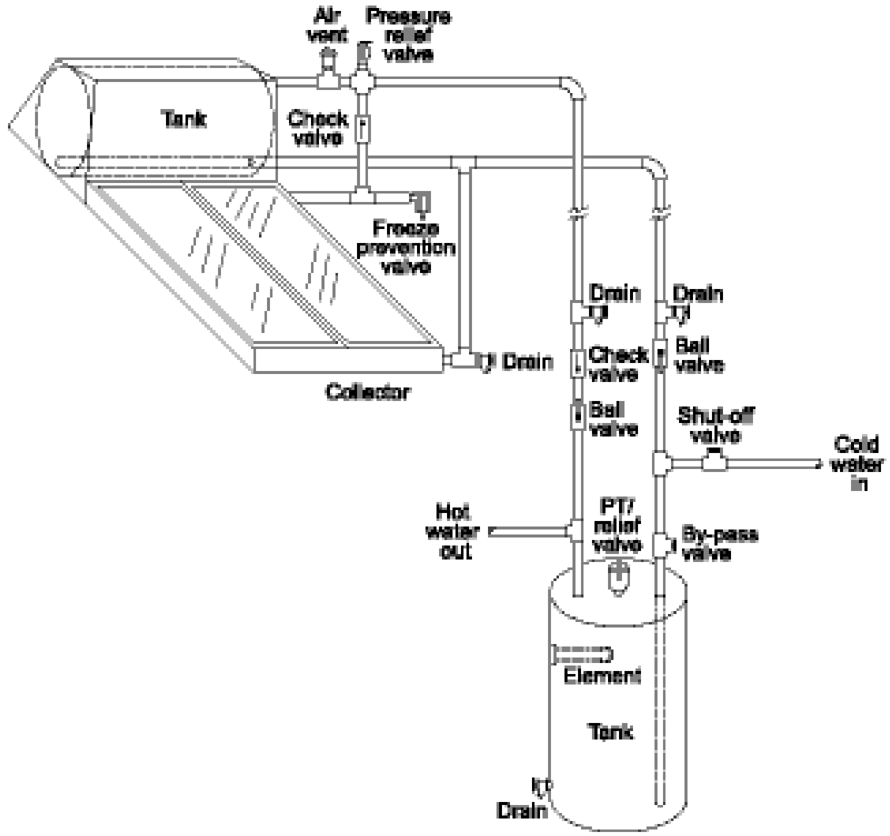

Figure 7: Thermosyphon System. “System Types.” *Florida Solar Energy Center*. N.p., n.d. Web. 2 May 2015.

Thermosyphon systems accomplish fluid circulation by convection and do not require ancillary pumps in order to circulate. Water tanks are elevated above the collector and the cold water in the bottom of the storage tank falls down through the solar collector. After being heated, the water rises back up through the system in a separate line, and settles on top in the storage tank (Machine-History.com).

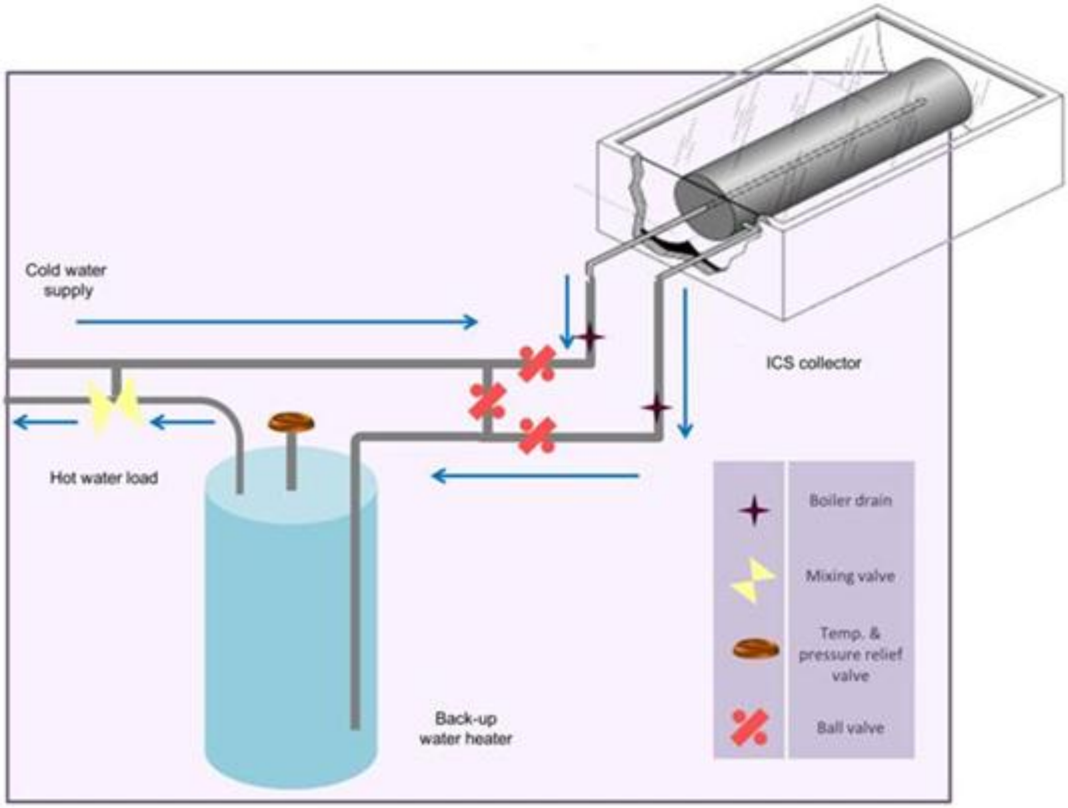

Figure 8: Integral Collector Storage. "Integral Collector Storage Solar Thermal System Layout." *Solar365*. N.p., n.d. Web. 19 July 2015.

Integral collector storage systems (ICS), combine the solar collector and hot water storage and are generally used in combination with a conventional water heater. These simple systems provide reliable preheating. The tank is housed in an insulated box that absorbs the sun's energy and heats the water. As hot water is withdrawn for use, cold water flows into the tank and settles at the bottom, gradually rising to the top as it heats up (Machine-History.com).

Active systems utilize pumps or other electrical components to circulate water or a heat transfer liquid through the system. This allows active systems to operate more efficiently than passive systems, but also introduces additional electricity costs. Unable to function during power outages, active systems require a source of backup power such as a generator or photovoltaic circulator (Brehm et al.7). An active system can also be direct (open loop) or indirect (closed loop).

Direct or "open loop" systems circulate potable water from the hot water storage tank directly through the collector. Direct systems contain temperature sensors that monitor the temperature of the water inside of the collector and the water inside the storage tank. When temperatures inside the collector exceed temperatures inside the tank, the sensors activate a pump which circulates water through the system, replacing colder water in the tank with hot water from the collectors. These systems are usually installed in warmer climates that do not experience freezing temperatures (Solar Hot Water Heaters Active Systems).

Indirect or "closed loop" systems utilize a heat-transfer liquid such as glycol anti-freeze or distilled water and are suitable for climates with freezing conditions. In these systems, the heat-transfer liquid is piped through the collector and returned to the hot water storage tank where heat exchangers transfer heat from the heat-transfer fluid to the water inside the storage tank (Brehm et al. 8).

Drainback systems are usually indirect but can also be direct in some cases (Machine-History.com). These systems use either water or a heat-transfer liquid and a pump to move fluid from the storage tank to the collector. Gravity helps the liquid to drainback into the storage tank from the collectors. Drainback systems come fitted with sensors that will allow liquid to drain from the collectors once temperatures in the collectors fall beneath a predetermined level. Since no water remains inside of the collector once temperatures fall, drainback systems provide excellent protection against freezing in colder climates (Shelton).

Evergreen’s evacuated tube and flat plate solar thermal combi-system supplies Modular Housing Unit 303 (Mod 303) with domestic hot water and radiant heated floors. It is an active indirect system (see Figure 9), consisting of two different types of solar

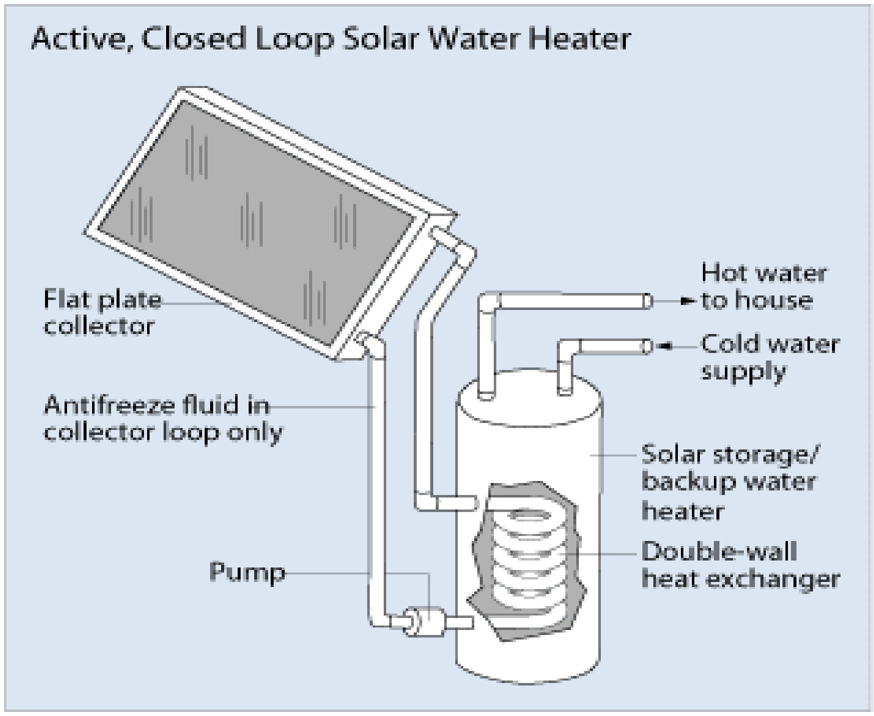

Figure 9. Active, Closed Loop Solar Water Heater. "Solar Water Heaters." *Energy.gov*. U.S. Department of Energy, 14 Dec. 2014. Web. 3 May. 2015.

thermal collectors: an Apricus AP-30 evacuated tube collector and a Caleffi NAS10410 flat plate collector. Each collector is designed to produce up to 42,000 Btu’s per day and the two work in concert to provide as much of the required water and space heating as possible for the eight residents occupying Mod 303.

