SOLAR 2013: DEVELOPING A TESTING FACILITY FOR THE USE OF SOLAR THERMAL COLLECTORS IN RESIDENTIAL HEATING AND COOLING APPLICATIONS

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ABSTRACT

Work conducted at the Renewable Energy Deployment and Display (REDD) Laboratory of the Desert Research Institute demonstrates the use of different types of solar thermal collectors for residential heating and cooling. The facility also generates electricity though solar and wind. The fully instrumented system provides a comparison between the systems in the application of driving an absorption chiller. Three solar thermal systems are used for comparison: a conventional glycol-based solar thermal collector (Array 1), a water-based envelope style collector (Array 2), and a site-constructed air system built by researchers at DRI. Array 1 and Array 2 supply energy to their own 120 gallon (454 L) water storage tank operating an absorption chiller for cooling or is plumbed to a heat exchanger in the furnace for heating. The air system is located in a separate building where it heats the facility directly or stores energy in two 120 gallon (454 L).

1. INTRODUCTION

Over the past decade, the Desert Research Institute (DRI) has developed capabilities and resources to conduct research in small-scale renewable energy systems. The first system constructed consisted of solar photovoltaic (PV) panels, wind turbines, an electrolyzer for hydrogen generation, and a fuel cell. The system was enhanced several times through various grants to be considered the Renewable Energy Center (REC), Renewable Energy Experimental Facility (REEF) and finally as the Renewable Energy Deployment and Display (REDD) Laboratory. The REDD Laboratory now comprises an off-grid capable facility that can be used for testing various small-scale renewable energy applications. The facility, consisting of a 1200 ft^2 residence (111.5 m^2), 600 ft2 (56 m^2) workshop, and several other stand-alone components, is powered by solar PV, wind turbines, and solar thermal collectors. Energy storage is achieved through chemical storage in batteries, thermal storage, and hydrogen production. To ensure reliable and secure energy, the hydrogen is combusted in an internal combustion engine (ICE) with an alternator, which can also run on propane as a back-up fuel. A layout of the facility, constructed on the DRI Reno campus, can be seen in Figure 1. The extensive list of components in this facility provides all the necessary resources to conduct world-class research on small-scale renewable energy components and systems.

The primary goal of the REDD Laboratory is to help grow DRI's capabilities and expertise in areas of renewable energy research, development, demonstration, and deployment. The creation of the facility also provides the following benefits:

- Integration of renewable power components and systems
- Energy auditing functions
- Showroom for DRI's renewable energy research and services
- Educational opportunities for students
- Large space for "pilot-scale" experimental work
- Collaborative interactions with commercial technology developers

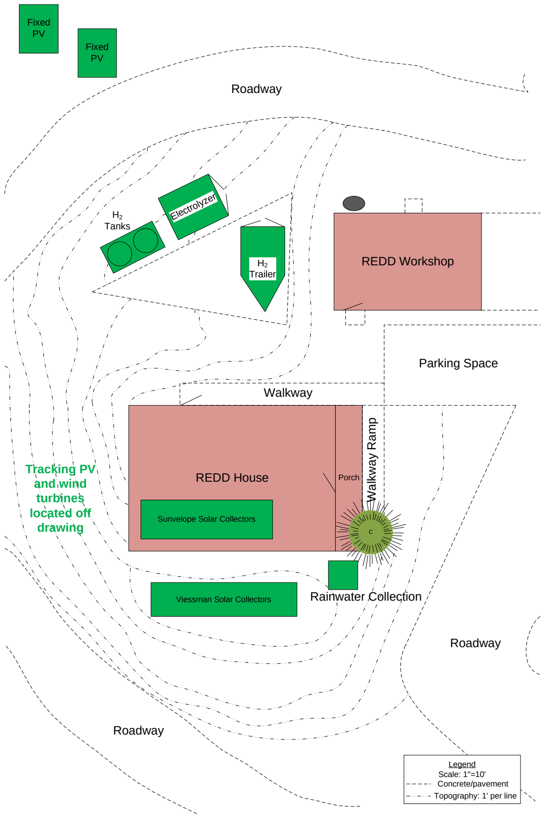

Fig. 1: REDD Facility Schematic.

