FINAL REPORT

DRI Renewable Energy Center

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Desert Research Institute

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Acronyms and Abbreviations

CFM	Cubic feet per minute
CFP	National Instrument Compact Field Point controller
CO_2	Carbon dioxide
DAQ	Data acquisition system
DDS	Duct distribution system
DOE	U.S. Department of Energy
DRI	Desert Research Institute
GHG	Greenhouse gas
GPM	Gallons per minute
GTI	Gas Technology Institute
H_2	Hydrogen
HE	Heat exchange
HHI	Home heating index
HHV	Higher heating value
HTC	Hydrothermal carbonization
HTP	Hydrothermal pre-treatment
HVAC	Heating, ventilation, and air conditioning
ICE	Internal combustion engine
kW	Kilowatt
NREL	National Renewable Energy Laboratory
NVR	Non-volatile residue
OEM	Original equipment manufacturer
PDU	Process development unit
pH	Measure of acidity in an aqueous solution
PID	Proportional integral derivative
P-J	Pinyon-juniper
PV	Photovoltaic
PWM	Pulse width modulation
R&D	Research and development
RDD&D	Research, development, demonstration, and deployment
REC	Renewable Energy Center
REEF	Renewable Energy Experimental Facility
RPM	Revolutions per minute
TF	Torrefaction
TGA	Thermogravimetric analysis
TOC	Total organic carbon
UNR	University of Nevada, Reno
USDA	U.S. Department of Agriculture
VDC	Volts, direct current
VFD	Variable frequency drive
VI	Virtual instrument
VOC	Volatile organic compounds

1. Background and Introduction

For many years, the Desert Research Institute (DRI) has been interested and involved in small-scale renewable energy systems – particularly in activities that integrate, monitor, control, and optimize the performance of systems consisting of multiple components. In 2007-2008, DRI undertook a planning study (with DOE funding) to define the steps necessary to develop a more formalized renewable energy center (REC) that would help grow DRI's capabilities and expertise in the areas of renewable energy research, development, demonstration, and deployment (RDD&D). As described in the final report for this DRI-REC planning study,[1] the overall mission for the DRI-REC was defined as follows:

1. Provide an organizational umbrella under which all of DRI's renewable energy RDD&D activities are organized and coordinated.
2. Provide a recognizable "point of entry" for sponsors, collaborators, and other supporters to interact with DRI in the area of renewable energy.
3. Provide a sound foundation of research expertise and capabilities from which DRI can build core strengths related to renewable energy RDD&D.

It was recognized that the topic areas related to renewable energy are extremely broad, and that it is not possible for DRI to have a significant impact in all areas. Therefore, part of this initial planning effort focused on identifying specific areas of emphasis, where DRI already had some relevant expertise that could reasonably be expected to grow in the future. Four specific areas of emphasis were identified, and plans were developed to coordinate these areas within the DRI-REC:

1. Integration of renewable energy systems
2. Enhanced wind energy research capabilities
3. Biomass and biofuels
4. Education and outreach

Following this initial planning effort, additional DOE funding was secured to help develop the DRI-REC, under a project called "Renewable Energy Center – Desert Research Institute: Phase II," or more simply, the "DRI-REC-II Project." The principal objective of this second project was to implement the plans developed under the earlier planning study. As described in the DRI-REC-II Final Report, this project enabled DRI to purchase, install, and utilize various research equipment and tools to enhance our expertise and capabilities in renewable energy RDD&D. [2]

Under the DRI-REC-II Project, we initially planned to reconfigure DRI's existing renewable energy system in more or less its current location, while adding a few additional components to increase the capacity and improve reliability. However, after this project was underway, DRI obtained separate funding from DOE that enabled the purchase and installation of a pre-manufactured house and detached garage/workshop. Together, these two structures (along with various supporting systems) are known as the DRI Renewable Energy Experimental Facility (REEF). Now having the REEF available, some of the DRI-REC-II Project activities were re-directed to utilize this facility as the focal point for DRI's renewable energy efforts.

Development of the REEF itself is described in another report.[3] The DRI-REC Project, which is the focus of the present report, utilized the REEF to accomplish many of its objectives.

2. Project Objectives

The principal objective of this DRI-REC Project was to utilize a flexible, energy-efficient facility, called the DRI Renewable Energy Experimental Facility (REEF), to support a variety of renewable energy research and development (R&D) efforts, along with education and outreach activities. This work included the following sub-objectives:

(1) Optimize energy efficient systems and devices to enable off-grid operation of the REEF House

(2) Develop a gas engine R&D testing platform to enable investigation of multiple gaseous fuels

(3) Develop and optimize pre-treatment technologies for converting Nevada-relevant biomass into higher value products

Both the REEF House and REEF Workshop were used to achieve these objectives. These buildings contain work space to house and support renewable energy research activities, as well as education and outreach programs. In addition, the REEF Workshop includes open bay type space where larger experiments can be conducted. Taken together, these two structures serve as a renewable energy laboratory, enabling an expansion of DRI's capabilities and expertise in areas of renewable power generation, energy efficiency technologies, and biomass/biofuels. Additionally, this facility can be used as a platform for application of energy efficiency measures within residential structures, and is a suitable venue for showcasing energy efficient technologies to the public.

While not stated explicitly as a sub-objective, it was also intended to utilize the DRI-REEF for education and outreach purposes – both during development of the facility, and subsequently, through on-going activities and events hosted at the REEF. All project objectives were met through successful execution of numerous individual project tasks. The main tasks are identified below. For each task, we discuss the activities that were undertaken and the accomplishments that were achieved.

3. Project Tasks

3.1 Develop Renewable Energy Capabilities of the DRI-REC

A major feature of the DRI-REC (also called the DRI-REEF) is an off-grid capable house. In addition, the REEF includes a garage (also called the REEF Workshop), which is not off-grid capable, but still contains many renewable energy features. The design and construction of the DRI-REEF were conducted as part of a different DOE-funded effort, although many of these activities were coincident with this project. A final report describing the design and construction of the REEF is available elsewhere. [3] This report describes and documents all activities undertaken to upgrade DRI's renewable energy capabilities and integrate these into the REEF. In addition, this project involved considerable education and outreach activities, which are also documented in this report.

In the sections below, the various tasks comprising the DRI-REC project are described. Although not strictly a part of this project, we begin with a brief description of development of the REEF itself, because this was so intertwined with the subsequent enhancements and utilization of the facility that occurred under the DRI-REC Project.

3.1.1 Development of the DRI-REEF

As shown in Figure 1, the REEF is located near the northwest edge of DRI’s Dandini Campus in Reno, Nevada. This site was previously used as a parking/storage lot for vehicles and other large field equipment (see Figure 2).

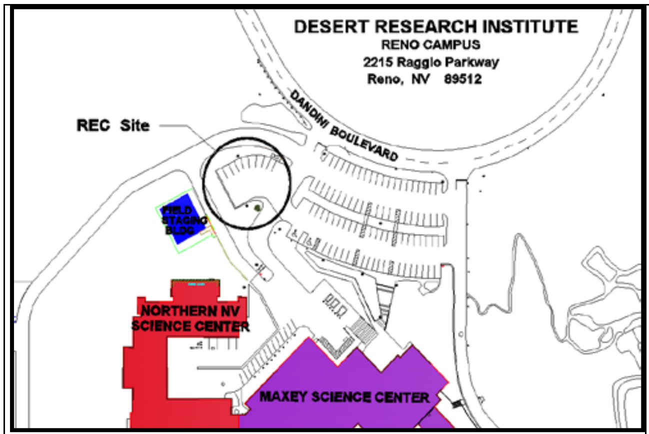

Figure 1. Location of DRI-REC (REEF) on Dandini Campus.

Figure 2. Photo of DRI-REC (REEF) site before start of construction.

Due to various complications, considerable delays were encountered with design and construction of the REEF. Originally, a 1400-ft^2 house was planned, but this was reduced to 1200-ft^2 due to funding constraints. Actual construction activities did not begin until January of 2011, with initial progress being hindered by inclement weather (see Figure 3).

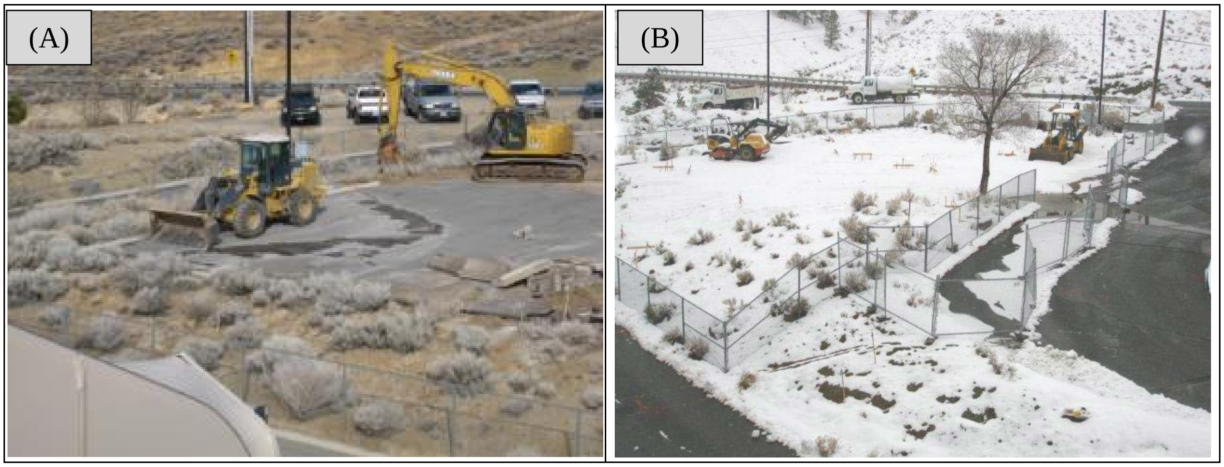

Figure 3. Photos of DRI-REEF construction site.
(A) Jan. 28, 2011: demolition work begins; (B) Feb. 18, inclement weather stops work.

An original schematic layout of the REEF site is provided in Figure 4, which illustrates the very limited space that was available for this facility. The 1200-ft^2 REEF House is situated near the center of the site; the 600-ft^2 detached REEF Workshop is located to the northeast of the House. Numerous other components (solar PV panels, solar thermal collectors, electrolyzer, etc.) are also located on the site, although their final placement varied somewhat from this original design.

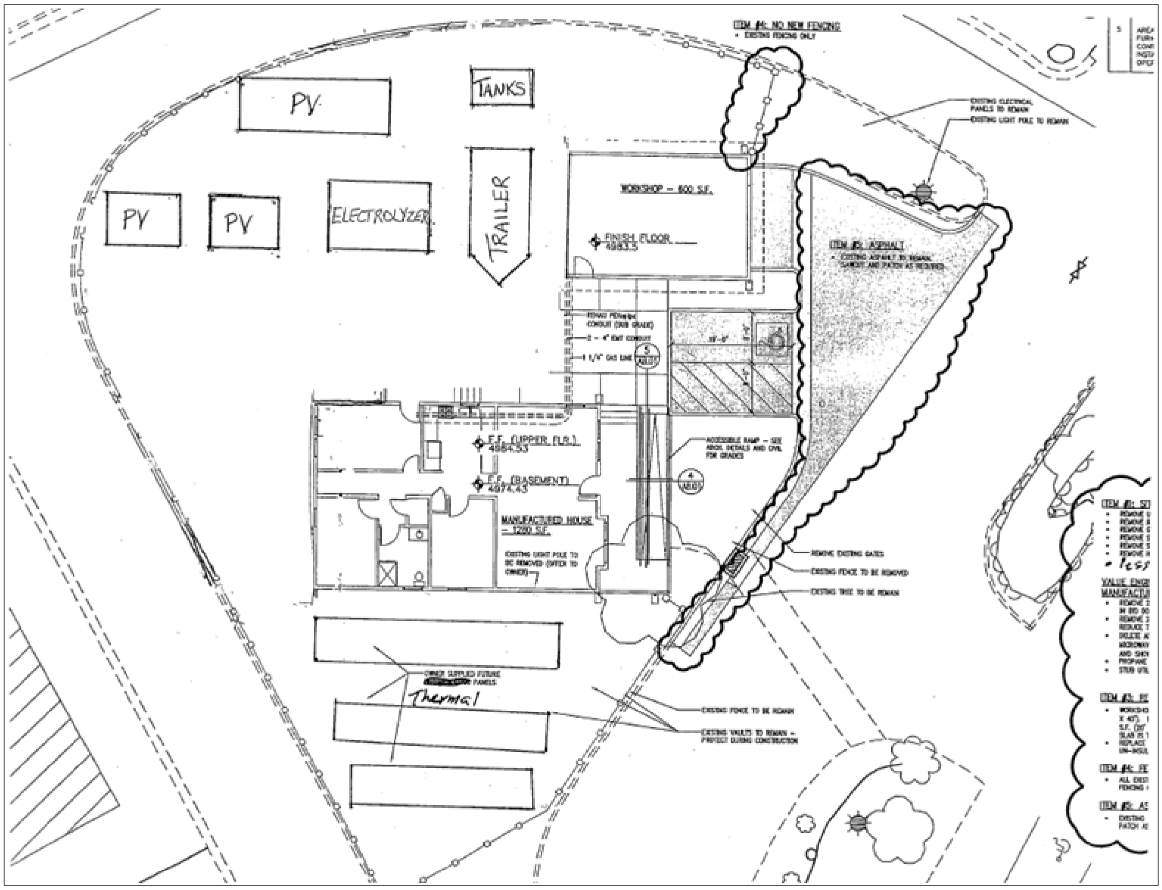

Figure 4. Schematic depiction of the DRI-REEF.

The REEF Workshop is a 600-ft^2 wood-framed structure that was built on-site. Besides housing much of the electronics and control systems for the off-grid operation of the REEF House, this Workshop provides a large, open space for conducting biomass/biofuels R&D that cannot be done in a typical indoor wet laboratory. Figure 5 provides photos of the REEF Workshop during its construction. A major feature of the Workshop is the solar thermal air system that was integrated into the roof during the construction phase of the project. More information about this is provided in Section 3.1.3, and in Appendix II.

Figure 5. Photos of DRI-REEF Workshop Construction.
(A) outside construction; (B) preparing roof for solar thermal collector; (C) completed outside; (D) inside view

The REEF House is a 1200-ft^2, factory-built structure. As documented in the photo collage of Figure 6, this house was delivered to DRI in two sections, which were then combined on-site and placed on the foundation prepared for it. Although the house was delivered in June of 2011, it was not ready for occupancy until September, as significant finishing work was still required, including wiring, plumbing, painting, carpeting, and installation of a sprinkler system. Once the house was approved for occupancy, we were able to introduce various modifications and enhancements to make it off-grid capable, and to serve as a testbed for different renewable energy components and systems.

Figure 6. Photos of DRI-REEF House installation.

(A) Foundation for house; (B) REEF-Workshop located behind the REEF-House foundation; (C-G) delivery and installation of REEF-House on June 30, 2011; (H) nearly completed house on July 18, 2011.

3.1.2 Upgrade and Expand Existing Renewable Power Equipment

Prior to the start of this project, DRI had a functioning, small-scale, integrated renewable power system, consisting of several components -- including two 1.0-kW Siemens Solar PV arrays and two 1.5-kW Bergey Wind Turbines that were connected to a 5-kW Stuart Electrolyzer through a busbar and inverter system. Hydrogen produced by the electrolyzer during times of excess renewable power was stored in a low-pressure tank (100 psi) and burned in an internal combustion engine/generator set when additional electrical power was needed. A battery pack for energy storage was also included as part of this integrated system. Under the present DRI-REC Project, enhancements were made to all these existing components, and additional components were incorporated into the system. These activities are described below for each of the major sub-systems comprising the renewable power system. A revised layout of the REEF site (showing the location of each major component) is provided in Figure 7.

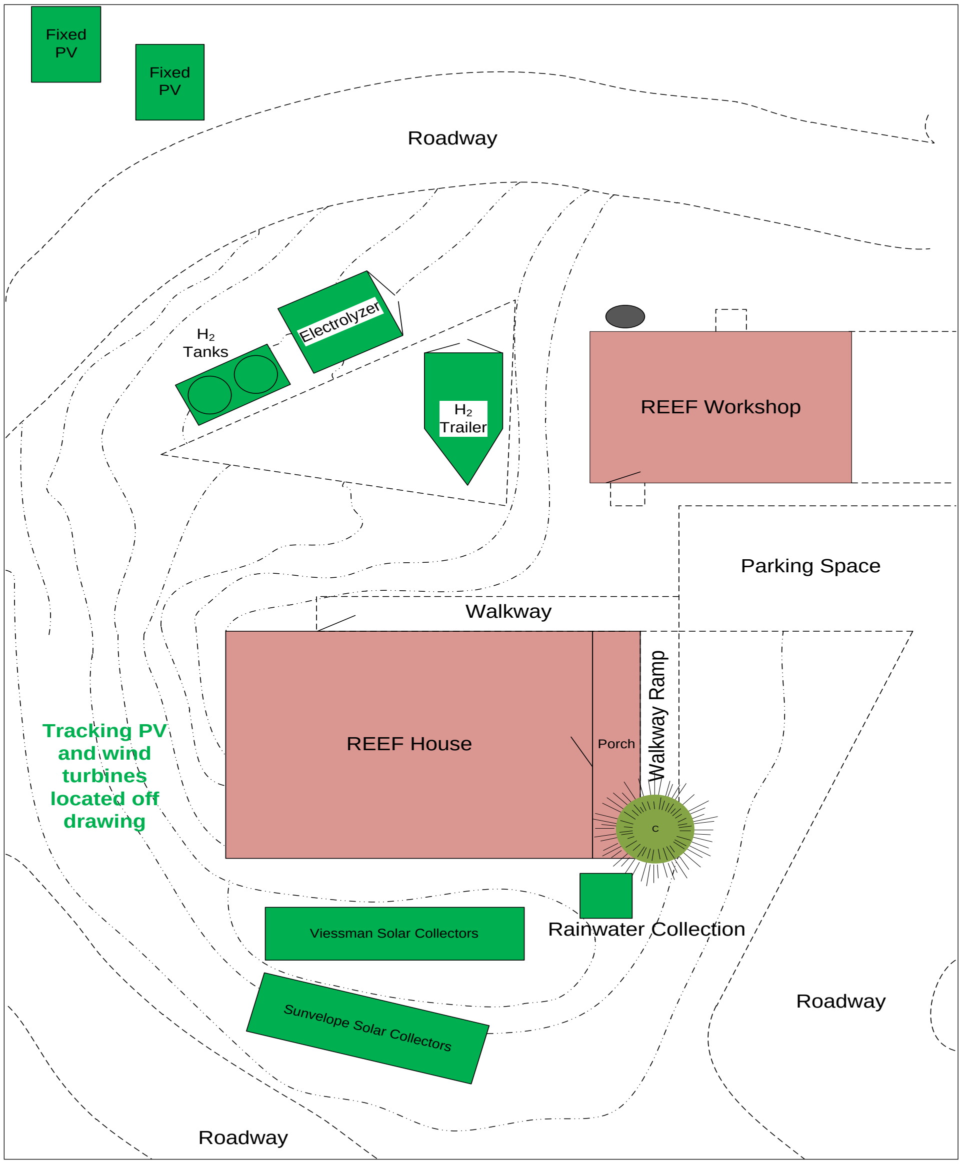

Figure 7. Revised layout of REEF site.

3.1.2.1 Wind Turbines

DRI's original renewable power system included two Bergey BWC1500 wind turbines that were mounted on 80-foot towers. Due to difficulties in accessibility and maintenance, the two 80-ft towers were replaced with two 20-meter, tilt-up towers. The new towers were placed on the same concrete foundations used for the old towers, although several new concrete anchors had to be installed. Photos documenting installation of these new towers are provided in Figure 8.

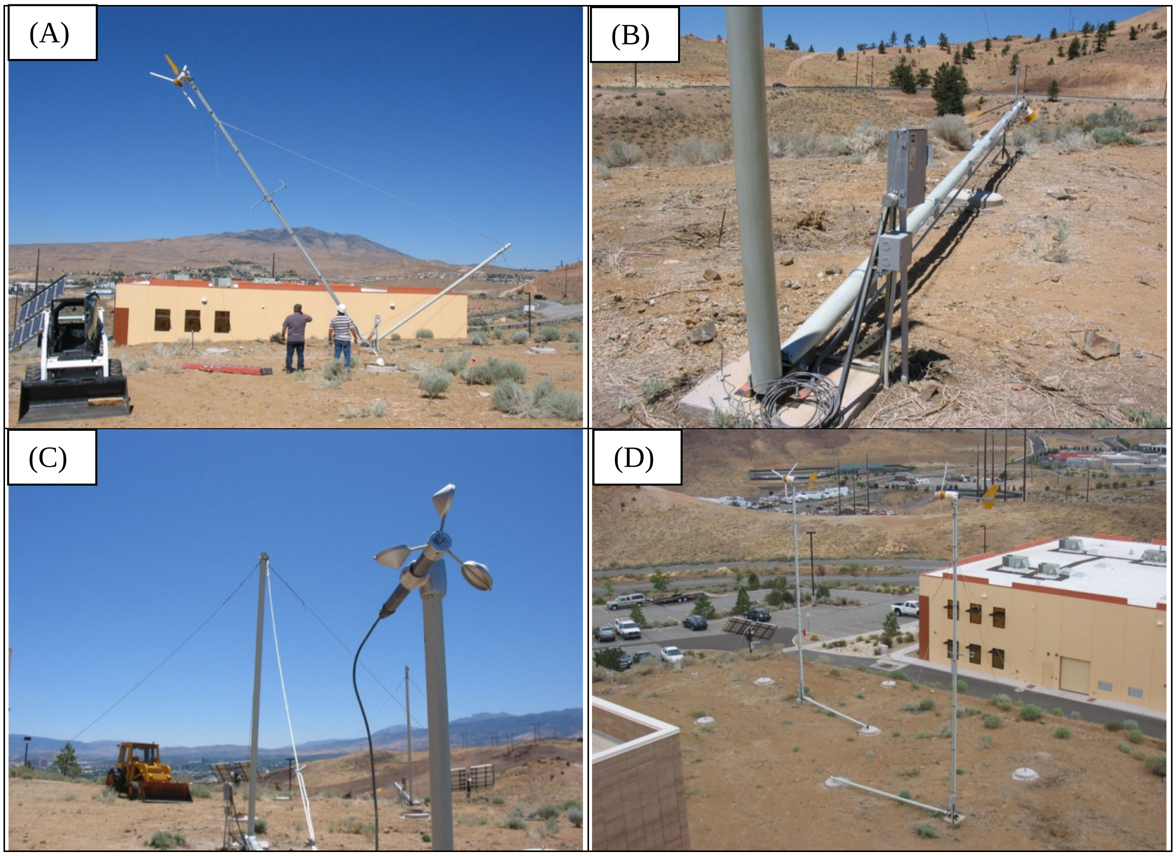

Figure 8. Erection of Bergey wind turbines on new, 20-m towers.
(A) tilt-up tower, (B) base of tower, (C) instrument arm on tower, (D) fully installed turbines.

To better integrate within the entire renewable power system, the Bergey wind turbines were converted to 48VDC configurations. These units are now routinely providing electricity to the REEF, and the performance of the system is being monitored continuously. In addition, meteorological instruments mounted on each tower are continuously transmitting data of solar radiation, wind speed, and wind direction.

3.1.2.2 Solar PV Arrays

Prior to the start of this project, DRI had two 1.0 kW Siemens solar PV tracking arrays that had been functioning for over 10 years. These units were incorporated into the DRI-REEF, although their physical location was not changed. However, these units were rewired from 24 VDC to 48 VDC. New wiring was also laid to connect these Siemens arrays directly to the REEF Workshop.

Under this DRI-REC project, we purchased two additional PV arrays (Samsung LPC 2355M-02) and installed them on fixed, horizontal racks north of the REEF. Each of these new mono-crystalline arrays consists of eight 235 W rated panels, for a total of over 3.5 kW. These arrays, which are wired at 48 VDC, face due south and are tilted at approximately 45°. Following initial installation, it was observed that at particular times during certain days of the year, one of these two arrays partially shaded the other. To eliminate this problem, the configuration was modified slightly, by adjusting the location of the frames holding each array.

The electrical output from all PV arrays was routed into the REEF Workshop for power conditioning, before being routed to power inverters, located within the enclosed trailer just west of the REEF Workshop. Photos of both the old Siemens PV arrays and the new units are provided in Figure 9. Both systems are now providing electricity for the REEF, with the current and voltage being monitored by a LabView control and data acquisition system.

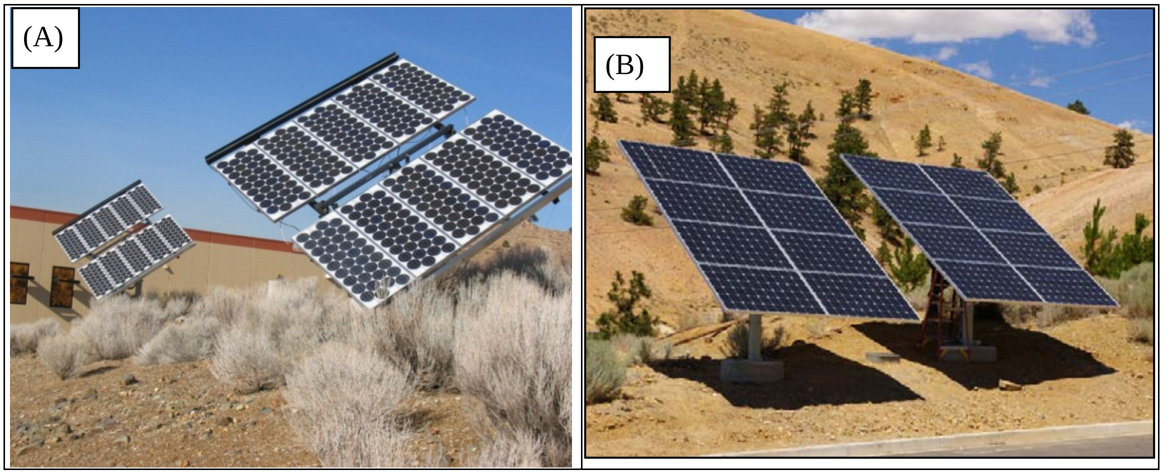

Figure 9. PV arrays included in the DRI-REEF: (A) 2.0-kW Siemens system; (B) 3.5-kW Samsung system.

3.1.2.3 Electrolyzer and Hydrogen Tanks

For several years prior to the start of this project, DRI had been using a Stuart Energy SunFuel 5000 electrolyzer to produce hydrogen from renewably-generated power originating from the Bergey wind turbines and Siemens PV arrays described above. This electrolyzer can draw up to 5 kW to produce 1 m^3 of H_2 per hour. Electrolysis is achieved in 13 KOH cells that are located within a shipping container.

While this electrolyzer was originally sized for use with two 1.5 kW wind turbines and two 1.0 kW solar PV arrays, which provide a total of 5 kW, it is quite rare that both wind turbines and solar panels produce maximum power simultaneously. Thus, the electrolyzer was typically not run at full power capacity, and had excess capacity to utilize in the current DRI-REC project. In addition to the original power inputs, electrical power from the two new micro-crystalline PV arrays was added to operate the electrolyzer. This addition enables the electrolyzer to function closer to its maximum capacity. However, it also produces more hydrogen than before, so a second hydrogen storage tank was required. (It was also anticipated that additional H_2 storage would be required to satisfy the power demands of the REEF House.) The volume of each H_2 storage tank is 2.5 m^3, and the tanks are rated to 120 psi. The electrolyzer is equipped with a mechanical pump to compress the H_2 to 100 psi. The tanks were pressure tested before putting them into service.

The electrolyzer and both hydrogen tanks have been relocated to concrete pads north of the REEF House (see schematic in Figure 7.) The concrete pad that the electrolyzer container sits on includes a curb that serves as a containment structure. Photos of the electrolyzer container and the hydrogen tanks are provided in Figure 10.

Figure 10. Electrolyzer and hydrogen storage tanks within the DRI-REEF.

The electrolyzer requires heating in winter, which accounts for a large energy draw against the renewable power system. In an effort to reduce this parasitic loss, a small (8'x8') solar air collector was built to rest against the south facing wall of the container. A small blower and ducting were attached to the air collector to blow warm air into the electrolyzer container. A photo of this solar thermal collector unit (in a horizontal position) is shown in Figure 10. A custom-built stand holds this air collector at a slope of 60°, which is ideal for collecting solar radiation during winter months.

A schematic showing the plumbing for the electrolyzer and H_2 storage tanks is provided in Figure 11. Piping was installed to deliver the produced H_2 from the electrolyzer to the storage tanks. From the storage tanks, a line delivers H_2 to the trailer, where an internal combustion engine (ICE) coupled to an electrical generator is installed. All these lines were also equipped with appropriate instruments and valves. In addition to the piping, electrical wiring was installed to power the electrolyzer.

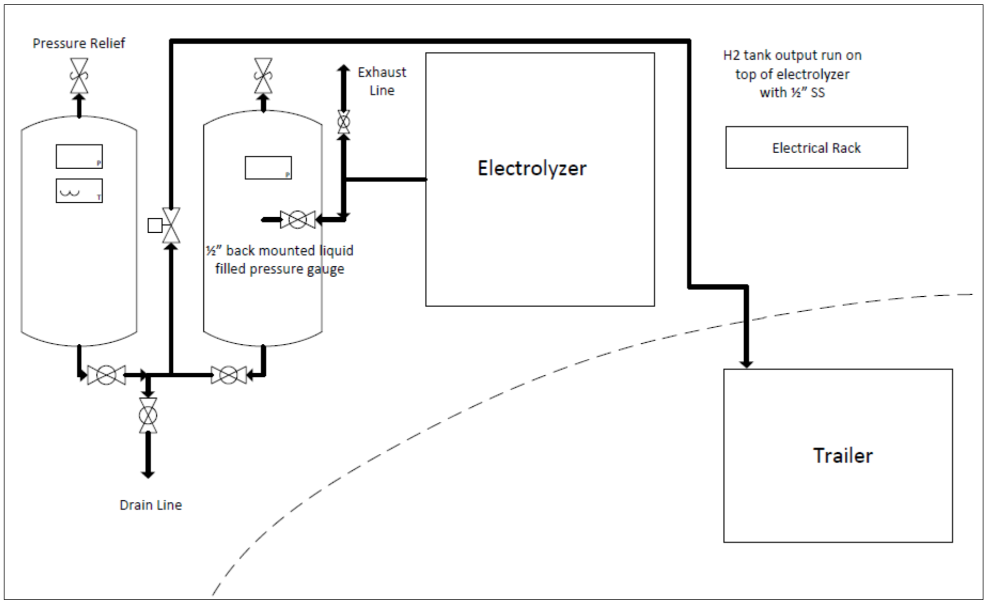

Figure 11. Piping schematic for hydrogen/electrolyzer system.

The electrolyzer was charged with the KOH solution and all associated electronics were connected. The computer that controls the electrolyzer unit was installed in the REEF Workshop. This computer also communicates with the National Instruments compact FieldPoint (cFP) unit that is located within the trailer. The cFP unit sends the computer a command for when to operate the electrolyzer, and how much electricity to use for electrolysis.

3.1.2.4 Trailer-Based Renewable Power System

Under a previous DOE-funded R&D project, a gaseous-fueled, spark ignition, 3-cylinder Daihatsu engine was modified, coupled with an electric alternator, and installed in a portable trailer.[2] This engine/genset is used to supply electrical power to the REEF during times when the direct renewable power supply (from solar PV and wind turbines) and battery-stored power are inadequate. The original system included both 24VDC and 48VDC components. Under the present DRI-REC project, all components were upgraded to a 48VDC configuration. Photos of the outside and inside of this trailer are provided in Figure 12. Other upgrades to the trailer system include the following:

(1) The compact FieldPoint (cFP) controller was modified to monitor the inverter current produced by the genset.

(2) An isolated power supply that operates from the 48V battery bank to power the REEF unit was installed.

(3) Power conductors were run from the genset alternator to the Outback inverter.

(4) A 100-amp circuit breaker was added on the DC side of the Outback.

(5) The alternator was wired through the breaker and onto the DC bus.

(6) 100-amp power cables were installed to connect the REEF Workshop bus to the battery bus inside the trailer.

Figure 12. Trailer-based renewable power components incorporated into the DRI-REEF. (A) Outside of trailer; (B) inside of trailer, showing Daihatsu 950G engine, Outback inverter system, and battery bank.

A control program in LabView was developed to operate the engine and verify satisfactory performance when using propane fuel. This included verifying the gas detectors, mass flow meter, and engine controls. Propane is normally used as the back-up fuel when hydrogen is not available, although different engine set-points are used for each fuel type. A flow chart of the control logic for the LabView program is shown in Figure 13.

Upon initial start-up of the engine it appeared that some of the electronics were affected while moving the trailer from its previous location to the REEF. In particular, the following problems were noted:

- The relay that controls the coolant pump was not functioning properly.
- The cFP channel for engine “auto start” was not working properly, so the starter was not receiving proper voltage.
- A faulty power supply was detected.
- New firmware had to be installed into the Woodward throttle control module.

After considerable troubleshooting, all these (and other) problems were solved, and the engine system was demonstrated to work satisfactorily.

This trailer-based system also includes a small battery bank that is used for energy storage, in addition to serving as a buffer for high load operations and component switching applications. Previously, this battery bank consisted of twelve 12 VDC gelled-electrolyte Deka batteries. In order to increase the capacity of the system for the REEF, the battery bank was increased to sixteen batteries. At a 50% depth of discharge over 20 hours, the battery bank has a capacity of 196 amp-hr. Figure 14 shows the battery capacity at different discharge rates. These batteries are located in the trailer and can be seen in Figure 12(B).