The Apricus AP-30 is an evacuated tube solar collector “ideal for residential households of 4-5 people, able to provide 60 - 80% of domestic hot water demand” (AP-30 Solar Collector). The AP-30 consists of 30 evacuated tubes, filled with a specialized fluid. As heat builds up, this fluid vaporizes and travels towards the heat exchanger where the heat energy transfers to the propylene glycol flowing through the collector. The glycol is then pumped into the hot water storage tank via electric pumps before returning to the evacuated tube collector.

The Caleffi NAS10410 is a flat plate collector, made with a copper absorber and covered with selective crystal coating capable of absorbing short-wave light while reflecting long-wave light (Selective Surface). This results in increased efficiency for the system. The absorber transfers heat to the flow tubes within the collector, which contain propylene glycol, and the glycol is pumped into the hot water tanks that serve Mod 303.

The two hot water tanks in the solar shed attached to the side of the modular housing unit each receive glycol from their individual collectors. The glycol is pumped from each collector and heads into one of two tanks containing cold water from the domestic mainline. The glycol flows through copper tubing running through the tank and transfers heat to the water within the hot water tank. The glycol is then pumped back up to the collectors, while the heated water is sent to the domestic hot water supply or the closed loop radiant floor system. Before reaching the end-use destination, hot water will pass through two tankless hot water heaters, which measure temperature and provide an extra heat boost if necessary. The tankless hot water heaters are also connected to a propane backup to provide continuous hot water to the modular in the event of a power outage or other emergency.

The flat plate and evacuated tube collector have each been outfitted with Caleffi iSolar BX Differential Temperature Controllers. The iSolar BX controllers control the system functions of the collectors. The controllers have both been set at a minimum operating temperature of 80° F. If glycol within the collectors does not reach this minimum temperature, the pumps will not turn on and begin circulating fluid through the system. The operating differential is set at 18/5. The collectors must be at least 18° F warmer than the hot water storage tank before turning on and will shut off when the temperature differential drops to 5° F (Solar Handbook 2). The controllers also send collector temperatures to a secure digital (SD) card. Solar thermal collector data for this research was obtained from each controller's SD card.

METHODS

Data Sources

The two primary data sets utilized in this research measured the temperature of the glycol within the collectors on Evergreen's Mod 303. Each collector and the associated hot water tanks have been fitted with an iSolar BX Differential Temperature Controller that saves the information to an SD card; that data can then be analyzed using computer software. The measurements include the date, time and glycol temperature in the collector. Temperature analyzed in this thesis was recorded in ten minute intervals from May 1, 2014 to May 27, 2015. Examination of glycol temperature data provides a basic and straightforward approach to evaluating the heating ability of the collectors and determining how well they function on this specific site.

Average hourly solar radiation and air temperature data served as the secondary sets of data for this research to assist in visualizing trends between hot water production and the amount of solar radiation reaching the collectors throughout the hours, days and months. Solar radiation and average air temperature were obtained from the Washington State University Agricultural Weather Network's southwest Tumwater location, approximately 8.5 miles south from the Evergreen State College. Comprised of 166 monitoring stations throughout Washington, AgWeatherNet measures many different climate variables. The solar radiation and average air temperature data records every five seconds and is summarized every fifteen minutes (AgWeatherNet). The southwest Tumwater site was chosen because of its proximity to the Evergreen State College and the wide range of available data.

Data Preparation

A combined date and time stamp for the collector temperature originally appeared in the same cell when the data were downloaded into Microsoft Excel. The first step involved separating day, month, year, and time so that the data could be filtered and analyzed more easily. Next, a new column was created, Hour, which categorized time from 1:00 to 24:00. Each of the six temperature measurements that occurred every hour were averaged into one hourly value, producing 24 measurements per day. This method was utilized to condense the data into manageable units and to achieve compatible hourly measurements with other data used for this research. Some hourly averages were not available due to the system being offline as a result of maintenance or when the SD card had been removed for data transfer. These cells were left blank and were not considered during analysis since there was no reliable method to estimate their values.

In parallel, solar radiation and air temperature data from AgWeatherNet was summarized hourly upon retrieval. Occasionally, the hours of 12:00 AM and 1:00 AM had not been included in the downloadable spreadsheets. Aligning this data with the hourly collector temperature data made it possible to identify missing values by filtering 12:00 AM and 1:00 AM in Excel, revealing each day that these hours were absent. Upon identification, these hours were manually included in the data. Solar radiation values for these times remained zero since there is no solar radiation in the early morning. Missing values for average air temperature at 12:00 AM and/or 1:00 AM were replaced by averaging the previous and next available hour’s temperatures.

Data from May, 2014 to November, 2014 were recorded in Celsius in Microsoft Excel. Data from March, 2015 to May, 2015 did not have an indication of Celsius or

Fahrenheit. Since, average hourly air temperature data was utilized to look for a relationship between collector temperatures, that designation was important. Collectors would naturally reach air temperature after cooling down at night. One year of air temperature data was compared to average hourly collector temperatures to conclude that the unit was indeed Celsius. All temperature data was then converted to Fahrenheit to maintain consistency with the air temperature data and multiple system settings that already utilized Fahrenheit.

Identifying Research Limitations

The data available on the solar thermal collectors is extremely limited. Since an advanced monitoring system has not been installed, only one variable has been measured: glycol temperature within the collectors. The absence of additional data prevents further investigation of:

- System efficiency,
- Cost-benefit analysis,
- In-depth collector performance, or
- Carbon offset potential.

However, temperature data from each collector allows for a generalized analysis focusing on the ability of each collector to heat glycol. Heating trends can be identified and compared between collectors, as can how each collector roughly responds to solar radiation. This analysis relies on the assumption that higher temperatures indicate increased hot water production, although after a point, this can also indicate system malfunctions associated with overheating.

One significant limitation in particular is the operating temperature differential, which presents uncertainty into any analysis of the available data. The operating temperature differential introduces extra requirements that regulate the operation of the pumps. First and foremost, the pumps will not turn on until the fluid in the collectors reach 80° F. However, the system is set at an 18/5 operating differential, meaning the pumps will not turn on at a collector temperature of 80° F unless the collectors are at least 18° F warmer than the water within the hot water tank. Furthermore, the pumps will not turn off until fluid temperature within the collector drops to 5° F below the water in the hot water tank. Although 80° F is the minimum collector temperature needed to activate the system, the lack of hot water tank temperature data makes it impossible to determine when the collectors were 18° F warmer or 5° F colder than the storage tanks. This means that during any times when the collector temperature reaches 80° F, the pumps may not actually turn on if the operating differential is not correct. Because of this, the following analysis does not consider operating differentials when evaluating solar thermal collector performance. The analysis focuses on collector temperatures above 80° F when pumps had the potential to begin circulating the heat transfer liquid, propylene glycol, if the operating differentials were in the ideal operating ranges.

Temperature measurements for the evacuated tube collector began on May 1st, 2014 and continued through the end of December. Measurements began for the flat plate collector on July 29th, 2014 and lasted through August 8th, 2014, at which point the system was taken offline due to abnormally high collector temperatures. Data collection resumed on September 3rd, 2014 and lasted through the end of December of that year.

Neither collector operated during January or February, 2015 while RAD and South Sound Solar employees evaluated the cause of irregular temperature readings and performed system maintenance. It appeared that the system had been delivering inaccurate temperature readings most likely due to pump cavitation. Cavitation occurs when bubbles or cavities form in areas of low pressure and implode around the impeller of a pump (Pump Cavitation Causes). Eventually, the force of these implosions begins to damage the pump and other surrounding components. There are several causes of pump cavitation:

- A drop in pressure at the suction nozzle,
- Increase of the temperature of the liquid being pumped,
- Increase in fluid velocity at pump suction,
- Reduction of the flow at pump suction,
- Undesirable flow conditions caused by obstructions or sharp elbows in piping, and
- Positive suction head requirements are not met.

In this case, it appeared that the system had been improperly commissioned and air had been trapped within the pipes. The pumps cavitated and caused the system to stagnate, or overheat. Stagnation is often a problem during the summer months when solar radiation and ambient air temperatures are high (Harrison, Lin, Mesquita 1). During the summer, hot water demand, and especially radiant heating, is low, which often results in overheating. Since the high temperatures will trigger an emergency shutoff of the pumps, the collector continues to heat up the heat transfer liquid. The liquid expands and can eventually turn into steam, causing a host of issues and potential damage to the many components of the system (Hausner, Fink 4).

It appears that stagnation may have happened in July, August and September but no conclusion has been reached as of this writing as to when exactly this happened or for how long any underlying issues may have influenced the data being collected. The glycol was flushed and replaced before temperature monitoring resumed on March 1, 2015. They have continued to operate and collect data since that date.

As a result of the issues just outlined, the temperature data sets are best used to gain insight into the first year of operation of the solar thermal collectors. It is important to recognize that inaccurate data entries are most likely due to overheating and false readings from pump cavitation.

Temperature Analysis

Knowing that the pumps begin circulating glycol through the collectors when temperatures reach 80° F, the total hourly temperatures equal to or greater than 80° F were identified and categorized as times when the system actively produced hot water for circulation throughout Mod 303. Any temperatures that reached the emergency shutdown limit of 270° F were noted as times when the collectors did not produce useable hot water. Counting the number of hours in each category revealed how many hours each collector actively fed hot water to Mod 303 as well as the percentage of hot water producing hours during the data collection period.

