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ABSTRACT

According to the U.S. Department of Energy, 40% of the energy consumed in the U.S. is used in buildings and almost half of that amount is used for heating or cooling. Current technologies allow for efficient thermal management, but most utilize energy harvested from fossil fuels or convert electricity directly into thermal energy. Alternative heating technologies such as heat pumps and solar thermal collectors can greatly reduce the energy used for heating while producing reliable heating performance.

This paper documents how an off-the-shelf residential heat pump water heater was integrated with a solar thermal system to improve overall heating performance. Solar thermal is the primary source of heat and the heat pump is used as a back-up when the sun is not shining with enough intensity. A primary/secondary pumping system is used to allow multiple modes of operation, including both hot water and hydronic heating. Since the heat pump water heater is located entirely inside the conditioned space, a secondary benefit/detriment for space cooling is noted based on the weather conditions.

An energy dashboard that evaluates the heating performance of this hybrid solar heat pump system in real time was developed. The primary efficiency metric is the Energy Factor (EF), which is the ratio of thermal energy delivered to electrical energy consumed. As a point of reference, heat pump water heaters earn an "Energy Star" rating for an Energy Factor of 2.2 under test conditions. During two-weeks of rigorous 24 hours a day testing in March of 2016, the instantaneous EF for the solar heat pump system varied from 1 to greater than 40 depending on the weather conditions. The overall average EF for the two weeks of continuous testing was 2.29, indicating an efficiency significantly higher than traditional direct electrical heating systems.

1. INTRODUCTION

According to the U.S. Department of Energy, 40% of the energy consumed in the U.S. is used in buildings and almost half of that amount is used for heating or cooling. Current technologies allow for efficient thermal management, but most utilize energy harvested from fossil fuels or convert electricity directly into thermal energy. Alternative heating technologies such as heat pumps and solar thermal collectors can greatly reduce the energy used for heating while producing reliable heating performance.

Because of the increasing trend towards net zero energy buildings, there are many ongoing projects to develop and deploy solar thermal heat pump systems (SHPS). One interesting system that is comparable to this research was recently developed and built at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD. Their Net Zero Energy Residential Test Facility is a full-size home that is evaluating a number of promising new residential technologies, including a SHPS. The NIST system used a heat pump with a rated COP of 2.6, which was coupled with flat plate solar thermal collectors on the roof of the home. Three important differences from this research are that the NIST system 1) included substantial solar storage, 2) was designed for domestic hot water only, no space heating, and 3) the air source heat pump was located in an unconditioned space. The NIST SHPS system achieved an annual Energy Factor (EF) of 2.39. An EF is a performance measure that is the ratio of useful heat delivered to the electricity used for operating the system. Equally important, the NIST research suggests that daily time of use patterns for residential hot water have an impact on the performance results that are achieved.

2. SYSTEM OVERVIEW

Figure 1 shows the main components of a newly constructed solar heat pump system (SHPS) located in the Applied Energy Laboratory at Purdue University in West Lafayette, IN. The primary components are solar thermal collectors, primary and secondary circulating pumps, a heat exchanger for generating domestic hot water, and a heat pump with a storage tank. The SHPS is monitored and controlled by a web-based building automation system that includes comprehensive monitoring of outdoor weather conditions and component-level energy use. The entire system circulates a 50% glycol/water solution for freeze protection during cold winter weather.