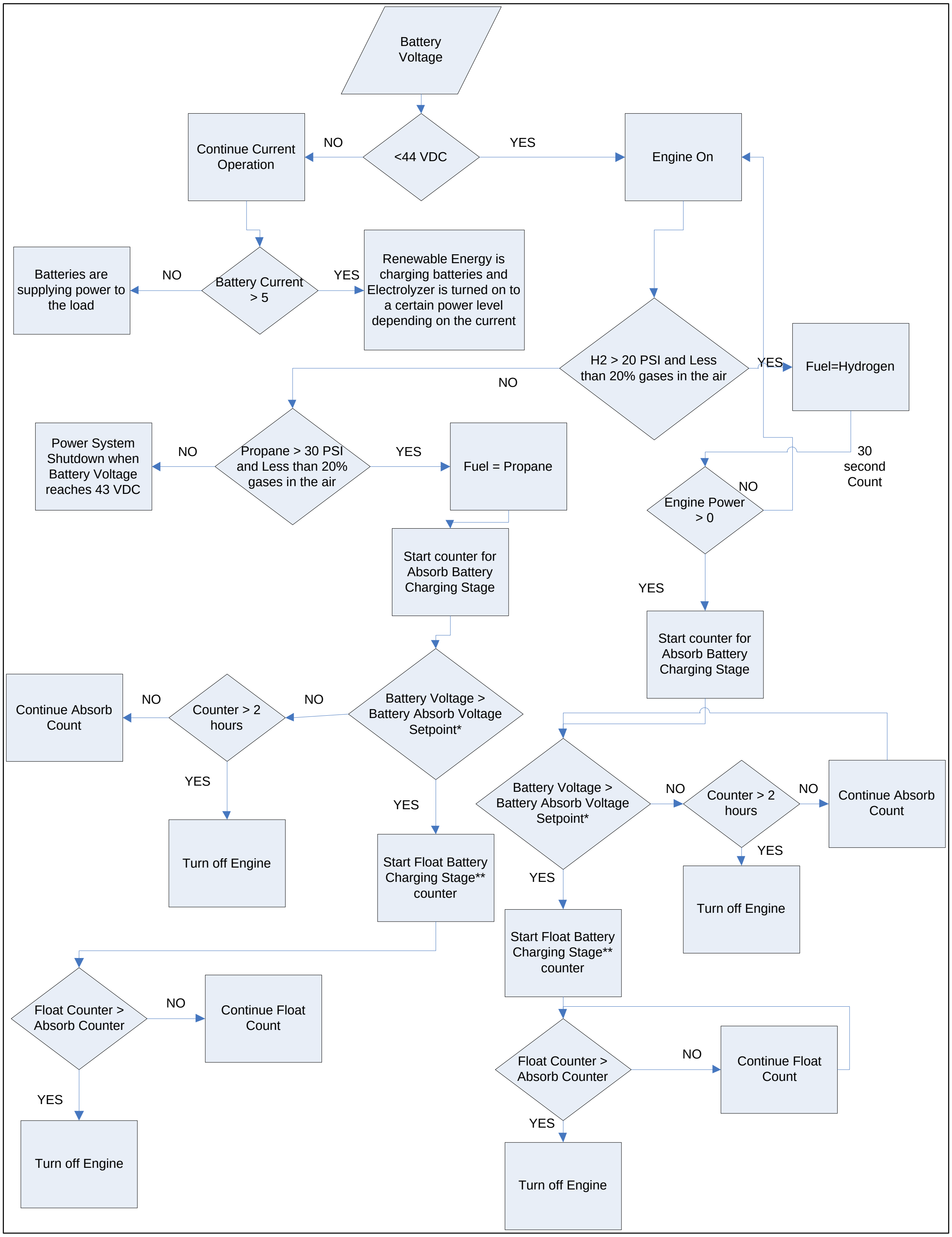

Figure 13. Control logic for engine/genset used in DRI-REEF.

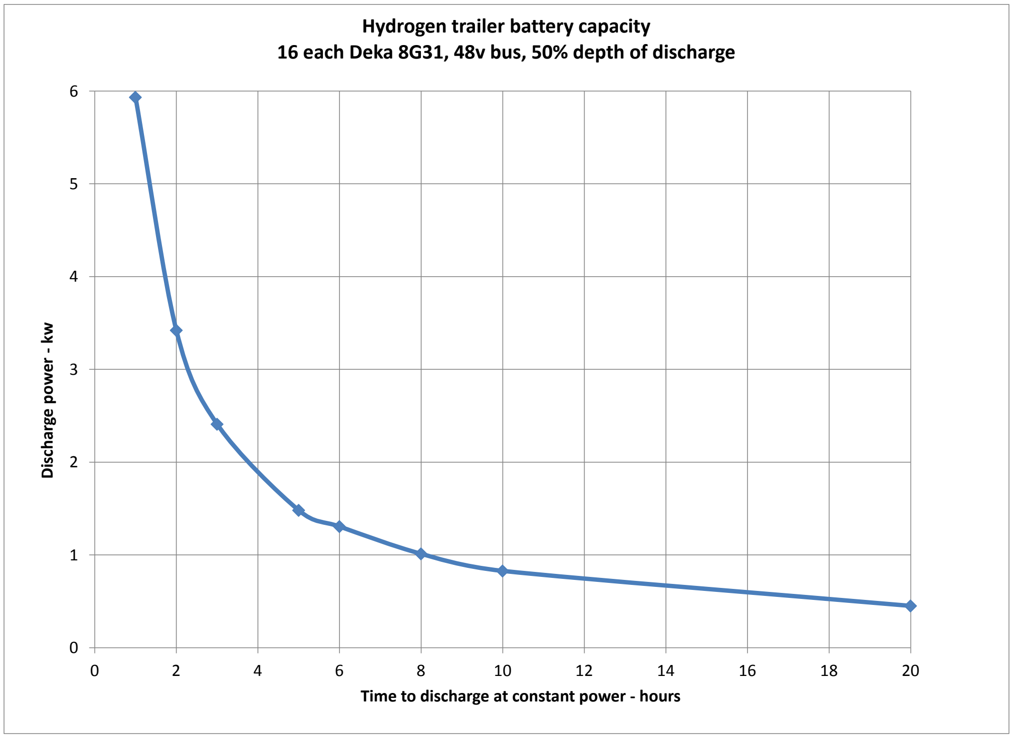

Figure 14. Testing of battery bank capacity.

3.1.3 Install Renewable Energy Systems in REEF Workshop

The REEF Workshop is intended to serve as a pilot-scale laboratory facility for conducting larger experiments than can be accommodated within a conventional laboratory. Because of anticipated large and variable electrical power demands, it was not suitable for the REEF Workshop to be configured for off-grid operation. However, several novel renewable energy capabilities were built into the REEF Workshop – particularly those enabled by collection and use of solar thermal energy. These features are described below in more detail. In addition, a separate report on the REEF Workshop is included as Appendix II.

3.1.3.1 REEF Workshop Solar Air Collection System

The REEF Workshop building shell was completed with a 45^{o} sloped roof facing north and south. The north side was conventionally shingled. On the south side, a 34-ft. by 17-ft. solar collector air heater was built on-site as the finished roof. The construction of this collector is documented in a separate report (see Appendix II). Key features of the construction are described below, and are illustrated in the photo collage of Figure 15.

Figure 15(A) shows the roof framed in with 2x4 wood studs. The perimeter was caulked, as were joints between the plywood sections forming the roof surface. Every two feet, 2x4 studs were screwed into the rafters below to form bays that support black sheet metal absorber plates and the glazing cover on top. Near the bottom of each bay is a 4 inch hole which allows air to enter the collector from a sheet metal header inside the building (see Figure 15(B)). Near the bay top is a similar exit hole and header where hot air exits the collector. The east and west bays are roof overhangs, so the adjacent bays have larger, 6” diameter feeder and exit holes to supply both bays.

Blocks of wood screwed onto the 2x4 studs hold the 22” wide black sheet metal solar absorbers 1 inch below the top surface. After the absorber sheets were installed, a fiberglass glazing was secured into place with metal battens. The glazing covers were installed from east to west, so the west side overlapped the east side, because in Reno weather typically blows in from the west. The glazing panels are 49-½“ wide, so they overlapped the 24” on-center studs. The batten holes were oversized and predrilled prior to screw insertion to prevent cracking of the fiberglass glazing, and to allow for glazing thermal expansion. A 1½” wide rubber gasket was inserted at the perimeter between the wood and glazing, and was compressed as the batten was secured. Where the glazing panels overlapped, a rubber strip was inserted. Figure 15(C) shows photos of the glazing-covered collector; Figure 15(D) shows the shingle roof cap installed for weatherproofing.

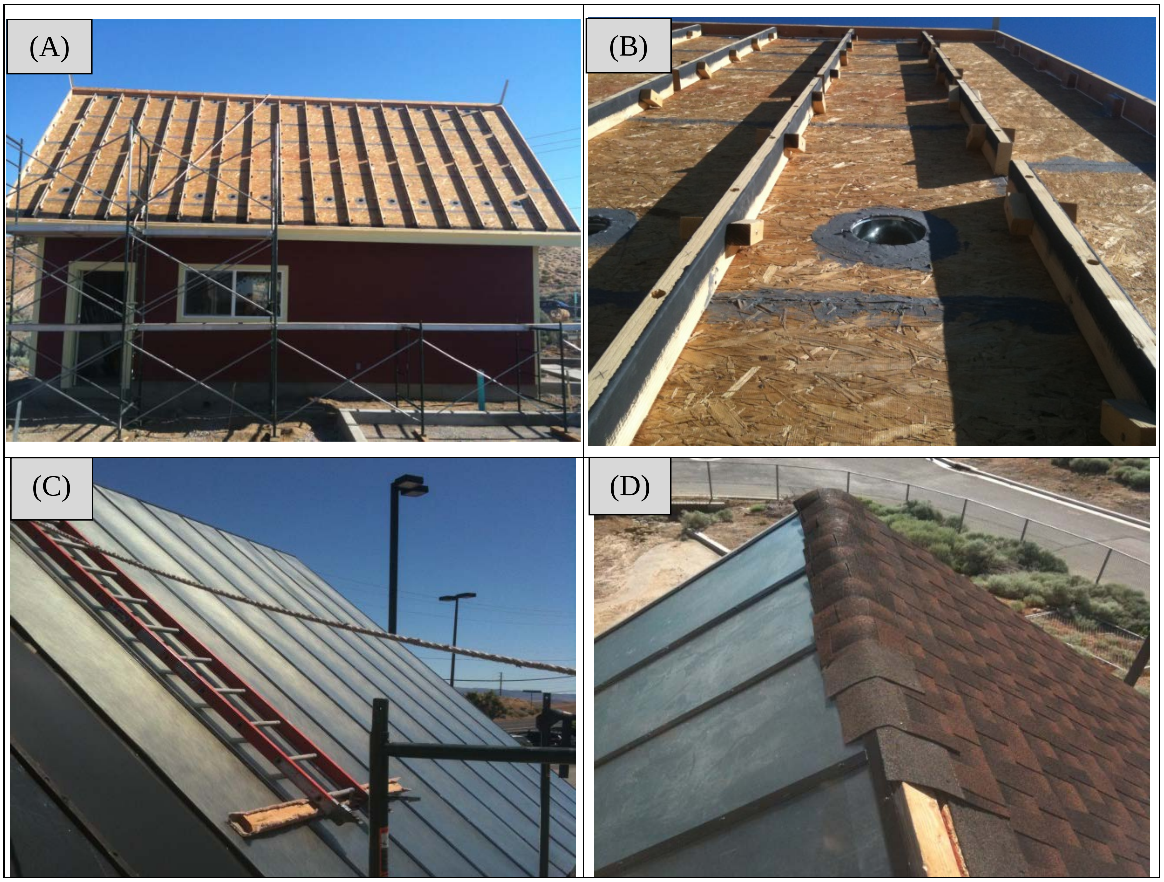

Figure 15. Construction of solar air collector system on roof of REEF Workshop.
(A) site-built roof solar air heater is framed with 2x4 studs; (B) looking up a flow bay with a sealed air intake collar; (C) fiberglass glazing panels are placed on the stud tops and secured with black aluminum battens; (D) roof caps are placed over the completed solar collector for weatherproofing.

The complete solar collector roof consists of 17 vertically-oriented bays (or channels) with 4” holes protruding inside the Workshop at the top and bottom of each channel to admit and extract air. Air is provided to and from the collector in each bay by two 14” diameter duct headers, located inside the building. One header is located near the roof peak to draw off heated air; the other is located near the collector bottom to supply air. Figure 16 shows a header located inside the Workshop, with flexible ducts connected to each outside channel. After the duct distribution system (DDS) was completed, it was insulated using R-19 fiberglass insulation.

Figure 16. REEF solar thermal air system header, inside Workshop.

Figure 17. Dayton 7C653 2100 cfm blower within REEF Workshop delivers air to the collector intake header.

A Dayton 7C653 blower, rated at 2100 cfm for no-load, was installed to blow air through the solar thermal collector for positive collector pressurization. A photo of this blower, located on a platform built within the rafters of the REEF Workshop, is provided in Figure 17. The blower air flow rate is managed by a programmable computerized controller to allow optimal operation under changing conditions. The computer allows flow rate to vary from 100% to around 40% of maximum. The air handler is mounted on rubber vibration absorbers to reduce noise and vibrations within the building. The blower delivers air into the bottom collector header, from whence the header delivers air to the 15 collector air inlets.

3.1.3.2 REEF Workshop Flooring Systems

The REEF Workshop's concrete floor (600 ft^2) was designed to demonstrate thermal storage as part of seasonal space conditioning. The floor was divided into three parts, each of area 200 ft^2. Two sectors have water tubes embedded under the floor, which allows solar heated water to flow through the tubes, heating the floor in winter. The water tube thermal storage area was divided into two sectors, so one could be charged while the other remained uncharged as a baseline. After research data have been collected, both sectors can be heated on a permanent basis. In winter mode, solar heated air will pass through an air-to-water heat exchanger unit, and the heated water will be pumped through the embedded tubes under the floor, heating the floor and storing heat into the floor. Figure 18 shows placement of the water tubes over the rebar during construction.

The third sector (200 ft^2) has hollow channels to allow air flow under the concrete floor. During construction, two inches of rigid insulation were laid on a sand layer. Then hollow concrete blocks were aligned to form air channels from the north end of the room to the south end (see Figure 19). At each end, a plenum was provided to allow air input and egress to/from the channels. Then 5 inches of rebar concrete was poured over the concrete blocks to form the finished floor. This system allows solar heated air to be directed through the hollow channels, heating the floor in winter mode.

Figure 18. Water tubes placed on rebar, over 2” of rigid insulation, prior to pouring the REEF Workshop concrete floor.

Figure 19. Holes in concrete blocks form air channels, allowing flow of heated air in winter and night-chilled air in summer.

This hollow floor can also be used to store cool air during summer nights, as part of a low-cost air conditioning system. Taking advantage of the low summer nocturnal temperature and relative humidity indigenous to Reno (and the Great Basin in general), cool air is inexpensively produced during summer nights, and this coolness can be stored in the hollow floors. Thus, even on hot summer days, the floor can be substantially cooler than an unconditioned floor.

Due to delays in finishing the REEF construction, full summer testing was not possible, although some summer data were collected in late August. During a period when daily high temperatures were 95^{o}F, an evaporative (swamp) cooler was installed on the north side of the Workshop, and chilled nocturnal air was passed under the hollow concrete floor from 5 pm to 8 am. At 8 am, the surface temperature of the cooled concrete floor was 56^{o}F, while the unconditioned floor surface temperature was 68^{o}F, and the room air temperature was around 60^{o}F. The conditioned floor remained cooler throughout the day, even as both sections absorbed heat from the room. Even at noon, a person standing over the conditioned section felt cooler than when he stood over the unconditioned area.

3.1.3.3 REEF Workshop Hydronic System

A major use of the solar thermal energy obtained by the roof collector system is to heat water. This provides convenient storage of excess solar energy for subsequent use in space heating and domestic hot water.

A schematic of the hydronic system installed in the REEF Workshop is provided in Figure 20. Heated air from the roof collector is blown directly into a box containing air-to-water heat exchanger (HE) units, where heat from the air is transferred to a water stream. MagicAire SHE-2-2525-10 air-to-water heat exchangers were selected based upon pressure drop and thermal conductance (UA) performance. One consideration was how many heat exchangers should be used in series. Analysis indicated that 1 heat exchanger would provide an estimated HE effectiveness ε = 0.41, 2 HE's ε = 0.63, 3 HE's ε=0.75, 4 HE's ε = 0.83, and 5 HE's ε = 0.88. Considering the point of diminishing returns, 3 HEs were connected in series to provide an estimated HE effectiveness ε = 0.75. To achieve highest efficiency, the flow was arranged so that the water direction flowed counter to the air flow. A photo of the insulated HE box, which was mounted in the rafters of the REEF Workshop, is shown in Figure 21.

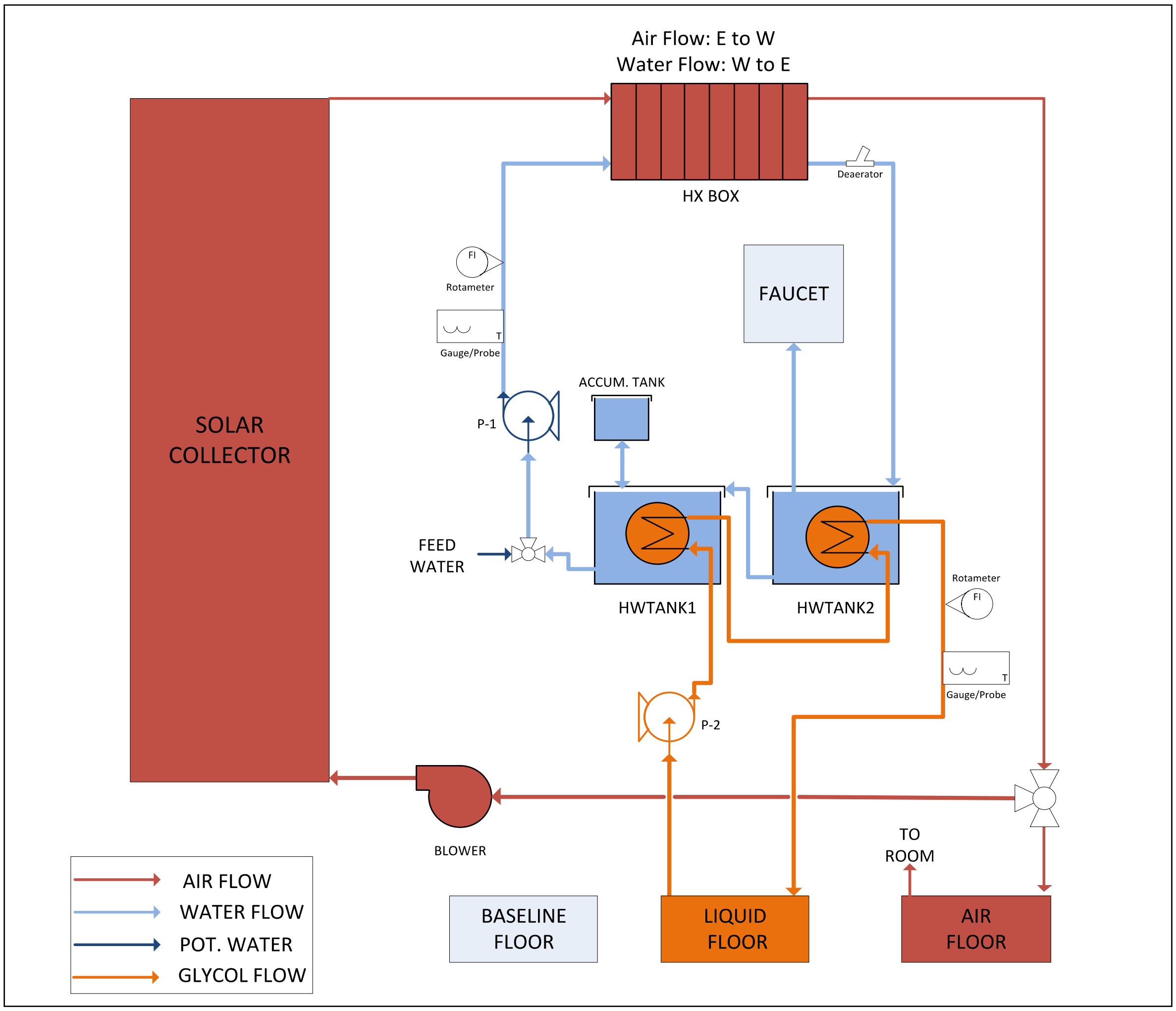

Figure 20. Schematic of hydronic system for the REEF Workshop.

Heated air from the roof solar collector is ducted into the east side of the heat exchange box by a 14" diameter insulated duct. Prior to encountering the heat exchanger unit within the box, a small insulated duct (lower center in Figure 21) can divert the hottest air to a solar dryer when needed. Most (or all) of the hot air passes through the heat exchanger unit, where circulating water is heated. In summer, air exiting the heat exchanger is returned directly to the solar collector, since heat is not needed for the building. This is depicted at the "T" joint in Figure 20 (lower right). In winter, the post heat exchanger air, which is still warm, is directed to a hollow concrete floor (bottom right of Figure 20) where the floor is heated for slow release to the room. For quick heating, there is an option to release this air directly into the room instead of going to the floor.

<table>
<tr><td></td><td></td></tr>
<tr><td>**Figure 21. Insulated heat exchanger box containing three MagicAire SHW-2 2525 10 heat exchangers.**</td><td>**Figure 22. Twin 120-gal. water tanks within the REEF Workshop, used to store potable water under city pressure.**</td></tr>
</table>

Figure 22 shows two 120 gallon water tanks (HWTank1 and HWTank2) that are installed in the REEF Workshop. They are plumbed in line, so water from the bottom of Tank 1 is pumped to the HE system where it is heated, then returned to the top of Tank 2. The bottom of Tank 2 is connected to the top of Tank 1, so a thermocline is established within the two tanks, and the hottest water is near the top of Tank 2. The water system is under city pressure, so the closed system has minimal pumping requirement. As hot water is consumed in the building (faucet in Figure 20), it is replaced by feed water.

Plastic pipes were laid under part of the concrete floor (“Liquid Floor” in Figure 20), so the floor can be heated in winter by hot water from the tanks. Winter floor heating can be compared in three modes: (1) hollow floor heated by air (air floor); (2) pipes under floor heated by water (liquid floor); and (3) a control (baseline) floor section with no heating.

3.1.3.4 REEF Workshop Control System

The REEF Workshop solar air collector thermal system has been instrumented for automated data collection and system controls to allow for continual performance monitoring. A program to accomplish this task was written using National Instruments’ LabVIEW software and FieldPoint data acquisition hardware (DAQ). The DAQ has 96 channels available, 48 for temperature measurement, 32 for insolation and air flow rate measurement, and 16 dedicated to control for various components in the system. The system’s performance is evaluated using thermocouples to measure temperatures, pitot tubes and pressure transducers to measure air flow rates, a pyranometer to measure solar radiation, and a heat flux sensor for use with the air floor. Thermocouples, analog inputs (pressure transducers, pyranometer, etc.), and analog outputs (blower control) are all wired to the FieldPoint array as shown in Figure 23. This communicates with a dedicated host computer in the Workshop via a serial connection.

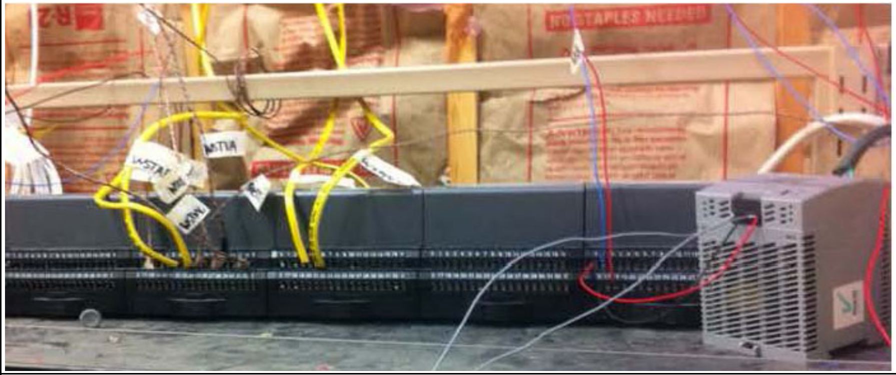

Figure 23. FieldPoint array with thermocouple wires and power supply.

Figure 24. Pitot tube, pressure transducer, and thermocouple probe installed in ductwork.

Figure 24 shows a pitot tube, pressure transducer, and thermocouple installed in the ductwork of the solar thermal air system to measure air flow and density. The thermocouples being used are Omega Type-K probes and beaded thermocouples. Insolation is measured by a Kipp & Zonen pyranometer that is mounted flush with the solar air collector (due south and 45^{o} slope). The pyranometer accuracy was checked against another unit and is estimated to be ± 5%. Air flow rates through the collector and air floor are measured by three Omega PX274-05DI pressure transducers and pitot tubes. Local wind velocity and direction measurements are recorded on two channels from an adjacent facility.

The LabVIEW program, or virtual instrument (VI), displays instantaneous values for various measurements on the front panel, and writes these values to a text file every 10 minutes for further analysis. Figure 25 shows an image of the VI's front panel, as displayed in a winter mode. Winter controls for the system are based on user-defined set point values for exterior solar radiation (W/m^2), temperature difference (D,ºC) between the middle of the solar collector and the interior temperature of the workshop, and a user-defined indoor target temperature (ºC). The VI checks first if the solar radiation, temperature difference, and indoor temperature are at or above the set point. If the conditions are satisfied, a signal is sent to the blower that turns it on at full speed for 5 minutes. If the conditions are not satisfied, the blower is turned off. Further refinement of the control logic will allow for variation of blower speed based on similar parameters instead of the current bang-bang control implementation.

Performance data are collected continuously, including hours during which the collector is not in operation, allowing for an analysis of the thermal storage capabilities of the air floor and water floor sections compared to the baseline floor. The data stored in the text files on the host computer are downloaded to an external source each day to ensure a high degree of redundancy. The VI and DAQ also include provisions for concurrent monitoring of the factory-fabricated solar system and absorption chiller of the adjacent REEF House (discussed in Section 3.1.4).

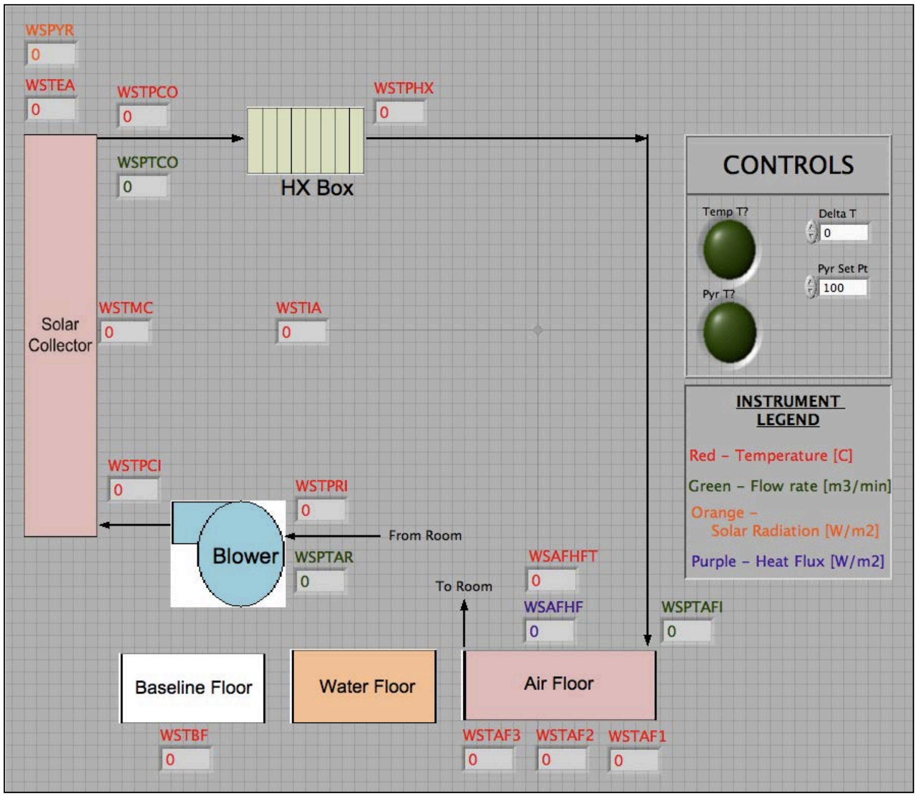

Figure 25. REEF thermal system LabVIEW VI front panel (measurement section) in winter mode

3.1.4 Install Renewable Energy Systems in REEF House

In addition to the PV and trailer-based renewable power systems that provide electrical power to the REEF House (as described above), several other renewable energy components were incorporated into this house. Taken together, these features allow for off-grid operation of the REEF House for intermittent periods of time. Described below are the solar thermal systems that were built into the house; and the heating, ventilation, and air conditioning (HVAC) system that was developed.

3.1.4.1 Solar Thermal Collectors for REEF House

Two different types of solar thermal collectors were used to satisfy the heating and cooling requirements of the REEF House: (1) Viessmann Vitosol 100-F and (2) Sunvelope Solar thermal panels. Ten Sunvelope collectors were mounted on the roof of the REEF House which sits at approximately 25 degrees tilt (see Figure 26). The total collector area of these panels is approximately 200 ft^2. The working fluid in the Sunvelope collectors is potable water. The collectors are plumbed directly to a hot water storage tank in the crawl space under the house. A drain-back system is not required for these collectors as water can freeze and boil inside the collector without causing damage.

The Viessmann Vitosol 100-F solar thermal panels were mounted on a rack supported by three ground supports located on the south side of the REEF House (see Figure 26). This rack allows the panels to be manually tilted from 25 – 60 degrees for changes in season. The rack holds eight collectors, having a total area of approximately 200 ft^2. A mixture of glycol and water passes through the Viessmann collectors and into the crawl space of the REEF House where a heat exchanger is mounted on the internal south wall. (To avoid complications during start-up operations, pure water was initially used in the Viessmann collectors.) The other loop of this heat exchanger contains water that circulates in a storage tank in the crawl space under the house. The flow rate and protection of this system is controlled by a Viessmann Devicon unit, which also incorporates the heat exchanger and pumps.

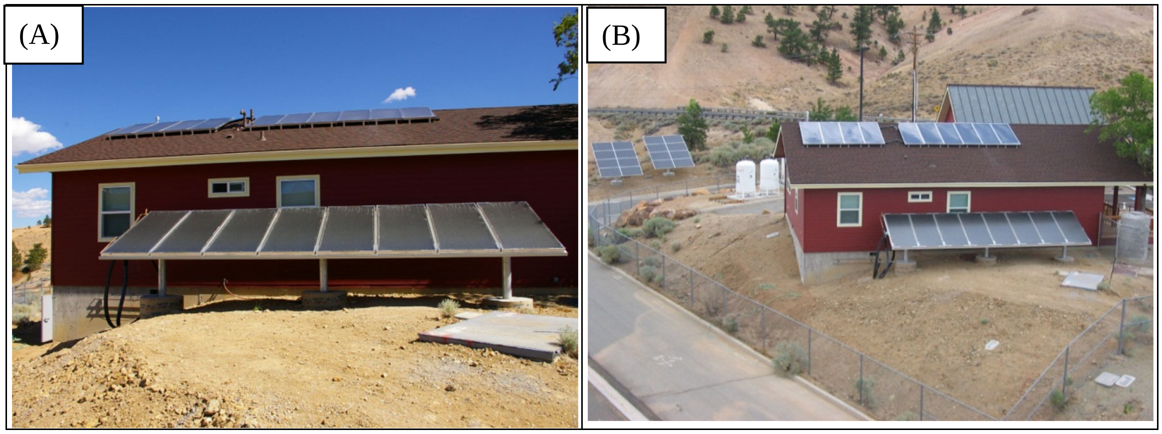

Figure 26. Solar thermal collectors in the DRI-REEF.

(A) Viessmann collectors on south side of REEF House, (B) Sunvelope collectors on roof of REEF House, solar air collector on REEF Workshop, and ground-mounted PV arrays.

3.1.4.2 REEF House HVAC System

The main power sources for both heating and cooling the REEF House are the Viessmann and Sunvelope solar thermal collectors described above. Two 80-gallon water tanks were installed under the house to store the heat generated from these collectors (see Figure 27). One tank is heated by the Viessmann solar collectors, while the other is heated by the Sunvelope collectors. This arrangement allows for independent evaluation of the performance of each collector system.

The outlets of the two hot water storage tanks were plumbed together and sent to a Yazaki WFC-FC5 absorption chiller, located in the utility room of the REEF House (see Figure 28). When heating is required, hot water bypasses the absorption chiller and is routed directly to a heat exchanger built into the house’s duct system within the furnace closet. The flow of hot water is managed by a pump using a variable frequency drive that is controlled based upon thermocouple temperature measurements throughout the system.

This Yazaki absorption chiller unit draws approximately 19 gpm of water at 180 °F to provide 5-tons of cooling. However, only about 2 tons of refrigeration is required for the REEF House, so the pumps are driven by variable frequency drives. The cold water from the absorption chiller is plumbed to a heat exchanger located in the ductwork of the house, just under the furnace. Both the heating heat exchanger and cooling heat exchanger are shell and tube style systems. The cooling heat exchanger has a face area of 4 ft^2 and a rated sensible heat capacity of 36,347 Btu/hr. The heating heat exchanger has a 4 ft^2 face area with a sensible heat capacity of 54,257 Btu/hr. A photo of these stacked heat exchanger systems is shown in Figure 29.

		
Figure 27. Water tanks for thermal storage installed under REEF House.	**Figure 28. Yazaki absorption chiller in utility room of REEF House**	**Figure 29. Heat exchangers to be located in REEF House ducting.**

A rough schematic of the entire HVAC system for the REEF House is shown in Figure 30; a more detailed "engineering-style" schematic is shown in Figure 31. Besides all the components mentioned above, a cooling tower for the absorption chiller was located just outside the utility room on a concrete pad that was poured for this purpose.

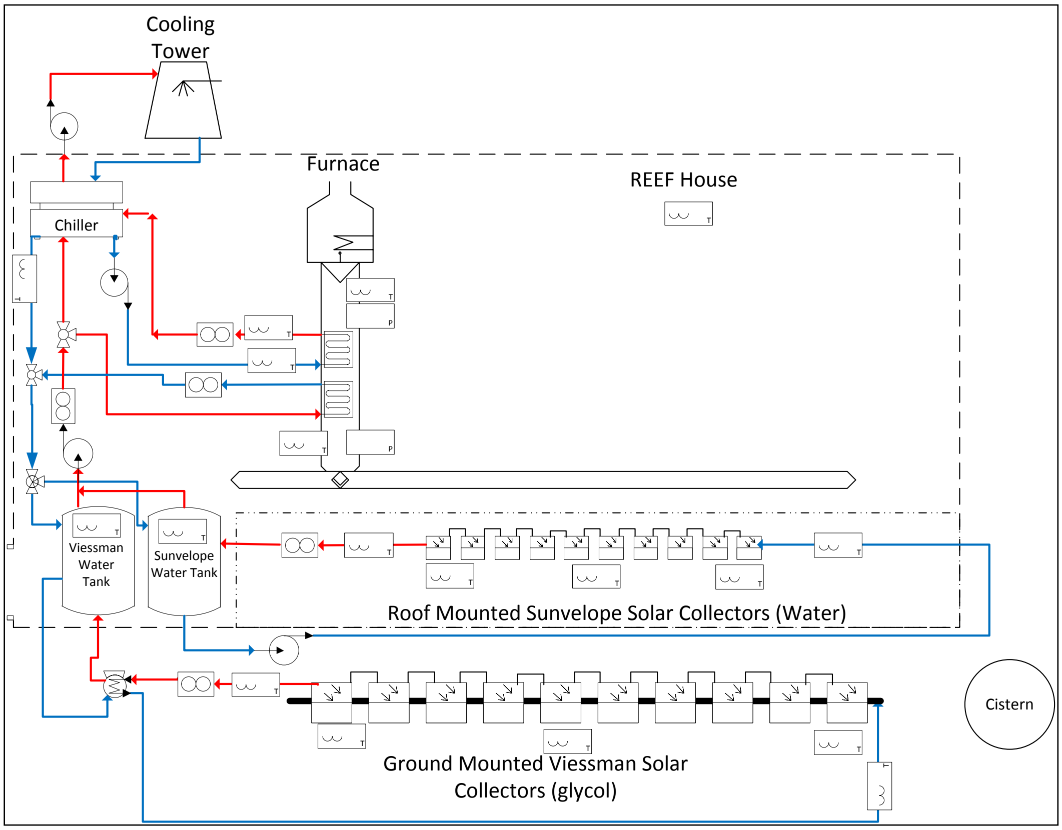

Figure 30. Rough schematic of HVAC system for REEF House.