Average hourly temperatures equal to or greater than 325° F were also identified due to the specific brand of propylene glycol used in the collectors. Both collectors contain Heliodyne DYN-O-FLO propylene glycol, which can reach a maximum temperature of 325° F with a periodic usage rating of 375° F (Heliodyne 5). Temperatures in excess of 325° F can cause the system to stagnate and result in component erosion (Ramlow). Therefore, recognizing periods when the collectors overheat is very important because these occurrences have the potential to cause permanent damage to the system.

The flat plate collector data required additional analysis of the ten minute interval measurements due to unusually high temperatures in the data set. This analysis consisted of pinpointing the exact times the flat plate collector reached temperatures high enough to trigger an emergency shutoff or cause glycol degradation. Since the hourly averages could be significantly influenced by one extremely high temperature measurement, it was necessary to look at the uncondensed data to gain a deeper understanding of the occurrence of temperature spikes.

RESULTS

The results of this study represent a preliminary analysis of the first operating year of the Evergreen Mod 303 flat plate and evacuated tube solar thermal collectors. The following information will provide an overview of the basic ability of each collector to heat glycol that is then pumped through solar hot water tanks as a heat transfer liquid. The findings of this research will supplement the available documentation on this project. These results can also assist individuals working with the solar thermal system and serve as a basis for comparison of future data collection. The first section that follows will evaluate collector temperature throughout the year, considering times when the system is active, inactive and operating beyond normal specifications. The second section explores the flat plat collector's emergency shutoff incidence rate, which was noticeably high throughout the year. The final section provides a brief summary of the findings after the emergency shutoff issues have been addressed and factored into the collector's performance.

Collector Temperature Analysis

As indicated earlier, all average hourly temperature measurements equal to or greater than 80° F turn on the pumps that circulate glycol through the solar thermal collectors. Hourly temperature was calculated to find the ratio between hours when the system started up and provided hot water to Mod 303 and hours when the system remained inactive. The values are presented in Table 1. The evacuated tube collector initiated the pumps 2,948 hours out of 7,912 total hours of online operation from May 1, 2014 to May 27, 2015. The flat plate collector initiated the pumps more frequently with 2,592 hours out of 5,146 total hours of online operation but reached temperatures that triggered the emergency shut off for a total of 142 hours, lowering the heat producing hours to 2,450. The flat plate collector supplies heat approximately 47.6% of the time, while the evacuated tube collector supplies heat approximately 37.3% of the time. This indicates that the flat plate collector has the potential to supply more hot water than the evacuated tube as long as it does not reach temperatures that will stop the pumps and hot water delivery too often. Although it appears that emergency shutoffs do not stop the flat plate from outperforming the evacuated tube, further observation will be needed to determine if this is actually the case. This will be particularly important through the months of June, July and August, when flat plate performance data was either extremely limited or not being collected.

	Evacuated Tube	**Flat plate**
Total Hours	7,912	5,146
Hours ≥ 80° F	2,948	2,592
Hours ≥ 270° F	0	142
Active Hours	2,948	2,450
Inactive Hours	4,964	2,696
Time Spent Actively Producing Heat	37.3%	47.6%

Table 1. Total Recorded Hours vs. Active Recorded Hours.

Average daily collector temperatures for each month varied between the collectors (see Table 2). The evacuated tube had a low daily average temperature of 50.2° F in November and a high daily average of 90.7° F in August. The flat plate exhibited a much larger range of a low daily average of 55° F in November and a high daily average of 240.8° F in July. Note, however, that the flat plate temperatures were only recorded for three days in July and eight days in August. This significantly limits the amount of measurements available to calculate an average daily temperature for either of these months. Graphical representation of this data is presented in Figure 10.

Month	Year	Average Monthly Temperature and Solar Radiation		
		Evacuated Tube °F	Flat-Plate °F	Solar Radiation W/m²
May	2014	81.4	NA	340
June	2014	84.5	NA	343.1
July	2014	88.4	240.8	397.8
August	2014	90.7	228.5	355.3
September	2014	84.2	161.8	293.1
October	2014	69.9	99.5	177.5
November	2014	55	55	127.4
December	2014	50.2	48.5	87.9
January	2015	NA	NA	94.5
February	2015	NA	NA	157.3
March	2015	68.7	83.1	231.9
April	2015	74.3	95.9	318.4
May	2015	81.2	97.1	325.3

Table 2: Average Collector Temperatures and Solar Radiation per Month.

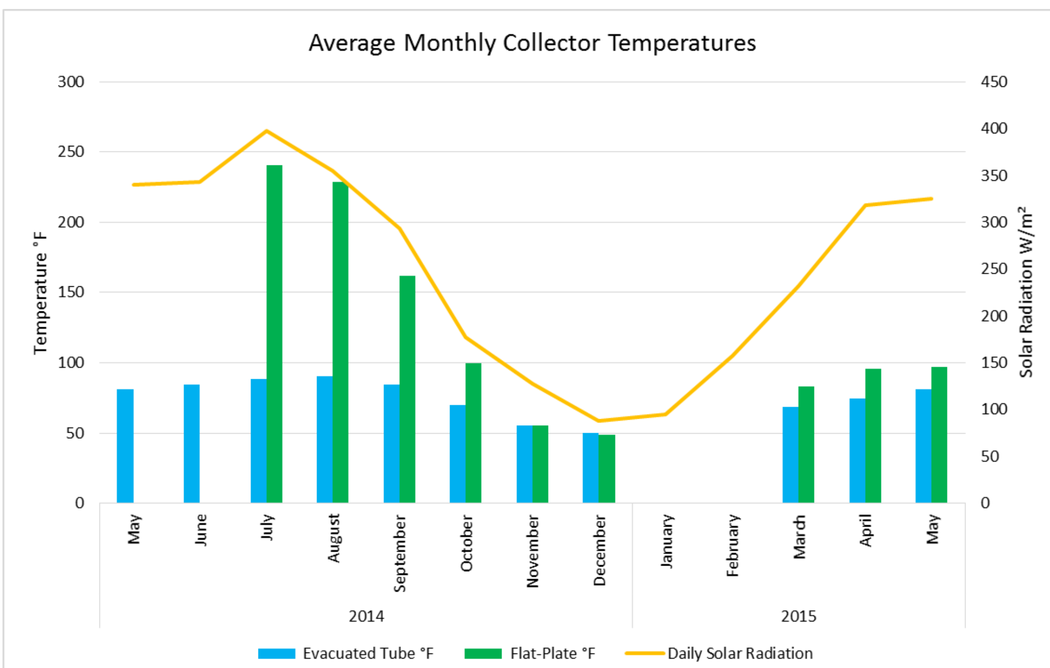

Figure 10. Average Monthly Collector Temperatures.

Figure 10 presents an interesting view of the heating and solar radiation trends from the beginning of the data collection period to the end. Note that the flat plate collector exhibited extremely high temperatures in July, August and September before reaching temperatures comparable to the evacuated tube collector through the end of the year, when solar radiation dropped significantly. Once data collection resumed in March, the flat plate collector produced temperatures much closer to the evacuated tube and did not reach the extremely high temperatures it had previously reached during August and September, despite comparable solar radiation (Figure 10). After system maintenance in January and February, which included a glycol flush and refill, it appeared the flat plate collector began working correctly and staying within safe operational temperatures. After stagnation, glycol begins to lose its effectiveness and can overheat more frequently and lose its antifreeze properties (Ruxton). A flush and refill of the system with new glycol is most likely the reason for a reduction in temperature spikes. However, it will be important to closely observe this collector in the future in case another unidentified issue is affecting heat production.

Interestingly, temperatures of the evacuated tube collector remained relatively flat throughout the year in comparison to the flat plate collector. Evacuated tube collectors are generally more efficient and capable of reaching higher temperatures than flat plates (Williams) yet it did not produce comparable heat until November and December. Evacuated tube collectors perform better in cold climates because they lose very little heat energy due to the vacuum of the tubes (Flat Plate versus Evacuated Tube Collectors). Although both types of collectors are very well suited for domestic hot water production, it comes as a surprise to discover the flat plate reaching consistently higher temperatures than the evacuated tube.

The following graphs depict average daily collector temperatures for each month (Fig. 11-21). These graphs are designed to serve as a visual representation of the general performance of both collectors. Each description includes information on average hourly temperatures as well, which are not practical to view in the context of this thesis. Solar radiation has been included to assist with the visualization of seasonal radiation and change in collector performance.

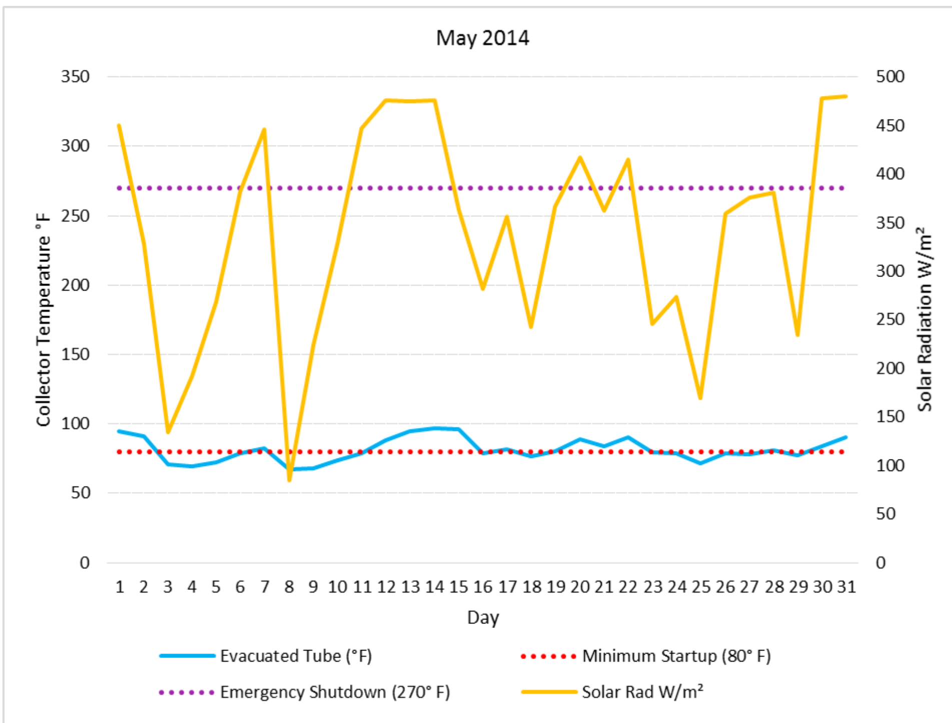

Figure 11. May 2014 Average Daily Collector Temperature and Solar Radiation.