1.1 REDD House

Electrons are generated for the facility through four solar PV arrays with an output of 5 kW. All of the arrays are south facing, and two of the arrays track from east to west. The arrays are of a conventional, monocrystalline construction. Two 1.5 kW small-scale wind turbines, mounted on 40 ft. (12m) tilt-up towers supplement the solar PV arrays. These components are somewhat scattered across the DRI Reno campus, but are all wired, with independent charge controllers, to a 48 VDC busbar located in the REDD Workshop. The busbar is connected to an inverter unit, located in the H_2 trailer (shown in Figure 1). A battery bank, consisting of 16 gelled-electrolyte 12 VDC batteries and wired for 48 VDC, is also located inside the trailer. The battery bank has a capacity of 196 amp-hrs which has the capability to provide 3 kw-hr at a slow discharge. Battery time to discharge is shown in Figure 2.

When excess electrons are generated, and the battery bank is fully charged, the control logic directs electricity to the 5 kW KOH hydrogen generator. At full capacity, 0.1 kg of H_2 is produced per hour and mechanically pumped to 100 PSI (6.9 bar). At this pressure, each H_2 tank can hold approximately 1.5 kg of H_2. The produced hydrogen is the fuel for the internal combustion engine once the batteries have discharged to their minimum voltage. The engine is then run until the batteries are charged to their maximum voltage; all while supply electricity to the facility. Each hydrogen tank can run the engine for approximately 45 minutes with an alternator output of 5 kW at 48 VDC.

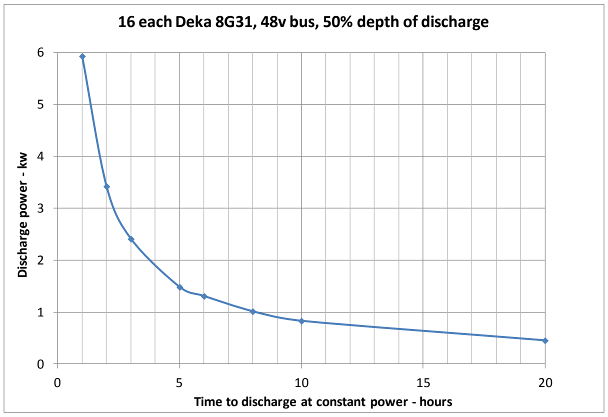

Fig. 2: REDD battery capacity.

During prolonged periods without renewably generated electrons, the control program will run the engine on propane. The control logic for the electrical system insures that the facility, including the parasitic losses in the solar thermal system will always have sufficient electricity.

The house is a factory-built modular design, set on a concrete foundation. Construction took place during the spring and summer of 2011. The house came fully equipped and included two bedrooms, utility room, one full bath, kitchen and living area. A porch was then added to the main entrance. The two bedrooms were converted into offices which are used by the DRI Green Power Program and the DRI Energy Auditing Team. The utility room houses the absorption chiller and accompanying components.

1.2 REDD Workshop

The workshop is an independent stick built design on a concrete pad. The concrete slab was divided into three sections which maintain a hollow air floor, a hydronic floor, and a baseline floor.[1] The workshop roofline is situated east-west so the solar air collector can face due south with a steep slope as to maximize collector performance during winter months. The workshop is equipped with electrical outlets connected to the renewable energy system, but also has grid-connected outlets to support biomass reactors. The workshop is connected to the house, H_2 trailer, and renewable energy components through underground conduit.

2. SOLAR THERMAL SYSTEM DESIGN

Although consisting of multiple buildings, the facility is divided into three systems based on functionality and controls; the electrical system, HVAC system for the house, and HVAC system for the workshop. This paper is focused on the HVAC systems for the house and workshop which are driven by solar energy.