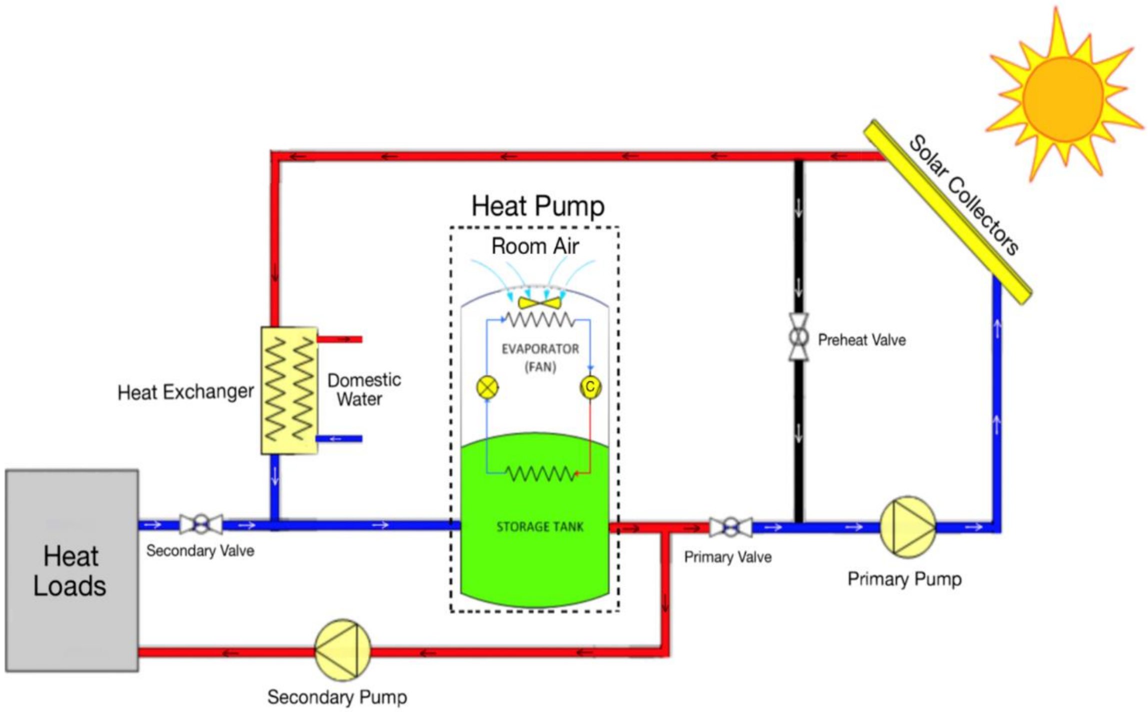

Figure 1: The SHPS has primary and secondary loops.

The primary loop of the SHPS consists of the primary pump, solar collectors, heat exchanger, and heat pump. The primary valve controls the glycol flow through the primary loop. When sufficient solar energy is available the primary pump circulates glycol through the solar collectors, heat exchanger, and heat pump. The collected heat is then used to provide domestic hot water via the heat exchanger or is transferred to the heat pump storage tank for later use. The heat pump supplements the solar heat as needed to maintain a storage tank temperature of 120°F.

The secondary loop of the SHPS consists of the heat pump, secondary pump, and heat loads. The secondary pump circulates the heated glycol to deliver space heating or domestic hot water through the heat exchanger. The secondary valve closes when there is no call for heating to isolate that loop.

The primary and secondary loops can operate independent of each other. This is necessary when but there is call for heating, but not enough solar energy is to maintain temperature. This mode is enabled by closing the primary valve, opening the preheat valve, and opening the secondary valve. The primary pump circulates flow to the solar collectors to gradually increase the temperature in the primary loop. The secondary pump circulates glycol through the heat pump and delivers it to the heat loads.

Figure 2 shows the solar thermal collector array located on the roof of the building including one evacuated heat tubes panel (left) and four flat-plate solar thermal panels (right). Various panel designs are used, however, each design operates in the same basic way. As sunlight hits the surface of the panels, the glycol solution pumped through the panels is heated by the solar energy. The heated glycol then circulates through the primary loop where the heat is transferred to either the heat pump storage tank or directly to the domestic water.

Figure 2: Solar thermal collectors for the SHPS.

Figure 3 shows the residential air source heat pump with an integrated 50-gallon storage tank that is used in the SHPS. The heat pump is necessary so that heating can be provided at night or any other time when solar energy is not available. In heat pump mode, the compressor transfers heat from the room air into the storage tank. Additionally, a resistive heating element provides rapid or backup heating for the system.

Figure 3: The residential air source heat pump has an integral storage tank.

3. ENERGY ANALYSIS

The SHPS is monitored and controlled by a sophisticated web-based building automation system that includes a large number of temperature, pressure, flow, and power monitoring sensors in addition to actuators for controlling the pumps and valves. An energy dashboard was created to coordinate and simplify this large amount of data into a few key metrics that quantify the performance of the SHPS in real-time. The graphical output of the energy dashboard provides a comprehensive visual summary of the heating system by displaying key metrics in a user-friendly format. The data includes not only current performance metrics, but trends over time so that users can identify equipment malfunctions or weather-related anomalies that effect the performance of the SHPS.

The primary efficiency metric is the Energy Factor (EF), which is the standard used by the U.S Environmental Protection Agency and the U.S. Department of Energy to rate water heating systems. The Energy Factor is the ratio of thermal energy delivered to electrical energy consumed. As a point of reference, a generic air source heat pump water heater can earn an EPA "Energy Star" rating for an Energy Factor of 2.2 under test conditions.