During the first month of data collection only the evacuated tube collector was online and sending collector temperature measurements to the iSolar BX controller. Data collection began on the first and continued throughout the rest of the month. Out of 744 hours recorded, the evacuated tube reached temperatures greater than or equal to 80° F for 353 hours, or approximately 47% of the time. It did not rise above 270° F.

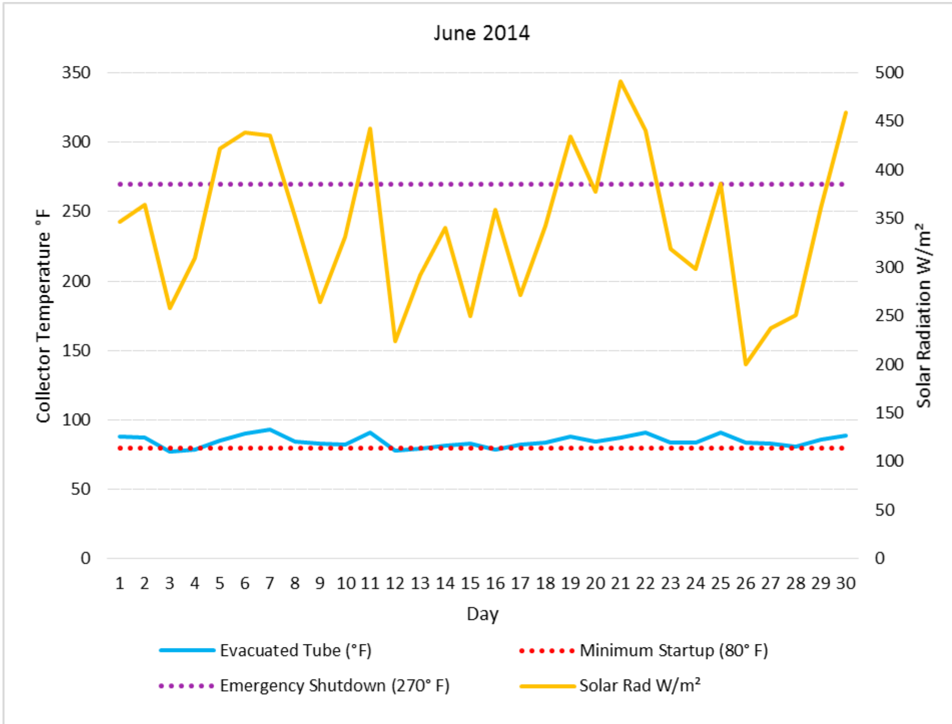

Figure 12. June 2014 Average Daily Collector Temperature and Solar Radiation.

Throughout June, the evacuated tube collector reached 80° F for 372 hours out of the 720 recorded, or approximately 52% of the time. Once again it did not reach temperatures above 270° F. Heat production remained relatively consistent even when solar radiation was high.

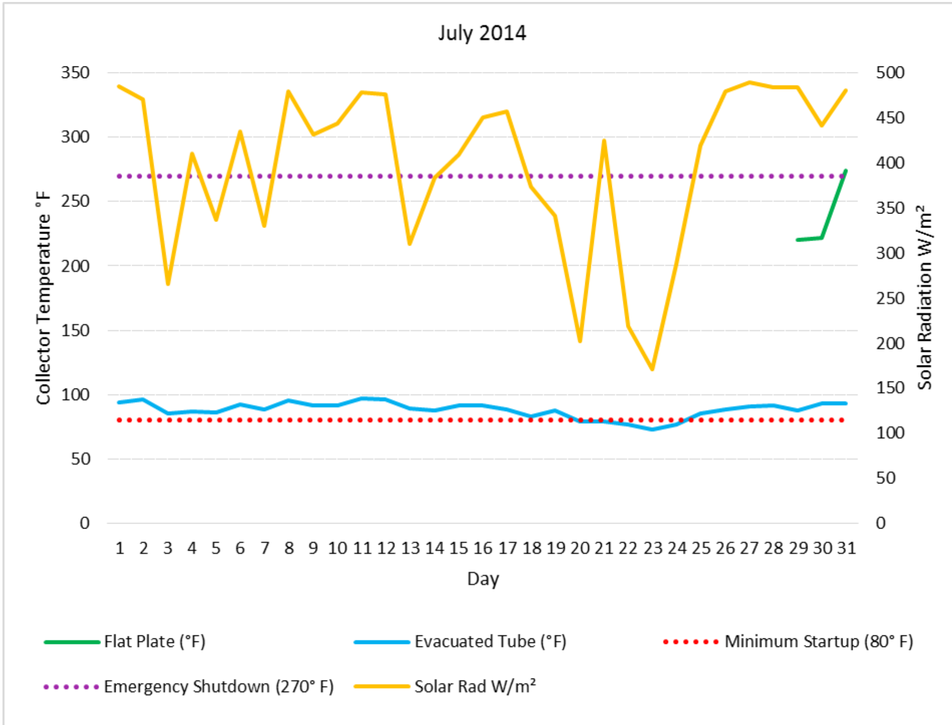

Figure 13. July 2014 Average Daily Collector Temperature and Solar Radiation.

The first temperature collector measurements for the flat plate collector occurred in July on the 29th, 30th and 31st. The flat plate collector reached temperatures higher than 80° F for all of the 65 recorded hours. Temperatures above 270° F totaled 20 hours as well as 13 hours of temperatures in excess of 325° F. The evacuated tube continued to steadily produce heat with minor response to fluctuations in solar radiation.

The evacuated tube collector continued operating as it did in May and June, reaching temperatures above 80° F for a total of 374 hours, or 50% of the time. No temperature measurements reached above 270° F.

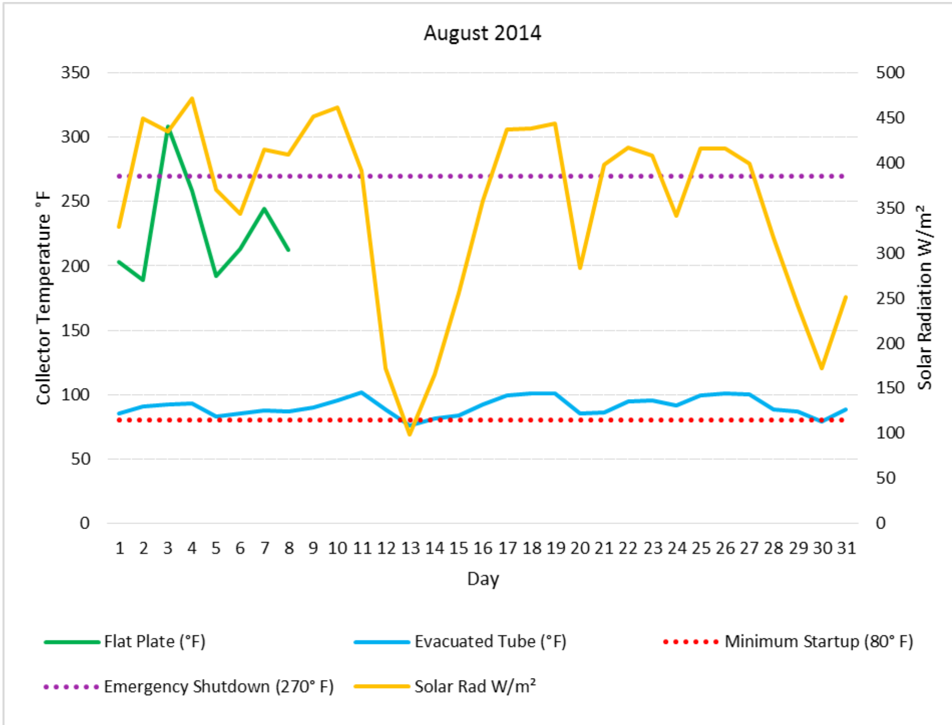

Figure 14. August 2014 Average Daily Collector Temperature and Solar Radiation.

Temperature measurements occurred for the first eight days of August at the flat plate collector. Yet again, 100% of the 182 recorded hours reached temperatures above 80° F while a total of 50 hours exceeded 270° F and 30 hours exceeded 325° F. The flat plate collector stayed within productive temperature ranges for 69% of the recorded hours. The flat plate's drastic fluctuation in temperature, apparent in Figure 14, is much different than the response seen from the evacuated tube collector during the past three months.

The evacuated tube collector maintained operational temperatures above 80° F for approximately 50% of the 744 total hours. Collector temperature continued to remain steady as solar radiation levels fluctuated.