2.1 REDD House HVAC

Heating and cooling, with the exception of a back-up propane furnace, is achieved through solar heated hot water. The system is driven by solar Array 1 and Array 2. Array 1 consists of eight 25 ft^2 (2.3 m^2) collectors comprising 200 ft^2 (18.6 m^2) of collector surface area. These collectors are considered conventional, utilizing copper pipes with a black absorber and glazing. They are mounted on a custom made rack on the south side of the REDD House, facing due south. With the use of turn buckles, the slope of the rack can be adjusted from 20˚ to 70˚ relative t horizontal for optimal seasonal heating. These collectors service a 120 gallon (454 L) water tank. These collectors are considered the test bench for the REDD facility as they are commercially available and OG-100 certified by the Solar Rating and Certification Company (SRCC). The working fluid in Array 1 is a glycol/water mixture is the working fluid in the collectors, exchanging energy to water through a double-wall heat exchanger unit external of the hot water tank. The water in the secondary loop then passes directly into the water tank.

Array 2 contains ten envelope flat-plate collectors, providing 210 ft^2 (19.5 m^2) of surface area. These collectors maintain a unique “envelope” design that is capable of expansion and retraction; allowing water to freeze and/or boil without harming the collector. This design allows the system to utilize potable water directly, without requiring a heat exchanger. The collector contains a black, stainless steel envelope (also acting as an absorber), and a glazing. These collectors were recently OG-100 certified by the SRCC. This system makes retrofit solar hot water systems less complicated as the existing water tank can be used without the need of an external heat exchanger. Furthermore, there is no requirement of charging the system with glycol, or risk of a glycol spill. Like Array 1, this array services a 120 gallon (454 L) water tank. Integrated piping draws hot water from both of these tanks to be used for heating and cooling of the REDD house. A schematic of the REDD house HVAC system is shown in Figure 3 and all of the solar thermal collectors can be seen in Figure 4.

The controls for the solar based heating and cooling of the REDD house are-governed by a conventional residential thermostat. When the thermostat is set to heating, and the temperature has dropped below the programmable set point, the hot water stored in the two 120 gallon tanks is pumped to a heat exchanger mounted below the propane furnace. A secondary thermostat determines when the water has dropped below the programmable set point of 140˚F (60˚C), in which case the propane relay in the furnace is powered on and the hot water pump is powered off. The blower for the furnace runs independent of the secondary thermostat. The heating heat exchanger has the capability to provide 54,257 Btu/hr (57244 kJ/hr) of heat at a flow rate of 8 GPM (30 LPM) and water at 180° F (82.2 ˚C).

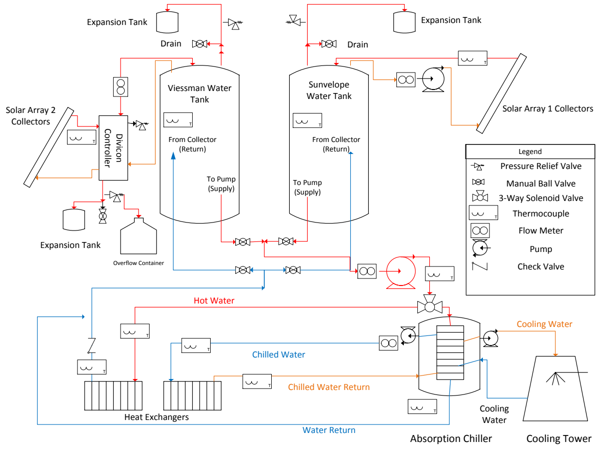

Fig. 3: REDD House HVAC Schematic.

Fig. 4: Solar Array 1 (rack mounted), Solar Array 2 (roof mounted); Workshop solar-roof air heater in upper right background.