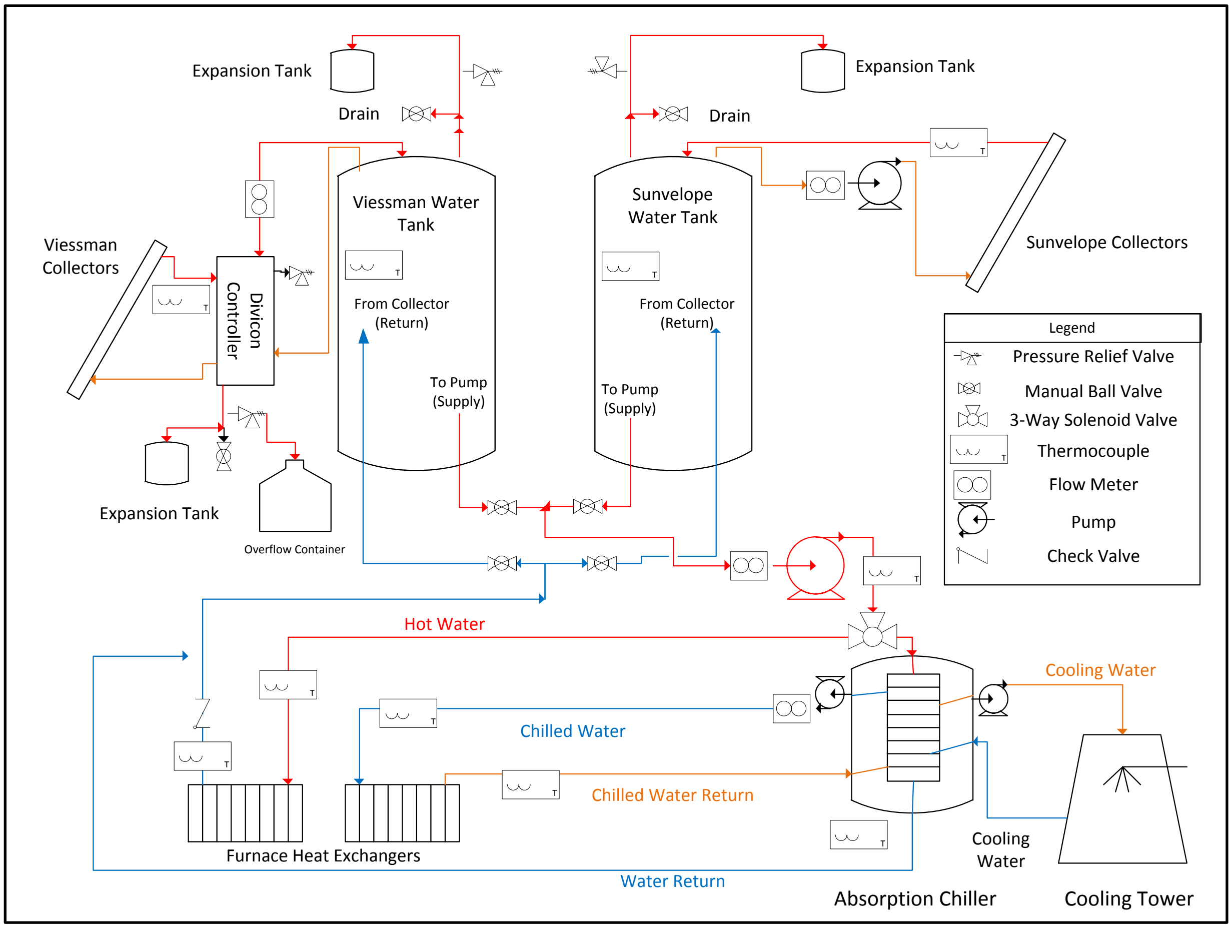

Figure 31. Detailed schematic of HVAC system for REEF House.

3.2 Test and Optimize Off-Grid System as an Entire Unit

Numerous instruments and control devices were incorporated into the REEF House and Workshop to determine the operating efficiencies of individual components. Data have been continuously collected from some of these components since the beginning of August, 2012. In this section, we present some of these data, to illustrate the performance of individual components, and to enable calculation of overall efficiencies of the system.

3.2.1 REEF Workshop Solar Air Collector System

Figure 32 graphically summarizes the performance of the REEF Workshop solar air collector system for multi-day periods in each of four months in 2012: August, September, October, and November. Displayed in each period are four continuous data traces. The air flow rate through the collector system, as measured by a pitot tube and pressure transducer, is shown as a red (or burgundy) line. The August period illustrates some start-up problems with the blower system, but the other three months showed relatively consistent behavior (with some disruptions in October). Although wired to a variable frequency drive (VFD), the blower is usually run at a constant frequency, since it was determined that a change in air flow rate did not have a large effect on the collector air temperature. Under typical blower conditions, a relatively stable air flow rate of about 80 m^3/min. was measured.

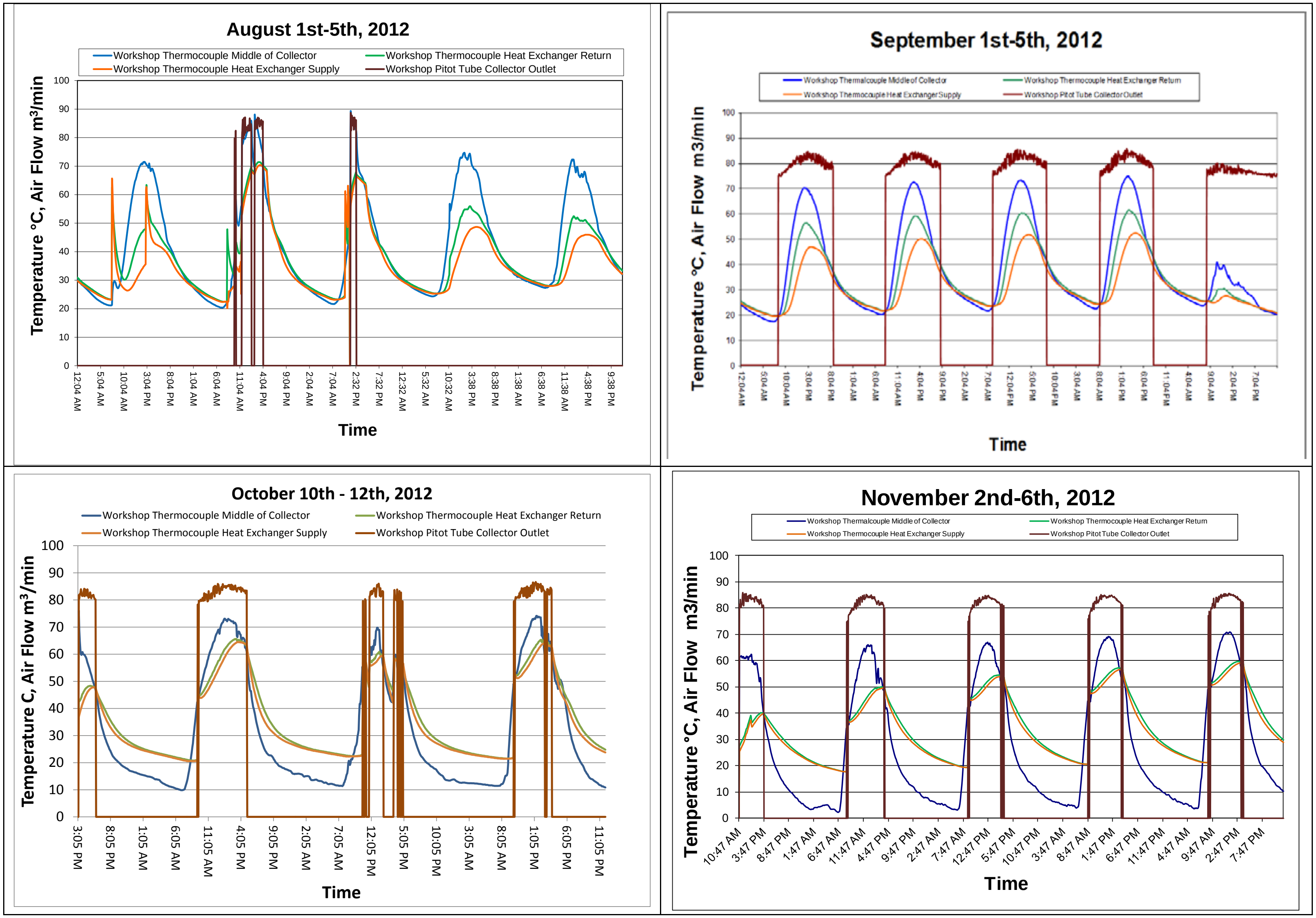

Figure 32. Performance data for REEF Workshop solar air collector over a 4-month period.

The other three data traces shown in Figure 32 are air temperature measurements: (1) middle of the rooftop collector (blue), (2) entering the heat exchangers used to heat water for the hydronic floor system (orange), and (3) exiting the heat exchangers (green). Other than the start-up period in August, these temperature datasets show considerable regularity for the multi-day periods monitored in each month. In all periods, the temperature inside the rooftop collector reached a maximum of about 60-70 °C – on sunny days. A significantly lower maximum temperature was measured on September 5, when the solar radiation was much lower.

3.2.2 REEF House HVAC System

A list of instrumentation used to monitor and control the heating and cooling of the REEF House is provided in Table 1. Data from this instrumentation allows for calculation of efficiency for the Viessmann solar collector system, Sunvelope solar collector system, Yazaki absorption chiller, heating coil heat exchanger, and cooling coil heat exchanger; thus allowing for calculation of overall system efficiency. Furthermore, the Viessmann and Sunvelope hot water storage tanks each have several temperature sensors within them to help understand the degree of temperature stratification inside each tank.

Table 1. Instruments used to monitor performance of the REEF House HVAC system

Drawing ID	Name	Description	Type	Signal	Port size	Make	Model
I-1	TWOGT	Tank water outlet gauge temperature	gauge	N/A			
I-2	STBT	Sunvelope tank bottom temperature	Thermocouple	mV	wall	omega	Type K
I-3	STTT	Sunvelope tank top temperature	Thermocouple	mV	wall	omega	Type K
I-4	VTBT	Viessman tank bottom temperature	Thermocouple	mV	wall	omega	Type K
I-5	VTTT	Viessman tank top temperature	Thermocouple	mV	wall	omega	Type K
I-6	VWFR	Viessman water flow rate	Omega	4-20/1-5	1 1/4	omega	FP7002
I-7	VCIWT	Viessman collector inlet water temperature	Omega	4-20/1-5	1 1/4	omega	FP7002
I-8	WFCGT	Water from chiller gauge temperature	gauge	N/A			
I-9	SWFM	Sunvelope water flow meter	Omega	4-20/1-5	1 1/4	omega	FP7002
I-10	SCIT	Sunvelope Collector inlet Temperature	Omega	4-20/1-5	1 1/4	omega	FP7002
I-11	CCWFCGT	Chilled water from coil gauge temperature	gauge	N/A			
I-12	CCWIFR	Cooling coil water inlet flow rate	Omega	4-20/1-5	1 1/2	omega	FP7002
I-13	CCWIT	Cooling coil water inlet temperature	Omega	4-20/1-5	1 1/2	omega	FP7002
I-14	HWFR	Hot Water Flow Rate	Omega	4-20/1-5	1 1/2	omega	FP7002
I-15	HCWIT	Heating coil water inlet temperature	Omega	4-20/1-5	1 1/2	omega	FP7002
I-16	HWGT	Hot water gauge temperature	gauge	N/A			
I-17	HCWOT	Heating coil water outlet temperature	thermocouple	mV	wall	omega	Type K
I-18	CCWOT	Cooling coil water outlet temperature	Thermocouple	mV	wall	omega	Type K
I-19	SCOT	Sunvelope collector outlet temperature	Thermocouple	mV	wall	omega	Type K
I-20	VCOWT	Viessman collector outlet water temperature	Thermocouple	mV	wall	omega	Type K
I-21	TWOT	Tank water outlet temperature	Thermocouple	mV	wall	omega	Type K
I-22	HAAT	House ambient air temperature	Thermocouple	mV	wall	omega	Type K
I-23	CIAT	Coil inlet air temperature	TC Probe	mV	wall	omega	Type K
I-24	COAT	Coil outlet air temperature	TC Probe	mV	wall	omega	Type K

Figure 33 graphically summarizes the performance of the REEF House HVAC system during the same multi-day periods discussed above. In this figure, water tank temperatures are shown for the Sunvelope collector system (green) and the Viessmann collector system (burgundy). In addition, the cooling coil water outlet temperature is shown (blue), which is an indicator of when the absorption chiller was operating to provide air conditioning to the house. For the August and September charts, the internal house temperature is also shown (red), but this varies only slightly with time, and therefore is not displayed in the October or November charts.

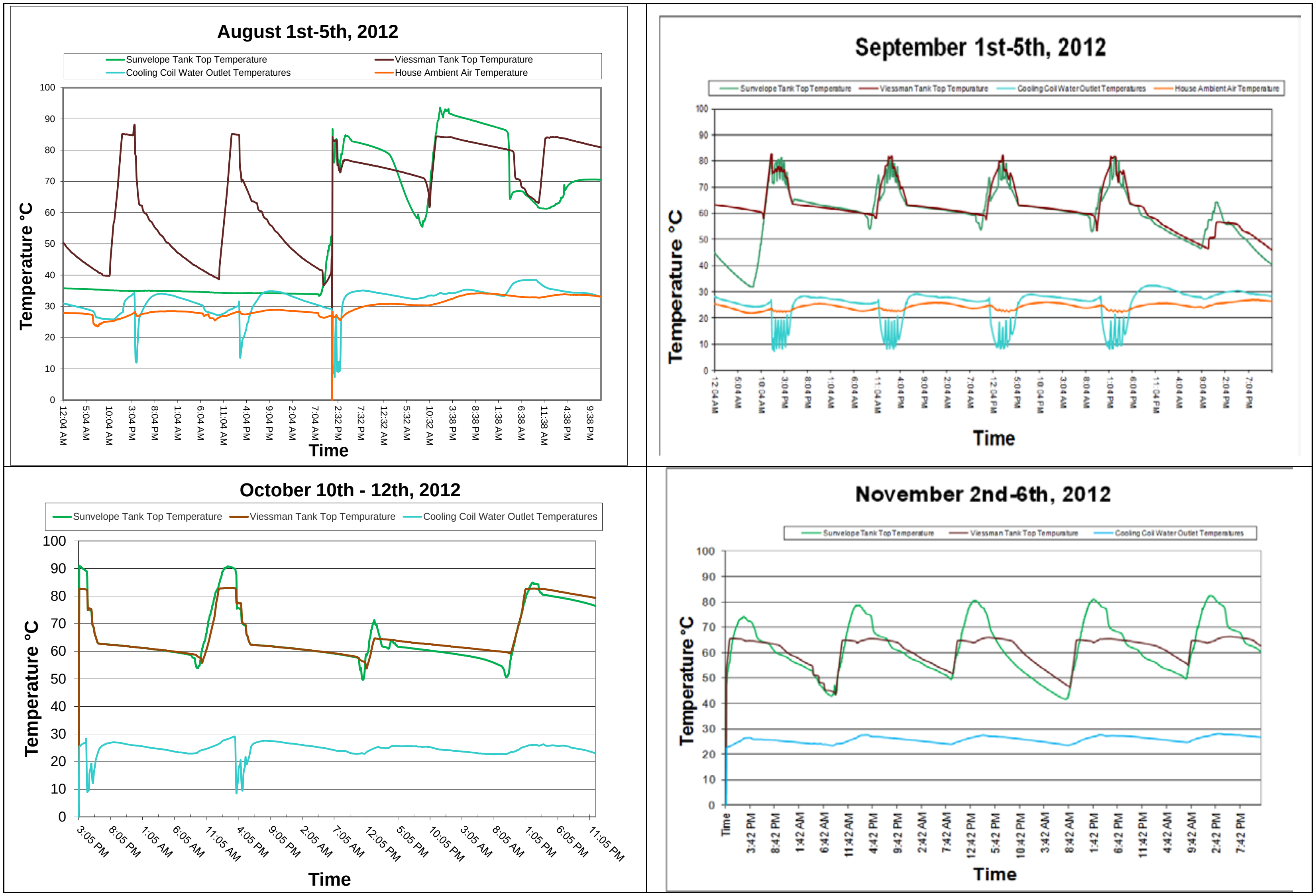

Figure 33. Performance data for REEF House HVAC system over a 4-month period.

Due to start-up difficulties in August, the data during this period is of limited value. The month of September provided the most useful and complete data, as there was a significant demand for air conditioning during this time. The first four days of September showed regular and consistent use of the absorption chiller for air conditioning. The temperature "fingerprint pattern" for the chiller operation corresponds with a similar pattern for the water tank temperatures.

Of note, the temperature fluctuations in the Sunvelope water tank were more extreme than fluctuations in the Viessmann tank. This is likely because of different operational designs of these two systems. In the Sunvelope system, water is circulated directly from the solar collector through the water tank. In the Viessmann system, a glycol solution is circulated from the collector through a heat exchanger, which then transfers heat into the water tank. Thus, the temperature in the Viessmann tank is "dampened" by this extra heat exchange step occurring between the collector and the tank. This effect may also be seen in the November data in Figure 33, where under conditions of reduced solar radiation, the Sunvelope tank temperature is considerably higher than the Viessmann tank temperature. This was true even though the angle of inclination of the Viessmann collectors was increased from 25° to 60° in November, to take full advantage of the wintertime sun. (The Sunvelope collectors are not adjustable, and are fixed at about 25° on the roof of the REEF House.)

Data analysis from the REEF House has shown that there is not enough solar energy being collected in the late afternoon to run the absorption chiller. (A minimum inlet water temperature of 140 °F is required for the chiller to operate.) This results in elevated temperatures inside the house before nightfall occurs. The well-insulated house then maintains these elevated temperatures (in excess of 80°F) until the following morning. To alleviate this night-time hot air situation, a custom-built economizer was constructed and installed in the attic of the house. The economizer allows for cool outside air to be drawn into the house when the enthalpy of the ambient air is lower than the enthalpy of the inside air. The enthalpy sensor communicates with the house thermostat and drives actuators that open a series of dampeners as required; allowing air to enter from outside, run through the HVAC system, and exhaust out the attic. Initial observations indicate this economizer system is working well. Photos of the economizer are shown in Figure 34.

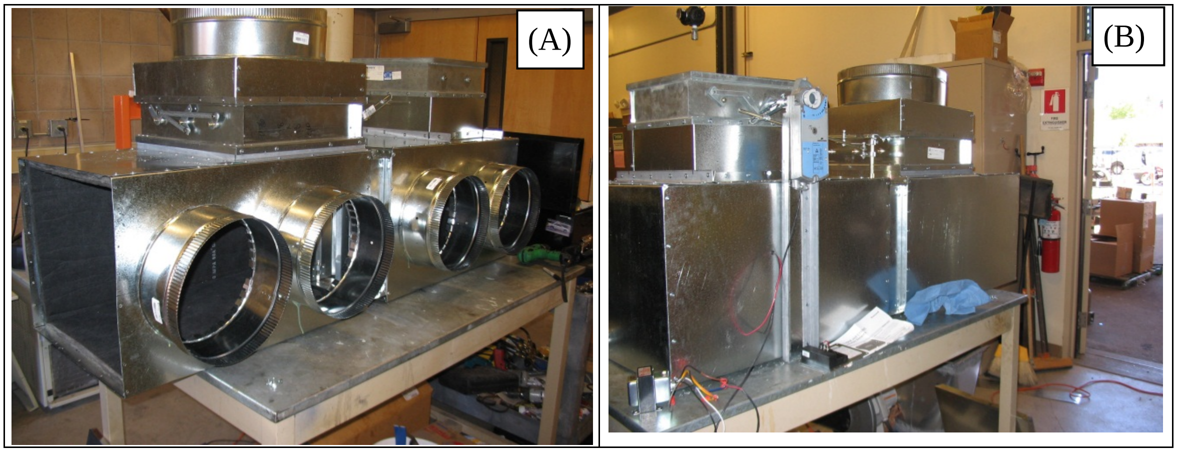

Figure 34. Economizer for HVAC system in REEF House. (A) duct lines, (B) actuator control

3.2.3 REEF House Electrical System

The electronic components comprising the renewable power system interface, monitoring, and control unit were previously located within the Energy Laboratory at DRI's Northern Nevada Science Center. Now, this unit has been moved into the REEF Workshop, and additional instruments and data acquisition modules were installed to expand the system. Photos of these components before and after moving them into the REEF Workshop are provided in Figure 35.

Figure 35. Moving of power monitoring and control equipment for renewable power system. (A) Old location within DRI's Energy Lab, (B) new location within REEF Workshop.

To supply the electrical demand of the REEF, electricity is produced through photovoltaics and wind turbines. The system includes two 1 kW tracking PV arrays, two 1.5 kW fixed mounted PV arrays and two 1.5 kW wind turbines. All PV arrays are wired to 48 VDC; the wind turbines are wired to 120 VAC. The generated electricity from these six sources is wired into the REEF Workshop where the charge controllers are located. The output from all charge controllers (48 VDC) is wired to a terminal and sent through a breaker to the hydrogen trailer where the Outback Inverter is located. The 48 VDC side of the inverter unit within the trailer is also wired to the battery pack, electrolyzer and generator output. The 240/120 VAC output of the inverter is wired to an electrical box with separate breakers for the REEF Workshop House. Inside the trailer is an internal combustion engine with a DC generator that can run on either H_2 (produced during times of excess renewable electricity) or propane. This generator, along with the battery pack, allows for 24/7 uninterrupted electrical output for the REEF buildings. A diagram showing the electronic configuration of the entire REEF power system is provided in Figure 36.

The data acquisition system that controls the four PV arrays, two wind turbines, electrolyzer, hydrogen storage, battery bank, and engine/generator equipment is located in the portable trailer. To provide better educational viewing, the associated computer and monitors will eventually be moved into the REEF House. A flow chart of the control logic for the REEF electrical system is shown in Figure 37.

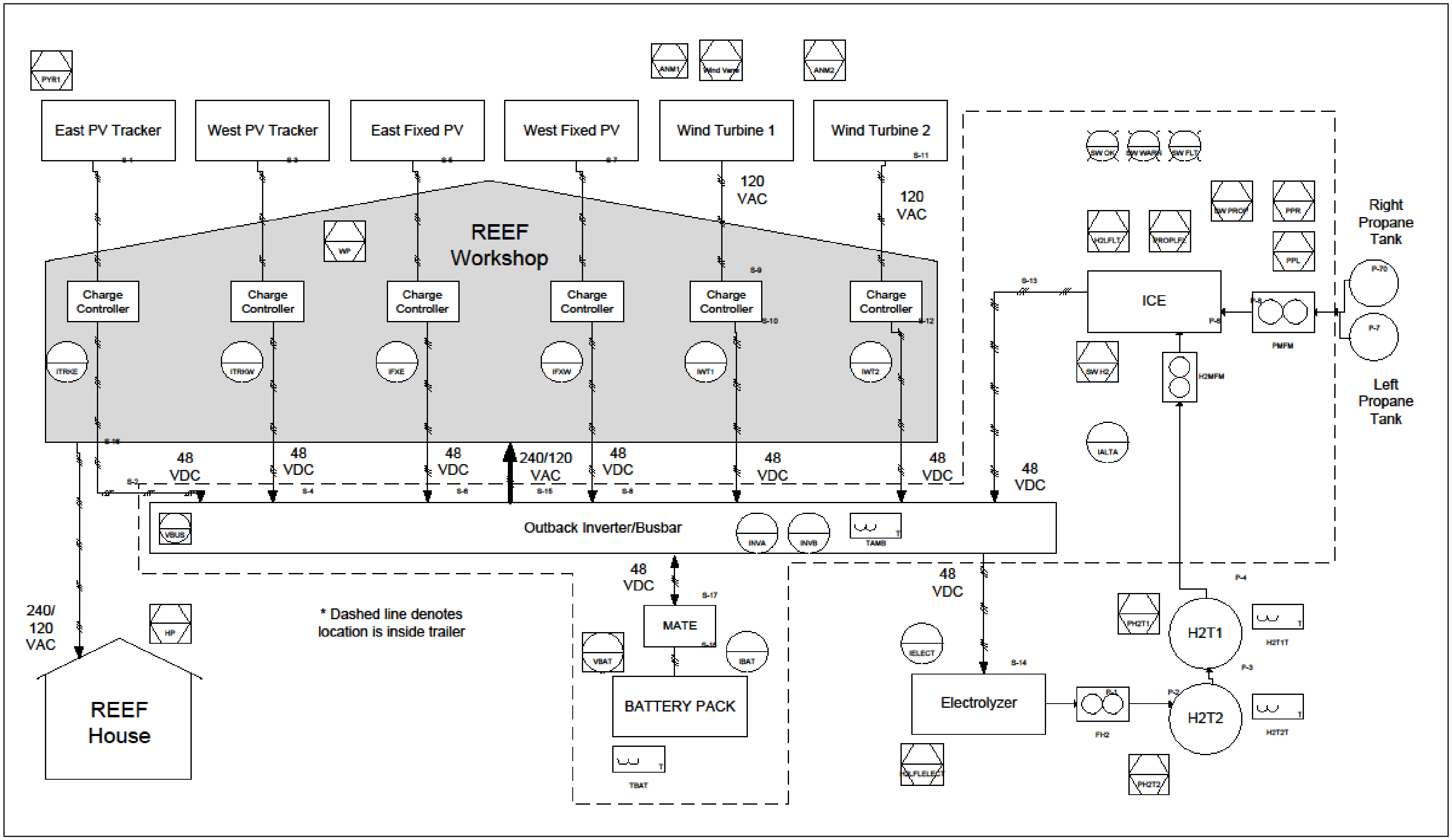

Figure 36. Diagram of electronic configuration within DRI’s renewable power system

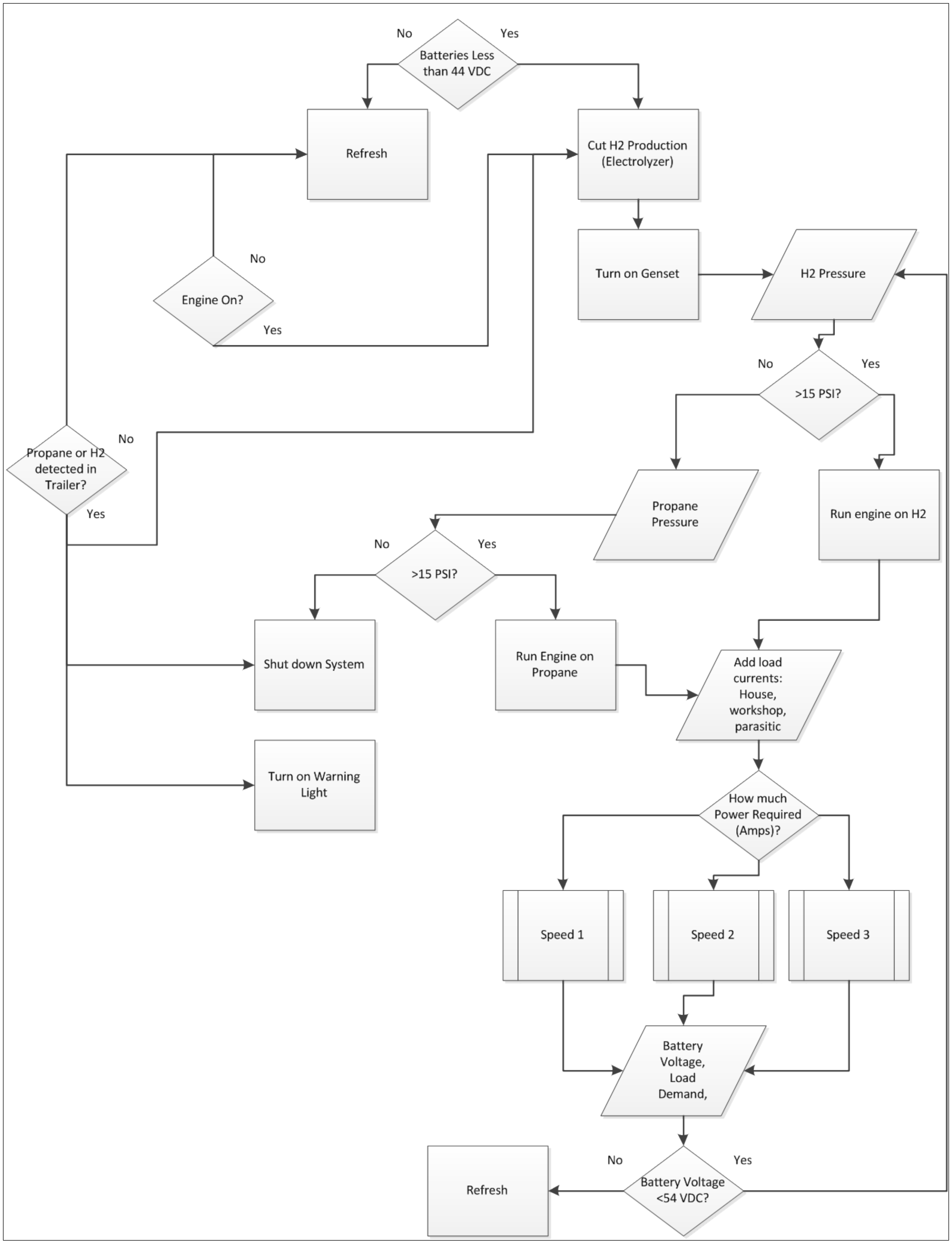

Figure 37. Control logic for REEF electrical system.

3.3 Task 3: Develop Gas-Fueled Engine R&D Platform

An area of growing interest is utilization of renewable gases for power generation. These gases can be produced by gasification of lignocellulosic biomass (woods and grasses) or by anaerobic digestion of organic waste materials (sewage sludge, food waste, de-lipidized algae, etc.). To enable DRI to become more active in this area, we obtained a natural gas engine and modified it to serve as a testbed for future renewable gas R&D projects. Described below are the efforts and results of this activity.

3.3.1 Design and Build the Engine Systems

Two 3-cylinder Daihatsu 950 internal combustion gas engines were donated to DRI by the Southwest Gas Company. One of these engines was modified and re-configured to operate as part of the REEF engine R&D platform; the other engine is being held in reserve for future needs. The engine modification work was performed by Collier Technologies at their facility in Sparks, NV.

Collier installed a programmable fueling and injection system, and connected the engine to a 5kW electric generator that had previously been attached to a Lister Petter gas engine. An adapter plate was made that allowed the mounting of this generator to the Daihatsu engine. The engine, generator, and adaptor plate are shown in Figure 38(A). When complete, this engine, along with its associated electrical generator, was installed in a water-proof metal cabinet on a base that can be moved with a forklift. To achieve the goal of all-weather operation, aluminum covers were attached to the top of the cabinet where cooling fans were originally located. A photo of this cabinet, while still under construction, is shown in Figure 38(B).

The Daihatsu engine was configured to accept a variety of gaseous fuels, such as natural gas, propane, hydrogen, synthesis gas, and digester gas. Electronics were installed to monitor and control fuel intake parameters as well as other functions necessary to operate the engine and generator through the use of manual controls and connection to a programmed laptop. The engine configuration maintained flexibility to determine power output and emissions in real-time.

Software obtained from Gill Systems was used to allow the ignition system to “read” the camshaft timing wheel on the Daihatsu engine. This software was validated using an identical Daihatsu engine on an engine dynamometer stand. Using the camshaft for ignition timing is very important for fuels containing significant fractions of hydrogen. The alternative of using the crankshaft for ignition timing, as was standard on this engine, causes a spark event to occur during the overlap period of the intake and exhaust valves. This event, also known as “wasted spark,” can cause engine backfire with hydrogen rich fuels.

Significant problems were initially encountered with the MegaSquirt fuel injection controller. Originally, this unit was mounted, along with the Gill ignition module, onto the enclosure of the electric generator. After several unsuccessful attempts at programming this unit in such a way as to affect engine start and run, the firmware in the electronics was inadvertently erased. It was surmised that the source of the problem was the strong magnetic field of the AC generator. The firmware was reinstalled and the unit moved some distance away from the generator. This eliminated the problem, and allowed for successful programming of both the Gill ignition and the MegaSquirt fuel injection system.