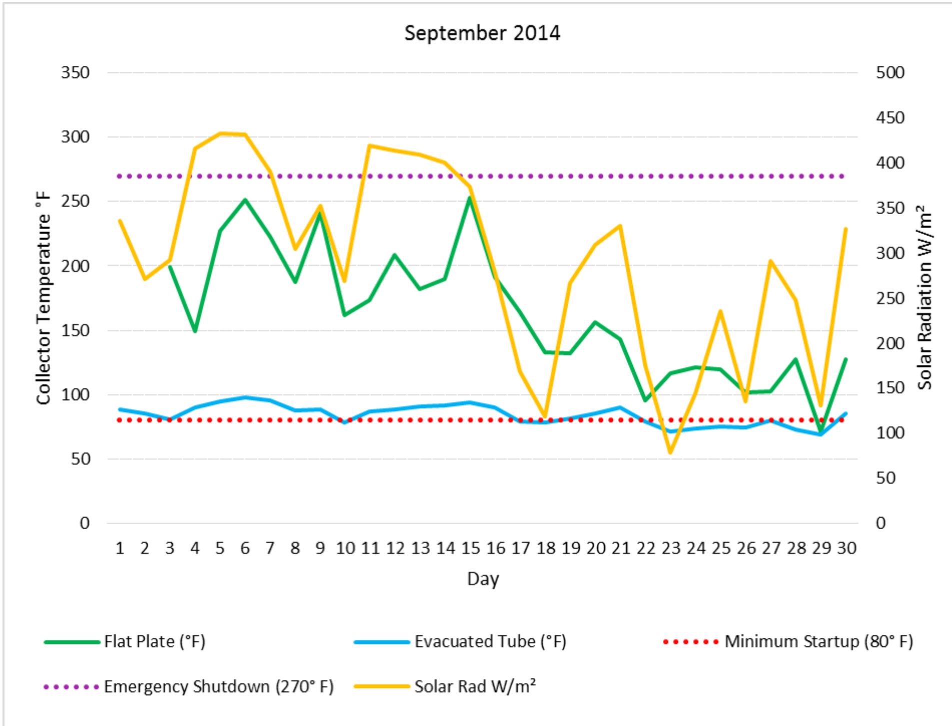

Figure 15. September 2014 Average Daily Collector Temperature and Solar Radiation.

Data collection for the evacuated tube collector occurred throughout September when solar radiation began to noticeably decrease. The evacuated tube reached temperatures above 80° F for approximately 43% of the recorded hours, the lowest percentage of active hours since monitoring began in May. It did not exceed temperatures above 270° F.

The flat plate came back online on September 3rd and continued through the end of the month. Out of 659 total hours, the flat plate reached temperatures above 80° F approximately 90% of the time. Average daily temperatures of the systems did not reach above 270° F. However, on an hourly basis approximately 9% of recorded hours were above 270° F and 5% were above 325° F. The first full month of flat plate monitoring revealed that this collector tracked solar radiation quite well, generally increasing and decreasing in temperature along with available solar radiation. This is unexpected since evacuated tube collectors generally outperform flat plate collectors. This may be an indication that one of the collectors was not functioning properly during the past several months: either the flat plate was overheating throughout the month (which it was, although how severely compared to normal stagnation occurrences is not known) or the evacuated tube was not absorbing a sufficient amount of solar radiation. Both of these scenarios may have been taking place simultaneously.

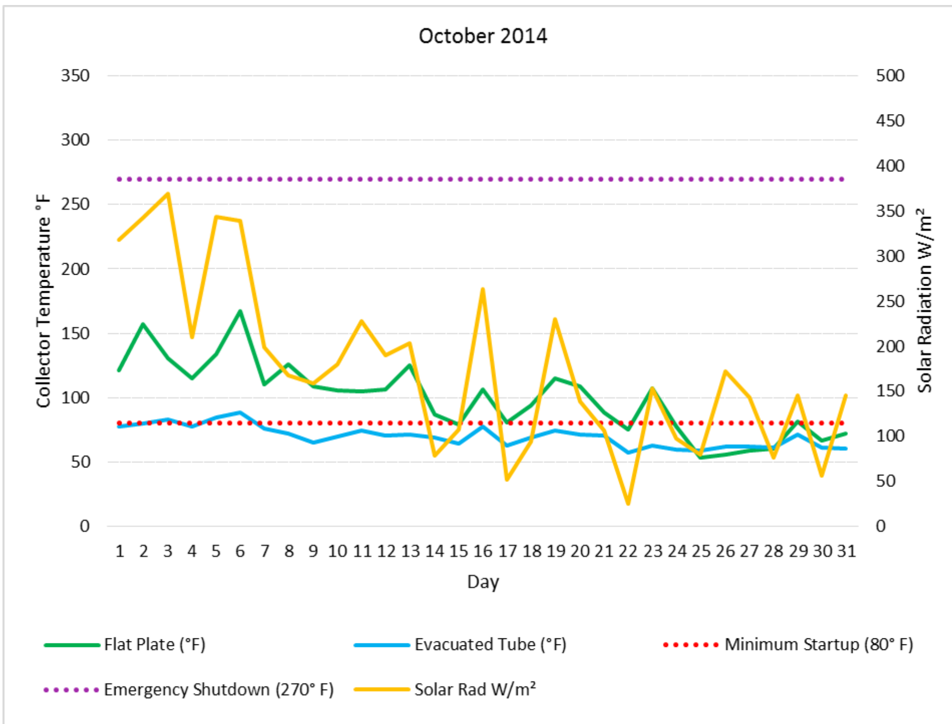

Figure 16. October 2014 Average Daily Collector Temperature and Solar Radiation.

Both collectors were in operation throughout October. The evacuated tube exceeded temperatures of 80° F for 30% of the 744 total hours recorded, compared to 43% the previous month. Once again, no hourly temperatures triggered an emergency shutoff. Heating capability clearly decreased along with solar radiation during October.

Flat plate performance decreased significantly in October, reaching temperatures greater than or equal to 80° F for approximately 62% of 744 total hours. Temperatures had exceeded 80° F 90% of the time during the previous month. However, in October, only eight hours exceeded 270° F and three exceeded 325° F, or 1% and 0.4% of the total recorded hours. The system began to overheat significantly less as daily solar radiation continued to fall.

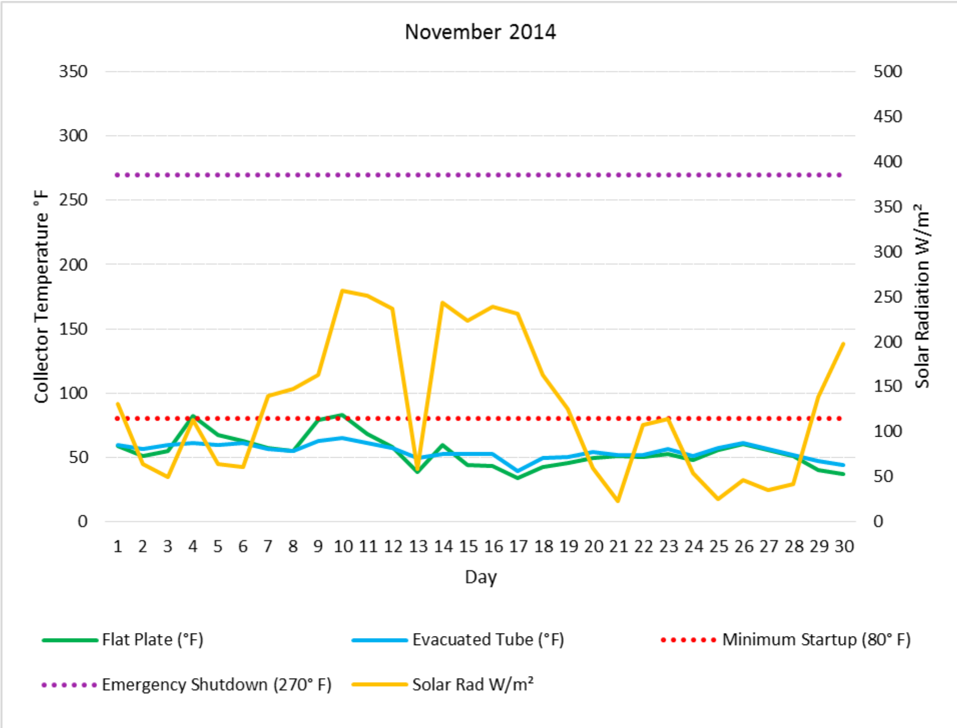

Figure 17. November 2014 Average Daily Collector Temperature and Solar Radiation.

During November, the evacuated tube collector did not reach average daily temperatures above 80° F and only reached average hourly temperatures above 80° F 12% of the time. No temperatures exceeding 270° F were recorded. These measurements are much different than those recorded during the summer months, when the evacuated tube consistently exceeded 80° F for approximately 50% of all recorded hours.

Average daily temperatures of the flat plate collector exceeded 80° F twice, and did not exceed 270° F. On an hourly basis, temperatures reached 80° F or higher for approximately 9% of the 708 recorded hours. No Temperatures exceeded 270° F.

November was the first month that the flat plate did not outperform the evacuated tube collector. Flat plate collectors are very susceptible to ambient air temperature since it can significantly affect their ability to produce heat. Unlike evacuated tubes, which hold in heat extremely well due to their vacuum design, flat plate collectors lose heat to the surrounding atmosphere as temperatures drop. Flat plate collectors also rely more on direct sunlight than evacuated tube collectors, which can absorb indirect light through the different angles of the tube. During the fall and winter months, temperatures drop sharply along with available solar radiation, which better suits the evacuated tube collector and leaves the flat plate experiencing a much more significant performance decrease.