When the house thermostat calls for cooling, controls are switched to the absorption chiller. The absorption refrigeration thermodynamic cycle provides efficient refrigeration through the absorption of the refrigerant into hot water (above 68˚C). By absorbing the refrigerant, a pump can be used instead of a compressor; a large energy savings. A schematic of the refrigeration cycle is shown in Figure 5. An absorption chiller rejects heat through a cooling water loop which requires a cooling tower to maintain operating temperature.

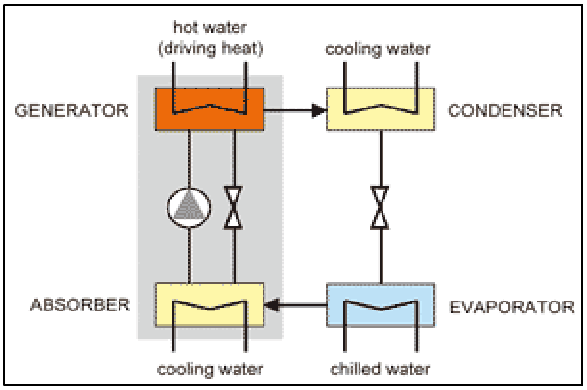

Fig. 5: Absorption Refrigeration Cycle [2]

This unit draws only 48 Watts (not including the hot water pump, and cooling tower water pump) to provide 17.6 kW of cooling. A Yazaki WFC-5 was chosen for this application as it is one of smallest units commercially available; still oversized for a 1200 ft^2 (111.5 m^2) house. If water is available at 180˚F (82˚C) and a flow rate of 19 GPM (72 LPM), the absorption chiller is capable of producing 5 tons of refrigeration. The produced chilled water, at 45˚F (7˚C) and 10 GPM (37.85 LPM), is then circulated to a second heat exchanger mounted under the furnace which has the capability to remove 42,635 BTU/Hr 44982 kJ/Hr) from the house. There is no backup cooling system for the house. However, it was quickly noticed that there was insufficient solar gain during summer evening hours to provide hot water at 155˚F (68˚C), although there was sufficient solar gain to continue heating the house. Since the building is unoccupied (no one is available to open the windows in the evening), a small-scale economizer was constructed and located in the attic. An enthalpy controller, and relay from the absorption chiller determines when a single actuator activates the dampeners such that air from inside the house is circulated with outside air whenever the enthalpy value is lower outside. The custom made economizer is shown in Figure 6. Although controls for the house are tied into the thermostat, the house is adequately monitored through a National Instruments data acquisition system that collects data 24/7.

2.2 REDD Workshop HVAC

The workshop is also heated and cooled through the use of renewable energy, using both solar thermal directly, and solar PV to power an evaporative cooler. The workshop utilizes a 578 ft^2 (53.7 m^2) site-built solar air collector. This air collector was built to demonstrate low-cost Do-It-Yourself (DIY) solar that can be built externally onto a house, or built in as the roof, such as is the REDD workshop. The collector acts as the steep (45˚) south facing portion of the roof, which can be identified in the background of Figure 4.

Fig. 6: Custom built economizer

The collector itself is a simple construction of sheet metal, wood, screws, and fiberglass for glazing specially made to resist Ultraviolet (UV) radiation for 20 years. Although the heat transfer characteristics of air are not as appealing as a liquid, the use of air offers several advantages; freezing or boiling problems are obviated, and air leaks are not important. In this particular design, air passes vertically up through channels and into a manifold that is ducted to a blower.

The solar heated air has several functions in the workshop. Firstly, the air passes through a series of heat exchangers containing water that is plumbed to two 120 gallon insulated water tanks. This hot water is then used for scientific experiments, hot water for the faucet, and to heat as storage for a hydronic floor system. After passing through the heat exchangers, and in heating mode, the air is channeled through a hollowed concrete floor section. Upon exiting the floor, the air is channeled into the room for space heating and to return into the collector. Furthermore, a slip-stream of hot air is used in a custom made laboratory drying oven specifically designed to dry energy-densified biomass. A schematic is shown in Figure 7.