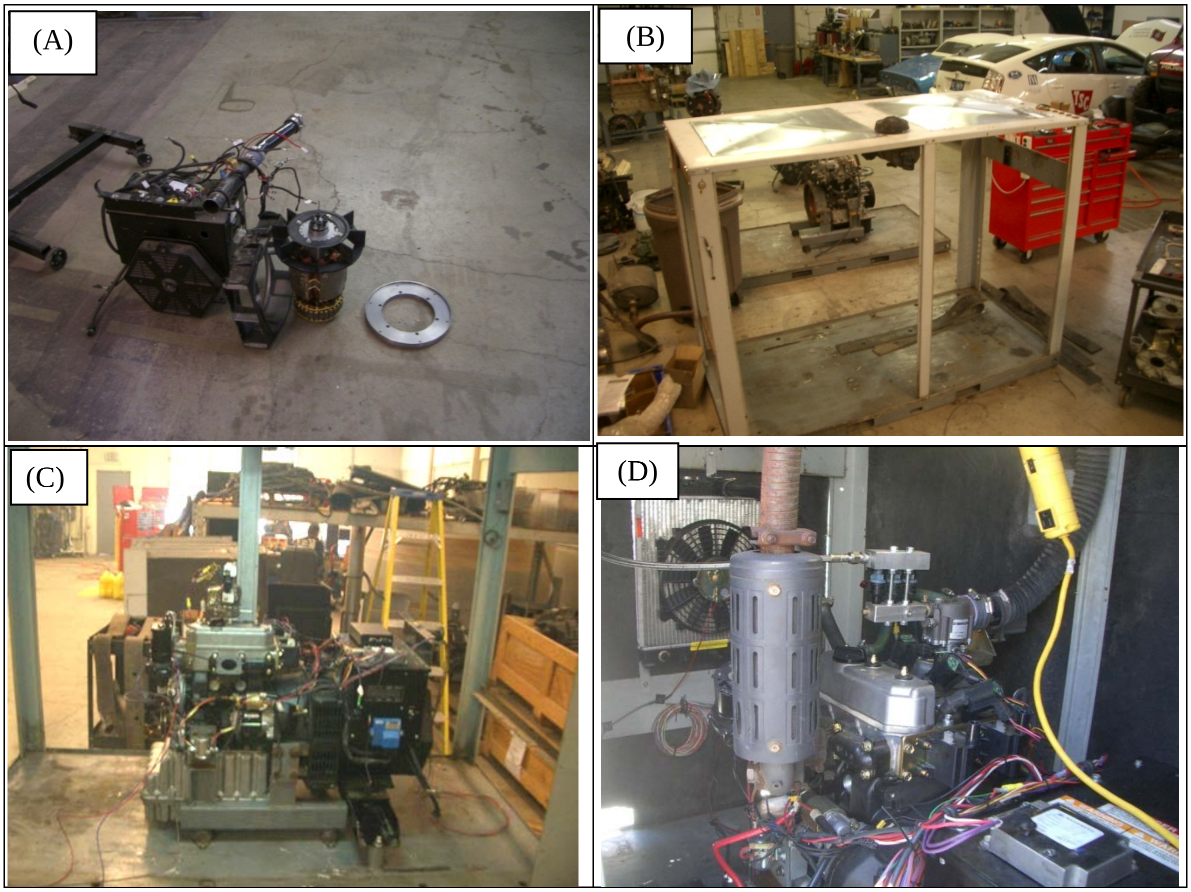

Figure 38. Photos documenting development of the gas engine testbed.
(A) Daihatsu 950 gas engine with 5-kW electric generator and adapter plate, (B) metal cabinet for holding engine/genset, (C) engine/genset mounted in cabinet, (D) completed unit on-site at DRI.

The speed control and engine generator diagnostic electronics from the previously used Lister Petter genset were incorporated into the new system. The engine sensors (oil pressure and cooling water temperature) from the Lister Petter engine were also successfully transposed to the Daihatsu engine. This allows the engine operating conditions to be accurately measured by the diagnostics control module.

An adapter to connect the Impco fuel-air mixer to the Daihatsu intake manifold was fabricated and installed. The throttle control actuator from the Lister Petter engine was also incorporated into this adaptation assembly. Fuel control is accomplished using Bosch natural gas fuel injectors. Fuel rails were fabricated and adapted to the Impco mixer. A Bosch water to air intercooler pump was added as there was no water pump originally installed on the Daihatsu engine. The engine generator module was then mounted to a modified cradle, which was placed into the cabinet using appropriate vibration isolators. The assembled engine generator located on the base of the cabinet is shown in Figure 38(C).

A Honda Civic radiator in conjunction with a Summit Racing electric fan was installed in the cabinet housing the 3-cylinder Daihatsu 950 internal combustion engine. The engine was operated successfully on natural gas and H_2 at a constant speed of 1800 rpm. Following this, the entire engine system, along with its housing cabinet, was relocated from Collier Technologies' shop to DRI. A photo of the complete unit at DRI is shown in Figure 38(D).

[The second Daihatsu engine (not used in the REEF engine R&D platform) was configured to operate only on natural gas, using the OEM Daihatsu ignition system and an Impco fueling system. This engine was wired for manual and computer control. A radiator was installed, but not an electrical generator. This engine was also placed in a water-proof metal cabinet mounted on a base that can be moved with a forklift.]

3.3.2 Test Engines with a Variety of Gaseous Fuels

Once the gas engine/generator system was delivered to DRI, it was intended to be used with a variety of gaseous fuels, such as natural gas, propane, hydrogen and synthesis gas - both in pure form and as blends. This testing was meant to demonstrate our ability to utilize biomass-generated gases in future R&D efforts. At the same time, we planned to monitor emissions with a 5-gas exhaust gas analyzer, and to control fuel intake parameters using the programmed laptop computer. Due to the engine's modifications, we are also able to vary the following parameters: injector opening, injector time, air/fuel ratio, throttle setting, spark timing curve, and other parameters included in the injector software. Engine speed will be held at 1800 rpm for optimized performance of the accompanying AC generator. Photos showing the Daihatsu engine/genset prepared for testing at DRI are included in Figure 39.

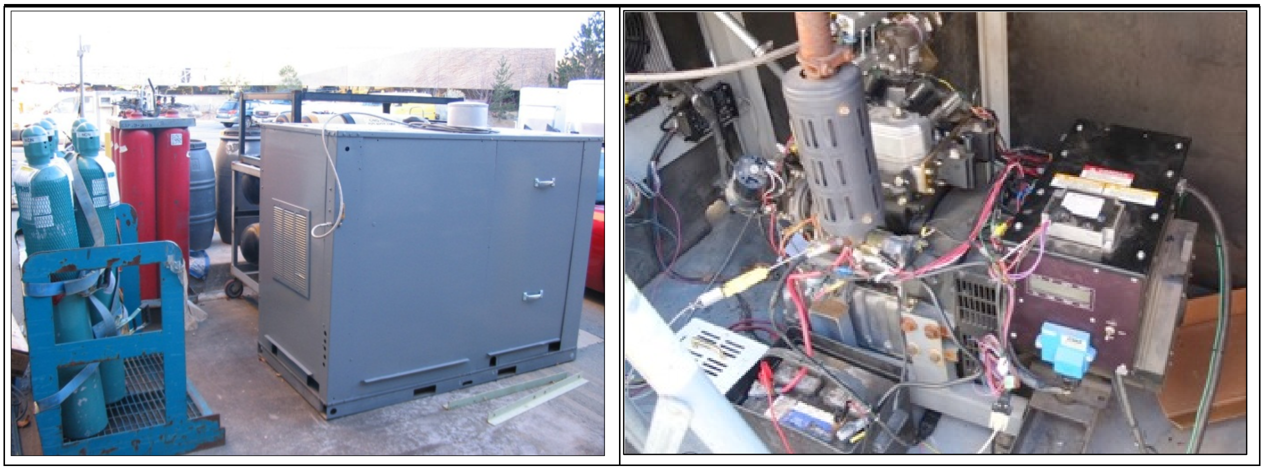

Figure 39. Daihatsu engine/genset for testing syngas mixtures.
(A) Engine cabinet with test fuel cylinders, (B) close-up of engine inside enclosure.

A testing matrix of five gaseous fuel blends was designed. These fuel compositions include 100% natural gas; 100% hydrogen; and three blends containing different ratios of H_2, CO, CO_2, and CH_4 to represent different syngas compositions. The planned test matrix is shown below in Table 2. A schematic depicting the planned testing arrangement is shown in Figure 40. All fuel gas mixtures were plumbed into a common manifold that feeds the engine through a mass flow meter. Sampling from the engine exhaust stream will be done to provide both continuous, real-time monitoring of the major exhaust gases by the 5-gas analyzer, and collection of canister samples for GC measurement of H_2, CO, CO_2, CH_4, and higher hydrocarbons.

Table 2. Gaseous Fuel Testing Matrix

Test	Fuel Mix	Time		Syngas				Electrical	Energy Content
		min.	Natural Gas	H2	CO	CO2	CH4	Load	BTU/ft3
1	A	15	100%	0%	0%	0%	0%	1 kW	1050
3		15	100%	0%	0%	0%	0%	3 kW	1050
5		15	100%	0%	0%	0%	0%	5 kW	1050
6	B	15	0%	100%	0%	0%	0%	1 kW	325
8		15	0%	100%	0%	0%	0%	3 kW	325
10		15	0%	100%	0%	0%	0%	5 kW	325
11	C	15	0%	60%	20%	15%	5%	1 kW	310
13		15	0%	60%	20%	15%	5%	3 kW	310
15		15	0%	60%	20%	15%	5%	5 kW	310
16	D	15	0%	40%	30%	20%	10%	1 kW	328
18		15	0%	40%	30%	20%	10%	3 kW	328
20		15	0%	40%	30%	20%	10%	5 kW	328
21	E	15	0%	30%	40%	20%	10%	1 kW	328
23		15	0%	30%	40%	20%	10%	3 kW	328
25		15	0%	30%	40%	20%	10%	5 kW	328

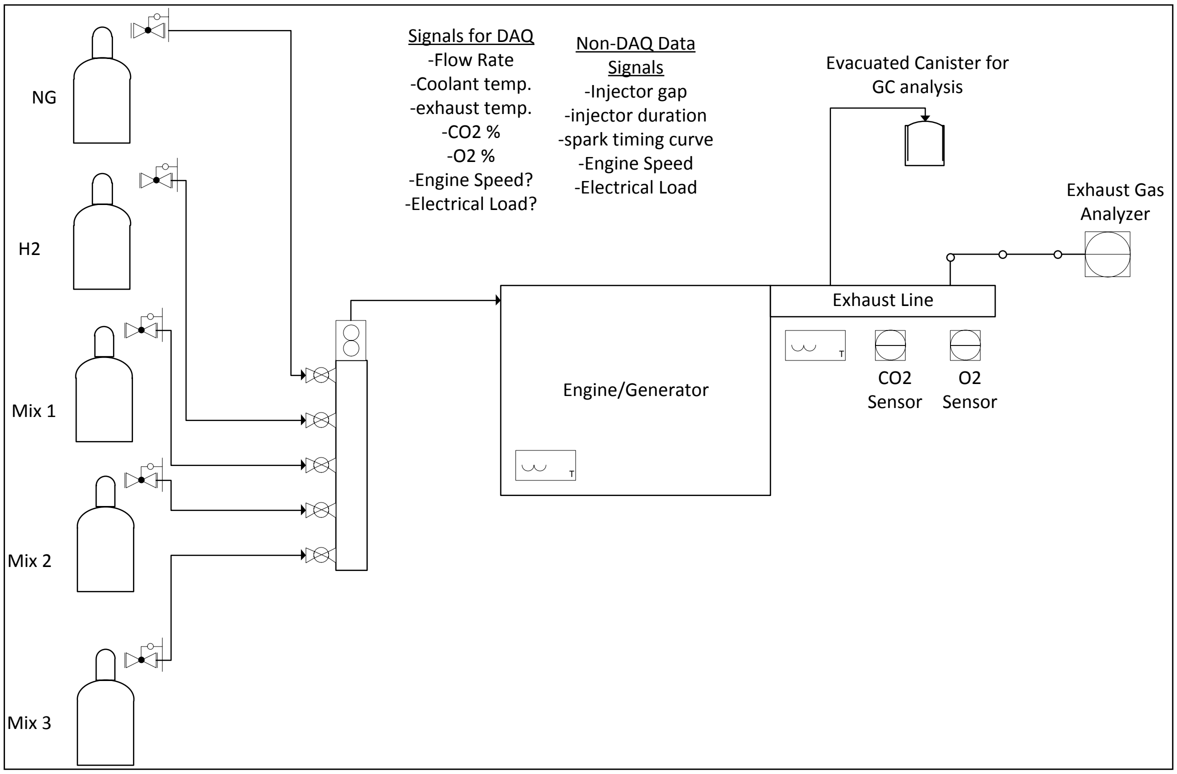

Figure 40. Gas engine testing schematic

Prior to testing the engine with different gaseous fuels, several engine components were tested and calibrated: the MegaSquirt MS1 computer unit, Gill Ignition Module, and Woodward APECS speed controller. The MegaSquirt MS1 controller is designed to establish optimal fuel parameters for fuel injectors. The Megatune software package is used to communicate with the MS1 controller in real time, and allows for adjustments while the engine is running. Megatune allows the user to set constraints for any particular engine, including engine stroke, number of cylinders and number of injectors. Additionally Megatune designates air/fuel ratios, pulse width modulation (PWM) for amount of fuel being injected, injector opening times, and number of injections per engine cycle. Making adjustments to these parameters allows use of the engine with different types of fuels, without sacrificing engine performance. The Megatune/MS1 parameters for natural gas are listed in Table 3.

Table 3. MegaSquirt MS1 Injector Tuning Parameters for Natural Gas

Injector opening time (ms)	1.0
Battery Voltage Correction (ms/V)	None
Peak Width Modulation (PWM) Current Limit %	70
Fast Idle Threshold (®F	0.0
Barometric Correction	Off
Control Algorithm Option	Speed Density
Injections per engine cycle	3
Injector Staging	Simultaneous
Engine Stroke	Four Stroke
Number of Cylinders	3
Injector Port Type	Throttle Body
Injectors	3
Spark Map Type	-
Engine Type	Even Fire

The data acquisition system and exhaust gas analyzer were also connected and tested. A LabJack U3-HV data acquisition device (DAQ) was interfaced via a USB connection to a netbook running the LJLogUD software. Sensors used in this experiment include: a Type K thermocouple in the exhaust stream, an Innovative Motorsports MTX-L Air/Fuel ratio gauge, and an ALICAT 6-M-50SLPM-D mass flow meter to determine fuel flow rate.

To measure the properties and compositions of the exhaust gas, the exhaust gas analyzer was connected to the computer. This computer required use of data logger software and a serial to USB adaptor to correctly interface with the analyzer. The exhaust gas analyzer is a DeJaye Technologies 5 Gas Analyzer, which was configured and calibrated to display and record real-time concentrations of NOx, CO_2, CO, O_2, and HC. Additionally, the analyzer calculates the engine rpm based on spark timing, temperature, and air to fuel ratio.

The data logger software (DJGAS) must be calibrated and setup to correctly record the data from the analyzer. For this series of experiments, a single phase calibration was used. With the exhaust probe removed and a calibration gas connected with known values of NOx, CO_2, CO, and HC, the analyzer compares the known values with the steady state measurements of the calibration gas. Before the data logger is ready to record data, the probe is connected to the analyzer and is bench zeroed outside of the engine. Once calibrated, the probe is inserted into the exhaust. Measurements were recorded in 10-second intervals and stored in an Excel spreadsheet.

Upon start-up of the engine for this series of gas fuel tests, several issues arose that needed to be addressed, including the following:

1. The firmware for the computer unit, a MegaSquirt I, had to be reinstalled.
2. A new adapter for the Gill Ignition Module had to be purchased.
3. The generator would not output the proper voltage even though the engine was running at 1700 RPM.

To help determine the causes of these problems, a new wiring diagram was created, as shown in Figure 41.

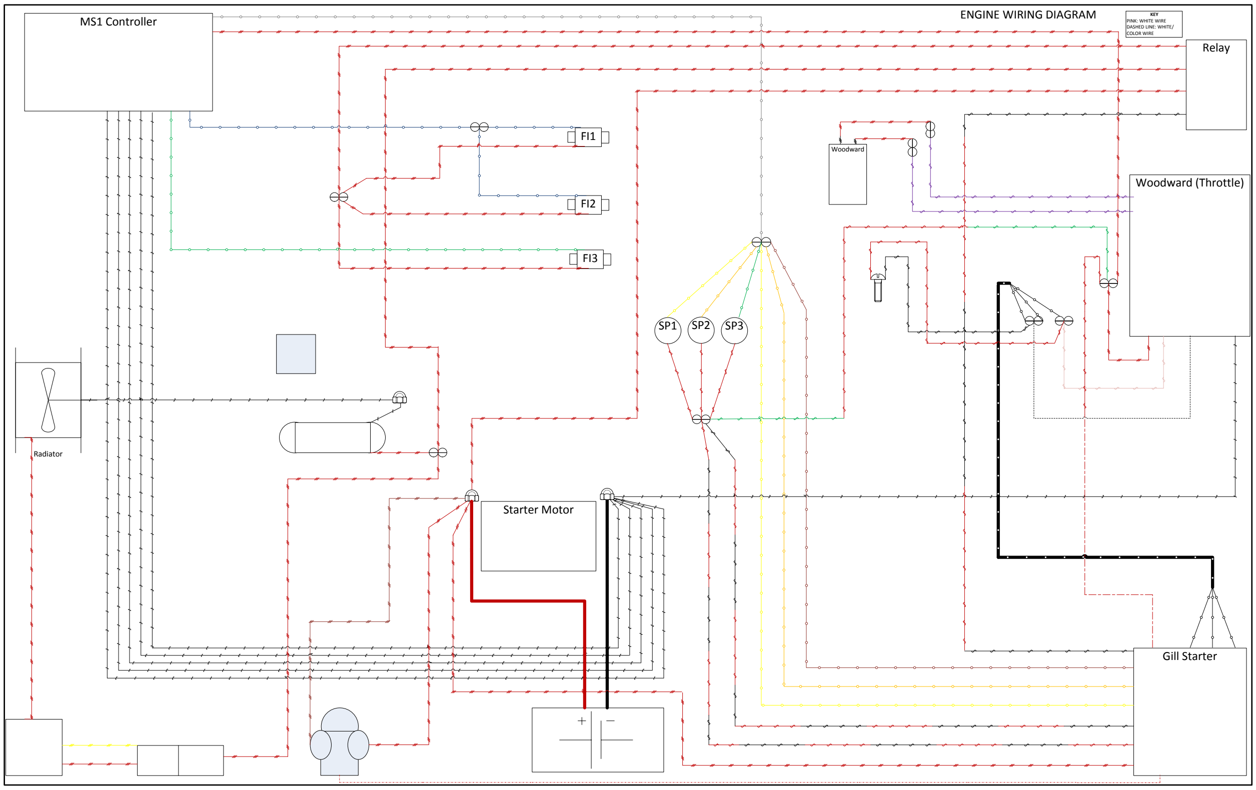

Figure 41. Wiring diagram for control of engine/genset

Although we planned to test the engine on several types of gaseous fuel (natural gas, hydrogen, and synthetic syngas mixtures), the problems noted above, combined with limitations of time and funding, prevented this. Consequently, only testing on natural gas was completed. Representative data collected during testing with natural gas are shown in Figure 42 and Figure 43. These data illustrate the unstable operation of the gas engine during this testing period.

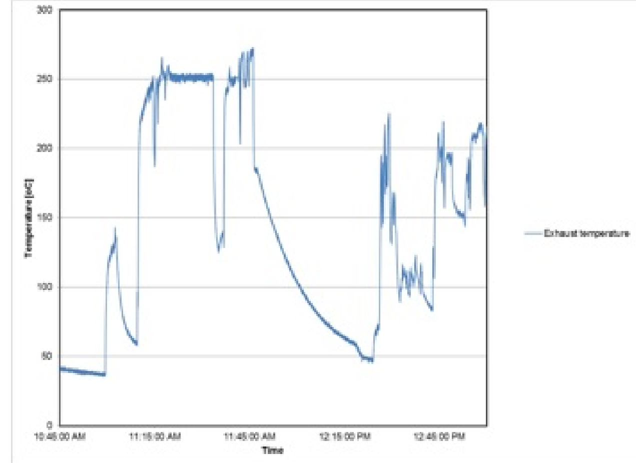

Figure 42. Exhaust temperature vs. time from engine test with natural gas.

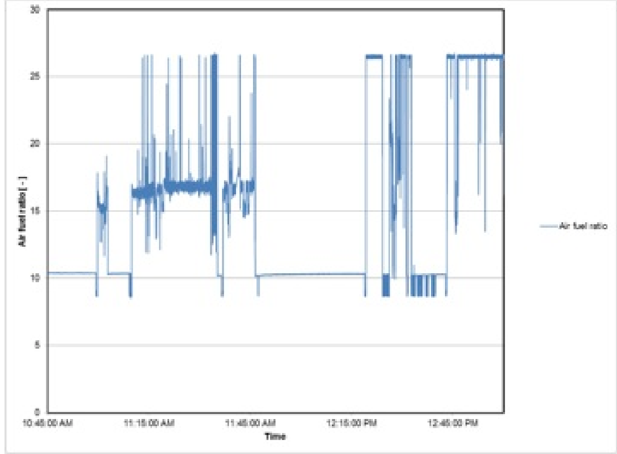

Figure 43. Air/fuel ratio vs. time from engine test with natural gas.

3.4 Task 4: Biomass Pre-Treatment R&D

In recent years, DRI [along with the University of Nevada, Reno (UNR) and the Gas Technology Institute (GTI)] have been exploring biomass pre-treatment methods that involve exposure to hot, pressurized water. This process, known as hydrothermal carbonization (HTC), is an attractive way of producing a friable, energy dense biochar that may be an excellent feedstock for gasification or combustion.[4,5] An additional benefit of HTC (and other pre-treatment processes) is its ability to produce a reasonably consistent and homogeneous biochar material, regardless of the biomass feedstock being used. Under separate contract (DE-EE0000272), DRI developed a small-scale semi-continuous HTC process development unit (PDU). In the current DRI-REC project, this HTC unit was moved into the REEF Workshop, and used to define optimum pre-treatment conditions for woody feedstocks of relevance for Nevada.

3.4.1 Locate the Continuous Hydrothermal Process Unit in the DRI-REEF

A schematic of the process development unit (PDU) designed for conducting HTC treatment of lignocellulosic feedstocks is shown in Figure 44. The PDU consists of a stainless steel tubular reactor vessel that is rated to accommodate pressures up to 1300 psi. Biomass feedstocks (typically wood chips) are loaded into the feed auger (shown on the left side of Figure 44). Water is then added, and the PDU is sealed and heated. Heating is accomplished using heating bands that are wrapped around the PDU. Five separate zones can be heated and monitored independently, by use of PID controllers. Once the desired HTC temperature is reached (typically 225 – 275 °C) both the feed auger and the product auger are activated to convey the biomass feedstock into the hot, pressurized water, and convey the hydrochar product into the accumulator vessel at the end of the PDU.

This PDU was also designed and built to enable collection of gas and liquid samples during (and after) the conduct of each HTC experiment. Hot liquid sampling is accomplished by briefly opening a valve near the bottom of the PDU, allowing the pressurized liquid to pass through a frit, and enter a small, tubular pressure vessel. Hot gas sampling is accomplished by briefly opening a valve near the top of the PDU, allowing the vapors to fill a 1-L Parr pressure vessel. After cooling this vessel, which causes the condensable material to drop out, the pressurized gases remaining are vented into a Tedlar bag for subsequent analysis.

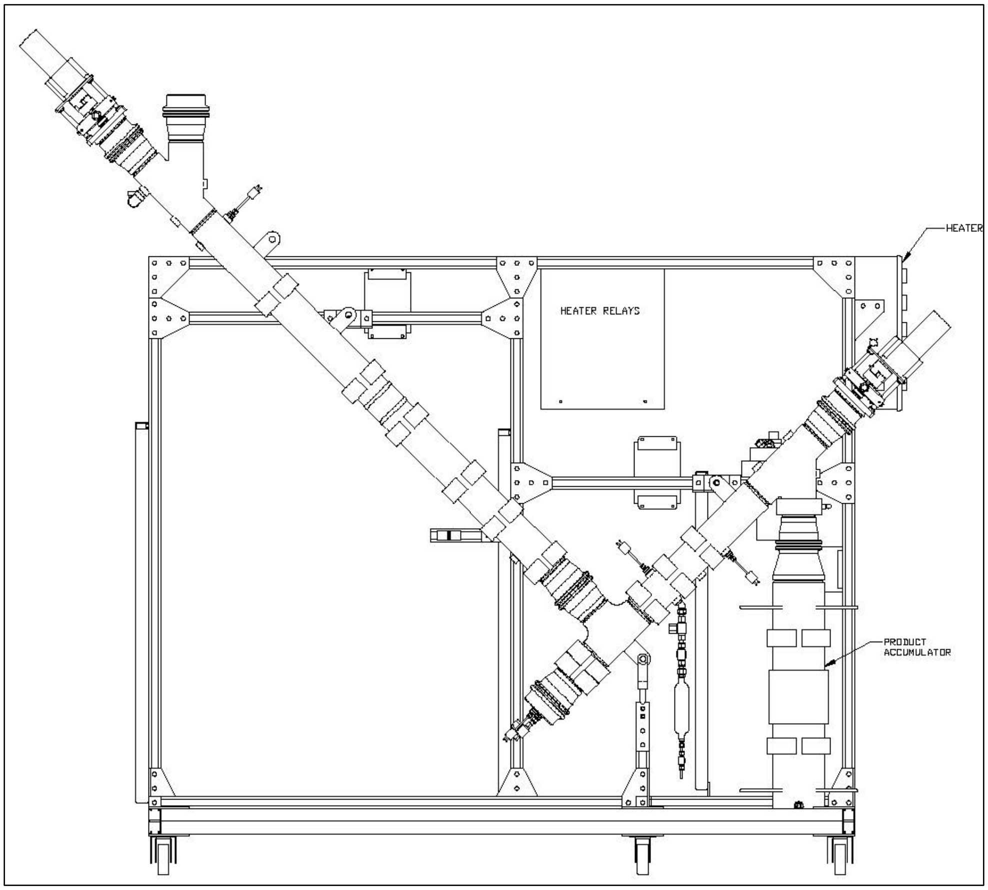

Figure 44. Schematic of PDU mounted on steel frame.

Fabrication of the major pressure vessel components of the HTC semi-continuous PDU was done by Custom Metalcraft of Springfield, MO (under separate contract). Due to delays in the fabrication schedule, the completed pressure vessel did not arrive at DRI until late December, 2011. Once on site, the PDU was mounted on a metal frame that had been built by DRI, and was installed in the REEF Workshop. The gas- and liquid sampling systems that had been designed and built by DRI were then added. A pressure relief line was also added to vent the system outside the building in case of emergency. All heaters, controllers, and thermocouples were installed, as well as two electric motors and controllers to operate the augers within the PDU. The photo collage in Figure 45 documents installation of the PDU in the REEF.

Several preliminary experiments were conducted to check-out certain aspects of the PDU's operation. These included a non-pressurized test (including water, but not high temperature) to demonstrate satisfactory operation of the auger-based conveyance system, tests to demonstrate satisfactory operation of the heating system (without water or feedstock), tests to calibrate the motors used to turn the augers, and tests to demonstrate satisfactory operation of data acquisition systems.

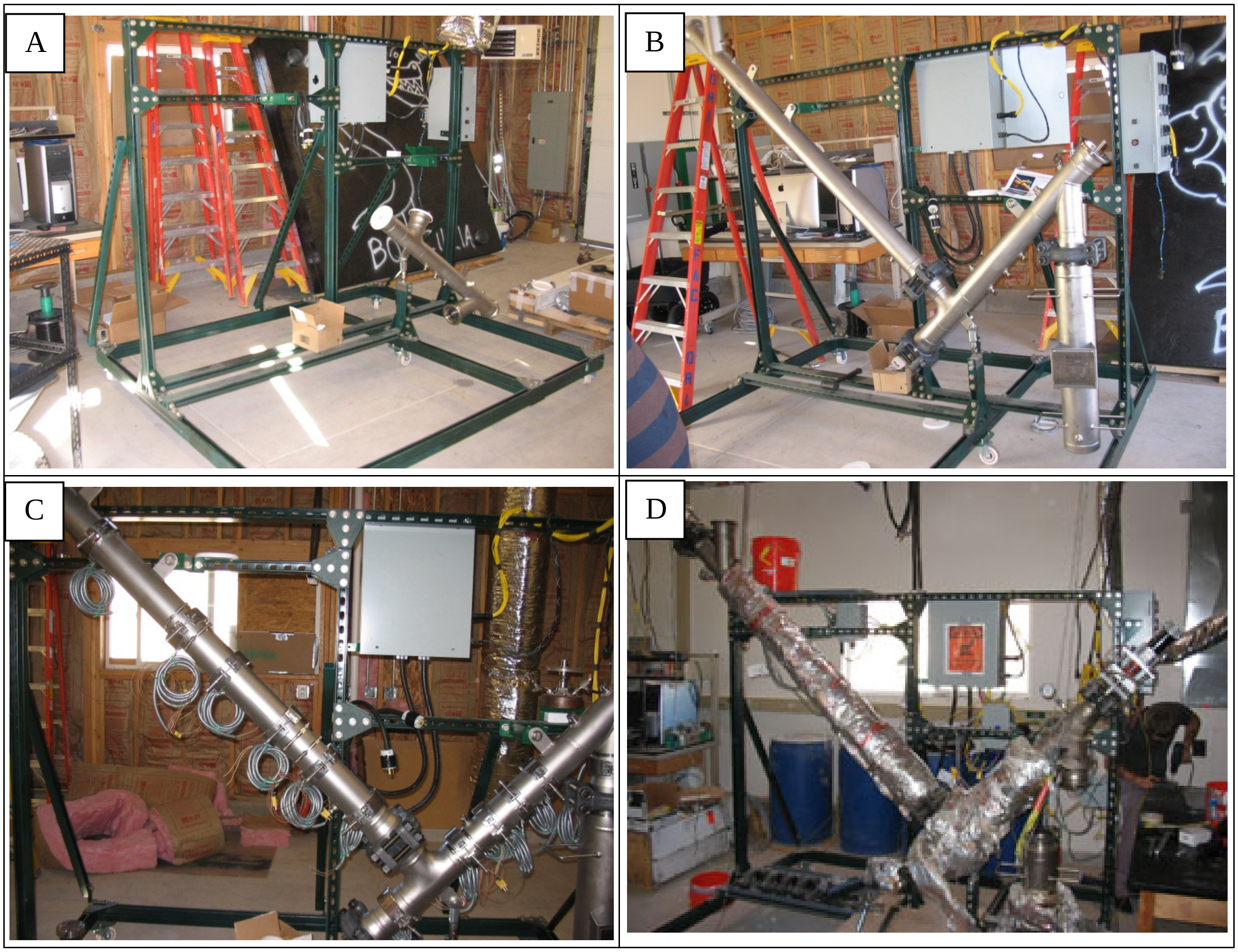

Figure 45. Installation of the semi-continuous HTC process unit (PDU) in the REEF Workshop. (A) Metal frame for holding reactor, (B) attaching PDU to metal frame, (C) positioning of heating bands, (D) completed unit, with insulation around pressure vessel.

Several accessories required to enable efficient utilization of the PDU were also designed, built, and installed in the REEF Workshop. First, a simple, manually-operated wood chip sizer was built, utilizing a common 30-gallon garbage can and a series of screens having varying hole sizes (see Figure 46A). Based upon earlier experiments with the PDU’s auger system, we believe that the optimum chip size range is ¼ – ½ inch. By placing a small screen near the bottom of the container, and a large screen near the top, we are able to exclude wood chips that are either too big or too small, and obtain only those that are in the desired size range.

A simple filtering apparatus was built to separate the hydrochar produced in the HTC process from the aqueous fraction. During operation of the PDU, the hydrochar is collected in a vessel that also collects condensed liquids. Following conclusion of the reaction process, the system is cooled overnight, and the collection vessel (accumulator) is removed from the rest of the PDU. The total contents of this collection vessel are poured into the top of the filtering device (see Figure 46B) to retain the solids on top of a screen, while the liquids drain into another collection vessel. Use of this strainer enables us to determine the mass of the solid hydrochar product – as well as the aqueous products – and obtain a mass balance for the process.

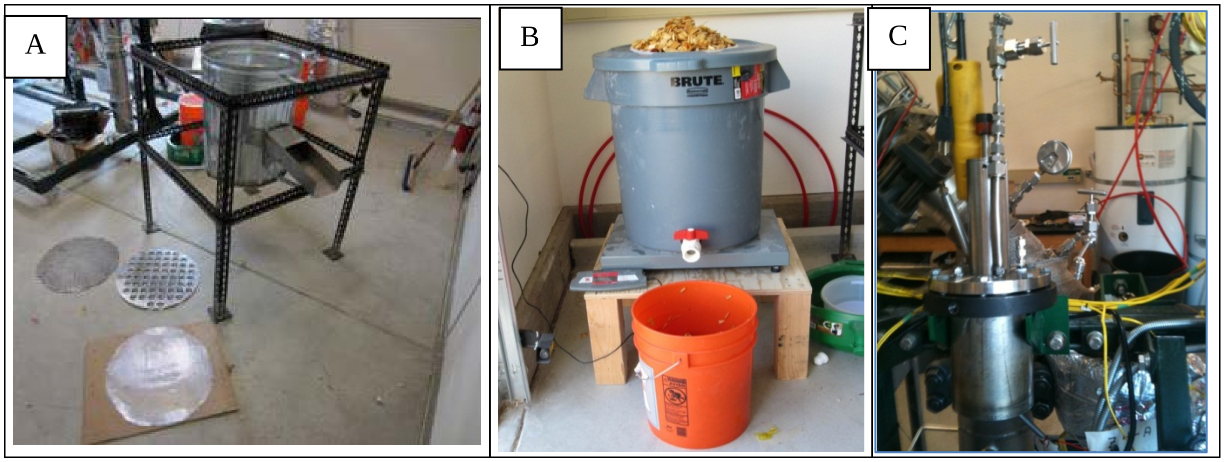

Figure 46. Other hardware items in support of PDU: (A) wood chip sorter, (B) sieve system for separating solid and liquid products, (C) gas sampling system.

Finally, a solar oven designed to dry wet hydrochar produced in the PDU was built, mounted in the REEF Workshop, and connected to a source of solar-heated air. A schematic and photo of this solar oven are shown in Figure 47. The inner chamber of this oven is heated by both direct and indirect contact with solar-heated air. As shown in the schematic, hot air enters the side of the oven. Most of this air is circulated around the outside of the inner chamber (within a 2-in. gap between the outer insulation and the inner oven chamber) before exiting the opposite side of the oven. A fraction of this hot air is drawn into the inner oven chamber by means of a small computer fan located at the bottom. This “slip stream” passes upwards through the oven chamber and is vented out the top. The hydrochar to be dried is spread out on trays that are stacked inside the oven chamber. Satisfactory performance of this oven has been determined by monitoring its internal temperature over the course of a day, and by actual drying of wet wood and hydrochar.

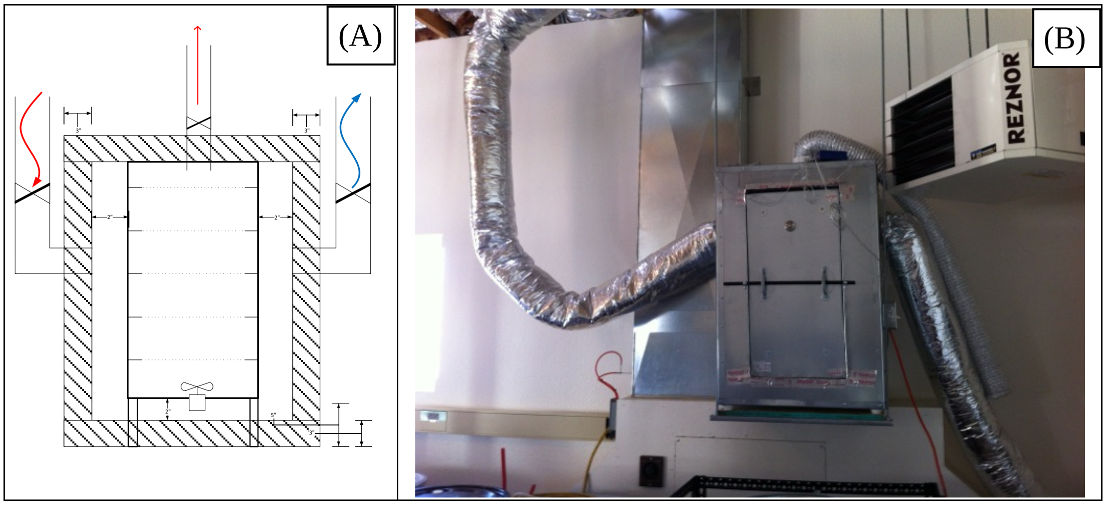

Figure 47. Solar oven for drying hydrochar produced by HTC.
(A) Schematic of indirectly-heated oven. (B) Photo of oven installed in the DRI REEF Workshop.