The EF computation for this research project is different from the computations for many other SHPS systems because the heat pump water heater is located inside the conditioned space. This arrangement has a secondary benefit/detriment for space cooling, based on the outdoor weather conditions, that must be accounted for in the EF computations.

3.1 Energy Factor Computations

Energy Factor (EF) is a key metric for evaluating the system's performance. As shown in Equation 1, EF is the ratio of energy collected (Qtotal) to energy consumed (Wtotal). More specifically, Qtotal is the amount of thermal energy collected by the SHPS and Wtotal is the amount of electrical energy used by the SHPS. In order to simplify the calculations, both Qtotal and Wtotal are calculated in Watt-hours (Wh). Furthermore, both Qtotal and Wtotal are comprised of multiple terms that are discussed in greater detail below.

$$EF = \frac{Q_{total}}{W_{total}} = \frac{Q_{solar}+Q_{hp}\pm Q_{air}}{W_{pump}+W_{hp}} \tag{1}$$

The first step in calculating the EF of the system is to determine the total electrical energy consumption of the system (Wtotal). As the denominator of equation 1 shows, Wtotal includes the electrical energy consumed by the primary circulating pump (Wpump) and the heat pump (Whp). In both cases the power of each device is measured in Watts and then integrated over time to determine the actual energy consumption in Watt-hours.

The next step in calculating the EF of the system is to determine the total amount of thermal energy collected by the SHPS (Qtotal). The total energy collected is made up of three parts. Solar energy (Qsolar), heat pump energy (Qhp), and air energy (Qair) all contribute to the thermal energy.

The first energy collection term, Qsolar, represents the amount of thermal energy collected by the solar panels. The heat transfer rate of the panels is calculated using real-time measured flow rates and temperature changes. Then the actual energy collection is determined by integrating the heat transfer rate over time.

The second energy collection term, Qhp, represents the amount of thermal energy collected by the heat pump. The heat pump has two modes of heating: heat pump and resistive. The resistive heating, which directly converts electrical energy to heat, is assumed to be 100% efficient. Therefore, the amount of energy provided by the resistive heating element is equal to Whp. In heat pump mode, however, the heat pump extracts energy from the ambient air and transfers that heat to the glycol solution in addition to the heat produced by the electrical energy used to run the heat pump compressor. Therefore, the total amount of output energy from the heat pump has the potential to be greater than 100% of the electrical energy consumption. The actual energy collected by the heat pump is determined by multiplying Whp by the coefficient of performance (COP) as determined by the specifications of the heat pump in use. In this case, the COP is set to 1.8 meaning that for every 1Wh of electrical energy consumption the heat pump provides 1.8Wh of thermal energy while operating in heat pump mode. The energy produced by the resistive heating and heat pump modes are then added together to determine the total energy collected by the heat pump (Qhp).

The third term, Qair, was included in order to account for the heat removed from the conditioned air of the lab. As previously explained, the heat pump is designed to extract heat directly from the conditioned air of the lab. During warm periods, when the outdoor air temperature is above 60°F, the cooling of the room air is an added benefit to the building. However, when the outdoor air temperature is below 60°F, the building must replace any energy extracted from the room air. The Qair term is included to account for the added benefit or penalty of the heat loss from air. Qair is positive when the measured outdoor air temperature is above 60°F and negative when it is below 60°F.
Equation (2) shows how Qair was calculated

$$Q_{air} = Q_{hp} - W_{hp} = W_{hp}(COP - 1) \tag{2}$$

4. TEST CONDITIONS

The solar heat pump system was evaluated over a two-week period from March 15th to March 28th, 2016. During the test period, the average day length (duration of daylight) was roughly12 hours and 14 minutes. On March 15th, the sunrise and sunset were 7:58AM and 7:55PM respectively. By March 28th, sunrise and sunset had shifted to 7:37AM and 8:09PM respectively.

The heating system was operated at close to 100% capacity for 24 hours a day in all 14 days of the test period. The load was applied by removing heat from the SHPS using finned tube radiators in an environmental chamber that was maintained at a constant temperature. Figure 4 shows the daily heating (Qload) cycles starting at 12:00AM on March 15th and ending at 11:55PM on March 28th. The daily load was 19 kWh each day, roughly the amount that the heat pump could supply if it operated continuously with a COP of 1.8 and without using electric reheat or solar energy.