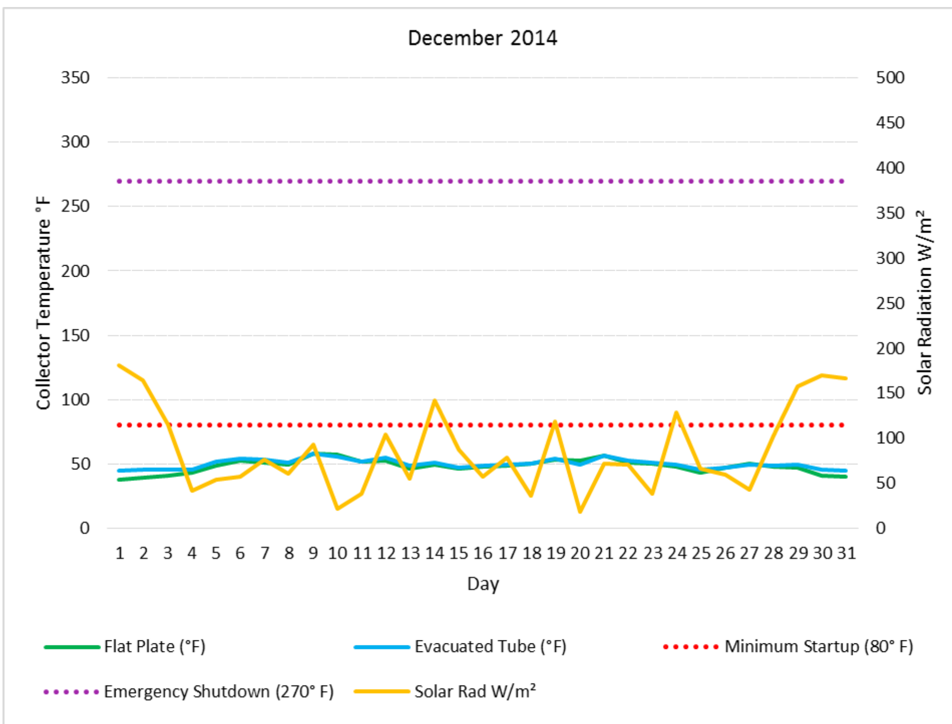

Figure 18. December 2014 Average Daily Collector Temperature and Solar Radiation.

In December, average daily temperatures for both collectors did not reach 80° F. The evacuated tube exceeded 80° F on an hourly basis only 24 times, or only 3% of the 744 hours recorded. Again, the flat plate produced less heat than the evacuated tube reaching temperatures above 80° F only 10 times, or approximately 1% of the 744 hours recorded.

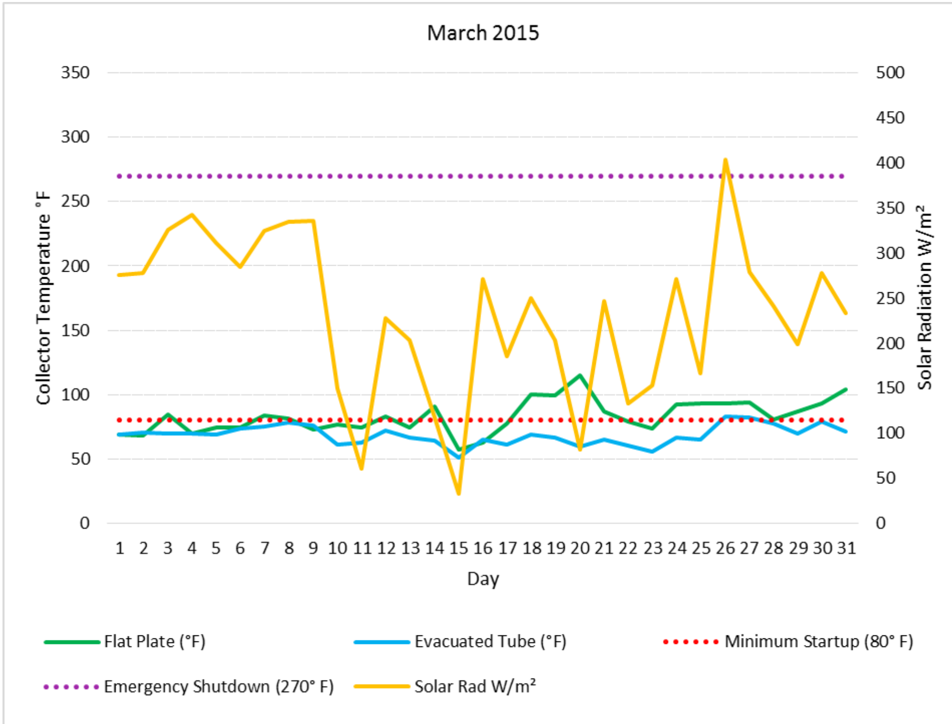

Figure 19. March 2015 Average Daily Collector Temperature and Solar Radiation.

After data collection resumed on March 1st, both collector's average temperatures began to rise again. Daily temperatures for the evacuated tube rose above 80° F twice at the end of March, and average hourly temperatures exceeded 80° F for 239 hours out of 735 recorded, approximately 33% of the time. No daily or hour temperatures reached emergency shutoff limits.

The flat plate collector began to outperform the evacuated tube once again, reaching average hourly temperatures for 349 out of 734 hours recorded, or approximately 48% of the time. Emergency shutoff was only triggered for one hour during March. This suggests that the system maintenance and glycol flush that occurred during January – February may have had a role in preventing incidences of overheating.

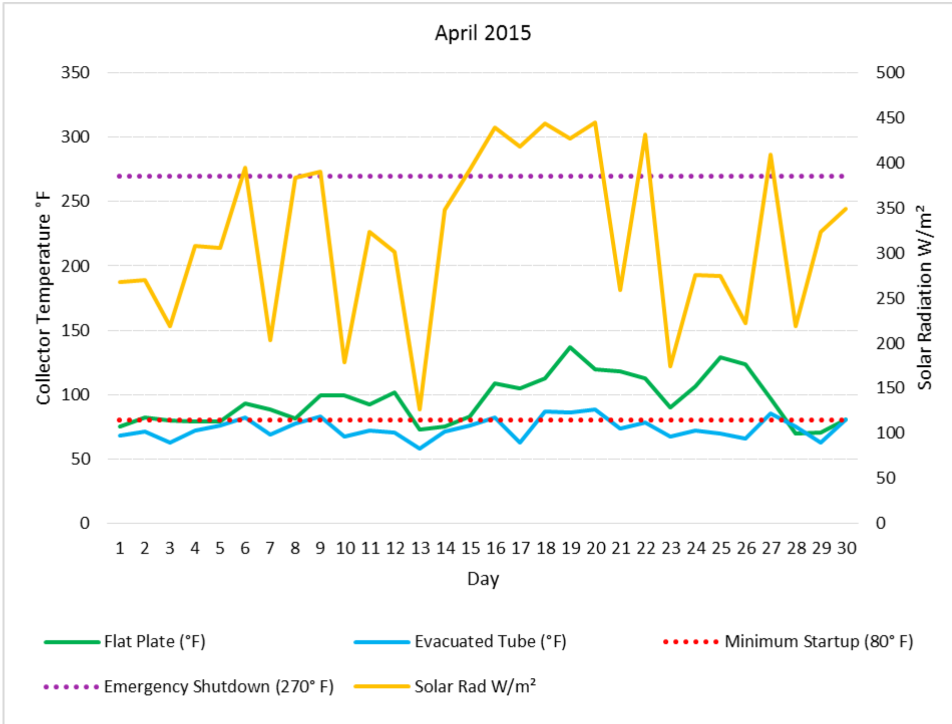

Figure 20. April 2015 Average Daily Collector Temperature and Solar Radiation.

In April, the flat plate collector continued to outperform the evacuated tube collector. The flat plate exceeded 80° F approximately 62% of the time for 431 of the 690 recorded hourly averages. Once again, emergency shutoff limits were only recorded during one hour in that month. The flat plate also began to respond to fluctuations in solar radiation much like it did during the previous summer and fall. Since the flat plate loses heat more easily than the evacuated tube, a larger range would exist between low and high temperatures due to cooling during times of low ambient air temperature and solar radiation.

The evacuated tube collector increased heat production over March, initiating the pumps at 80° F or more for 276 of the 686 recorded hourly averages, or 40% of the time. Performance almost returned to the previous summer's average heat production of approximately 50% and continued to not exceed 270° F. Lower heat production from this collector remains an unexpected observation due to the evacuated tube's ability to absorb more light from multiple angles. This should be noted for further consideration in future analysis.

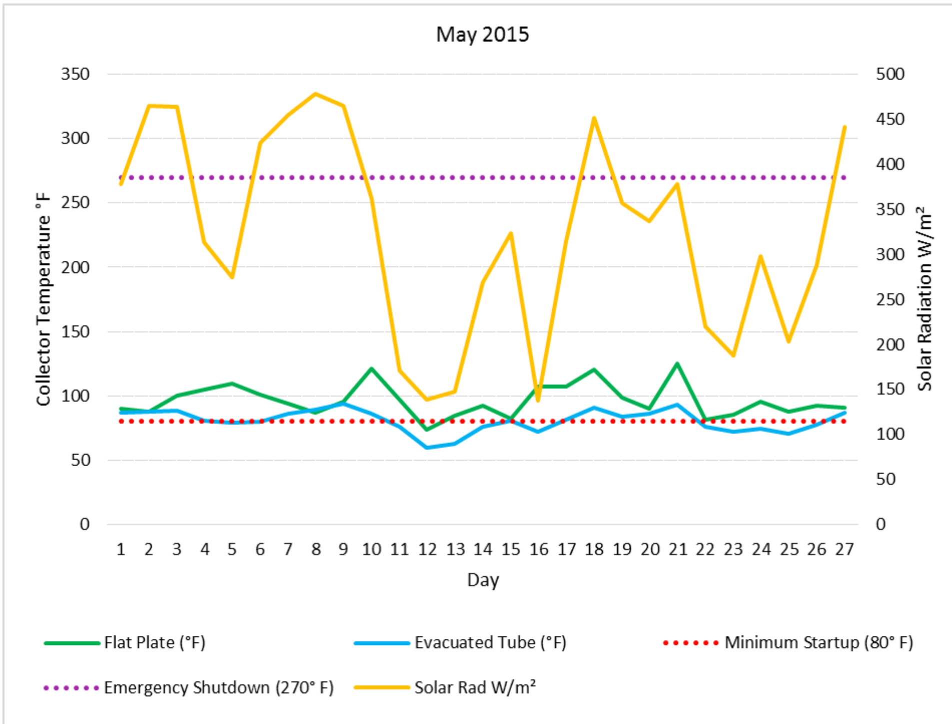

Figure 21. May 2015 Average Daily Collector Temperature and Solar Radiation.