3.4.2 Optimize Hydrothermal Conditions in Small-Scale Experiments

Because of delays in completing the fabrication and installation of the PDU, there was not sufficient time to utilize the unit to the extent originally envisioned for the purpose of optimizing HTC conditions. Therefore, to more thoroughly define pre-treatment conditions for the HTC reactor, numerous small-scale pre-treatment experiments were conducted using a 2-Liter, stirred Parr pressure vessel. In each experiment, approximately 90 g of biomass was combined with water in an 8:1 water: biomass ratio (w/w). The reactor and its contents were heated, while stirring, to a desired temperature, which was maintained for a prescribed period of time. The reactor was then removed from the heated well and placed in an ice bath to quench the process. After cooling, the reactor was opened to collect and characterize all gaseous, aqueous, and solid products. A schematic illustrating the experimental setup is given in Figure 48. Figure 49 shows temperature and pressure traces for a typical HTC experiment.

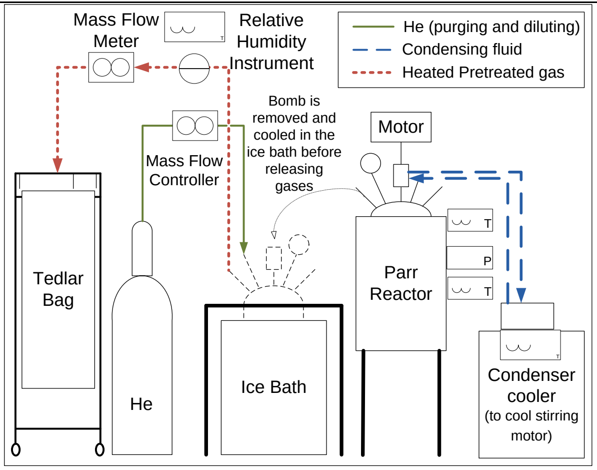

Figure 48. Schematic of Parr Reactor system used for the HTC process.

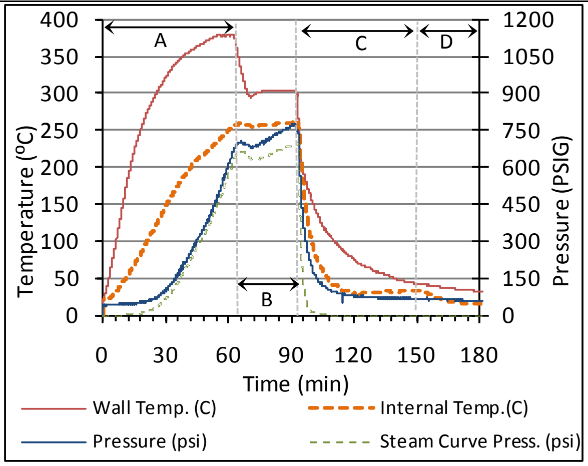

Figure 49. Temp. and pressure profile for HTC process of Tahoe Mix at 255ºC. Zone A = reactor heat-up; Zone B = reactor hold time; Zone C = reactor cooling; Zone D = reactor venting.

The types of laboratory analyses performed for each HTC experiment are summarized in Table 4. A more complete flow chart showing the processes, products, and analyses is provided in Figure 50.

The setup of the Parr reactor experimental system, and the development of analytical methodologies to characterize the products, were funded largely under separate DOE contract. In addition, earlier work involved a matrix of HTC experiments using a single woody feedstock, called Tahoe Mix, treated under different temperature and time conditions.[6] Results are given in Figure 51, which shows that increasing reaction temperature decreases the mass of biochar, but increases the energy content of the biochar. Increasing reaction time has similar (but smaller) effects upon biochar recovery and energy content as does increasing reactor temperature. A useful way of depicting the energy densification benefit of the HTC process is by means of a Van Krevelen diagram, as shown in Figure 52. Our experimental data are plotted here to show that HTC treatment in the range of 255-275ºC converts raw Tahoe Mix feedstock to a biochar having energy density similar to that of low-grade coal.

Table 4. Laboratory analyses performed on products from HTC experiments

Product	Measurements
Gases	Total volume CO_2, CO, CH_4, H_2 (by GC)
Liquids	Total mass recovered Sugars, Organic Acids (by IC) Total Organic Carbon (TOC) Non-volatile content (by oven-drying) pH
Solids & Raw Feedstocks	Total mass recovered Moisture (by oven drying) Energy content (by calorimetry) C,H,N,S, O

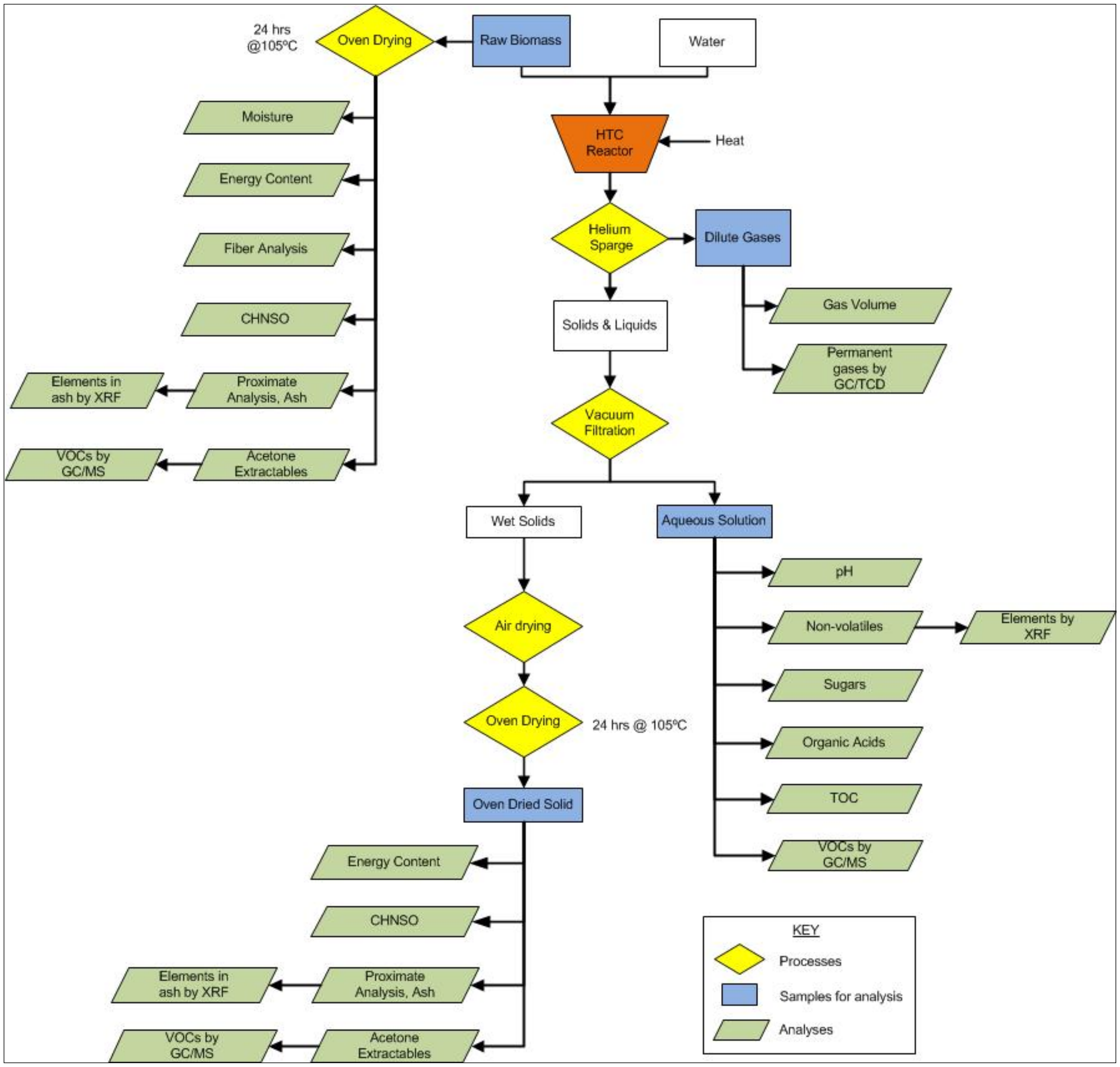

Figure 50. Flow chart for HTC experiments

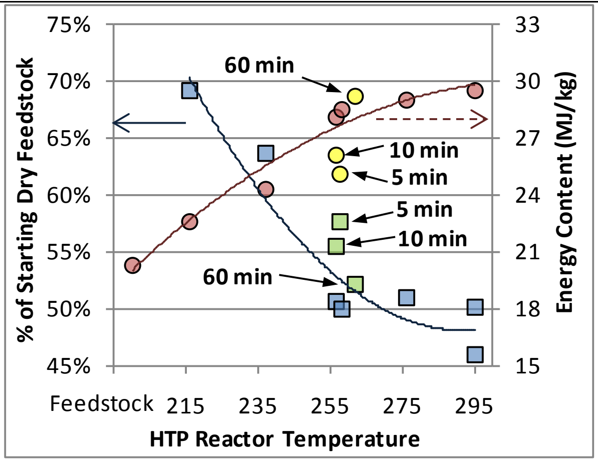

Figure 51. Effects of reaction temperature and hold time on mass recovery and energy content of biochar from HTC of Tahoe Mix. (Hold time = 30 minutes, except where otherwise indicated.)

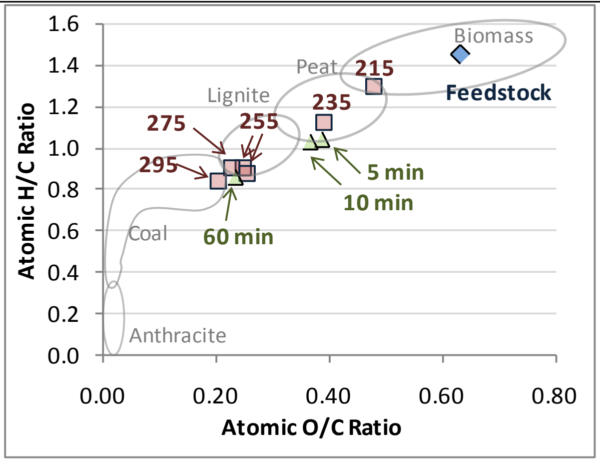

Figure 52. Van Krevelen Diagram of Biochar from HTC of Tahoe Mix. Hold time = 30 min. except where indicated. Temperature at 255ºC for indicated hold times.

In this DRI-REC project, we extended the Parr reactor HTC experiments to other feedstocks and conditions. Pinyon-Juniper (P-J), rice hulls, rice straw, sugarcane bagasse, and corn stover were all examined. Table 5 shows the combinations of feedstocks and temperature conditions that were used.

Table 5. Matrix of HTC Experiments Conducted in 2-Liter Parr Reactor

Feedstock	Hold Time	Temperature °C							
		155	175	195/200	215	235	255	275	295
Tahoe Mix	30 min	3	1	2	2	1	3	3	1
Tahoe Mix	5 min						1		
Tahoe Mix	15 min						1		
Tahoe Mix	60 min						1		
Pinyon/ Juniper	30 min		1		1	1	1	1	1
Loblolly Pine	30 min		1	4	1	2	1	1	2
Rice hulls	30 min		1		1	2	1	1	2
Rice straw	30 min				1		1		
Sugar cane bagasse	30 min		1		1	1	2	1	2
Corn Stover	30 min		2		1	1	1	1	2

The benefits of the HTC process in producing hydrochars of higher energy density are seen in Figure 53. This figure shows that substantial energy densification (about 35-40%) occurred at temperatures >250º for all feedstocks, except for rice hulls. The poorer performance of rice hulls is largely a consequence of their high ash content (about 20%) as compared to all the other feedstocks. This work has recently been published. [7]

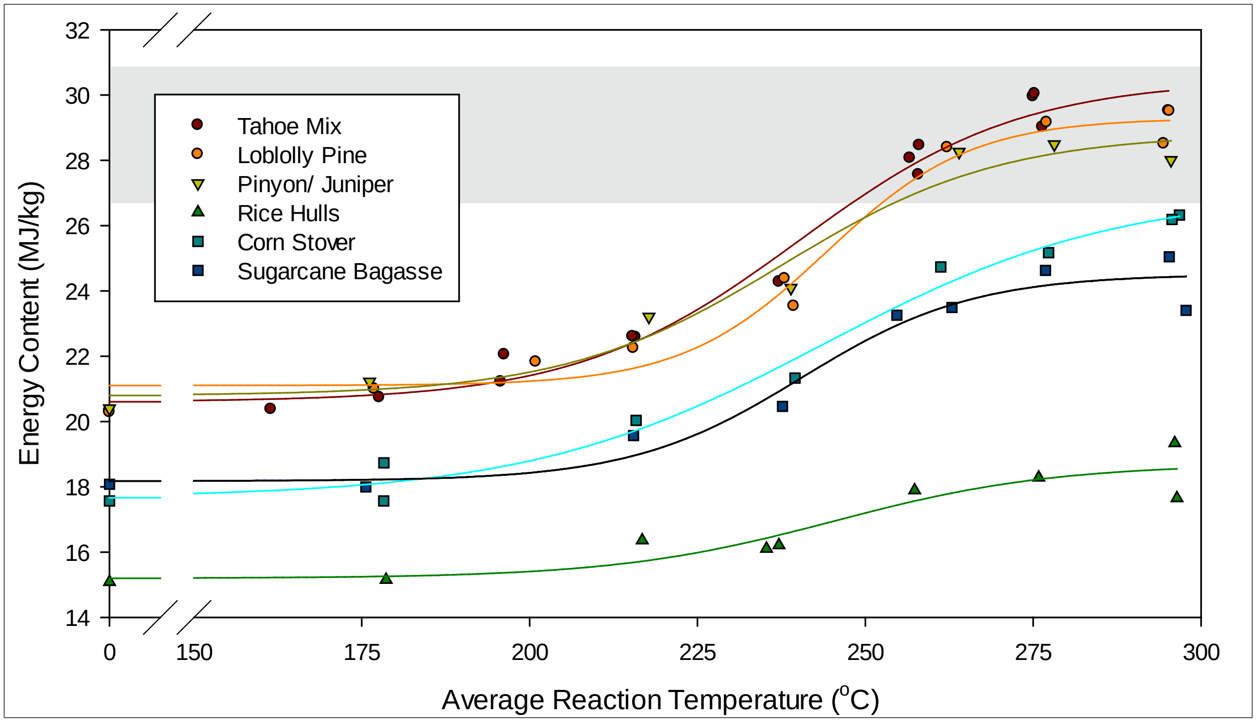

Figure 53. Effect of HTC reaction temperature on energy content of hydrochar produced from different biomass feedstocks. All reactions had a 30-minute hold time. (Shaded region represents typical coals.)

The main objective of these experiments was to define operating conditions for maximum energy densification of the biomass, so that we would have a reasonable operational starting point when using the semi-continuous PDU. The most influential parameter in determining energy densification is reaction temperature. The results in Figure 53 indicate that the largest degree of energy densification (with all six feedstocks) occurred between 215° and 275°C. A greater degree of energy densification occurred with some feedstocks than with others. In general, higher energy densities were achieved with the woody feedstocks as compared to the herbaceous feedstocks. Based upon these results, we determined that the initial temperature range to explore for optimum bio-char production in the PDU is 225-275°C.

3.4.3 Application of Optimized HTC Conditions to PDU Experiments

Based upon the wealth of information obtained from the HTC experiments conducted in the 2-L Parr reactor (discussed above), we determined that suitable initial temperatures for operation of the PDU are 235°C and 275°C. At 235°C, only slight energy densification of the hydrochar product was expected, while much greater energy densification was expected at 275°C.

A 2x2 experimental matrix was used in which two temperatures (235° and 275°C) and two auger speeds (fast and slow) were employed. Auger speed is related to reaction time, although it is not possible to define a precise reactor time corresponding to a particular speed. Previous experiments were conducted to determine approximate transit time for wood chips to pass through the entire PDU and reach the accumulator vessel used to collect the hydrochar product. This showed that a “slow” auger speed corresponded to a transit time of about 12 minutes, while a “fast” auger speed corresponded to a transit time of about 6 minutes. The actual HTC reaction time would be shorter than this, because the feedstock is submerged in the hot, pressurized water for only a fraction of the total time.

After each of these 4 experiments, the PDU was allowed to cool overnight. The following day, the reactor was vented (to release gaseous products). A port at the bottom of the unit was opened to drain out most of the water. Then the accumulator was removed, and its contents were filtered to recover the hydrochar product. Additional hydrochar was recovered by running the reactor auger in reverse, and collecting the solid material that fell out the bottom of the reactor. Following this, the feed auger was activated, and additional solids that fell out the bottom of the reactor were collected. The PDU was left in an open configuration for at least 24-hours, allowing the inside to completely dry out. This drying released a small amount of hydrochar that had adhered to the auger and reactor walls. Compressed air was used to blow this material out the bottom of the reactor. Thus, at the end of each experiment, the total hydrochar was collected in four fractions. Photos of these four fractions are provided in Figure 54. The mass recovery and the energy content of each fraction are shown in Table 6.

Figure 54. Four hydrochar fractions recovered from HTC experiments in PDU.

Table 6. Hydrochar Recovery from PDU Experiments with Slash Pine Micro-Chips

Hydrochar Fractions	235° Reactor Temperature				275°C Reactor Temperature			
	Slow Augers		Fast Augers		Slow Augers		Fast Augers	
	Mass %	Energy, MJ/kg	Mass %	Energy, MJ/kg	Mass %	Energy, MJ/kg	Mass %	Energy, MJ/kg
Accumulator	52.50	22.79	49.00	22.28	40.10	28.43	35.40	28.67
Reactor auger	13.10	24.63	10.40	24.98	10.40	28.62	15.10	28.54
Feed auger	0.40	24.95	0.10	24.74	0.20	28.96	1.60	28.23
Wall residues	3.70	23.12	1.40	24.49	2.90	27.86	2.10	26.93
Total Recovery	69.70		60.90		53.60		54.20	

Note: Energy content of starting feedstock was 20.2 MJ/kg

These results demonstrate that most of the recovered hydrochar was obtained from the accumulator, although a significant amount was also obtained from the reactor auger. Relatively little char was obtained from either the feed auger or the wall residues. Expected differences were seen between chars produced at low and high temperatures. At higher temperatures, total recovery of hydrochar was reduced, but the energy content of the hydrochar was increased.

The total mass recoveries of 61-70% at 235°C and 53-54% at 275°C agree well with results obtained in earlier HTC experiments with woody biomass using a small (2-Liter) Parr pressure reactor. Similarly, the energy contents of 22-24 MJ/kg at 235°C and 27-29 MJ/kg at 275°C are in good agreement with values obtained in these previous Parr reactor experiments (refer to Figure 53) . This gives us confidence that the PDU provides a realistic scale-up of the Parr reactor experiments, and that the HTC results obtained using other feedstocks in the Parr reactor are also transferrable to the PDU.

No consistent effects of auger speed were observed in these reactions. Total hydrochar recovery was higher using the slow auger speed at 235°C, but not at 275°C. Also, the energy contents of all char fractions were very similar between the two speed conditions. Thus, it appears that the effects of auger speed (or biomass residence time) are small in comparison to the effects of reaction temperature.

The results in Table 6 show little variation in energy content among the four hydrochar fractions obtained from a single PDU experiment (especially at the higher temperature condition). Based upon this, we conclude that all four hydrochar fractions from a single experiment within the PDU can simply be combined and characterized together. This greatly simplifies sample handling logistics and minimizes laboratory expenses.

3.5 Education and Outreach

Numerous activities were undertaken as part of the Education and Outreach task of this project, most of which involved participation by engineering students from the University of Nevada, Reno (UNR). The major activities are described below.

3.5.1 Energy Production and Use within the REEF Workshop

Student involvement in developing and operating the renewable energy components and systems within the DRI REEF were extensive. As an example, prior to constructing the solar thermal air collector as part of the REEF Workshop roof, the students built and tested a small prototype model to ensure that the pressure drop was not excessive at the required flow rate. After testing of this prototype was satisfactorily completed, the unit was reconfigured and converted to an 8’ x 8’ solar thermal collector for heating the electrolyzer that is part of the renewable power system for the REEF (see Figure 10).

Students were also instrumental in the design and fabrication of various ancillary items within the REEF Workshop – including the wood chip sorter and solid/liquid separator (Figure 46) and the solar drying oven (Figure 47). In addition, students performed much of the computer programing necessary to control the integrated components within the REEF House and Workshop, and to monitor their performance.

Finally, students contributed significantly to writing the stand-alone report describing development of the REEF Workshop (included as Appendix II). This report discusses the design, construction, and operation of the site-built solar thermal system. Also included in the full report are installation costs for the system. The total cost of materials and labor (including the duct distribution system and blower; but excluding the heat exchanger, liquid storage tanks, pumps, and monitoring system) was estimated to be $14,800. Based upon the collector's gross area (34' x 17'), this equates to $25.60/ft^2. However, as explained in the REEF Workshop Report (Appendix II), this could be reduced to $16.73/ft^2 by simple improvements to the duct distribution system (DDS) and the blower. Similar rough economic calculations indicate that the purchase and installation costs for the Viessmann and Sunvelope systems are $46.28/ft^2 and $38.71/ft^2, respectively.

3.5.2 Public Outreach in Energy Efficiency

Throughout the course of this project, several engineering students have become familiar with the DRI home energy audit equipment, have reviewed the energy audit literature, and have written informational articles for the DRI "Self Audit" Website. Three students, along with their faculty mentor, have conducted several home energy audits and have completed written reports on these audits. An instructional manual was also prepared to serve as a guide in conducting future home energy audits. This manual is included here as Appendix III.

Students also prepared material resource guides that were put on the DRI energy website to better inform the public about the value of renewable energy and energy efficiency. Six articles were researched, prepared, and posted on the DRI website at http://www.dri.edu/energy-assessments. Copies of these articles are included here as Appendix IV. These articles are intended to assist homeowners and other laymen in making informed decisions about the technical and economic practicality of installing renewable energy devices. Specifically investigated were the following topics:

1. Economics of Residential PV Power Systems (17 pp)
2. Home Heating Index (HHI) (5pp)
3. Weatherstrip Doors (2 pp)
4. Insulate Garage Doors (2 pp)
5. Save Money On Your Lights (1 pp)
6. Save Money with Shades and Blinds (3 pp)

3.5.3 Host Public Meetings

One of the objectives of the DRI-REEF is to facilitate outreach to the public, and provide education regarding energy conservation and renewable energy utilization within a residential setting. To help achieve this objective, two formalized meetings were held to introduce and explain the REEF.

First, a presentation/discussion was held with the Sunrise Sustainable Resources Group [a local organization of sustainable energy enthusiasts (see: http://www.sunrisenevada.org/)]. Approximately 30 people attended this meeting, held on May 16, 2012. A copies of the meeting notice and presentation materials used during the meeting are included here as Appendix V-1.

On September 21, 2012, a 1-hour seminar on the REEF was held for all DRI faculty and staff. At this meeting, each of the major project participants presented an overview of the REEF design, construction, objectives, and accomplishments. Copies of the meeting notice and presentation materials used in this seminar are included here as Appendix V-2. The seminar was followed by an open house at the REEF, where those who were interested could get a more detailed explanation of some special features in both the REEF House and Workshop, and see how these features are integrated into a coordinated system.

Both of these meetings generated considerable interest in the REEF. In the future, we intend to hold other periodic seminars, demonstrations, training classes, and open houses at the REEF.

4. Conclusions

The principal objective of this DRI-REC Project was to utilize a flexible, energy-efficient facility, called the DRI-REEF, to support a variety of renewable energy R&D efforts, as well as education and outreach activities. This objective was achieved by utilization of both the REEF House and REEF Workshop. The REEF House has proven to be an effective laboratory for demonstrating and comparing the operation of various renewable energy components and systems – especially those associated with the house’s heating and cooling systems. The REEF Workshop contains open bay space, which is critical to purse larger-scale biomass/biofuel research at DRI. Taken together, these two structures serve as an effective renewable energy testing laboratory, enabling an expansion of DRI’s expertise in areas of renewable power generation, energy efficiency technologies, and biomass/biofuels.

One sub-objective of this project was to enable off-grid operation of the REEF House. This was accomplished by integrating and controlling several individual components – including PV arrays, solar thermal systems, wind turbines, hydrogen production and storage, a gaseous internal combustion engine/genset, and others. While off-grid operation was demonstrated for short periods of time, there remain several areas for improvement. For example, more effective production and use of hydrogen is possible, and improved monitoring/control of all systems is necessary to optimize the overall efficiency. In the REEF Workshop, the rooftop solar air collector system often provides more heat than can be effectively utilized; thus, additional uses of this readily-available energy resource should be sought.

A second sub-objective was to develop a gas-fueled engine R&D platform. This objective was achieved by converting an existing Daihatsu natural gas engine to a more versatile form that can be operated on a variety of gaseous fuels. While this engine modification was satisfactorily completed, and acceptable operation was demonstrated in the engine shop where the work was done, the engine performance was less than desired once the system was relocated to DRI. Further work will be required to achieve reliable operation of this engine when used in subsequent experimental projects that involve testing of multiple gaseous fuels.

A third sub-objective was to use the REEF Workshop for development and testing of biomass/biofuel systems. This component has been very successful. The large, open bay type of space within the REEF Workshop has enabled deployment of a process development unit (PDU) used to convert woody biomass (such as wood chips) into a solid char (called hydrochar) that is friable, hydrophobic, and similar to low-grade coal in energy content. The space requirements for the PDU and associated components are far too large to be accommodated within a typical laboratory at DRI. Also, the ready availability of solar thermal energy within the REEF Workshop is useful in supporting operation of the PDU, both by providing hot process water and by providing hot air to dry the hydrochar product.

Finally, the DRI-REEF is meant to promote education and outreach in topic areas related to renewable energy nd energy conservation. Part of the education component was achieved by direct, hands-on involvement by students in the DRI-REC Project. Similar student involvement in other R&D projects that utilize the REEF are anticipated. In addition, education/outreach efforts involve interactions with the public, using the REEF itself as a showcase for renewable energy utilization, as well as a convenient venue for seminars and other formalized meetings. Some of these activities have already occurred. It is expected that they will become more frequent in the future.

5. Products and Technology Transfer

Peer Reviewed Publications:

Hoekman, S.K., Broch, A., and Robbins, C., "Hydrothermal Carbonization (HTC) of Lignocellulosic Biomass," *Energy and Fuels*, **25**, 1802-1810 (2011).

Hoekman, S.K., Broch, A., Robbins, C., Zielinska, B., and Felix, L., "Hydrothermal Carbonization (HTC) of Selected Woody and Herbaceous Biomass Feedstocks," *Biomass Conversion and Biorefinery*, accepted for publication, Dec. 2012.

Conference Presentations:

Hoekman, S.K., "Effective Utilization of Indigenous Biomass as a Renewable Fuel," Air Quality and Climate Conference, sponsored by the Air and Waste Management Association, Kona, Hawaii, March 14-19, 2011.

Hoekman, S.K., Broch, A., Robbins, C., Yan, W., Coronella, C., Felix, L., "Renewable Solid Fuels via Hydrothermal Carbonization (HTC) of Cellulosic Biomass." Biomass'11 Conference, Grand Forks, ND, July 26-27, 2011.

Felix, L., Farthing, B., Irvin, J., Snyder, T., Hoekman, S.K., Coronella, C., "Employing Hydrothermal Carbonization for the Production of Energy-Dense Fuels from Lignocellulosic Biomass." TCBiomass 2011 Conference, Chicago, IL, September 28-30, 2011.

A. Broch, S.K. Hoekman, C. Robbins, C. Coronella, L. Felix, and W. Yan, "Renewable Solid Fuels via Hydrothermal Carbonization (HTC) of Cellulosic Biomass," Pacific West Biomass Conference, San Francisco, CA, Jan. 16-18, 2012.

S.K. Hoekman, A. Broch, C. Robbins, C. Coronella, L. Felix, W. Yan, and G. Coble, "Renewable Solid Fuels via Hydrothermal Carbonization (HTC) of Cellulosic Biomass," Electric Utilities Environmental Conference, Phoenix, AZ, Jan. 30- Feb. 1, 2012.

S.K. Hoekman, A. Broch, C. Robbins, C. Coronella, L. Felix, W. Yan, and G. Coble, “Hydrochar as a Renewable Biofuel,” International Biomass Conference and Expo, Denver, CO, April 16-19, 2012.

Internal Presentations:

S.K. Hoekman, R. Jacobson, C. Robbins, P. Ross, and R. Turner, “DRI’s Renewable Energy Experimental Facility (REEF),” presented to Sunrise Sustainable Resource Group, Reno, NV, May 16, 2012.

S.K. Hoekman, P. Ross, R. Jacobson, R. Turner, and C. Robbins, “DRI’s Renewable Energy Experimental Facility (REEF),” presented to DRI Faculty and Staff, September 21, 2012.

6. References

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2. Renewable Energy Center - Desert Research Institute: Phase II. Occurrence No. 22 of Subcontract No. AXL-9-99200-01, 2011.
3. Ross, P.; Final Report: Renewable Energy Center - DOE Award DE-EE0002221. 2012.
4. Libra, J. A., K. S. Ro, C. Kammann, A. Funke, N. D. Berge, Y. Neubauer, M.-M. Titirici, C. Fuhner, O. Bens, K. Jurgen, and B. Emonts; Hydrothermal Carbonization of Biomass Residuals: A Comparative Review of the Chemistry, Processes and Applications of Wet and Dry Pyrolysis. *Biofuels,* 2, (1), 89-124. 2011.
5. Peterson, A. A., F. Vogel, R. P. Lachance, M. Froling, M. J. Antal, and J. W. Tester; Thermochemical Biofuel Production in Hydrothermal Media: A Review of Sub- and Supercritical Water Technologies. *Energy Environ.Sci.,* 1, 32-65. 2008.
6. Hoekman, S. K., A. Broch, and C. Robbins; Hydrothermal Carbonization (HTC) of Lignocellulosic Biomass. *Energy & Fuels,* 25, 1802-1810. 2011.
7. Hoekman, S. K., A. Broch, C. Robbins, B. Zielinska, and L. G. Felix; Hydrothermal Carbonization (HTC) of Selected Woody and Herbaceous Biomass Feedstocks. *Biomass Conversion and Biorefinery,* In Press, 2012.

7. Appendices

7.1 Renewable Energy Projects Hydrogen Safety Plan

7.2 REEF Workshop Report

7.3 Home Energy Audits

7.4 Energy Efficiency Bulletins

7.5 REEF Presentations

APPENDIX I

Desert Research Institute

Renewable Energy Projects
Hydrogen
Safety Plan

Renewable Energy Projects
Hydrogen Safety Plan

Signature Page

Author: Amber Broch

Signature: ____________________ Date: 01-07-2011

Principal Investigator: Kent Hockman

Signature: ____________________ Date: 01/07/11

CTREC Director: Alan Gertler

Signature: ____________________ Date: 01/07/11

EH&S approver: Martha McRae

Signature: ____________________ Date: 01/07/11

Renewable Energy Projects
Hydrogen Safety Plan

Table of Contents

1.0 Introduction

The generation or use of gaseous hydrogen in renewal energy (RE) projects presents the potential for fire hazard. Hydrogen is generated in renewable energy projects through a variety of means including electrolysis. Some of these projects also generate or use methane and/or carbon monoxide, which are also flammable. As part of the hazard evaluation of RE projects, such hazards will be identified and mitigated.

This Hydrogen Safety plan (HSP) is developed to meet the guidelines of DOE and National Hydrogen and Fuel Cells Code and Standards Coordinating Committee and industry standards and to enhance existing DRI policies and procedures that when implemented will minimize risks to personnel, facilities, and the environment. The policies and procedures are based on currently accepted safety practices established at academic, government and industrial research sites. This plan is used in conjunction with other existing DRI safety plans such as the DRI Chemical Hygiene Program and compressed gases and cryogenic liquid use, handling and storage guidelines.

1.1 Purpose

This Hydrogen Safety Plan is prepared for the RE research activities sponsored by DOE performed through and by the Desert Research Institute in Reno and Las Vegas, Nevada and its associated project field locations. For these DOE sponsored projects using hydrogen, the plan is a guidance document used to identify the relevant information and components required for any project using, handling, or storing hydrogen during the experimental processes of a project.

1.2 Scope

This plan describes procedures, personal protective equipment, and work practices employed to protect DRI employees from hazards associated with hydrogen used or generated) and fuel cells used in DRI projects. Per the proposed guidelines and industry standards, the plan must include standard operating procedures for safety and health; criteria for the implementation of control/detection measures; measures to ensure proper operation of engineering controls; provisions for training and information dissemination; designation of responsible personnel; and identification of hazards.

2.0 Responsibilities

2.1 **Division and Center Directors** have ultimate responsibility for environmental health and safety within her/his division and associated facilities. It is the director's responsibility to promote good environmental health and safety practices (best management practices) within the Division and to ensure that principal investigators/supervisors understand their responsibilities and are committed to the implementation of safe work practices on their projects, including the applicable DRI EH&S policies, programs and procedures and development of Standard Operating Procedures (SOPs) specific to individual project operations.

2.2 **Principal Investigators (PIs)/Project Managers/Supervisors** are responsible for the health and safety of all personnel working on their projects. As such they are responsible for.