A specially designed manifold was built to introduce the hot air into the hollowed out concrete floor. An evaporative cooler is mounted on the backside of this manifold, to be used during cooling periods. The nighttime-generated cool air then passes through the floor of the workshop and channels into the room, same as the hot air in the heating mode. The evaporative cooler is powered by the renewable electrical system that utilizes solar PV, wind turbines, as well as energy storage in batteries and hydrogen. Furthermore, the solar air collector becomes a closed loop during cooling periods such that hot water is still generated. The concrete floor of the workshop is divided into three sections for further research in the facility. The western one-third of the floor is a standard concrete floor to act as a baseline. The center one-third contains the hydronic system, and the eastern one-third is the hollowed out air system.

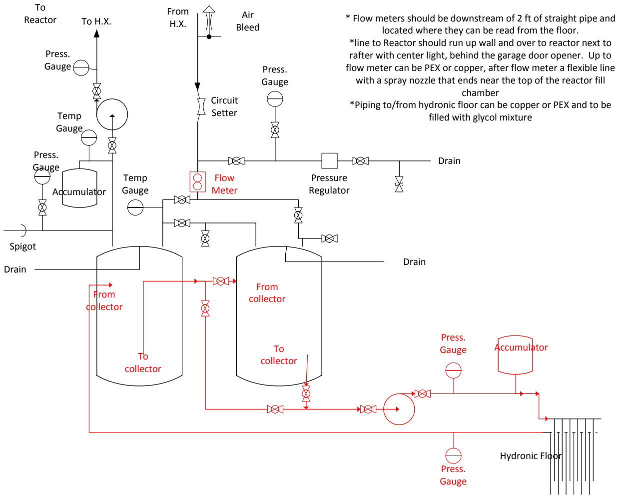
* Flow meters should be downstream of 2 ft of straight pipe and located where they can be read from the floor.
*line to Reactor should run up wall and over to reactor next to rafter with center light, behind the garage door opener. Up to flow meter can be PEX or copper, after flow meter a flexible line with a spray nozzle that ends near the top of the reactor fill chamber
*Piping to/from hydronic floor can be copper or PEX and to be filled with glycol mixture

Fig. 7: REDD Workhop HVAC System.

The workshop is monitored and controlled through a National Instruments data acquisition system to ensure sufficient information is available and allow for continued research. This system records data 24/7.

It is anticipated that the Workshop will eventually power a large distillation unit. If waterless toilets were employed in the house, then only gray water would be produced. By utilizing the solar system to evaporate this gray water, the necessity for a sewer connection or septic tank would be obviated.

3. RESULTS

Certain aspects of the system have been operational for over one year, while others are still not online. Data from the solar thermal applications in the REDD Laboratory have been generated for months; however, data from September 1st-5th of 2012 will be highlighted in this manuscript. The following graphs have been put together to demonstrate and compare the use of solar generated hot water to maintain the heating and cooling requirements of a small residence.

3.1 REDD House

Data were collected over several days to look at trends in the hot water storage tank temperatures as well as chilled water produced from the absorption chiller. Data for Figure 8 were obtained via thermocouples attached to the walls of pipes and tanks. The data shows that during the period of September 1st thru September 5th, both solar thermal system on the REDD house reach tank temperatures of roughly 80˚C (176°F) and could revive this tank temperature after several absorption chiller cycles; resulting in chilled water at 10˚C (50°F). Both systems reached this temperature at roughly the same time during the day. The orange line in the graph represents the air temperature inside the house which rises above the thermostat set point in the evening. At this point the economizer (which alleviates this temperature increase) had not yet been installed. The graph also shows that the absorption chiller operated for short intervals roughly 5 times throughout the day for short intervals. The team acknowledges that this operation may not represent the most efficient use of the chiller.