As daily average solar radiation approached levels comparable to the previous August and September, the flat plate still did not reach emergency shutoff limits on a daily basis. Production continued to increase, exceeding 80° F for approximately 70% of the 620 recorded hourly averages, a total of 436 hours. Emergency shutoff temperatures were not reached on an hourly basis. Since being serviced, it appeared the flat plate collector had been running within much safer temperature ranges. However, this collector should be carefully monitored until next fall when solar radiation begins to drop once again.

The evacuated tube maintained its flat temperature profile as solar radiation continued to rise. It kept the pumps activated above 80° F for 47% of the 620 recorded hours, a total of 292 hours. No emergency shutoff limits were reached.

These monthly graphs clearly show how solar radiation influences collector performance. As expected, months with higher levels of solar radiation exhibit increased solar thermal production while months with lower solar radiation exhibit a decrease in solar thermal production. The evacuated tube collector generally maintains consistent heat production although it does not reach temperatures as high as the flat plate collector. The flat plate collector is much more reactive to fluctuations in solar radiation and demonstrated ongoing issues with overheating and triggering emergency shutoffs of the system.

Emergency Shutoff Analysis

As discussed previously, when either collector reaches temperatures above 270° F the pumps automatically shut down. This preserves the system and prevents overheating, which can cause the pumps to cavitate and the glycol to eventually stagnate within the collectors. It is important to identify temperatures equal to or greater than 270° F because the pumps shut down and do not circulate fluid through the collectors during these times. Temperatures higher than 270° F were included in the analysis since they represented inactive periods of operation.

Evacuated tubes can reach temperatures in excess of 400° F, however, the Apricus AP-30 did not reach temperatures this high during the year of data collection (Wondrausch). Usually capable of reaching temperatures around 180° F, the Caleffi flat plate installed on Mod 303 can handle temperatures up to 350° F (Caleffi Hydronic

Solutions). The flat plate reached temperatures well above the emergency shutoff point numerous times during the year. Since both collectors are capable of reaching temperatures that are higher than the emergency shutoff point and the glycol operating limits, this analysis assumes that any temperatures above those two points are possible. However, due to the lack of monitoring ability built into the system, it is not possible to determine the difference between the maximum temperature reached and when false measurements were being recorded due to stagnation and sensor failure.

Average hourly temperature calculations show that the evacuated tube collector did not reach temperatures of 270° F or higher during the year. However, it did reach temperatures above 270° F for a period of five consecutive ten minute measurements on April 27th, 2015 between 12:30 pm and 1:10 pm. These temperatures triggered an emergency shutoff for fifty minutes. Collector temperature did not exceed 370° F at any point in time, therefore the glycol did not reach levels of stagnation.

The flat plate collector reached average hourly temperatures of 270° F or higher for 142 hours during the year. Out of those 142 hours, 80 were above 325° F. The raw, uncondensed data becomes increasingly significant at this point. Due to these findings, it became clear that an evaluation of the ten minute measurements for each collector would be necessary. Over 65,000 flat plate collector temperature measurements were recorded at ten minute intervals during the year. The flat plate collector triggered an emergency shutdown 939 times; 489 of these measured 325° F or above. Measurements reaching 270° F or higher are shown on the next page by month (Fig. 22).

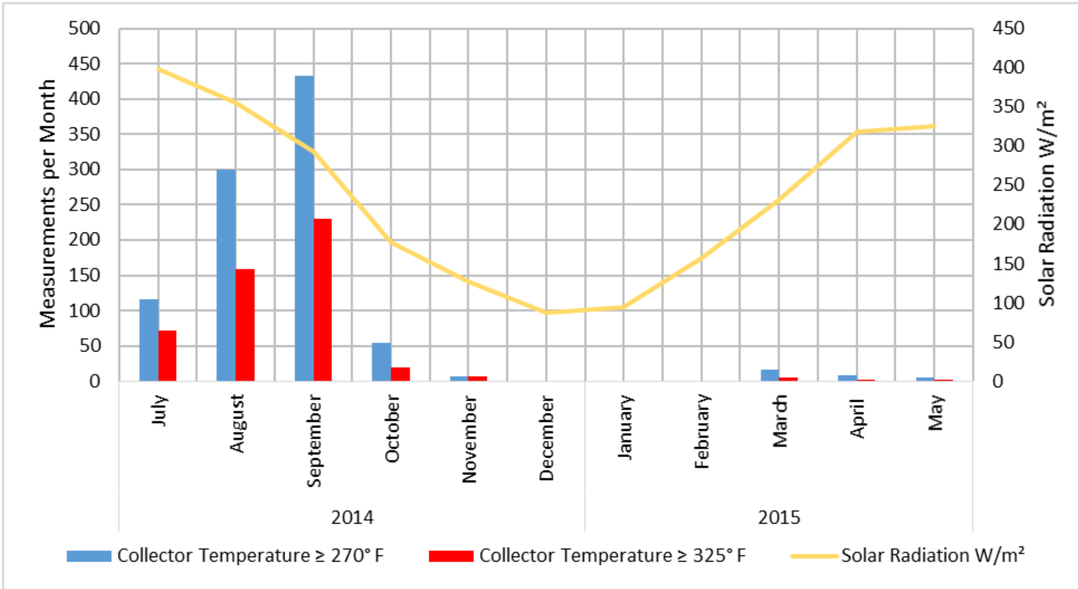

Figure 22. Flat Plate Temperatures ≥ 270° F.

In Figure 22, there does not appear to be a direct relation between total monthly measurements greater than or equal to 270° F and total monthly solar radiation. However, only three days at the end of July are represented, a total of 385 ten minute measurements. Of those, 116 triggered emergency shutoff. In August, temperatures reached above 270° F 299 times out of eight recorded days or 1,086 total measurements. If data was collected for the full months of July and August there would most likely be an extremely high incidence of emergency shutoff. Data collection halted for the remainder of August while the flat plate collector and temperature sensors were inspected, as these sensors were the suspected cause of the high temperature measurements. However, when demand is low and collector temperatures are high, stagnation can become a problem in collectors and cause various operational issues such as:

- Acceleration of the breakdown of sealants and fittings,
- Pump cavitation,
- Component stress due to pressure spikes and drops,
- Acceleration of glycol decay causing,
- Increased acidity of glycol,

- System component corrosion, and
- Loss of antifreeze properties allowing the system to freeze (Ruxton).

Since sensors generally give off high or false temperature readings to indicate a system failure, this is a probable explanation for the unexpectedly high temperature measurements. Another cause may have been faulty setup of the monitoring system, which was a concern with both systems due to the obstacles encountered during the initial commissioning.

Data collection resumed in September and continued through December, when solar radiation began to significantly drop. The flat plate collector continued to reach high temperatures during this time, although the frequency decreased along with solar radiation. As mentioned above, monitoring of the flat plate collector did not occur during January or February, 2015. Emergency shutoff was only triggered thirty times from March 1st to May 27th and did not increase along with increasing solar radiation. Table 3 below displays total temperature measurements each month. It also displays the amount of measurements greater than or equal to 270° F and the amount of time spent at 270° F or above.

Month	Year	≥270° F	≥325° F	Total Monthly Measurements	≥270° F	≥325° F	Total Solar Radiation W/m²
July	2014	116	72	326	35.58%	22.09%	398
August	2014	299	158	1,086	27.53%	14.55%	355
September	2014	433	230	3,945	10.98%	5.83%	293
October	2014	54	19	4,460	1.21%	0.43%	177
November	2014	7	7	4,243	0.16%	0.05%	127
December	2014	0	0	4,458	0.00%	0.00%	88
January	2015	0	0	0	0.00%	0.00%	95
February	2015	0	0	0	0.00%	0.00%	157
March	2015	16	5	4,402	0.36%	0.11%	232
April	2015	9	2	4,125	0.22%	0.05%	318
May	2015	5	1	3,713	0.13%	0.03%	325

Table 3. Flat Plate Total Recorded Hours vs. Active Recorded Hours.

A close look at Table 3 reveals the strange relationship between excessive temperatures and solar radiation. The small amount of measurements taken in July exhibited the highest percentage of high temperatures, although this is difficult to gain insight from due to the small sample size. The eight days of collection in August also exhibit a relatively high percentage of high temperatures as well as a decrease in average solar radiation. Beginning in September, the first month of full data collection, the percentage decreases again along with solar radiation. From October through the end of the year, frequency of high temperatures continued to decrease along with a decrease in solar radiation until eventually reaching zero in December. December also had the lowest average solar radiation.

The surprising observation takes place in March through May, when solar radiation continues to increase, reaching levels comparable to the previous September. In March, only 0.36% of the measurements are temperatures capable of triggering an emergency shutoff and this number continues to decline in the following months while solar radiation increases. This suggests that the routine system maintenance and glycol flush during January and February may have resolved any lingering issues from the previous summer’s stagnation and cavitation events. However, it is still early enough in the year that overall solar radiation and ambient air temperature may not be high enough to cause another stagnation event. This will be an interesting observation to keep in mind during next year’s analysis.

Collector Performance Summary

The evacuated tube collector performed without any noticeable issues. Data collection occurred approximately 90% of the year. Average hourly collector temperatures ranged from 20.7° F to 213.4° F throughout the year, which fall within an acceptable range. The collector reached temperatures that triggered an emergency shutoff for a total of fifty consecutive minutes during one hour of the year but did not reach levels above 325° F. Overall, of 7,912 average hourly temperatures collected, 2,948 hours show active hot water delivery to Mod 303 hot water tanks.