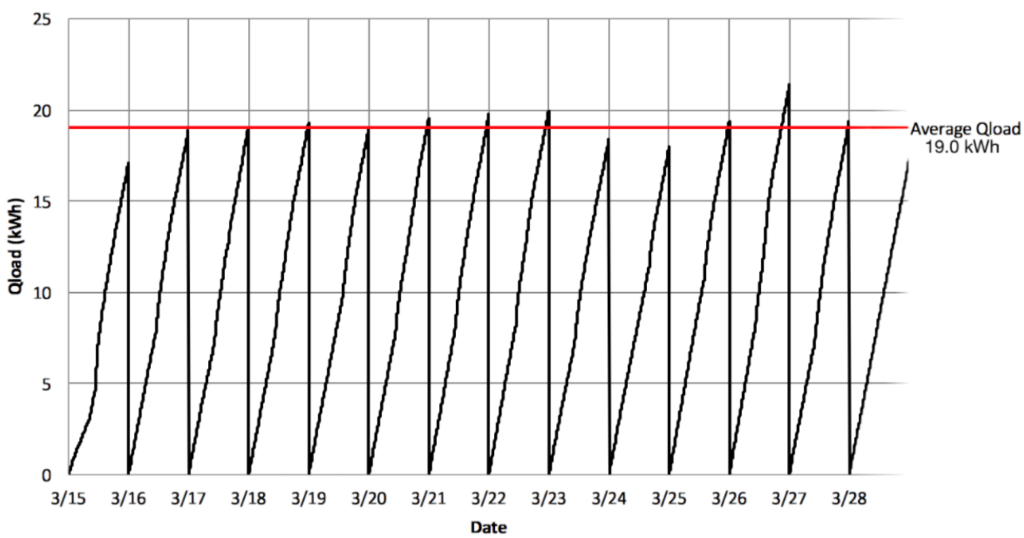

Figure 4: Two weeks of continuous testing was conducted.

As Figure 4 shows, the rate of heat demand was relatively constant for all 14 days. Furthermore, the demand was constant throughout each 24-hour period meaning that the system was rigorously and consistently tested during periods of both daytime and nighttime. Solar energy was used when available but at night or on cloudy days the heat pump was used to meet the load demand. This meant that regardless of the solar energy collection during the day, the heat pump was still loaded at night. At midnight Qload was reset to zero so that the total heat demand for each day, represented by the peaks, could be determined.

The average daily heat demand during the test period was 19.0 kWh, which is 2.6kWh higher than the average hot water energy demand for Midwestern homes (United States Department of Energy's Office of Energy Efficiency and Renewable Energy, March 2012). The higher demand put more stress on the heating system, but was deemed acceptable because the system is designed to provide both domestic hot water and space heating. Furthermore, the graph above shows that the daily heat demand was relatively consistent throughout the test period, which was important for comparing the performance values of each day.

The two-week test period also included a variety of weather patterns. Both solar intensity and outdoor air temperature were measured throughout the test. Each test day was categorized by its average measured solar intensity. A sunny day was defined as any day with an average solar intensity greater than 200 W/m2 whereas a cloudy day was any day with and average less than 100 W/m2. A partly cloudy day was any day with an average solar intensity between the two limits. The test period included eight sunny days, three partly cloudy days, and three cloudy days.

Similarly, each test day was also categorized by the amount of time during the day at which the outdoor temperature was above 60°F. The 60°F limit was used because it is also the point at which the Qair term in Equation (1) begins to be treated as a benefit to the building. Therefore, a cold day was defined as any day in which the outdoor temperature never reached 60°F. A warm day was any day in which the outdoor temperature reached 60°F but for less than 50% of the time. And a hot day was defined as any day in which the outdoor temperature was above 60°F for more than 50% of the time. The test period included one hot day, eight warm days, and five cold days.
Furthermore, the test period occurred during an ideal time of the year.

Figure 5 shows the average daily global horizontal irradiance (blue) and outdoor temperature (orange) for West Lafayette, Indiana (40°24'36.0"N 86°54'00.0"W) based on values from 2010 to 2014 (National Renewable Energy Laboratory, 2016). The vertical shaded area designates the test period and the horizontal shaded area demarcates the average outdoor temperatures measured during that time.