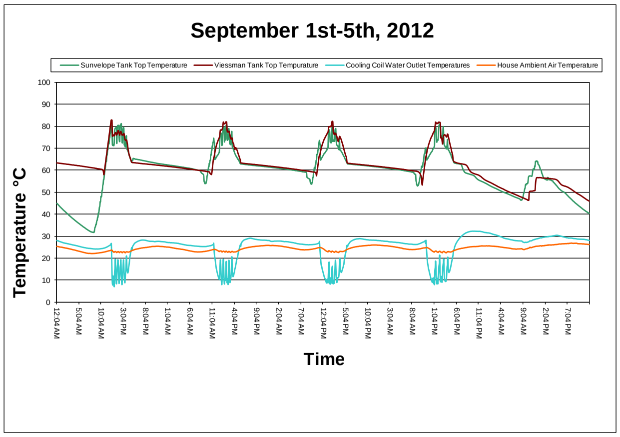
September 1st-5th, 2012

Fig. 8: Absorption Chiller Operation.

In a comparison of collector and system design between Array 1 and Array 2, there is stark contrast in rate and duration of heat exchange. Figure 9 shows that the Array 1water side of the system experienced large temperature increases through the heat exchanger but did not run for as long a duration as the Array 2 System. For comparison, the graph shows the inlet and outlet temperature of the

Array 2 collectors and the inlet and outlet of the water side on the double-wall heat exchanger for the Array 1 System. These points were chosen as the Array 2 system utilizes tank water directly while the Array 1 system utilizes a glycol mixture in the collectors. The difference shown in the graph is believed to be a result of differences in the control logic. The Array 1 system does not run the water side of the heat exchanger until the glycol side has reached high temperatures whereas the Array 2 system circulates water directly as soon as there is a 12˚ temperature advantage in the collector compared to the tank. However, note that in Figure 7 both tanks reached their highest temperature at approximately the same time.

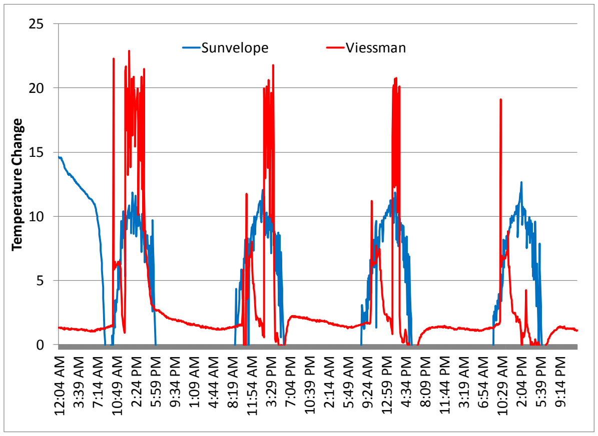

Fig. 9: Working Fluid Temperature Increase.

Because of concern about operation of the flow meters in the house system, it was assumed that flow rates remained constant. However, efficiencies of the systems were calculated with an understanding that these results may vary. During a time of operation when the pumps were run constantly throughout the day, a comparison of collector efficiency versus solar radiation was calculated; showing a wide range of results. A main variable affecting the efficiency results is that the absorption chiller ran at times, drawing energy from the tanks. However, there is an apparent cluster of data points over 50% during peak solar radiation for both collectors. Efficiency of each system is shown in Figure 10 and calculated as:

$$\eta= Q_{out}/(\text{Solar Radiation} * \text{Collector Area})$$ [3]

Q_{out} is the useful energy out of the collectors, calculated as follows:

$$\text{Qout [BTU/Hr]}=60*\nu*\rho*Cp*(T_{out} – T_{in})$$ [3]

For this equation, ν□is the volumetric flow rate, and ρ is the density of the working fluid. Solar radiation data was being collected with a Zipp & Konen pyranometer.