- Implementing the plan in their RE projects
- Approving planned hydrogen related activities and the hazardous chemicals involved
- Developing written SOPs specific to their project operations that address the health and safety of operations, especially those that involve hydrogen uses or generation
- Ensuring all lab personnel receive appropriate safety training
- Ensuring that appropriate engineering controls, project specific safety equipment and personal protective equipment (PPE) are available and in working order, and that employees have been trained in the proper use of such equipment
- Reporting any deficiencies in laboratory/facility safety equipment (such as fire extinguishers, chemical hoods, safety showers and eyewashes, and emergency lighting) to Facilities via the work request system.
- Performing periodic safety assessments and initiating any corrective action
- Ensuring proper maintenance and repair of equipment and systems is performed regularly to extend safe working operations
- Handling and disposing of hazardous waste in accordance with DRI policies and regulatory requirements
- Reporting project related injuries and illnesses to the Worker's Compensation Office, EH&S and responsible Division Director, ensuring necessary forms are completed and participating in incident investigations. Similarly, fires, explosion and hydrogen/chemical release incidents will be reported to EH&S and the responsible Division Director.
- Maintaining a current inventory of hazardous chemicals for their project in each lab or location.
- Ensuring that materials safety data sheets (MSDSs) and other sources of chemical hazard information are available to personnel, and that workers know how to access this information

2.3 RE Project Workers

All workers (faculty and staff, graduate students, hourly workers and volunteers) are directly responsible for their own safety, as well as the safety of other employees and persons on DRI premises. Specific responsibilities include:

- Conducting laboratory and project activities in accordance with the DRI HSP and project specific standard operating procedures.
- Participating in required training
- Utilizing engineering controls, safety equipment, and PPE in an appropriate manner
- Informing the PI/supervisor of any accidents or unsafe conditions

2.4 Environmental Health and Safety (EH&S) Department has responsibility for the development and implementation DRI EH&S policies, programs and procedures. Additional responsibilities include:

- Assisting PIs and laboratory/project Supervisors in development and implementation of lab specific procedures and work practices
- Assisting PIs and Supervisors in conducting hazard assessments
- Performing laboratory inspections and audits of lab practices to ensure the DRI Chemical Hygiene Plan (CHP) is implemented

- Reviewing safety plans annually
- Determining if exposure monitoring is necessary
- Determining if medical surveillance is necessary

2.5 Laboratory Safety Committee (LSC)

The Lab Safety Committee acts as an advisory body to EH&S on specific health and safety issues that come to the attention of EH&S or LSC members. In that regard the LSC is responsible for:

- Providing input to EH&S concerning deficiencies in DRI labs and/or DRI projects
- Reviewing and approving generic SOPs and safety guidelines
- Facilitating the dissemination of information to personnel in their division
- Discussing safety issues or events that have occurred on a project.

3.0 GENERAL DRI SAFETY INFORMATION

3.1 DRI Related Policies and Procedures

3.1.1 DRI has developed and implemented safety policies and procedures appropriate and relevant to the safe handling of laboratory chemicals and hazardous materials in the following documents: Chemical Hygiene Plan, Chemical Storage, Handling, and Use , DRI Procedure for Transporting/Moving Chemicals , Safe Work Practices for Using the Laboratory Hood . Compressed gases (Use, Handling and Storage of Compressed Gases and Cryogenic Liquids). The comprehensive Chemical Hygiene Plan covers particularly hazardous substances, generic storage and handling guidelines for carcinogens, reproductive toxins, acutely toxic chemicals, compressed gases, corrosive substances, cryogenic liquids, flammable and combustible liquids, highly reactive chemicals and oxidizing agents.

3.1.2 DRI safety programs also include environmental management programs including the proper handling of hazardous waste, occupational health, emergency response, and field safety. These programs have been developed and implemented in the DRI facilities with training provided to project personnel identified through a collaborative method between principal investigators, supervisors, and EH&S personnel.

3.1.3 Training is documented.

3.2 Hydrogen experience

3.2.1 The experience of the principal investigators gained through past research is leveraged in a collaborative manner to ensure experience and knowledge is shared between research groups and the EH&S department. This knowledge is used to evaluate risks, develop operational processes, define operating limits, and define necessary safety systems and processes.

3.2.2 DRI continues to participate in research relating to alternative energy, renewable energy, and hydrogen generation.

4.0 PROJECT SAFETY

4.1 Identification of Safety Vulnerabilities (ISV)

4.1.1 The risks and hazards assessment associated with each project are performed through a comprehensive risk assessment developed through a collaborative effort between the DRI EH&S and the project principal investigator(s). Hazardous materials identified with each project are noted and their associated hazards and steps for mitigating risk are included. For the purposes of this plan the hazard identified is hydrogen.

4.1.2 Hydrogen, also considered a fuel gas, is in the class of flammable gases and can be ignited in air.

- It is a flammable gas that forms a flammable mixture with air at ambient temperature and pressure, at a concentration of 13 percent by volume or less, or
- At ambient temperature and pressure, forms a range of flammable mixtures with air wider than 12 percent by volume, regardless of the lower limit.
- Hydrogen is an odorless, colorless, tasteless, flammable and nontoxic. It is the lightest gas known, with a density of 0.07% of air.
- Hydrogen burns in air with a pale blue flame that is almost invisible in normal conditions.
- The flammable limits of hydrogen in dry air at atmospheric pressure are 4.0-74% hydrogen by volume.
- When attaching to a regulator or manifold, hydrogen cylinder valves should not be "cracked" before connecting, as self-ignition of the hydrogen may occur. When the cylinder is in use, the valve should be fully open to minimize the self –ignition potential.

4.2 Risk Reduction Plan

To mitigate the risks and hazards identified, standard safety practices are implemented. For the use of compressed hydrogen, the safety procedures clearly outlined in the DRI compressed gases procedures must be followed at all times. The following list outlines these procedures and mitigation steps:

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4.2.1 Personal protective equipment (PPE) is provided by the project and minimally includes safety glasses, lab coat, and gloves, as appropriate

4.2.2 Exhaust control is provided through the use of a certified laboratory hood (when available), a local exhaust system, or adequate air flow to ensure disbursement and exhaust of residual gases.

4.2.3 Gas detection – For hydrogen generation experiments and/or projects, one or more hydrogen sensors are installed in appropriate locations, to detect low concentrations of gas. An audible alarm is set and enunciated throughout the project location, and necessary adjacent areas.

4.2.4 Fire hazards – A fire extinguisher, ABC type, is located in the immediate work area, but not adjacent to the gas source (to assure access during an emergency). Additionally, most work areas are equipped with a sprinkler system or smoke detectors and audible alarms.

4.2.5 Physical hazards – hot surfaces, sharp edges, cold surfaces and their associated hazards will be mitigated through appropriate PPE or retro-fitting, as appropriate.

4.2.6 Special equipment/instrumentation

Hydrogen generator/electrolyzer failure –

An auto shut off system is in place and when a leak or failure is detected, the system is shut down. This covers system components including but not limited to the shut down of components, i.e. compressor, the electrolyzer, supply lines, as appropriate.

- An audible local alarm sounds to notify workers. Hydrogen storage tanks and electrolyzer(s) are located in outdoor locations, ideally distant from occupied buildings and/or laboratories.

4.3 Operating Procedures

Within the DRI REEF- Phase 2 project, several subtasks will utilize hydrogen and hydrogen storage. These tasks are as follows.

Task 1

Under Task 1, existing renewable energy infrastructure and systems will be relocated and tested with two zero energy structures (ZES) on the DRI Northern Nevada Science Center campus (NNSC). The equipment and systems to be relocated include:

- Two Siemens 1kW PV panels
- Two 1.5 kW Bergey wind turbines (will be placed on tilt-down towers)
- A 5 kW Stuart electrolyzer
- A trailer containing components of an off-grid renewable system
- A small battery bank,
- Sensors, computer controllers, inverters and various other electronic devices to control the energy flow.
- A low-pressure hydrogen storage tank

Once these components have been moved, they will be re-integrated into a renewable off-grid system, and all components will be thoroughly tested. The off-grid system involves using the energy produced from the solar PV panels and wind turbines to power a 5kW Stuart electrolyzer which will produce hydrogen. When not enough power is produced to maintain the facility, the H_2 is used to provide power via combustion in an internal combustion engine which has been modified to run on either H_2 or propane. A small battery bank is also used to stabilize the system, which is controlled through computer programming and numerous sensors and other electronic devices.

The electrolyzer and off-grid system will be located outside of the ZES in an open courtyard. The H_2 produced by the electrolyzer is stored at 100 psi in a large tank. The O_2 produced during electrolysis is vented to the atmosphere. An SOP of the electrolyzer and safety procedures is included in Appendix I.

Task 2

Under Task 2, one or more natural gas test engines provided by Southwest Gas Corporation will be reconfigured to accept a variety of gaseous fuels, including H_2, propane and synthesis gas. Long term testing of the engine(s) will be conducted at Collier Technologies. Any testing with H_2 as the fuel will utilize canisters of gases purchased from a gas supplier such as Air Gas. Once on-site, the engine (located in its own enclosure) will be free standing outside of the facility. Gas detectors for H_2 and Propane will be located inside the enclosure with a relay to controls for a system shutdown. (Synthesis gas is 50% H_2 so the detector will be programmed appropriately).

Compressed hydrogen cylinders

4.3.1 Hydrogen compressed gas must follow all procedures as defined in the *Compressed Gases--Generic Procedure for Safe Handling and Storage* document on line, including the guidelines for flammable gases as found in the DRI generic gas procedures found at http://safety.dri.edu/LabSafety/CHP_generic_gas09.pdf

4.3.2 Special Precautions

- Manifold systems shall be designed and constructed by competent personnel who are thoroughly familiar with the requirements for piping of hydrogen. Manifolds shall comply with the standards of a recognized safety authority (i.e., Underwriters Laboratories, Compressed Gas Association). Consultation with the gas supplier before installation of manifolds is recommended.
- Valves on hydrogen cylinders must be shut off when the laboratory is unattended and no experimental process is in progress.
- Flames involving hydrogen must not be extinguished until the source of the gas has been safely shut off; otherwise it can reignite causing an explosion.

4.3.3 Storage

- Storage of compressed flammable gases (hydrogen) must not exceed 2000 ft^3 per control area. To ensure these limits are not exceeded, it is highly recommended that only one compressed cylinder of hydrogen be stored as back up at point of use. Other back-up or secondary cylinders should be stored in a well ventilated, monitored distant location proximate to the use area(s).

Hydrogen generation apparatus/large scale electrolyzer

- The hydrogen (H_2) generator/large scale electrolyzer, is located within its own shipping container and positioned on a concrete slab surrounded by a secondary containment unit.
- Water supply and salt (potash) are supplied to the unit for the generation of O_2 and H_2 gases.
- The O_2 is bled off above the unit through an exhaust pipe and the H_2 is contained in adjacent storage tanks.
- The unit consists of electrolysis units, potash container, DI water supply, a compressor, and power (provided via solar or wind turbines).
- The H_2 is piped to the storage tank and stored at 70-120 psi. Depending on need, hydrogen gas flows from the storage tank(s) to an internal combustion engine.
- Hydrogen gas detectors are located within the electrolyzer shipping unit. When an adverse condition is determined above a predetermined level, an alarm sounds

causing the solenoids to be activated for shut down of the system components as well as the hydrogen supply line(s).

- See SOP (Appendix I) for more details regarding the operation of this unit.

4.4 Management of Change Procedures

4.4.1 When changes to the technology, chemicals, equipment, procedures, or materials are considered, these are reviewed first by the principal investigator, EH&S and other collaborating personnel to ensure safety procedures and safety to personnel are not compromised.

4.4.2 Should changes be made to the process, including safety processes, these will be promptly disseminated amongst all project personnel, EH&S and support personnel.

4.4.3 The procedural changes will be posted in a conspicuous location near the experimental areas and distributed to all project personnel via email or similarly effective means.

4.4.4 Prior to commencement of the changes, training will be provided and acknowledgement of the changes will be documented.

4.5 Project Safety documentation

4.5.1 All standard safety documentation, i.e. policies programs and procedures, are accessible via the DRI website EH&S link. These are reviewed periodically and updated as necessary to reflect organizational changes, i.e. facilities, equipment.

4.5.2 The specific project safety plans or SOPs (see Appendix I) will be available at the work area. The location of the plan/SOPs will be clearly defined and personnel will be informed during safety training. As noted before, should changes be made, the changes will be disseminated promptly to all affected personnel.

4.5.3 Information pertaining to the technology and equipment/apparatus of the RE project are defined.

- Technology –
  - An image, diagram, equation or other depiction is shown in the SOP or safety plan for clarification. Also, the experimental process and procedures are described to ensure the operation and the safety aspects are understood and defined.
- *Equipment/Apparatus info* –
  - If an operations manual including safety issues is available, it can replace an SOP or safety plan. The plan/SOP addresses construction, electrical, pressure relief, ventilation, codes/ standards, material and energy balances, as relevant to the system.
  - If an operation manual is not available, the safety plan or SOP summarizes procedures and safety concerns. .

4.5.4 Additional safety documentation shall include:

- MSDSs
- DRI safety policies, programs and procedures
- Pertinent reference documents, i.e. handbooks, standards

5.0 COMMUNICATION PLAN

5.1 Employee Training

Through the partnership of EH&S and project personnel, training is defined, provided, and documented. All project personnel will be provided with hydrogen safety and other relevant safety training. Training will include chemical handling, use, and storage, transporting/moving chemicals, proper use of chemical hoods, storage, handling and use of compressed gases, and storage.

5.2 Safety Reviews

Safety reviews will be conducted periodically throughout the development and lifetime of the project. They will be an integral of the project design, development and operational phases. The project PI, in collaboration with EH&S, will ensure that risks are considered and addressed in a timely manner. Safety plans are reviewed and updated as required. As processes are performed requiring additional review or oversight, the PI shall ensure that these reviews occur in a timely manner and any adverse situations promptly reported and discussed with DRI EH&S.

5.3 Safety Events and Lessons Learned

Lessons learned and experience from past projects will be taken into consideration to ensure proper design and operation of the project systems. Pertinent lessons learned will be discussed during training, pre-project meetings, and the next regularly scheduled safety committee meeting to ensure project personnel, EH&S, and other departments learn from such events.

Training will include how project staff report incidents to EH&S and sponsoring agencies, the use of DRI incident analysis procedures, ensuring corrective action is taken, how necessary changes are completed and that changes are communicated throughout the project team.

Note: The dissemination and discussion of these issues will ensure better team preparation for handling any potential incidents during the performance of the project.

5.4 Emergency Response

Should an emergency occur, project personnel shall follow the emergency response procedures established by DRI. This information is posted throughout DRI facilities and on the web. Lab specific emergency information is posted on each lab interior door. This includes work area specific procedures, emergency contacts, location of nearest fire extinguisher, safety shower/eye wash station, AED and first aid kit. Evacuation Maps showing routes with location of fire extinguishers, pull stations, exits and fire enunciators are located through out DRI facilities. All DRI personnel are trained in whom to call for emergency response. Project-specific procedures will be performed as defined in project operation documentation.

5.5 Safety Plan Approval

This plan has been approved by the project principal investigator and EH&S, identified on the cover sheet of this Renewable Energy Projects Hydrogen Safety Plan.

Appendix I

Stuart SIPS SunFuel 5000 Hydrogen Generator
Standard Operating Procedures

SOP#:

SOP Title: Stuart SIPS SunFuel 5000 Hydrogen generator

Author: Rick Purcell.	
Signature:	**Date:** 12/15/10

Principal Investigator: Roger Jacobson	
Signature:	**Date:** 12/15/2010

EHS Approver (if necessary): Martha McRae	
Signature:	**Date:** 12/15/10

1.0 Introduction

Stuart Energy Systems has built and commissioned a 5 kW "stand alone integrated power systems" (SIPS) for DRI for generating hydrogen as a renewable fuel for varying projects. The primary power source for SIPS system is renewable DC power, provided through the on-site wind turbine or solar panels. Hydrogen , through electrolysis production, provides the main energy storage component, supplying a direct fuel source to vehicles, generators, or fuel cells. .

2.0 Purpose

The SunFuel 5000 hydrogen generator operates as a stand alone plant, operating automatically with operator intervention required only during fault situations and for filling the water tank. The SunFuel 5000 SIPS commissioned by DRI will be used for fueling hydrogen fuel cell vehicles, fueling DC power generator for a renewable energy experimental facility, and future renewable energy projects.

3.0 Scope

The SunFuel 5000 Hydrogen plant utilizes 13 electrolysis cells linked electrically in series for a total nominal voltage of 26 VDC (Volts Direct Current). Common headers collect the off-take gases, both hydrogen and oxygen, from the individual cells. Oxygen gas goes directly to the oxygen side of the gas holder/water seal and is bubbled through to the oxygen compartment. Hydrogen gas runs through a mist eliminator to strip away much of the potassium hydroxide (KOH) mist and then enters the hydrogen side of the gas holder/water seal . The water seal function serves to balance the hydrogen and oxygen pressures on the cells. The gas holder temporarily holds hydrogen gas ready for compression. Oxygen gas is vented from the gas holder to atmosphere.

When the gas holder is full, a compressor is turned on to compress the hydrogen gas up to 100 psi. The gas is passed through filters and a catalytic purifier and then stored in the hydrogen storage tank, ready for use.

The SunFuel 5000 operation's manual describes the process for operating the system in great detail. Comprehensive operating procedures, safety precautions, hazard and mitigation controls are included in the manual. The operating procedures include Plant Start up and shut down; initial start up and purging procedure; water tank fill; normal operation including normal operation on hydrogen, routine checks and shut down of the compressor; alarm faults and diagnotiscs; maintenance schedule for gas purity, KOH concentration in the electrolyte, filling the water seal, cleaning the de-mister, hydrogen compression and catalytic purification, and the hydrogen filters including replacement of the filter elements. Many of the specific components have an Appendix dedicated to the operation and maintenance of the component. Additionally, an Appendix is dedicated to the electrical and control system for a description of the electronic and computer controls of the plant. Complete operations manuals for the controller hardware, the compressor, the gas sensor/transmitter, switching power assembly, DC/DC converter, regulators, temperature controllers, solenoid valves, etc are included.

To ensure a reasonable overview of the gas generation steps are included in this SOP, an abbreviated process description is included in Section 8.0, Procedural Steps.

4.0 Responsibilities

Please select the general categories of personnel who could obtain approval to perform the process or experiment:

1. x Principal Investigator	2. ☐ Graduate Students	3. ☐ Undergraduates
4. x Technical Staff	5. ☐ Post Doctoral Employees	
6. ☐ Other (Describe):		

Please list the specific personnel and their approval level (Attach an addendum to this form for additional personnel):

1. Rick Purcell	X Trained	Initial. Training Date: October, 2000
2. Curtis Robbins	☐ Trained	Initial Training Date:
3. Amber Broch	☐ Trained	Initial Training Date:
4. Roger Jacobson	☐ Trained	Initial Training Date:
5.	☐ Trained	Initial Training Date:

The Principal Investigator will update this section when any personnel changes occur. If changes occur, document the changes (include the record of training of additional personnel) in the laboratory's files and submit an addendum to the DRI EH&S Office with all training documentation.

5.0 Hazards

SunFuel 5000 SIPS Manual provides general remarks and safety concerns as they relate to the hydrogen plant. The hazards associated with the plant are as listed below and are discussed in detail.

- hydrogen
- oxygen
- caustic potash (potassium hydroxide)
- electrical safety
- oxygen deficient atmospheres
- hydrogen explosion hazard.

6.0 Hazard Control Measure and Limitations

The plant is provided with means to identify system faults and hazardous conditions. In these cases fault alarms are activated. Any of the following fault alarms will cause the hydrogen plant to shut down. Even if the fault goes away, the fault alarm indicator will remain RED and the plant will reamin off until the operator resets the system by turning the Plant Start off for a few seconds and then on again.

Fault Alarms/Shutdown:

* **Area H2 level High** - Ambient hydrogen level is about 40% of LEL (LEL=4.0%). This results in complete shutdown on the production side (i.e. pumps, cells) of the plant (except for monitoring side of system, i.e. controller and gas detector).

* **Battery Low** - Indicates the Controller battery backup is discharged

* **Cell Termperature high** - A cell temperature exceeds 70 degrees C

* **Circulation pump Overload Fault** - The circulation pump motor is overloaded

* **Circulation pump run Fault**- The circulation pump has run more than 1/2 hour continuously

* **Compressor inlet pressure low**- There is a loss of pressure at the inlet to the compressor which also indicates loss of positive pressure in the gas holder.

* **Compressor overload Fault** - The compressor motor is overloaded.

* **Compressor Run fault** - The compressor heat trace has run more than 1/2 hour continuously. (***Rick please check on this.)

* **H2 Detector Fault** - H2 gas detector output goes out of range

* **Gas impure** - Hydrogen gas stream from the compressor has too high oxygen content (>1%).

* **Input Current High** - Incoming current exceeds 220A (Amps)

* **Overflow Tank high** - The overflow tank liquid level hits high alarm level.

* **Water Seal Low** - The gasholder liquid level hits the low alarm level.

***Storage Tank Filled** - Notification when H2 storage tank is to capacity.

Process or experiment shall be performed only in the following designated areas.

Check all that apply:

1. ☐ Demarcated Area in Lab (Describe):	
2. ☐ Fume Hood	3. ☐ Glove Box
4. X Other (Describe): As a stand alone system, the SunFuel 5000 SIPS plant is housed in a metal shipping container in a containment basin placed in an appropriate outside location. Remote monitoring controls are included.	

7.0 Personal Protective Equipment

All Personnel are required to wear the following minimal personal protective equipment whenever performing the process or experiment:

- Proper Laboratory Attire (i.e. pants or dresses/shorts below the knees, sleeved shirt, closed-toe shoes)
- Safety Glasses
- Lab Coat

Personnel may be required to wear additional Personal Protective Equipment when working with this material/process/system/unit. The Principal Investigator should contact the DRI EH&S department to confirm the selection of the appropriate protective clothing (i.e., long-sleeved shirts, aprons, suits, protective footwear, and gloves) and respirators. Please check all that apply:

1. X Safety Splash Goggles	2. X Face Shield
3. X Protective Gloves (Describe) KOH resistant, Ansell Sol-Vex nitrile gloves or similarly resistant gloves must be worn	
4. X Protective Clothing (Describe) Long-sleeved shirt and long pants must be worn when working with KOH	
5. X Protective Splash Apron (Describe) When handling large quantities of 30% +/- 5% KOH, a nitrile splash apron should be worn over lab coat and long pants	
6. ☐ Respirator (Describe)	
7. X Other (Describe) Face shield over safety glasses shall be worn when handling 30% KOH	

8.0 Procedural Steps

The comprehensive operation manual is provided by Stuart Energy for the SunFuel 5000 hydrogen generator. Included in the manual are the Gas Generating Steps. These follow in an abbreviated format. For the complete process description, the operator(s) must refer to the manual.

Gas Generating System (GGS) procedures:

1) The GGS is capable of producing up to 1 NCMH(normal cubic meter/hour) of hydrogen gas and 0.5 NCMH of oxygen at 0 degrees C and 1 bar at the design current of 200 A.

2) The GGS consists of thirteen electrolytic cell stacks connected electrically in series, a water seal, all interconnecting piping, various protective devices and controls for automatic operation

3) Solar power at 24/48 volts is supplied through a circuit breaker installed at the Control Panel. The circuit breaker installed at the control panel serves to provide short circuit protection. The breaker is for stopping the process under emergency conditions.

Note: A manual lockable disconnect is located within the container. Additionally, a second lockable disconnect is located in the Energy Lab (NNSC 265).

4) DC current is supplied to the electrolytic cells through copper bus bars. When DC current flows through the cells the water in the cells is converted into hydrogen and oxygen gases. the rate of evolution of gas is directly proportional to the DC current.

5) From the electrolytic cells the hydrogen and oxygen gases flow through gas collection chambers to the water seal. The water seal serves to equalize the hydrogen and oxygen gas pressures in the

collection chambers and to prevent reverse flow of hydrogen from the down stream process when the cells are idle.

6) From the water seal, the hydrogen flows to the mist eliminator where KOH mist entrained in the hydrogen is removed. The entrained mist separated from the hydrogen drains back to the water seal.

7) From the mist eliminator, the hydrogen flows onward to the compressor. The oxygen vents to atmosphere is vented above roof level, as it is not recovered.

8) The liquid in the cells is a 32% (by weight) solution of KOH in water. The potassium hydroxide is not used up as gas is generated. The only raw materials supplied to the cells apart from electric power are KOH solution and pure water, to replace the water converted into hydrogen and oxygen. KOH solution is circulated automatically to each cell stack. At full current, the 13 cells will require approximately 1 L/hr of pure feed water.

9) Two manually operated gas purity testers are supplied for measuring the purity of the hydrogen and oxygen gases.

10) A gas analysis system is provided by DRI to measure the trace oxygen in the hydrogen.

Hydrogen compression system:

1) From the mist eliminator, the hydrogen gas flows onward to the compressor

2) From the compressor, the hydrogen flows through the filters, the catalytic purifier, and the filter to the storage tank.

Hydrogen filtering system:

1) Hydrogen leaving the compressor flows through filters where moisture, oil droplets and oil vapor are filtered out.

2) The hydrogen then passes through the catalytic purifier where the oxygen is removed to less than 2 ppmv (ppm/volume).

3) The purified hydrogen then passes through a cooling coil and coalescing filter where the moisture is condensed and removed and any particulate materials are also removed.

4) From the filter, the hydrogen flows through the back pressure valve.

5) From here, the hydrogen fills the storage tank.

6) The storage tanks (2) each have a storage volume of 600scf. The tanks are designed for a pressure of 125 psig, but normal maximum pressure is 100 psig or less.

9.0 Training Requirements

- Review of current MSDS.
- Review of the DRI Chemical Hygiene Plan.
- Special training provided by the department/supervisor (Right to Know).
- One-on-One hands-on training with the Principal Investigator or other knowledgeable laboratory personnel.

Other required training topics:

- MSDS required – KO H (potash), Hydrogen (H2)
- Use, handling, and storage of compressed gases and cryogenic liquids
- Flammable compressed gases safety – See compressed gases in the DRI Chemical Hygiene Plan
- Spill clean up
- Management/clean up of liquid in containment basin

10.0 Emergency Procedures

Emergency notification instructions and location of fire and other safety equipment is posted on all laboratory doors. Should an emergency occur, personnel shall follow the standard DRI procedures for emergency response.

It must be noted that should an environmental hydrogen leak be detected a red light will appear on the control panel of the detector, and the hydrogen plant will shut down. In the event of a fire, the hydrogen gas will dissipate immediately and the flames will burn out rapidly. As a safety precaution, the hydrogen plant is located outside occupied buildings to minimize risk to DRI personnel and property.

11.0 Special Procedures and Precautions

11.1 Equipment under Pressure and/or Vacuum

		Yes	No	N/A
1.	Source of pressure (+/-): **compressor** which provides pressurized H2 to the H2 storage tank.			
2.	Maximum source pressure: ambient PSIG			
	Maximum operating pressure: 100 PSIG			
	Maximum allowable storage pressure: 125 PSIG			
	Pressure relief device set point: 110 PSIG			
3.	Is a pressure vessel involved?	X	☐	☐
	If yes, has the pressure vessel been tested, approved and rated for the operation and experiments?	X	☐	☐
	The necessary pressure vessel documentation is on file in the project office.			
4.	Are the equipment's "materials of construction" compatible with all process materials?			
	Valves/Reliefs	X	☐	☐
	Seals	X	☐	☐

		Yes	No	N/A
	Gauges	X	☐	☐
	Hoses/Tubing	X	☐	☐
	Fittings	X	☐	☐
	Gaskets	X	☐	☐
	Vessel	X	☐	☐
5.	Have calculations been done to assure adequate headspace for expansion/decomposition during operations?	☐	☐	X
	If yes, INCLUDE calculations in section 12.0 attachments.			
6.	Are all components (valves, gauges, piping, hoses, etc.) rated above pressure relief device set point?	X	☐	☐
	If no, list components and pressure ratings:			
7.	Are there any pressure safety interlocks?	☐	X	☐
	If yes, describe			
	If yes, location of quarterly log:			
8.	What precautions have been taken in the event of a pressure system failure? Overpressure valve vents excess pressure within containment enclosure			
9.	Are rotameters shielded?	☐	☐	X
	If yes, how?			
10.	Is a barricade or shield required to protect personnel from a catastrophic release?	X	☐	☐
	If yes, describe: The hydrogen plant is located outside occupied buildings			
11.	Are gauges located properly (i.e. facing operator, correct position in line)?	X	☐	☐
12.	Are gauges the proper range for the application?	X	☐	☐
13.	Are gauges compatible with materials used in the project?	X	☐	☐
14.	Any mismatched fittings or tubing?	☐	X	☐
	If yes, describe:			
	If yes, is the mismatch approved by the manufacturer?	☐	☐	X
	Describe management of change process for future fitting changes.			
15.	Are relief device outlets pointed in a safe direction and unrestricted to vent?	X	☐	☐
16.	Is the relief device suitable for dual phase (gas and liquid) operations?	☐	X	☐
17.	At what temperature will relief devices be operated? -10° to 40°C			
	Are relief devices rated for this temperature?	X	☐	☐
18.	Have relief devices been inspected/tested?	X	☐	☐
	If yes, date of the most recent inspection: date of manufacture - 1998			
19.	Have the consequences of potential leaks been considered?	X	☐	☐
	If yes, describe: Any tank leaks will vent to the atmosphere; compressor leaks (internal) will be vented to the ventilated enclosure. Any such leakage is low volume. Within the enclosure any hydrogen will immediately be exhausted by an exhaust fan.			

*** Additional Comments:**

11.2 Use of Gases in the Process/Experiment

One gas per sheet, submit multiple pages as necessary.

		Yes	No	N/A
1.	Name of gas: hydrogen.			
	Potential Hazards: flammable, odorless, colorless flame, others as noted in plant safety operation manual. (Oxygen is vented to atmosphere).			
2.	Gas Source:			
	House Supply	☐	☐	☐
	Vendor Cylinder	☐	☐	☐
	Dewar	☐	☐	☐
	Gas Generator	X	☐	☐
	Division or Project Owned Cylinder	☐	☐	☐
	Has the cylinder been inspected?	☐	☐	☐
3.	Maximum supply pressure: ambient. PSIG			
4.	Maximum operating pressure: 100 PSIG			
5.	Maximum allowable storage pressure: 125 PSIG			
6.	Pressure relief device set point: 125 PSIG			
7.	Are all components (valves, gauges, hoses, etc.) rated above pressure relief device set point?	X	☐	☐
	If no, list components and pressure ratings:			
8.	Are all components compatible with this gas?			
	Valves/Reliefs	X	☐	☐
	Seals	X	☐	☐
	Gauges	X	☐	☐
	Regulators	X	☐	☐
	Hoses/Tubing	X	☐	☐
	Fittings	X	☐	☐
	Gaskets	X	☐	☐
	Reactor/Vessel	X	☐	☐
9.	Does the process require cleaning before use (e.g. oxygen)?	☐	X	☐
10.	Are there any gas safety interlocks?	X	☐	☐
	If yes, describe: gas holder/water seal interface is safety interlock at generation site			
	If yes, what is the location of the quarterly log: n/a			
11.	Are there any gas sensors/detectors?	X	☐	☐
	If yes, describe: hydrogen detectors are located in the enclosure.			
	If yes, what is the calibration schedule: monthly			
12.	What precautions have been taken in the event of a pressure system failure? Overpressure valve vents excess pressure at H2 tank and within the containment enclosure			
13.	Are gauges located properly (i.e. facing operator, correct position in line)?	X	☐	☐
14.	Are gauges the proper range for the application?	X	☐	☐
15.	Are check valves needed?	X	☐	☐
	If yes, explain: check valves are used as required			
16.	Is there a potential for cross contamination?	☐	X	☐
	If yes, explain:			
17.	Are lines properly installed and labeled?	X	☐	☐
18.	Are there any mismatched fittings or tubing?	☐	X	☐
	If yes, explain:			

		Yes	No	N/A
19.	Inspection frequency of pressure regulators:			
	6 months	☐	☐	☐
	2 years	☐	☐	☐
	No scheduled tests	X	☐	☐
	Date of the most recent inspection(s):			
20.	Are relief device outlets pointed in a safe direction and unrestricted to vent?	X	☐	☐
21.	At what temperature will relief devices be operated? -10° to 40°C			
	Are relief devices rated for this temperature?	X	☐	☐
22.	Have relief devices been inspected/tested?	X	☐	☐
	If yes, date of the most recent inspection: date of manufacture - 1998			
23.	Is the gas flammable? (Detail in an attachment in section 12.0.)	X	☐	☐
	If yes, what precautions are in place? The hydrogen tank and generator are located outside of occupied buildings. The system includes engineering controls and check valve. Any failure or fire would rapidly burn and/or dissipate. This is a low probability/high consequence scenario. To avoid entrapment of hydrogen in the enclosure, the enclosure is fitted with an exhaust fans that are located at 5 ft and are always on during hydrogen generation operations.			
24.	Is gas corrosive/toxic?	☐	X	☐
	If yes, describe what precautions have been taken? (Detail in an attachment in section 12.0.) Also attach any PHS registrations.			
	Is a scrubber or pollution control device required?	☐	X	☐
25.	Is the cylinder protected from exposure to heat sources or flammable liquids?	☐	☐	X
26.	Where is the gas cylinder kept and how is it secured when in service? The hydrogen is stored in an external 600 scf storage tank.			
27.	Where is the gas cylinder kept and how is it secured when not in service?			

- **Additional Comments:**
  The Stuart SunFuel 5000 Hydrogen Generator Operations Manual with schematics is available in the DRI Energy Lab.

12.0 Attachments

None

Appendix II

References

1. *Handbook of Compressed Gases*, Fourth Edition, (1999), Compressed Gas Association, Inc. Kluwer Academic Publishers.

2. OSHA Regulation for Hazardous Materials 29 CFR 1910.101-105, see http://www.osha.gov/pls/oshaweb/owasrch.search_form?p_doc_type=STANDARDS&p_toc_level=1&p_keyvalue=1910

3. OSHA Regulation for Hydrogen – 29 CFR 1910.103 http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9749

4. US Department of Energy- Hydrogen, Fuel Cells, and Infrastructure Technologies Program, *Safety Planning Guidance for Hydrogen and Fuel Cell Projects*. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/safety_guidance.pdf

5. Hydrogen and Fuel Cell safety, http://www.hydrogenandfuelcellsafety.info/

6. Department of Energy, Hydrogen Safety Facts, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/doe_h2_safety.pdf

7. NASA Safety standards for hydrogen and hydrogen systems, http://www.hq.nasa.gov/office/codeq/doctree/canceled/871916.pdf

8. Hydrogen Best practices, http://h2bestpractices.org

9. International Partnership for the Hydrogen Economy – Hydrogen, safety codes and standards, http://www.iphe.net/docs/Fact_Sheets/Hydrogen_Safety_Codes_and_Standards.pdf

10. DRI policies and procedures, http://safety.dri.edu

11. DRI Chemical Hygiene Plan, http://safety.dri.edu/LabSafety/CHPappendicesandTOC.pdf
12. DRI Compressed Gases--Generic Procedure for Safe Handling and Storage, http://safety.dri.edu/Programs/Compressed.pdf
13. Chemical Storage, Handling and Use, www.safety.dri.edu/Programs/chem._storage_handling.pdf
14. DRI Procedure for Transporting/Moving Chemicals , www.safety.dr.edu/Programs/Procedures_Transporting_Chemicals_final.pdf
15. Safe Work Practices for Using the Laboratory Hood, www.safety.dri.edu/Programs/DRIHOODS.pdf

APPENDIX II

REEF Workshop

by

Robert H. Turner, PhD, P.E.
Nicholas S. Baker

Introduction

The American Great Basin – Southwest Region features abundant year round sunshine with cold winters. Since energy has been historically cheap, buildings and water are heated via fossil fuel derived sources, and the vast solar heating potential is largely untapped. In areas where summer comes with authority, buildings are cooled by refrigeration air conditioning, which can instigate power brownouts. In typical households water is obtained from rivers or wells and is once-used before being discarded to treatment plants or septic tank fields. As populations increase this permanent demand on limited fossil-fuel and water resources is non-sustainable, so a sustainable approach must be developed.