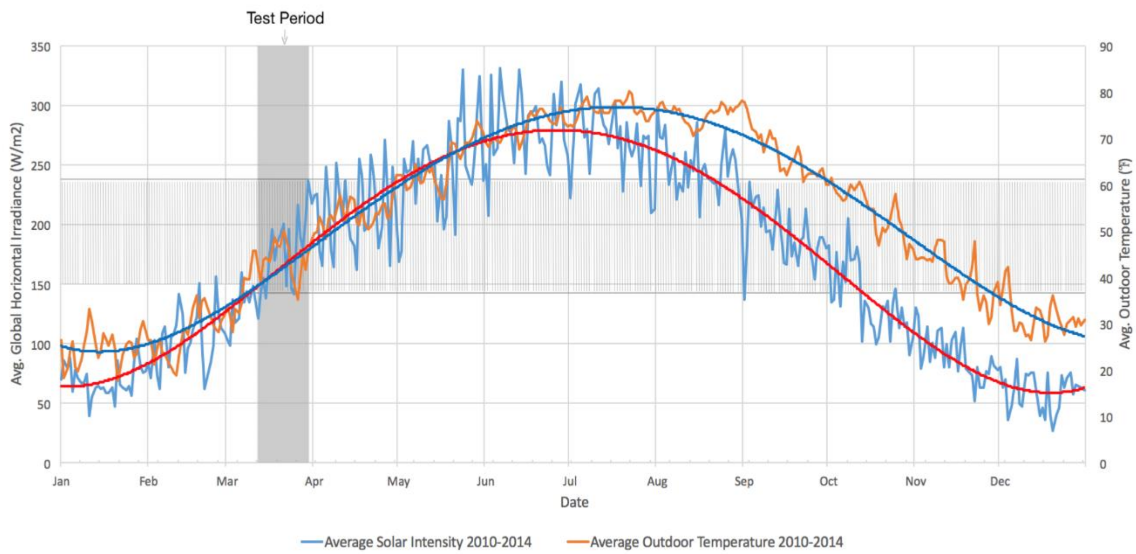

Figure 5: Solar Intensity and Outdoor Air Temperature Averages for 2010 to 2014

As Figure 5 indicates, the test period occurred at an intermediate time of the year. Specifically, the median of the measured solar irradiance during the test period was nearly identical to the median of the values shown in the graph. Figure 5 also shows that the range of measured outdoor temperatures during the test period encompasses a large, central portion of the outdoor temperature averages shown in the graph. All of this suggests that the measured performance of the heating system during the two-week test period is a good estimate of the annual performance of the system. As previously mentioned, both the energy dashboard program and the solar heat pump system were evaluated during the test period. The dashboard needed to provide a comprehensive and user-friendly summary of the system's energy performance. The goal of the solar heat pump system evaluation was to achieve an overall average energy factor of 2.0 or greater.

5. RESULTS

As previously discussed, the actual performance of the solar heat pump system was evaluated during the test period. The system was loaded 24 hours a day for 14 days. Of those 14 days there were three cloudy, three partly cloudy, and eight sunny days. Similarly, there were five cold days, eight warm days, and 1 hot day.

Table 1 shows the two-week averages of the solar EF, heat pump EF, and overall EF values, which are the key metrics used to evaluate the SHPS. As previously discussed, EF is the ratio of collected to consumed energy. The values shown in the table were determined by averaging the fourteen daily EF values for each of the systems. The system achieved an average EF of 2.29 during the two-week test period.

Table 1: Average Measured Energy Factors

# of Days	Solar EF	Heat Pump EF	Overall EF
14	26.95	1.25	2.29

Table 2 shows the average EF values for the cloudy, partly cloudy, and sunny days. Instead of determining the average daily EF values for all fourteen days, as shown in the previous table, the respective daily EF values were averaged separately for each type of day. As expected, there was a significant difference in the solar EF values between the cloudy, partly cloudy, and sunny days. The average solar EF value was 35.68 for the eight sunny days and 2.77 for the three cloudy days. The average value during the partly cloudy days predictably fell between the two ranges at 18.67. The results also show a correlation between the average solar intensity and the overall EF. The driving factor of this correlation is obviously the amount of energy collected by the solar panels, which was directly effected by the amount of sunlight and is reflected in the solar EF values.