3.2 REDD Workshop

The solar air collector was operated continuously throughout the day in an effort to reach maximum temperature. During summer months, the water temperature in the two tanks reached 160˚F (71˚C) by 11:00 am; sufficient for the absorption chiller. Although the area is larger, 577 ft^2 (53.7 m^2) versus 410 ft^2 (38 m^2) for the two solar thermal liquid collectors, the team was uncertain that the required temperature of 155˚F (68.3 ˚C) could be reached in both tanks. With cooler temperatures in September, the two tanks only reached 131 ˚F (55˚C) to 140 ˚F (60˚C) by midday, as shown in Figure 11. It also appears that heating a single tank would not yield adequate temperatures to operate the absorption chiller, since the air collector absorber only reached 158 - 167˚F (70- 75˚C) during this period.

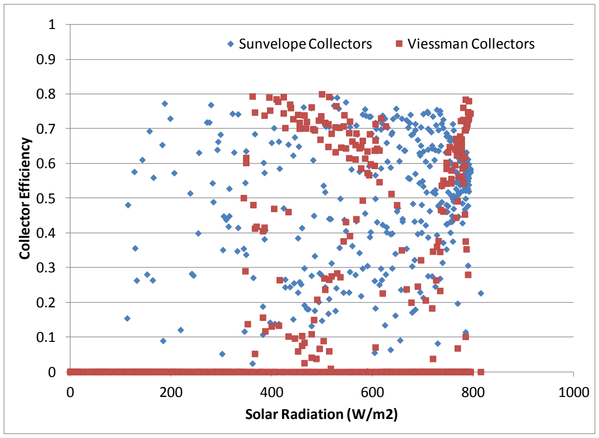

Fig. 10: Efficiency Comparison.

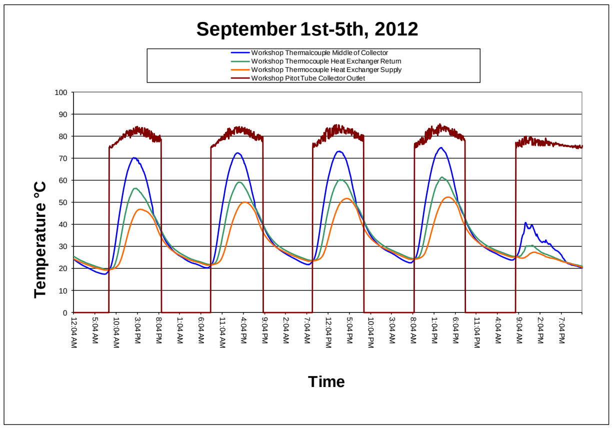

Fig. 11: Workshop Air Collector Operation.

4. DISCUSSION

After extensive testing of the REDD Laboratory HVAC system, a few observations have been made by the team:

- Both Array 2 (210 ft^2) and Array 1 (200 ft^2) are sufficient to run the absorption chiller until mid afternoon during summer months in Reno, Nevada
- Although the Array 1 system appeared to be more efficient (56% versus 50%), with economies of scale, the Array 2 system should reduce the installed cost.
- Additional cooling techniques are required to maintain a comfortable temperature during the evening hours of summer months. In this case, an economizer was sufficient; however, a larger hot water storage, and additional cold water storage, may be of greater benefit
- The site-built solar air collector can reach the temperature necessary to operate the absorption chiller, but it is unclear whether the system would be able to maintain several operating cycles of the absorption chiller
- Proper control logic can have a large impact on both the effectiveness and efficiency of each system. For example, the controller for Array 1 occasionally shut down the system due to overheating of the collectors. The system then remained inactive until the following day.
- Absorption refrigeration is a viable method for efficient air conditioning; however, it is a more complicated and expensive system compared to conventional central air conditioning units. Developing an economical small-scale absorption chiller should be researched.
- Separate logic should be used for heating and cooling modes; however, switching back and forth in the swing seasons may have a large impact on operation of the system.

In conclusion, the team will continue to optimize the system through improvements in plumbing, collector designs, and control algorithms. An estimated financial cost can be found in Reference 1; however, a more in-depth economic analysis will be performed.

5. ACKNOWLEDGEMENTS

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