The Desert Research Institute, consistent with its name, is investigating a systemical solution to the above described problems employing the Region's most abundant and obvious resource ~ solar energy. The REEF (Renewable Energy Experimental Facility) Workshop was built to test the technical and economic feasibility of using a large inexpensive solar collector to heat space and water, and also to reuse water via distillation of (previously used) grey water. By incorporating energy storage into the building floor, night-generated coolness can be stored in the floor in summer, reducing energy consumption and ameliorating peak demand.

The first phase of this project has been successfully completed and the solar potential demonstrated. A 578 ft^2 (54 m^2) solar air heater was built into the Workshop roof, which proved more than capable of heating the workshop on a sunny winter (2011-12) day, the effect which lasted into the night. Measurements on the hollow air floor proved that winter solar heat could be stored in the floor for night release, and during summer nights the coolness generated by an evaporative cooler could be stored in the same floor for daytime release.

During a 2012 summer day the solar system heated 240 gallons (890 liters) of water in excess of 160°F (71°C). Although this far exceeds the hot water requirement of a normal household, it does provide the potential to evaporate and recover in potable form via distillation all the gray water produced by the house. In a household where waterless toilets (common in parts of Europe) are employed so no black water is produced, solar distillation can continuously reuse water. Such an approach obviates the necessity for a sewer hookup or septic tank, and the money thus saved can pay for most of the overall system, making it cost effective! The large distillation system constitutes a future demonstration.

Background

Although solar heating systems have been employed for over a century, the high cost of commercially fabricated and installed systems has limited deployment. During the Solar Decade (1975-84) federal tax credits (40% of solar system cost) and state tax credits (55% in California) stimulated widespread installation of solar DHW (domestic hot water) and space heating systems, but after the tax credits were discontinued the market evaporated. Many liquid based systems failed due to leaks or freeze damage. The economic non-viability of commercial solar systems absent government or utility incentives persists to this day, which is why they are rare even in sun-blessed areas.

Site built solar air heating systems can be built into a building much less expensively than equivalent commercial solar heating systems, both retrofit and new construction. Site built solar hot air systems are: (1) simple; (2) robust; (3) easy to maintain; (4) have no liquid to leak, freeze, overpressure (boil), corrode, or degrade; (5) very flexible; and (6) cost 1/3 relative to commercially installed solar collectors.

Figure 1 shows a residential 600 sf solar air-heating collector built into a new construction residential roof in 1991 in the Sierra Nevada Mountains near Reno, Nevada at elevation 6000 feet.

Figure 2 shows a 208 sf solar air heater retrofitted to a house roof in Bend, Oregon in 2005. This unit was built from basic materials by the homeowner and provided year round DHW and winter space heating. With a State of Oregon tax credit the system was economically attractive.

Workmen with modest skills can retrofit a solar space heater on the south wall of a house. The unit in Figure 3 heats a house in Reno, Nevada and demonstrated a 3 year simple payback period without external incentives.

Figure 1

Figure 2

Figure 3

There are many advantageous to site-built solar air heaters. The house itself is the collector support, and house insulation is also the collector insulation. The collector is the building exterior finish (roof or south wall) and even irregular geometry blends into the architecture of the building (Figure 3). There is no liquid to leak, freeze, overpressure (boil), corrode, or degrade. The approach is widely applicable for new construction or retrofit, and is easy for architects, builders, homeowners and others to comprehend and implement. Its manufacturer guarantees the external glazing for 20 years, validated by the house in Figure 1. The system is easy to build; the list of materials consists of: fiberglass glazing; thin black metal sheets; 2x4 wood studs; 1½ inch wide aluminum strips; various screws and bolts; caulk; rubber stripping; a blower; thermostat; and ducting. If DHW heating is intended, then an air-to-water heat exchanger and solar hot water storage tank are also specified. All materials are widely available and most are made in America. Beginning level contractors and many homeowners possesses the requisite skills. Money paid for labor stays in the local community. The system is robust and maintenance requirements are minimal.

An extensive 1992 study conducted on the new residence shown in Figure 1 indicated a three year simple payback, which proved accurate. The 2008 230 square foot homeowner-built retrofit application in Figure 3 cost $1200 to build (including $300 for a labor assistant) and saves about $400/year in propane heating costs. The simple payback period is 3 years, and if government or utility financial incentives had been available the payback period would be less. If a 230 sf commercial system had been installed the cost would have approximately $10,000, and even with incentives the homeowner would not have bought it.

Advantages claimed for a site-built air heating solar collector over hydronic (liquid filled) collectors include: (1) Cost; (2) Small leaks are unimportant; (3) Hydronic systems can over-pressure in summer; (4) Freeze problems eliminated; (5) Part of the expense is defrayed by not having to install a conventional roof or wall finish; (6) The solar system blends into the building architecture; (7) economic efficiency higher; (8) can be built by skilled laymen; and (9) money for construction stays in the local community, instead of supporting foreign economies.

However, there are many reasons that site-built solar air heaters have not been implemented. Market impediments include:
(1) Public perception that solar collectors are only available commercially in factory standard sizes, and are hydronic. This is because solar contractors promote what can make them money, and site-built systems obviate such middleman companies.
(2) Ignorance how to properly prospect a site, size and design a solar system, obtain a building permit, and build it without mistakes. Authoritative guidance is needed.
(3) Uncertainty about the technical and economic performance of site-built solar systems.
(4) Difficulty obtaining a building permit for non-commercial solar systems.
(5) Lending institutions are unfamiliar with the site-built solar approach.
(6) Non-commercial systems may not qualify for some economic incentives.

Although full-scale working site-built solar air-heating systems have been demonstrated to be cost effective, their technical performances are not quantified. Nor are they available for fully integrated research experiments, such as large-scale distillation of grey water. The REEF Workshop fills this need.

REEF Workshop Construction

A component of the Renewable Energy Experimental Facility (REEF) Program involves demonstrating cost-effective solar heating applications. A second goal is to demonstrate the potential for a minimal resource consumption house in the Great Basin Region. This demonstration will be conducted in the REEF Workshop, which is a new-construction stick-built rectangular building 20 feet by 30 feet with a large garage door on the east side.

The first step was to select a solar collector that would provide:
(I) domestic space heating;
(2) domestic hot water (DHW) heating;
(3) heat for thermal storage;
(4) sufficient heat to evaporate large quantities of gray water (which could make a house independent of a sewer hookup or septic tank, presuming that the house were furnished with waterless toilets);
(5) heat for other experiments peripheral to the workshop; and
(6) the possibility that the heat provided could be cost competitive.

Active solar space and water heating technology has existed for decades but has not been adopted by mainstream US society, primarily due to high initial first cost. However, it has been demonstrated that site-built air-heating solar collectors cost much less than factory fabricated collectors for the same performance capacity. Therefore, a large air heating solar collector was built on to the REEF Workshop roof in the summer of 2011. This solar collector will provide hot air for direct space heating, and also water heating via air-to-water heat exchangers.

A second large solar facility will be constructed to service the REEF House, less than 40 feet from the REEF Workshop, and will feature a large array of commercially supplied hydronic solar collectors, which will be charged with a propylene-glycol mixture to avoid freezing. Thus, this project will quantify the technical and economic performance comparison, including simple payback periods contrasting the two approaches, and help determine the relative cost effectiveness of each system. To achieve this comparison, performance data will be gathered from both solar systems, and the value of the useful heat compared to determine the technical and economic performance of each on a seasonal basis.

When the REEF Workshop was constructed, two types of thermal storage were built into the concrete floor to accommodate thermal storage. 200 square feet of the floor feature channels under the poured concrete formed by hollow concrete blocks, which themselves are above rigid insulation. This allows air to flow under the concrete floor, heating the floor in winter and cooling it in summer at night via agency of an evaporative cooler. The other 400 square feet of floor have water tubes embedded, so solar heated water can heat the floor in winter.

SITE-BUILT AIR-HEATING SOLAR COLLECTOR

One objective of this project is to help educate the general public about the feasibility of using site built solar air heaters to defray fossil fuel heat sources. Also, the hollow concrete floor is not common to public consciousness. Therefore, the construction of both collector and hollow floor will be described in detail, as a prelude to producing step-by-step manuals to guide architects, builders, laymen, decision makers, homeowners, business people, politicians, and plan check offices.

The south-facing workshop roof is 34 feet long by 17 feet wide and inclined at 45^o from horizontal. The north side of the roof is conventionally finished with asphalt shingles, but the south side was left unfinished, so the collector could be built in place. The solar collector is the roof south side finished roof.

The first step was to seal all of the spaces between the 4-by-8 plywood sheets to prevent any air leakage, shown in Figure 4. Then the perimeter was framed in with 2-by-4 studs. The studs were attached by drilling holes through the 3½” width, with a ¾” countersink hole to accommodate a washer, so a 5” screw could attach the stud to the rafter studs below the plywood (Figure 4). The outer periphery studs were well caulked.

FIGURE 4 Collector Framing Detail, also showing a heavily caulked air inlet port

Then studs were screwed in every two feet, with spacing between studs to allow air transport between adjacent bays. Prior to installation, small wood blocks were screwed in 1” below the stud top to eventually hold the sheet metal absorber. These blocks had in unforeseen benefit of aiding the workman, as he worked on the 45^o slope roof (Figure 4). The completed framework is shown in Figure 5.

Figure 5 Completed Roof Collector Framework Ready for Absorber and Glazing

4” diameter holes were drilled near the bottom and top of each bay to admit and extract air. Since the two end bays could not be fed from inside the building, 6” holes were drilled on the extreme west and east bays accessible from inside the house. Then duct connector collars were screwed into each hole and heavily caulked both inside and outside (Figure 4).

For the absorber, black sheet metal strips 22” wide were placed on the wood blocks in each bay and screwed using oversized holes (to allow for thermal expansion), two bays at a time, starting on the east end; see Figure 6. Spaces between the absorber plates were left at the top and bottom to assure air to flow in both the upper and lower plena.

Figure 6 Black Sheet Metal Sheets are screwed onto the support blocks to become the Absorber. Air exit holes into the building are shown at the top of each bay.

After absorber plates had been installed into two adjacent bays, a 17 foot long fiberglass panel was screwed over the bay to form an air channel. The panels are specially made for this application and are 49½" wide, so they can overlap either 16" or 24" on-center studs. The fiberglass glazing has a UV coating and is guaranteed against degradation for 20 years; the glazing is 60 mil thick. The collector is built from east to west, so at glazing overlap points the west panel covers the east panel, because in Reno storms blow in from the west.   The panels are secured to the stud below by black aluminum battens that are 1½" wide and 3/16" thick. The screws are spaced every 16". At the collector outer periphery, and also at panel overlap locations, a caulking is applied and a 1½" wide piece of rubber is inserted to provide a watertight seal between stud and glazing when the batten is screwed down. Figure 7, looking east, shows the collector after 5 glazing panels have been applied, with the collector ready for installation of the sixth glazing panel.

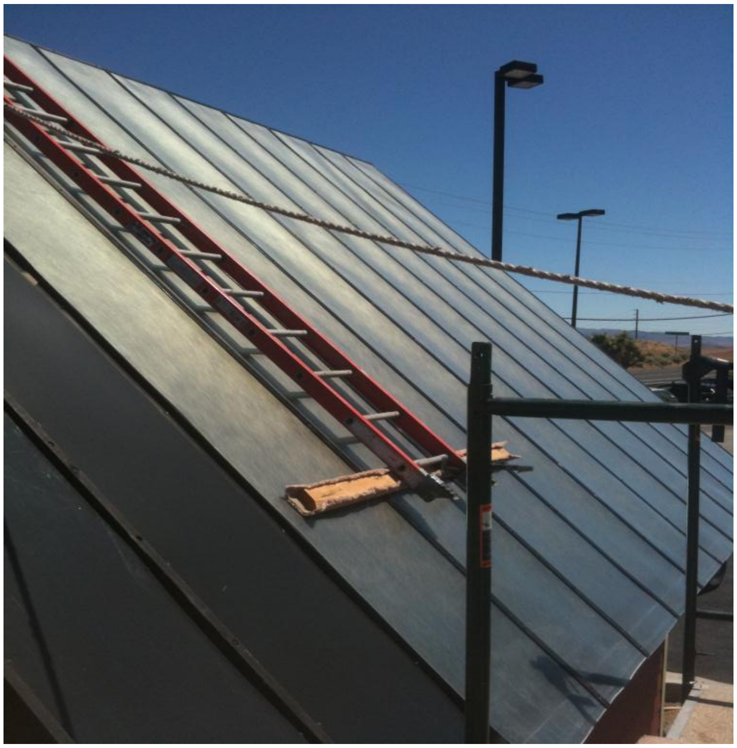


Figure 7 Glazing panels are secured by black aluminum battens. The area to the lower left awaits a glazing strip.

After the last panel has been secured, a top ridge is placed, shown in Figure 8. Inside the building the roof underside is insulated with 12 inches of fiberglass insulation (R_38), which also serves as the collector backside insulation. The overhang sections are also insulated with R-19. The completed solar collector is shown in Figure 9.

Figure 8 Ridge Caps are the last step to completing the roof collector

Figure 9 578 square foot (34’ by 17’) site-built roof-integrated solar air heater. The backside (building roof and overhangs) is insulated.

Air is provided to and from the collector in each bay by 14” diameter duct headers, both located inside the building. One header is located near the roof peak to draw off heated air, and the other by the collector bottom to supply air. Figure 10 shows a 4” diameter collar being caulked to prevent air leakage, the collar having previously been screwed to the 14” diameter header. Three University of Nevada mechanical engineering students were involved in the construction of the solar system, and the duct distribution system was completely built, installed and insulated by the students and Dr. Turner. The duct was then secured so duct collars match up with corresponding collars under the solar collector, and connected by flexible ducts. The duct distribution system (DDS) was then insulated with R-19 fiberglass insulation; see Figure 11.

In smaller air heating solar collectors no DDS is required, just holes at either collector end to allow air inlet and exhaust. With hindsight, the system designer Dr. Turner would not have used a DDS but would have used a simple air intake port at one end of the collector and an exit port at the other end, as he did on other projects (Figures 1, 2 and 3. This would have saved about $2000 and made construction much simpler!

Figure 10 A 4” diameter collar is screwed then caulked to the 14” diameter header. The header ducts are then assembled in place with the collars aligned to the collector collars inside the roof. Corresponding collars are then connected with flexible ducting.

Figure 11 Each of two headers comprising the duct distribution system is connected to the solar collector through 15 sets of collars which support flexible ducting. In the upper right the silvered insulated duct from the blower connects with a 14” diameter duct which is insulated with tan exterior wrap. Insulated silvered collars connect with the collector every 2 feet. A similar header at the top delivers heated air to the heat exchanger box.

A Dayton 2C800 blower rated at 2100 cfm for no-load was installed to blow air into the collector for positive collector pressurization (to avoid drafting dust into the collector), and to have the blower operate at the coolest possible temperature; see Figure 12. The blower air flowrate will be managed by a programmable computerized controller to allow optimal operation under changing conditions. The computer allows flowrate to vary from 100% to around 40% of maximum. The air handler is mounted on rubber vibration absorbers to reduce noise and vibrations in the building.

The blower delivers air into the bottom collector header, from whence the header delivers air to 15 collector air inlets. The two overhang inlets are serviced by the two end collars and connecting flexible ducts, which are 6” diameter instead of 4” as for the other set of 13 collars (because the end collar sets must service two bays instead of one).

Figure 12 The 2100 cfm blower delivers air to the collector intake header.

The 20’ by 30’ concrete floor is divided into three parts. One-third (10’ by 20’) has hollow spaces under the floor to allow air flow to condition the floor. The second third has water tubes under the floor, to allow heated water to heat the floor in winter. The third section is conventional to serve as a standard base case.

Figures 13 and 14 (right) show construction of the hollow concrete floor. First a sand layer was laid and leveled, over which 2” of rigid insulation was applied. Then hollow concrete blocks were positioned with the holes aligned (Figure 13 and 14). Then a conventional 5” concrete floor with conventional rebar reinforcement was poured over the concrete blocks. At both ends a header allows air to be introduced to and exit from the concrete air channels. In winter solar heated air flows through the concrete channels, heating the concrete floor. The thermal mass of the floor releases the heat throughout the night. Since humanity’s thermostats are located in its feet, a warm winter floor allows cooler air temperatures in the house, with concomitant reduced heat loss from the building envelope, with a net energy saving. In summer, the cool dry nights allow cold air (45-50^{o}F) to cool-condition the floor, allowing the floor to absorb heat the following day.

Measurements taken while the floor was thermally conditioned indicated the floor was 5-7°F warmer in winter and 5-7°F cooler in summer, and an observer standing over the hollow floor could definitely feel the comfort difference compared to the acclimatized floor.

Figure 13 Hollow Concrete blocks were positioned to align holes into air channels. The blocks were sited over 2" of rigid insulation. 5' or concrete floor were sited over the blocks. At either end headers allow air to pass through the channels. In winter, solar heated air passes through the channels, heating the concrete floor for night release. In summer evaporative cooled air passes through the hollow floor at night, storing night coolness for release the following day.

A 10' by 20' segment of the floor was constructed with water tubes embedded; see Figure 14 (left). This allows solar heated water to condition the floor in winter. This is a developed standard technology, but is useful for comparative purposes.

Solar Heating Options within REEF Workshop

Workshop floor divided into three segments:

- One uses circulating hot water for heating
- One uses hot air through hollow blocks
- One has no heating capabilities

Figure 14 The left photo shows water tubes (red) spaced 9” apart over 2” of rigid insulation. Rebar (black) is over the pipes to reinforce the concrete floor. The right photo shows the hollow air channels being formed.

<u>Component Selection</u>

Each system component must be selected to harmoniously integrate with each other for an optimized design. For the REEF Workshop the collector size and characteristics are specified, and all other components must be sized around the collector. When sizing the various components their mutual interactions must be considered. For example, an increased number of heat exchangers will increase heat exchanger effectiveness, but at penalty of increased air and water pressure drop, which lowers flowrates and possibly performance. Then the blower must be designed to account for increased load, possibly increasing pump power. The rationale for selecting each component is discussed below.

(1) System Components

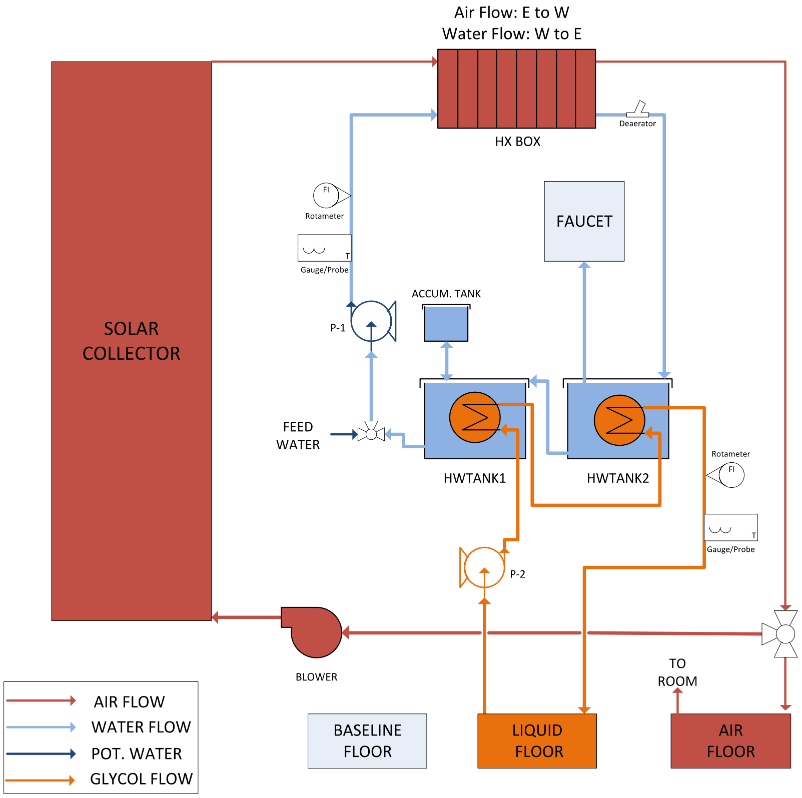
Figure 15 depicts a schematic of the system, showing how the various components are linked. A blower forces air through the solar collector (large on left) after which the solar heated air passes through the Heat Exchanger (HE) box. Air-to-water heat exchangers allow transfer of heat from the air to water loop. The still warm air then goes to the hollow concrete floor in winter (or directly into the room if heat immediately needed), after which the room itself serves as a return air duct to the blower. In summer mode the air is ducted directly to the blower and collector.

Not shown in Figure 16 is a 4” diameter insulated duct that can draw the hottest air from the HX Box before it has passed through the heat exchanger. This maximum temperature air is blown into a solar dryer (in a residential application this could be the clothes dryer), where soggy material from another research demonstration is dried. See Figure 16.

Two 120 gallon tanks (HWTANK1 and HWTANK2) were installed in series to store potable hot water; see Figures 15 and 17. A pump (P-1) draws water from the bottom of the cool tank and after passing past a temperature probe and rotometer (to measure flow rate) the water passes through the heat exchanger units where it is heated. The warmed water then goes to the top of the hot water tank. , where the maximum temperature water is available for consumption (faucet). When water is withdrawn from the system (faucet) the make up water is introduced to the bottom of the cooler tank. Having the two tanks ganged in the fashion shown essentially provides a thermocline by reducing mixing of heated and less-heated water.

During winter Pump-2 passes glycol-water mixture through coil heat exchangers in the two tanks, allowing heated glycol to pass through the tubes beneath the concrete floor (Figure 14 left), shown as the orange loop in Figure 16.

An accumulator tank with rubber bladder allows for thermal expansion of the potable water, since the tanks are at city pressure. The tanks feature standard safety devices, such as pressure-temperature release valves and a deaerator valve (located at the highest point) for filling and draining the system.



NOTE

- All pipes with water = 3/4" ID
- P-1 is Grundfos UP26-96F Pump (10GPM)
- P-2 has possibly been sourced by Curt
- Each HWTANK has 120-Gallon capacity

Figure 15 System Schematic Showing Component Interactions.

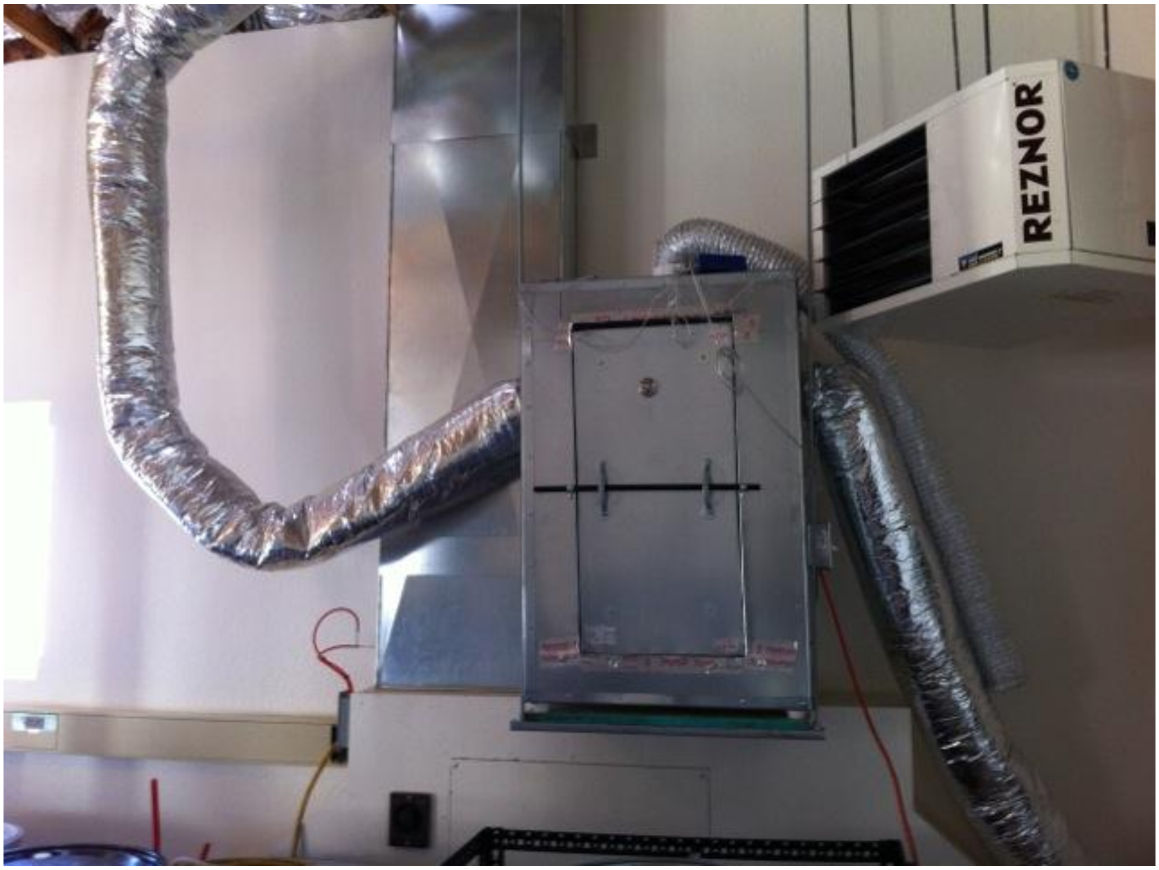


Figure 16 Solar dryer uses the hottest air in the system (insulated duct at left), passes the air through the material to be dried (on screens) then ejects the air and moisture from the duct on right.

Figure 17 Twin 120 gallon water tanks store potable water under city pressure. They are connected as depicted in Figure 15. Water is circulated by the red pump (upper center)

(2) Blower

If the airflow through the collector is too low the air temperature rise will be high, pressure drop through the system will be reduced, pump power will be low, but total heat gain will be minimized. If the airflow rate is too high, pump power will be high, pressure drops will be high, and air temperature change will be low, although the total heat collected will be high because collector heat loss is reduced. Therefore, the applications for the solar heat must be considered. For example, if winter space heating is the only intended application then a high airflow rate might be specified to maximize heat, as long as the delivery air temperature is above 110^{o}F. If DHW is required then the airflow rate might be less to increase the air temperature so hotter water can be produced from the air-to-water heat exchanger unit. If process water is required (perhaps for distillation) then a yet lower flow rate might be necessary.

A blower capable of delivering 1800 cfm through the 578 ft^2 solar collector was judged to be appropriate, and the electrical installation allows for the blower output to be diminished as conditions and applications change. The air pressure drop through the collector, header ducts, connecting ducts and heat exchanger system was estimated as a function of flowrate, accounting for the 4700 foot elevation of the DRI (where air density is 86% of sea level density). Then the blower performance characteristics published by the manufacturer was compared to the system pressure curve to select the proper blower .

A Dayton blower (model 2C800 powered by an A.O. Smith ½ hp belt motor rated at 2100 cfm for no-load was installed to blow air into the collector for positive collector pressurization (to avoid drafting dust into the collector), and to have the blower operate at the coolest possible temperature; see Figure 18. The blower air flowrate will be managed by a programmable computerized controller to allow optimal operation under changing conditions. The computer allows flowrate to vary from 100% to around 40% of maximum. The air handler is mounted on rubber vibration absorbers to reduce noise and vibrations in the building.

Figure 18   Blower pressurizes the solar collector

(3) Heat Exchanger Unit Selection

Technical data provided by Magic-Aire for their model SHE-2 2525 air-to-water heat exchangers were used to estimate performances under the expected REEF conditions. The data were corrected for Reno atmospheric pressure conditions (86% that of sea level) and expected higher air temperatures than the 80°F in the Magic-Aire literature. Model SHE-2 2525 means two water passes, with the air face 25" by 25". Physically, the unit looks like a truck radiator.

Calculations in Appendix I indicated that a single Magic-Aire SHE-2 2525 HE would have an effectiveness of $\epsilon = 0.43$ when 1800 cfm of heated air flows through the fins, and the water flowrate is 10 gpm. Two HEs in series counterflow arrangement would have $\epsilon = 0.656$, and three HEs would have $\underline{\epsilon = 0.785}$. A fourth and fifth HE would produce $\epsilon = 0.863$ and $\epsilon = 0.91$ respectively, but these additional heat exchangers are past the point of diminishing returns, so three heat exchangers were selected. For three HEs the Number of Transfer Units $NTU = UA/(mc_p)_{air} = 1.83$.

The three HEs are plumbed together as a single unit and placed into an insulated plywood box. The unit is placed on a catwalk so solar heated air from the solar collector flows directly into the box, where it must pass through the HE unit.

The air pressure drop through each heat exchanger was determined to be (for expected REEF conditions and accounting for elevation)

$$\Delta P = 0.084\ (V/2000\ \text{cfm})^{1.75}$$

where ΔP = in H_2O
V = cfm

Thus three such heat exchangers in series with V = 1800 cfm will manifest a pressure drop $\Delta P = 0.27$ in H_2O, This was in important design input for the blower specification.

(4) Pump Selection

The highest incident insolation likely on the collector is I = 300 BTU/hr-ft^2. The working area of the solar collector is A = 540 ft^2. The collector efficiency high side is $\eta = 0.70$. Then with the HE $\epsilon = 0.785$ the maximum heat that the collector can heat the water is

$$Q = I*A*\eta*\epsilon = (300\ \text{BTU/hr-ft}^2)(540\ \text{ft}^2)((0.7)(0.785) = 89{,}000\ \text{BTU/hr}$$
$$Q = 1484\ \text{BTU/min}$$

Also $Q = 1484\ \text{BTU/min} = 8.35*m*c_p*\Delta T$

Where

m = water flowrate (gpm) [Recall 1 gal = 8.35 lb water]
c_p = 1.0 BTU/lb-^{o}F Water
ΔT = Water Temperature Rise thru HE ~ ^{o}F

Now if we restrict maximum water temperature rise to $\Delta T = 15^o$F then

$$m = Q/c_p\Delta T = (1474\ \text{BTU/min})/(1\ \text{BTU/lb-}^o\text{F})(15^o\text{F})(8.35\ \text{lb/gal})$$

m = 11.8 gpm is the maximum water flowrate that will ever be required.

The Magic-Aire literature indicates for the SHW-2 2525 10 model the following water flowrates (gpm) versus Pressure Drop (ft-water Head)., displayed in Table 1. Table 1 also shows the pressure drop for three HE units in series in the last column.

Table 1

Pressure Drop through Heat Exchanger Band versus Water Flowrate

Water Flowrate	ΔP each unit ft-Head	ΔP 3 HEs Series ft-Head
9.8 gpm	2.77 ft-H_2O	8.31 ft – H_2O
11.2 gpm	3.43 ft	10.29 ft
12.5 gpm	4.11 ft	12.33 ft

Since the insolation will generally be less than assumed above, and efficiency diminishes (in summer) as collector inlet temperature increases during the day, the normal temperature rise will be appreciably less than $\Delta T = 15^oF$. Thus, we will search for a pump that can provide approximately 10 gpm.

With 10 gpm the pressure drop through the three heat exchangers ganged in series is about $\Delta P_{HE} = 8.5$ ft-H_2O (Table 1). Estimate the pipe length connecting the system to be $L_l = 50$ feet. Then if smooth 1" I.D. pipe is used, which can be copper or PVC, the water velocity V is

$V = (10\ gal/min)(4)/(7.48\ gal/ft^3)\pi(1/12\ ft)^2$

$\underline{V = 245\ ft/min = 4.09\ ft/sec}$ Water velocity in 1" tube for 10 gpm

The viscosity of water at 100^oF is $\mu = 1.648\ lb_m/ft\text{-}hr$, the water density is $\rho = 62\ lb_m/ft^3$, and the kinematic viscosity of water $\nu = \mu/\rho = 0.0266\ ft^2/hr$. Then the Reynolds Number is

$Re = V*D/\nu = (4.09\ ft/sec)(1/12\ ft)(3600\ sec/hr)/(0.0266\ ft^2/hr) = 46{,}100$

Re = 46,100 Quite turbulent!

Then from a Moody Diagram for a smooth pipe, Re = 46,000 ➔ $\underline{f = 0.020}$

The Friction Factor f = 0.02.

Now estimate there will be twelve 90^o smooth bends in the pipe network. From the Cengel & Turner textbook ('Thermal Fluid Sciences', 2nd Ed.) on page 529, we find for the right bend geometry K = 0.3, and then the equivalent length of the 90^o bend is

$\underline{L_b = D*K/f} = (1/12\ ft)(0.30)/0.02 = \underline{1.25\ ft}$ for each bend

Then for 12 bends the equivalent flow length relative to friction drop is (12*1.25') $L_B = 15$ feet. Thus, the total equivalent flow length for 50 foot pipe with 12 bends is $L = L_l + L_B = 50' + 15' = 65'$. $\underline{L = 65\ ft}$.

The pressure drop due to friction is

$\Delta P_F = f(L/D)(\rho*V^2/2*g_c)$

$= (0.02)(65\ ft)(62\ lb_m/ft^3)(4.09\ ft/sec)^2/2(1/12\ ft)(32.2\ lb_m ft/lb_f sec^2)$

$\Delta P_F = 251\ lb_f/ft^3 = 1.74\ psi = 4.0$ ft-Water head

Then the total pressure drop is $\underline{\Delta P} = \Delta P_{HE} + \Delta P_F = 8.5$ ft + 4.0 ft = $\underline{12.5 \text{ ft-Water.}}$

$\underline{\Delta P = 784\ lb_f/ft^2}$

Since the entire system is filled and under city pressure, the height of the heat exchanger box above the water tanks does not enter the calculation. All water is contained within the insulated and heated building, obviating freeze concerns.

For the considered water flow parameter set, namely: 10 gpm, V = 4.09 ft/sec in 1" I.D. pipes, L = 65 feet, and $\Delta P = 12.5$ ft $= 784\ lb_f/ft^2$

$W = F*V = \Delta P*A*V = (784\ lb_f/ft^2)[\frac{1}{4}\pi(1/12\ ft)^2](4.09\ ft/sec) = 17.5\ ft\text{-}lb_f/sec$

$\underline{W = 17.5\ ft\text{-}lb_f/sec\ =\ 0.032\ HP\ =\ 0.043\ kW}$

[Recall 1 HP = 550 $ft\text{-}lb_f/sec$ = 1.341 kW]

Actually the required pump power will be greater due to inefficiencies and the difficulty of matching a pump with a load at its maximum efficiency. But the ballpark calculation indicates that the power draw for the pump should be quite low.