Table 2: Average Measured EF Values for Sunny, Partly Cloudy, and Cloudy Days

Type of Day	# of Days	Solar EF	Heat Pump EF	Overall EF
Cloudy	3	2.77	1.20	1.23
Partly Cloudy	3	18.67	1.27	1.74
Sunny	8	35.68	1.24	2.75

Similarly, Table 3 compares the average measured EF values for the cold, warm, and hot days of the test period. The respective daily EF values were averaged separately for each type of day. As previously discussed, the outdoor temperature directly effects the heat pump EF value due to the inclusion of the Qair term in the calculation. Specifically, on cold days the expected heat pump EF values is 1.00, which matched the measured average exactly. Similarly, the measured averages for both the warm and hot days fell within their respective expected ranges of 1.0-1.8 and 1.8-2.6. Again, there appears to be a correlation between the overall EF and the outdoor air temperature with the heat pump EF being the driving variable. However, there also appears to be a correlation between the outdoor air temperature and the solar EF value. In both cases, further testing is required to verify the significance of the correlations.

Table 3: Average Measured EF Values for Cold, Warm, and Hot Days

Type of Day	# of Days	Solar EF	Heat Pump EF	Overall EF
Cold	5	18.21	1.00	1.66
Warm	8	27.76	1.32	2.38
Hot	1	36.65	1.81	3.53

During the test period energy consumption and collection values for both the solar and heat pump sub-systems were measured. Figure 8 contrasts the two forms of energy in this system. The pie chart to the left compares the average electrical energy consumption of the solar and heat pump systems. The pie chart to the right shows the average contributions of the solar and heat pump systems. As the charts show, the heat pump consumed the majority of the electric energy, roughly 9.13 kWh per day as compared to the 0.32 kWh per day consumed by the solar energy system. On the other hand, the heat pump only contributed 11.24 kWh per day compared to the 8.91 kWh per day collected by the solar panels.

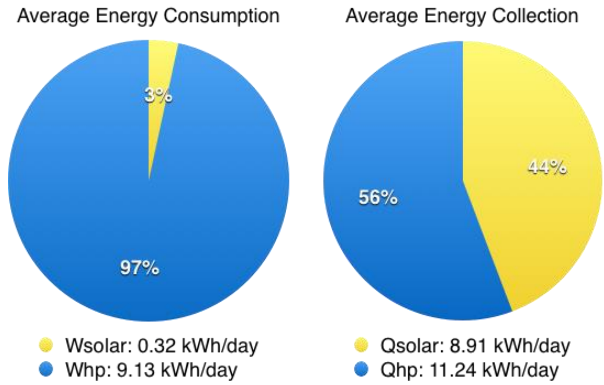

Figure 8: Average Consumption (left) and Collection (right) Percentages

6. CONCLUSIONS

During the two-week test period the SHPS achieved an average EF of 2.29. The average solar and heat pump EF ratings were also as expected. Specifically, the average solar EF rating was roughly 27 and the average heat pump EF rating was roughly 1.3. The solar EF was significantly effected by the amount solar intensity throughout the day. Similarly, the outdoor temperature had a significant effect on the heat pump EF. In particular, the percentage of each day spent over 60°F closely correlated to the EF rating of the heat pump. The outdoor temperature also appeared to have an effect on the solar EF. The solar and heat pump EF values directly effected the overall EF rating. Therefore, solar intensity and outdoor temperature also had similar effects on the overall EF value.

The fact that the heat pump was responsible for the majority (97%) of the electrical energy consumption but provided just over half (55%) of the energy collection was a concern. On the other hand, the solar collection system was extremely efficient when solar energy was available. Despite only accounting for 3% of the total electrical energy consumption the solar energy provided just under half of the total heating (44%). All of this indicates that the overall efficiency of the system could potentially be improved by minimizing the use of the heat pump and maximizing the use of solar energy. However, some heat pump electrical consumption is necessary for the system to adequately provide heat even when solar energy is not available.

The solar heat pump system was very successful in meeting the heating demand placed on the system. The average daily load on the SHPS was 19.0 kWh per day and the system was loaded day and night meaning that it could not rely solely on solar energy to meet the demand. During the night and during cloudy days, the heat pump was necessary. Despite the heavy demand the heat pump rarely resorted to resistive heating, which helped the system to achieve a higher EF rating. The fact that the SHPS was able to meet the high demand, even in the absence of sunlight, was very important because it showed that the SHPS is a viable heating solution. Many of the features of the system are meant for educational purposes, however, the results of the energy dashboard test revealed that it also has potential as a commercial heating system.

NOMENCLATURE

EF	Energy Factor	
Q	Energy (heat) collected	(Wh)
SHPS	Solar Heat Pump System	
W	Electrical energy consumed	(Wh)

Subscript

air	Conditioned lab air
hp	Heat Pump
load	Heat load
pump	Primary circulating pump
solar	Solar collection system

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