The flat plate collector reached operating temperature more often than the evacuated tube, but also triggered emergency shutoff and reached temperatures that can cause glycol degradation if sustained for extended periods of time. Data collection occurred approximately 59% of the year. Average hourly collector temperatures ranged from 20.5° F to 1248.1° F. Out of 5,146 average hourly temperatures, the flat plate collector fell within normal operating temperatures for 2,450 hours. A total of 142 hours reached temperatures above 270° F and caused an emergency shutdown, with 80 of these hours exceeding temperatures of 325° F. After being adjusted for actual ten minute interval data, total time lost due to emergency shutoff equals 156.5 hours, an increase of 14.5 hours over the average hourly estimate. 81.5 hours exceeded temperatures of 325° F.

Validity of the Results

Due to the limitations and obstacles that were identified while working with available data, all results could potentially have been influenced by basic performance assumptions, false temperature measurements (due to overheating and unidentified factors) and other generally unknown variables and system malfunctions. These obstacles did serve a purpose, as they shed light on specific problems that will require action in order to fully understand this specific project.

DISCUSSION

After being awarded the grant on September 12, 2012, installation of the solar thermal collectors began. Through a collaborative and creative effort, various individuals stepped in to finish commissioning the system and keep it operating throughout the year. Through the changing of hands, information related to maintenance, adjustments and general operation has naturally slipped through the cracks and created uncertainties and operational issues regarding the system. As a result,

- Documentation on the design, construction and initial setup of the project is limited;
- Detailed records of maintenance, iSolar BX Differential Temperature Controller settings and data management methods are difficult to come by;
- There are uncertainties concerning basic system operations; and
- Much of the information needed for in-depth analysis is lacking.

These issues have the potential to significantly influence the results of this analysis and future analyses. As stated earlier, it is not possible to perform the following analyses:

- System efficiency,
- Cost-benefit analysis,
- In-depth collector performance, or
- Carbon offset potential.

Did the Comparative Solar Project Meet the Specified Goals?

Once again, the purpose of the Comparative Solar Project was:

- To install two different kinds of solar panels with similar collection capacities for the purpose of comparison,
- To develop relationships between Residential and Dining Sustainability Crew student-employees, faculty, and local companies involved in sustainable design, and
- To foster a conversation between the above mentioned groups in order to develop an academic understanding of the possibilities presented by solar hydronic systems in the Pacific Northwest.

Unfortunately, these goals have not yet been reached to their fullest potential, although the process of fulfilling each of these goals has begun. Two different solar thermal collectors are now installed and operating at Mod 303. A comparative analysis has been performed to the fullest extent possible with the data and resources available. However, the results of the analysis echo the limitations currently surrounding the system. It is absolutely critical that additional variables be monitored in the future so that the next analysis will be able to fully evaluate the system and yield concrete evidence on the collector's performance.

Relationships between Residential and Dining Sustainability Crew student-employees, faculty, and local companies have been built throughout the process of getting this project off the ground. Realistically, these relationships are just beginning to be forged. A complete understanding of this system will take continuing dedication from students, faculty and industry professionals. These groups will need support from each other as the project moves along.

The Comparative Solar Thermal project has definitely opened up avenues for conversation between these groups. There are many questions left to be asked and many solutions to be found. Once this first solar thermal system has reached its fullest operating potential and can be comprehensively analyzed, the involved parties will be able to begin to explore possibilities of expansion and the future of solar thermal at Evergreen.

Theoretical Savings and Carbon Offset Analysis

One easily accessible method for estimating electricity and carbon savings can provide some insight into the potential impact this technology can have at Evergreen. Caleffi and Apricus both provide collector output calculators for their individual products online. Using this method, a rough estimate of annual energy output can be produced as a general reference to the potential of these collectors. Each of these output calculators takes into account average annual insolation level in $kWh/m^2/day$ and the solar collector in question. The average annual insolation level selected by Caleffi for the Olympia area is 3.69 $kWh/m^2/day$. Apricus originally selected 3.62 $kWh/m^2/day$ for Seattle, but the value was adjusted to 3.69 $kWh/m^2/day$ to maintain consistency with the Caleffi calculator since this value was not adjustable on the Caleffi website. The Apricus AP-30 evacuated tube collector and the Caleffi NAS10410 flat plate collector were selected for evaluation. After running the programs, it was determined that the average estimated energy output of the Apricus AP-30 evacuated tube was 2,659 kWh (Collector Output Calculator). The Caleffi NAS10410 had an estimated energy output of 1,497 kWh (Caleffi Hydronic Solutions).

In 2014, Evergreen's average electricity cost was $0.086/kWh after all charges and renewable energy certificates were applied by Puget Sound Energy (Utility/Energy Consumption by Fiscal Year 2014). At this rate, the Apricus AP-30 would save Evergreen $228.67/year while the Caleffi NAS10410 would save $128.74/year, totaling $357.41.

These estimates can also be used to determine the rough carbon offset potential of each collector. Puget Sound Energy's 2012 CO_2 emissions profile from all generating sources was 1.48 lbs/kWh (Lo 9-1). At an estimated annual energy output of 2,659 kWh, the Apricus Ap-30 would offset approximately 3,935 pounds of CO_2 emissions. In comparison, the Caleffi NAS10410 would offset 2,216 pounds of CO_2 emissions. For comparison, these emissions savings are the equivalent of not burning 6.5 barrels of oil or not driving over 6,600 miles (Greenhouse Gas Equivalencies Calculator).

According to the online calculators, the Apricus AP-30 evacuated tube collector will produce more hot water than the Caleffi NAS10410. There are 19 modular housing units located at Evergreen. If the same system was installed on each unit, with a second evacuated tube collector replacing the flat plate, there would be 38 evacuated tube collectors delivering hot water to the modulars. Theoretically, this would save 101 MWh of electricity and $13,581/year. In comparison, Evergreen spent $1,182,498 on electricity and used 13,787 MWh in 2014 (Utility/Energy Consumption by Fiscal Year 2014).

Moving Forward with Solar Thermal Hot Water Heating at Evergreen

The theoretical analysis portrays the opposite of what has been observed from the evacuated tube and flat plate collectors installed on Mod 303. According to the results of this research, the Caleffi flat plate collector is the ideal choice for producing hot water at Mod 303. The flat plate collector outperformed the evacuated tube collector throughout the year, with the exception of December, when the evacuated tube operated a negligible 1.7° F warmer on average than the flat plate. However, when combined with the theoretical analysis, these results, although very rough, indicate a need for further research before claiming one type of collector outperforms the other. These circumstances should be evaluated over the next year because they could drastically alter the next steps in evaluating and possibly installing further solar thermal hot water at Evergreen.

Enhanced monitoring systems and maintenance procedures are the key to fully comprehending the potential role of solar thermal hot water at Evergreen. A new monitoring system could provide details of all the variables necessary to perform the analyses listed at the beginning of this chapter. These variables include:

- Hot water storage tank temperature,
- Temperature of water entering the hot water tanks,
- Temperature of heat transfer liquid inside of the collector,
- Temperature of heat transfer liquid entering the hot water tanks,
- Temperature of heat transfer liquid, and
- Pump speed.

The ability to monitor these variables would significantly broaden the range of analyses that could be performed. Heat loss through different components and stages of the system could be identified and minimized, parameters could be adjusted for improved efficiency and heat production and system failures or other issues would be much easier to diagnose and correct.

Recording all maintenance procedures and operating specifications in a secure and accessible location and format would also assist in future troubleshooting and speculations. All current system settings should be recorded and updated when any changes occur. Important details to keep record of include:

- Type of glycol or heat transfer fluid,
- Maintenance receipts,
- Maintenance records,
- Strange operational observations,
- Times when system is offline,
- System or component failure, and
- Any other relevant observations and information directly related to system performance and maintenance.

Communication of any changes and observations will be very important for the parties involved. While working through this data it appeared that different individuals held different pieces of information and varying perspectives about the solar thermal system. This makes sense considering the difficulties encountered while commissioning the system and dealing with the original company responsible for the installation. The recommendations covered here can be added to the Solar Handbook as useful guidelines when recording and saving relevant information regarding the solar thermal hot water system.

CONCLUSION

This research delivers insight into the first operational year of the Comparative Solar Project installed on Mod 303 at The Evergreen State College. The comparative analysis performed on the Apricus AP-30 evacuated tube collector and the Caleffi NAS10410 flat plate collector indicates that the Caleffi flat plate collector outperforms the Apricus evacuated tube collector throughout the year with the exception of December. Designed to perform better in cold and cloudy climates, the Apricus AP-30 produced temperatures averaging 1.7° F warmer than the Caleffi in December. The results gathered from this research show a need for further evaluation of both collectors over the next year in order to provide a fully informed recommendation on which solar thermal collector is best suited for serving Mod 303.

Due to the limitations of available data, there was great difficulty determining how well each collector actually performed. The Caleffi flat plate collector was plagued with overheating and pump cavitation issues, which significantly affected the ability to accurately judge the data collected by the temperature sensors. The Apricus evacuated tube collector did not display any significant operational issues, but curiously produced lower temperatures than the flat plate collector, which was unexpected since evacuated tube collectors generally reach higher temperatures than flat plate collectors.

Most importantly, this research displays the need for advanced monitoring resources and abilities. An extensive, comprehensive monitoring system will make possible in depth analyses such as carbon offset potential, cost-benefit analyses, accurate performance comparisons and system efficiency analyses. In order to fully appreciate the initial $15,000 investment made in this project, it is highly recommended to seek and provide funding for an advanced monitoring system that will allow this project to reach its fullest potential as a possible future source of renewable energy and guaranteed collaborative medium at The Evergreen State College. Despite the unforeseen obstacles encountered while commissioning this project, the Comparative Solar Thermal Project prevented the release of up to 6,150 pounds of carbon emissions into the atmosphere over the past year, providing a valuable contribution to the College's efforts of reaching its carbon neutrality goals.

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