Let us examine the diameter of the $L_l = 50$ feet of tubing to determine its effect on pump work W. We will derive W = W(m,D) to assess the impact of varying m and D.

$W = F*V = \Delta P*A*V = [f(L/D)(\rho*V^2/2*g_c)]\ [\frac{1}{4}\pi D^2]V = \pi fLD\rho V^3/8g_c$ (1)

Recall (m = mass flowrate ~ lb_m/sec) $V = m/\rho A = 4m/\rho\pi D^2$ (2)

Then inserting (2) into (1) yields $W = 8fLm^3/\pi^2 g_c\rho^2 D^5$ (3)

For a given system with constant density ($\rho = 62\ lb_m/ft^3$) a given effective pipe length (L = 65'), and a (near) constant friction coefficient (f), Equation (3) becomes for the pump work (K = a determined Constant)

$W = K\ m^3 / D^5$ (4)

Equation (3) and (4) asserts that pump work (W) to overcome pipe friction is proportional to mass flowrate to the cube power, and inversely proportional to pipe inner diameter (D) to the fifth power. For 10 gpm the pressure drop through the heat exchanger is 8.5 ft-H_2O (Table 1), and the pressure drop due to the 1" diameter pipe is 4.0 ft-H_2O. Although the HE design is beyond our control, we can specify the pipe diameter. Since the HE ΔP is double the pipe friction ΔP, the pipe is properly sized at 1".

Note if the pipe ID were 0.75, then the power component attributable to the pipe loss would increase by a factor of $1/(.75)^5 = 4.2$, and the pipe power requirement would be greater than the HE power, indicating a need to increase pipe diameter.

Over 35 years of experience suggests a Grundfos pump has always proved reliable; the Grundfos factory is in Clovis, California. Grundfos makes a 3-speed single-shaft motor-pump, and the pump is so quiet that often the observer cannot hear it.

Now we search for a pump that can deliver 10 gpm. Although the head loss was estimated to be 12.5 ft-H_2O, for pump specification purposes we will use $\Delta P = 18$ ft-H_2O. Inputting those two data points into the Grundfos Pump Finder System pulls up the three speed **MODEL: UPS 26-99 FC.** Note the pump has three speeds, and at different speeds draws power: (1) 150 W; (2) 179 W; and (3) 196 W.

The Grundfos UPS 26-99 FC was installed (Figure 17, upper center). It cost around $400.

SOLAR AIR HEATER THEORETICAL MODEL PERFORMANCE

The observed technical performance of the solar collector is to be compared to theoretical performance. The analysis below estimates the solar air heater performance, and specifically estimates F_R and U_L. With these parameters performance curves similar to Figure 11 can be produced, which highlight the impact of air flow rate on efficiency.

Figure 19 depicts the solar collector, and also shows heat resistances between components. Both convective and radiative resistances are important for heat loss upward from the glazing, and conduction predominates for downward loss to the building (although it will be shown that downward conductive heat loss is minimal due to high insulation on the collector underside ~ R-40). Furthermore, for winter the back conduction loss is nearly zero, since most of the heat would go inside the conditioned building shell.

However, the mass of the plywood backing requires an initial energy investment (IEI) to heat the plywood, generally paid in the morning, and some of the IEI heat is recovered in the afternoon. Therefore, in the morning collector efficiency measurements may tend to under-estimate the efficiency, because the collector is not working at steady state since some of the input heat is applied to heating the plywood roof. Similarly, in the afternoon the warmer plywood back may release some of the heat back to the flowing air, manifesting an apparent higher efficiency than the standard definition would warrant.

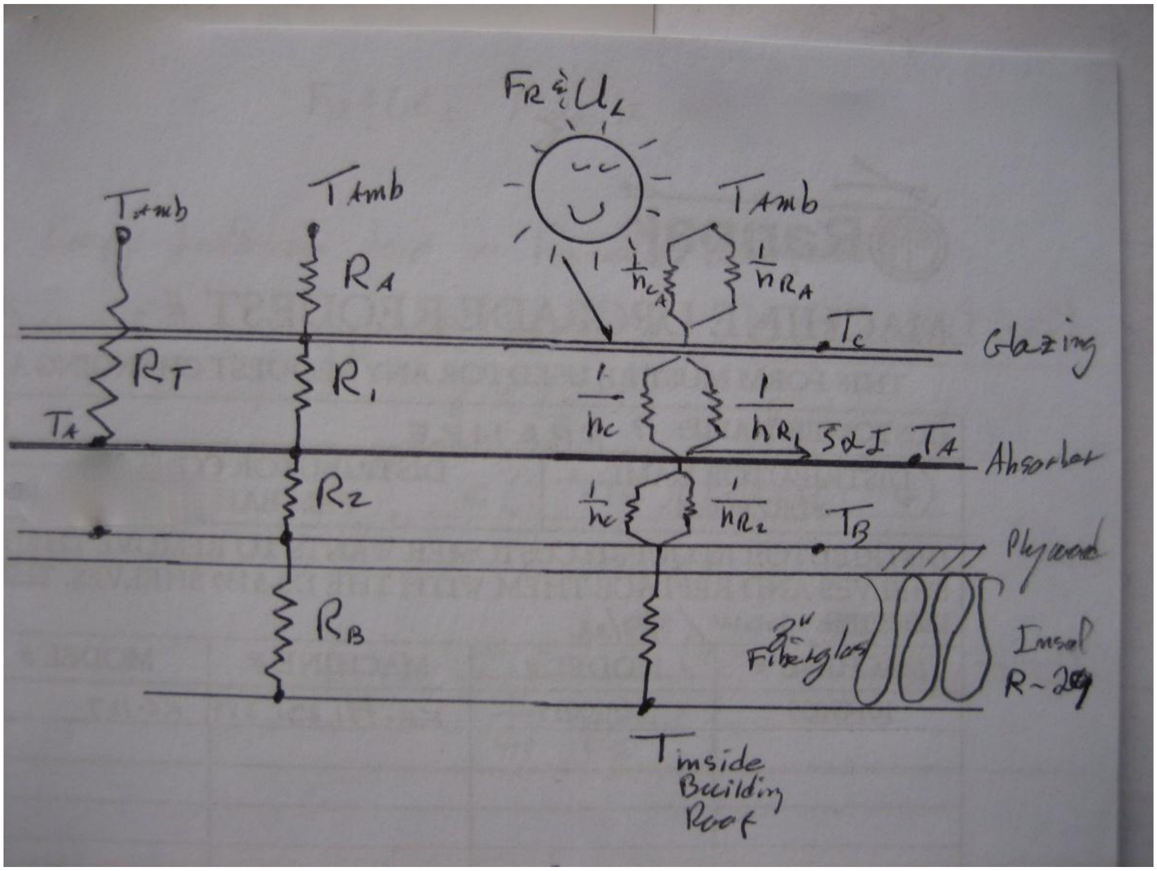


Figure 19: Heat and Thermal Resistance Diagram for the single glazed solar collector.

<u>Linearized Radiation Heat Transfer Coefficient h_R</u>

The linearized radiation heat transfer coefficient h_R between two large parallel surfaces is

$$h_R = 4\sigma T'^3 / (1/\varepsilon_1 + 1/\varepsilon_2 - 1) \qquad Q_R = h_R A(T_1 - T_2) \qquad (4)$$

Q_R = Radiation heat transfer between two large parallel plates [BTU/hr]
h_R = Linearized radiation heat transfer coefficient [BTU/hr-ft^2-^{o}F]
σ = 0.1714x10^{-8} BTU//hr-ft^2-^{o}R^4 [Stefan-Boltzmann Constant]
T' = Average Temperature between the two surfaces [^{o}R ~ Degrees Absolute]
ε_1 = Emissivity of surface 1 [~]
ε_2 = Emissivity of surface 2 [~]

The radiative connection between the backside of the unpolished bare steel absorber plate (for which $\varepsilon_1 = 0.3$) and the unfinished plywood roof surface ($\varepsilon_2 = 0.9$) is, via Equation 4,

h_{R2} = 0.57 BTU/hr-ft^2-^{o}F when T' = 200^{o}F = 660^{o}R High End Estimate
h_{R2} = 0.43 BTU/hr-ft^2-^{o}F when T' = 140^{o}F = 600^{o}R Low End Estimate

Thus we see the range of h_R is relatively low, and exact values are not essential for estimating overall collector performance, especially since the convection heat transfer coefficient h_c is greater. Therefore, with minimal error this analysis will assume $\underline{h_{R2} = 0.50\ \text{BTU/hr-ft}^2\text{-}^o\text{F}}$.

The radiation heat loss coefficient between the flat black absorber plate ($\varepsilon_1 = 0.95$) and the inner glazing surface ($\varepsilon_2 = 0.95$), again using Equation 4, is

h_{R1} = 1.48 BTU/hr-ft^2-^{o}F when T' = 160^{o}F = 620^{o}R Hot Summer Estimate
h_{R1} = 1.09 BTU/hr-ft^2-^{o}F when T' = 100^{o}F = 560^{o}R Cold Winter Estimate

Again we see the range of linearized radiative heat transfer coefficient is not great, although h_{R1} is the same order of magnitude as the convection heat loss coefficient. For this analysis we will take $\underline{h_{R1} = 1.29\ \text{BTU/hr-ft}^2\text{-}^o\text{F}}$.

The linearized radiative heat loss coefficient from the glazing to ambient is $h_A = 4\sigma\varepsilon T'^3$, with $\varepsilon = 0.95$ for the glazing. Then

h_A = 1.21 BTU/hr-ft^2-^{o}F when T' = 110^{o}F = 570^{o}R Hot Summer Estimate
h_A = 0.92 BTU/hr-ft^2-^{o}F when T' = 60^{o}F = 520^{o}R Cold Winter Estimate

Thus for this analysis we will take the average $\underline{h_A = 1.08\ \text{BTU/hr-ft}^2\text{-}^o\text{F}}$.

Convective Heat Loss Coefficient h_C inside the Collector

The system blower and motor are sized to deliver 2100 cfm at no load, and test experience has shown it will deliver 1800 cfm to 2000 cfm when forcing air through the solar collector. Since a heat exchanger bank is planned to be permanently added to the blower load, we will assume V" = 1700 cfm is the normal high air flowrate through the collector. There are 17 flow bays in the solar collector unit, so each bay will feature V' = 100 cfm. Each bay is 3.5 inches high by 22.5" wide, for a flow area of $\underline{A_F = 0.55\ \text{ft}^2}$. Then the average air velocity through each collector bay is

$V = (100\ \text{ft}^3/\text{min})/[(0.55\ \text{ft}^2)(60\ \text{sec/min})]$ $\underline{V = 3.03\ \text{ft/sec}}$

The first step in estimating h_c is to calculate the Reynolds Number for the air flow.

$Re = V^*D_h/\nu$

D_h = 2*plate spacing = 7" = 0.583 ft

$\nu = (1.8 \times 10^{-4}\ ft^2/sec)/(0.86 \sim$ Reno altitude correction)
$\nu = 2.1 \times 10^{-4}\ ft^2/sec$ Kinematic viscosity at T = 100°F and Reno altitude
k = 0.0154 BTU/hr-ft-°F   Air Thermal Conductivity at 100°F
Pr = 0.71   Prandtl Number for air
Then

$\underline{Re = V^*D_h/\nu}$ = (3.03 ft/sec)(0.583 ft)/($2.1 \times 10^{-4}\ ft^2/sec$) = $\underline{8412}$ Turbulent!

There are many equations that can be used for air flow through a rectangular channel. For smooth unobstructed interior surfaces we might use the Dittus-Boelter Equation. The surfaces are generally smooth, but the absorber plate inserted in the flowstream doubles the wetted surface area, and should therefore double the friction factor (f). Then for this special circumstance we will use the Chilton-Colburn analogy, expressed as (e.g. Cengel, Y.A., “Heat Transfer ~ A Practical Approach”, page 381)

$$Nu = h_cD_H/k = 0.125^*f^*Re^*Pr^{.33} \qquad (5)$$

For a smooth duct with Re = 8412, a Moody Diagram (Cengel, page 381) gives f = 0.032, and since we are doubling the friction factor to account for the absorber plate, in Equation 5 use $\underline{f = 0.064}$, in which case

$Nu = 0.125^*f^*Re^*Pr^{.33} = (.125)(0.064)(8412)(0.71)^{.33}$ $\underline{Nu = 60.0}$ Nusselt Number

$h_c = Nu^*k/D_h$ = (60)(0.0154 BTU/hr-ft-°F)/(0.583 ft) $\underline{h_c = 1.58\ BTU/hr\text{-}ft^2\text{-}^oF}$

This heat transfer coefficient is low, even though the flow is turbulent, because the air flowrate is low.

Convective and Radiative Heat Loss Coefficient h_E above the Collector

Heat is eventually lost from the collector glazing to the environment above via radiation and convection. The linearized radiation coefficient was estimated above to be $\underline{h_A = 1.08\ BTU/hr\text{-}ft^2\text{-}^oF}$. Duffie and Beckman (“Solar Engineering of Thermal Processes, 2nd Edition, page 174) estimate that for wind blowing over a solar collector

$$h = 1.0 + 0.2V \qquad h_A = BTU/hr\text{-}ft^2\text{-}^oF \qquad V = \text{Wind Velocity (ft/sec)} \qquad (5')$$

and D&B suggest that Equation 5 includes the effects of radiation and natural convection. Since $h_A = 1.08\ BTU/hr\text{-}ft^2\text{-}^oF$ is greater than that value given in Equation 5’ when V=0, Equation 5’ will be modified to be

$$h_E = 1.2 + 0.2V \qquad (5)$$

which will include both radiation and convection effects. Assume a wind velocity V = 5 mph = 7.3 fps and we get $\underline{h_E = 2.66 \text{ BTU/hr-ft}^2\text{-}^o\text{F}}$.

Collector Overall Heat Loss Coefficient U_L

Reference to Figure 13 shows that the radiation and convection coefficients and resistances can be combined, using the electrical analogy.

$R_1 = 1/(h_{R1} + h_c) = 1/(1.29 + 1.58) = 0.35$ hr-ft^2-^{o}F/BTU
R_1 = Thermal Resistance between absorber and glazing

$R_E = 1/h_E = 1/2.66 = 0.38$ hr-ft^2-^{o}F/BTU
R_E = Thermal Resistance between glazing and environment

$R_2 = 1/(h_{R2} + h_c) = 1(0.5 + 1.58) = 0.48$ hr-ft^2-^{o}F/BTU
R_2 = Thermal Resistance between glazing and plywood roof

$R_I = 40$ hr-ft^2-^{o}F/BTU (12 inches of fiberglass insulation = R-40)

$\underline{U_B = 1/(R_I + R_2)} = 1/(40+0.48) = \underline{0.025 \text{ BTU/hr-ft}^2\text{-}^o\text{F}}$ Back Loss Coefficient

$\underline{U_T = 1/(R_1 + R_E)} = 1/(0.35+0.38) = \underline{1.37 \text{ BTU/hr-ft}^2\text{-}^o\text{F}}$ Top Loss Coefficient

$\underline{U_L = U_T + U_B = 1.40 \text{ BTU/hr-ft}^2\text{-}^o\text{F}}$ Collector Heat Loss Coefficient

Collector Heat Removal Factor, F_R

The heat removal factor, F_R, relates the actual useful energy gain of a collector to the useful gain if the whole absorber surface were at the fluid inlet temperature. D&B (page 277) give an expression for F_R as a function of now known quantities, namely for air

$$F_R = N[1 - \exp(-1/N)] \qquad N = (m' * c_p)/(A_c * U_L) \qquad (6)$$

For a typical condition of interest we get, for T = 100^{o}F and Reno altitude (density correction factor = 0.86)

$m' = \rho V' = (0.071 \text{ lb}_m/\text{ft}^3)(0.86)(1700 \text{ ft}^3/\text{min}) = 103.8 \text{ lb}_m/\text{min}$
$= 1.73 \text{ lb}_m/\text{sec}$
Air mass flowrate at high output = $\underline{m' = 6228 \text{ lb}_m/\text{hr}}$
Then
$N = (m'*c_p)/(A_c*U_L) = (6228 \text{ lb}_m/\text{hr})(0.24 \text{ BTU/lb}_m\text{-}^o\text{F})/(528 \text{ ft}^2)(1.40 \text{ BTU/hr-ft}^2\text{-}^o\text{F})$
$N = 2.02$
So from Equation 6 $\underline{F_R = 0.79}$ Collector Heat Removal Factor

Collector Efficiency Equation

Recalling Equation (2), namely $\eta = \tau*\alpha*F_R - F_R*U_L[(T_{in} - T_{amb})/I]$, we can now estimate the efficiency for conditions of interest. Thus, with $F_R = 0.79$ and

$$\eta = (0.88)(0.95)(0.79) - (0.79)(1.40)[(T_{in} - T_{amb})/I]$$

$$\underline{\eta = 0.66 - 1.11[(T_{in} - T_{amb})/I]} \qquad (7)$$

Equation 7 indicates a straight line with the η-intercept (y-intercept) = 0.66 and the Flow Parameter $[(T_{in} - T_{amb})/I]$ intercept (x-intercept) = [0.66/1.11=] 0.595. As field data become available from the collector monitoring activity, the data will be compared against Equation 7. Current empirical data suggest that 0.66 in equation (7) is a little low, and the value 1.11 in equation (7) is also a bit low. Now that the automated data acquisition system is installed, a large quantity of experimental data will be collected and reduced, and Equation 7 will be compared to observed performance.

SOLAR AIR HEATER PERFORMANCE CHARACTERISTICS

Most commercially fabricated solar collectors sold in the United States are tested and performance characterized by the Solar Rating and Certification Corporation (SRCC), an independent non-profit clearinghouse. The SRCC provides standardized comparisons of solar thermal collectors, and affords consumers objective rankings of candidate solar collectors and product credibility confidence. It also provides rational and defensible criteria for tax credit qualifications and other solar incentive programs.

SRCC has evaluated dozens of hydronic solar collectors, and commercial air-heating collectors for seven companies. SRCC does not evaluate site-built solar air heaters, and each site-built collector would be different because there is not (as yet) a standard design. Therefore, DRI must accurately determine the performance characteristics of the REEF roof collector to facilitate reliable technical and economic analyses, including comparisons against other systems.

Prior to the roof collector construction, a 4’ by 16’ solar air heater was built and tested to determine pressure characteristics of the full-scale collector, to expedite the overall design. That smaller collector was rebuilt to a more practical 8’ by 8’ configuration, which is a size compatible with a residential solar domestic hot water (DHW) heating system. This smaller collector will also be evaluated for technical and economic performance, under conditions of a permanent assigned heating load. The smaller collector has a double glazing, as contrasted to the single glazed REEF Workshop roof collector.

The efficiency of a solar collector is defined as

$$\eta = \text{(Useful Heat)/(Incident Solar Intensity)} = \rho * V' * c_p * \Delta T / I * A_c \qquad (1)$$

where

η = Collector efficiency
ρ = Density of air entering the collector (lb_m/ft^3)
V' = Volumetric air flowrate at collector entrance (cfm or ft^3/hr)
c_p = 0.24 BTU/lb_m-^oF
ΔT = Air temperature gain across the collector (^oF)
I = Incident Solar Intensity (BTU/hr-ft^2)
A_c = Working area of the solar collector (538 ft^2)

The efficiency can be shown to take the form (e.g. Duffle and Beckman, Solar Engineering of Thermal Processes, second edition, 1991)

$$\eta = \tau * \alpha * F_R - F_R * U_L[(T_{in} - T_{amb})/I] \qquad (2)$$

where

τ = Transmissivity of the glazing system ($\tau = 0.88$ for the fiberglass glazing)
α = Absorptivity of the absorber plate ($\alpha = 0.95$ for the flat black sheet metal)
F_R = Collector heat removal factor
U_L = Collector heat loss coefficient (BTU/hr-ft^2-^oF)
T_{in} = Temperature of air entering the collector (^oF)
T_{amb} = Temperature of air exiting the collector (^oF)

Equation (2) describes a straight line, and experience has shown that most flat plate solar collectors manifest linear performance when η is plotted against the flow parameter $(T_{in} - T_{amb})/I$, the abscissa in Figure 19. The ordinate is $\tau * \alpha * F_R$.

Midday collector data were gathered under steady solar conditions over a period of time. These data are preliminary because the air flow pitot tube was newly installed. The collector efficiency data points are plotted against the flow parameter ($\Delta T/I$) in Figure 20. The scatter is expected because wind conditions impact on efficiency. A best-fit curve to the Figure 19 data is

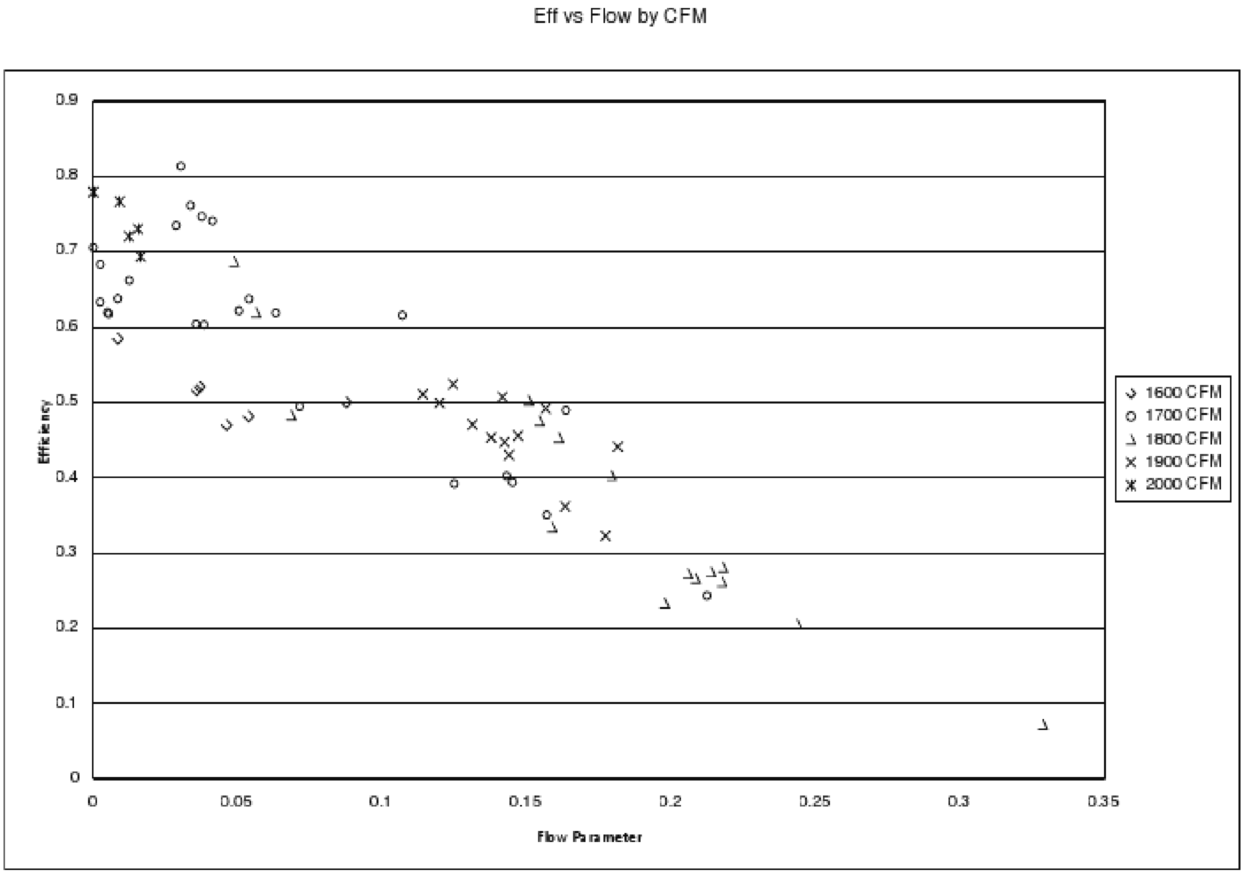
$$\eta = 0.73 - 2.0(\Delta T/I) \qquad (3)$$

from which

Heat Removal Factor $F_R = 0.873$

and

Collector Heat Loss Coefficient U_L = 2.0 BTU/hr-ft^2-^{o}F = 11.4 kW/m^2-^{o}C



page 17 of 17

Figure 20 Preliminary efficiency data from the REEF Workshop Solar Air Heater

Determining the technical performance of the solar air heater will be an ongoing project. After the computerized data acquisition system is installed, performance data will be continually collected for different conditions, seasons and flowrates, and refined curves based on hundreds of data points similar to Figure 20 will be produced. But Equation 3 is expected to be close to the more advanced result

Compare the empirical collector performance equation $\eta = 0.73 - 2.0(\Delta T/I)$
to the theoretical prediction equation calculated above $\eta = 0.66 - 1.11(\Delta T/I)$.
It seems that the heat removal factor F_R was underestimated by about 10%, but the Heat Loss Coefficient U_L was underestimated by about 80%. This could be due to the fact that the data in Figure 19 were collector mostly in summer, and in Reno the wind often comes up around noon, increasing U_L substantially.

REEF Solar Systems Economic Comparisons

The costs for the solar air heater system in the REEF Workshop and the two solar hydronic systems in the REEF House are compared. Costs of data collection systems are not included because this is a research facility, but in a normal application they would not be applicable. Commentary relating to system and approach differences is discussed as they reflect on costs.

(I) REEF Workshop Solar Air Heater Collector Cost

The installation cost of the REEF Workshop roof solar collector is estimated to be \$14,800. This includes labor, materials, the duct distribution system (DDS), and the blower. It does not include heat exchangers, liquid storage tanks, pumps, nor the monitoring system. This breakout is shown in Figure 21.

A major and unnecessary design error was inclusion of the DDS. The original and better design featured a single return air inlet at the lower west corner and heated air extraction from a hole in the upper east corner; the engineer responsible for the system design has successfully used the two hole approach in dozens of similar designs over the past 35 years, including his own solar houses. During design he allowed himself (against his better judgment and experience) to be persuaded that it would be easier to get the plans through the municipal plan check process if each flow channel had its own air supply, and so early traded a simple problem with quick solution for a much more complex problem requiring a more expensive solution (\$2700). He did not fully appreciate how much more expensive and complicated the DDS would be over the simpler and familiar approach…and relearned an old lesson!

Thus, if the system were being constructed again, the \$1900 DDS with \$800 (student and donated) labor (Total DDS = \$2700) would not be included, and the cost of the collector would be [\$14,800 - \$2700(DDS) - \$1100(blower) =] <u>\$11,000</u>.

The collector gross area is (34' by 17') 578 ft^2, and the working area (which excludes interior stud supports) is 538 ft^2. Then the unit cost is [\$11,000/578ft^2 =] \$19/ft^2 (based on gross area), and [\$11,000/538ft^2 =] \$20.45/ft^2 based on working area. These numbers apply to a retrofit situation, where a finished roof is already in place and no financial credit can be defrayed by building the collector.

But in a new construction building (REEF Workshop) a finished roof would have to be installed in any case. So it is valid to detract the cost of installing a conventional shingle roof (nails, tarpaper, overhang freeze protection underlayment, edge trim and shingles) from the collector cost. The estimated cost to shingle the 578 ft^2 roof is [\$1300(labor) and \$700(materials) =] \$2000. Then for new construction the unit cost is [\$9000/578 ft^2 =] **\$15.57/ft^2** (gross area) and [\$9000/538 ft^2 =] **<u>\$16.73/ft^2</u>** (based on net area)

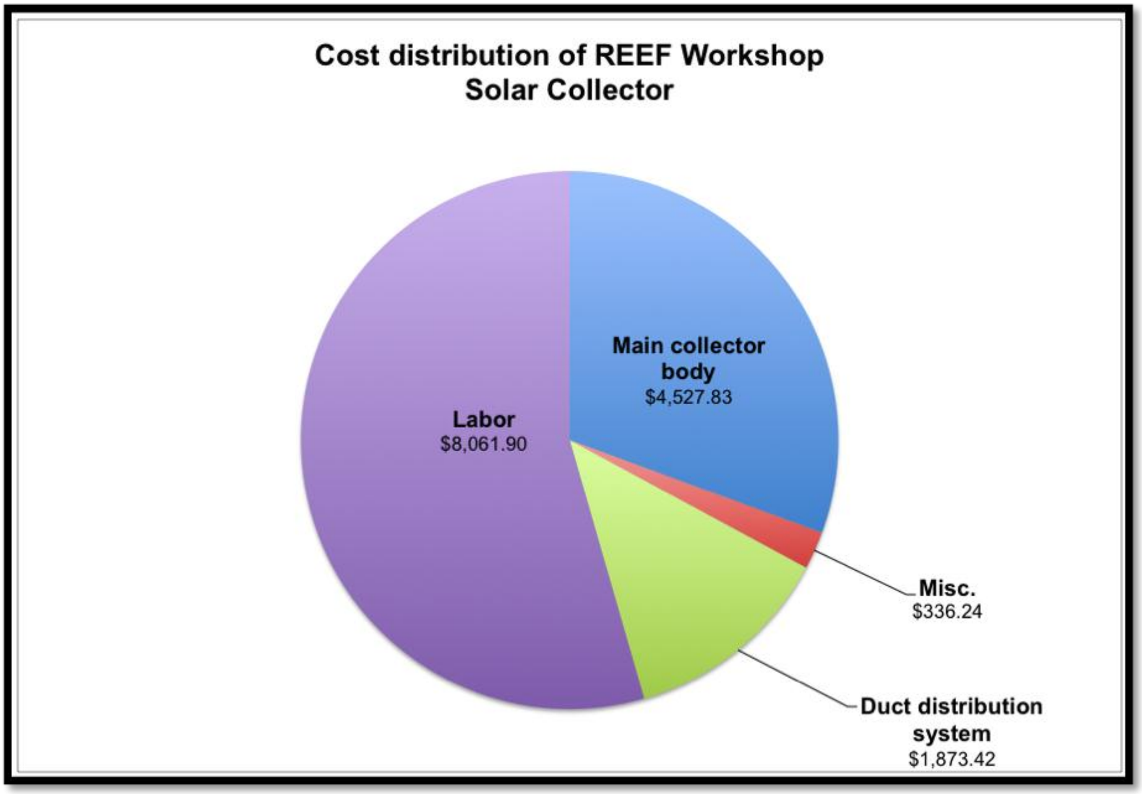


Figure 21: Cost of the REEF Workshop site built roof solar collector was $14,800 which includes the $1100 blower and $2700 (with labor) DDS

The operation and maintenance (O&M) costs are expected to be minimal relative to the capital cost, since a ½ HP motor powers the blower and water pumping costs should be very low. The DRI Team has experience with similar systems, a similar one of which has lasted for 20 years with near zero maintenance.

II. REEF House Hydronic Solar Collectors

Two separate hydronic solar collector systems were purchased and installed in the REEF House. 200 ft^2 of Viessmann units comprise half of the solar collector area, and 200 ft^2 of Sunvelope collectors encompass the other half.

(1) Viessmann Collectors

These German imported collectors cost $5127 for 8 units of 25 ft^2 each, or 200 ft^2. The Viessmann Vitosol 200-F units feature a selective surface absorber to reduce heat loss at high temperatures by reducing the collector heat loss coefficient. Glycol runs through serpentine tubes that are attached to the absorber plate underside. They use glycol as the fluid medium to protect against freezing and subsequent collector loss. Glycol transport fluid requires a double-wall water-water heat exchanger to avoid contaminating potable water, and is a financial discredit to any glycol system; this heat exchanger with controls cost $2670. Although at the DRI REEF House site the Viessmann collectors were mounted in an expensive manner due to severe site space restrictions, an installation charge of only $1000 will be assessed for mounting, in the interests of having valid cross-system comparisons. Each of the 8 units weighs 90 pounds empty, and 95 pounds when charged with glycol.

The costs relating to the Viessmann collector system, but not including storage except for the generically necessary specialized heat exchanger, are listed below.

Viessmann Solar Collector System (200 ft^2)

Component	Comments	Cost
200 ft^2 Solar Coll	High Temperature Performance Glycol Units	$5127
HE/Controller	Codes require a double wall HE with potable water	$2670
Installation	$1000 is a low estimate for collector field installation	$1000
Connections	Viessmann provided specialized insulated Solar-Flex	$ 459
	TOTAL =	**$9256**

Then the Unit Cost of the Viessmann solar collector field (not the system) is [$9256/200 =] **$46.28/ft^2**

(2) Sunvelope Collectors

10 Sunvelope S21-FP solar collectors were installed for a total collector area of 200 ft^2. The Sunvelope collectors are manufactured in Sparks, Nevada. They have a web internal-flow absorber plate that is designed to expand if/when water freezes internally, so potable water can be used as the working fluid. The web assures a higher heat removal factor than serpentine tubes welded beneath the plate, because there is less fin area and more direct access of solar gain to the working fluid. The absorber plate is a selective surface, reducing heat loss at high temperatures. Since water is the working fluid (as compared with glycol in the Viessmann unit) potable water directly from a storage tank can be used and a specialized heat exchanger is obviated. The simpler Sunvelope system will cost less to install. Each of the 10 units weighs 90 pounds empty, and 95 pounds when charged with water.

Costs relating to the Sunvelope collector system are tabulated below.

Sunvelope Solar Collector System (200 ft^2)

Component	Comments	Cost
200 ft^2 Solar Coll	High Temperature Performance Water Units	$6000
Installation	$1000 is a low estimate for collector field installation	$1000
Tubing, Fittings, etc	Materials required to install collectors on roof	$ 741
	TOTAL =	$7741

Then the Unit Cost of the Sunvelope solar collector field (not the system) is [$7741/200 =] **$38.71/ft^2**.

III. Comparing the three REEF Solar Collectors

The REEF Facility has three generically diverse solar collectors; (1) site-built air heater, (2) Viessmann glycol working fluid collector, and (3) Sunvelope water collector. Advantages can be claimed for each approach, but first we shall compare costs, recapitulated from the above analyses.

Cost Comparisons of the Three REEF Solar Collectors

REEF Solar Collector	Active Area	Active Area Unit Cost
Site-Built Air heater	538 ft^2	\$16.73/ft^2
Sunvelope Water-Charged Unit	200 ft^2	\$38.71/ft^2
Veissmann Glycol-Charged Unit	200 ft^2	\$46.28/ft^2

There may be some economy of scale in the larger site-constructed solar air heater, but the effect is small, and a unit half the size would have cost nearly half as much. Site-built air units are inherently less expensive than commercially supplied liquid collectors for several reasons:

(1) Fewer components are needed. Insulation, unit housing, and installation support generally come with the building, whereas they are separately incorporated into commercial units.

(2) Installing commercial liquid units requires several trades including plumbing and carpentry.

(3) Air heaters are simple in concept and can be built by handymen with basic skills.

(4) Many people handle and require profit from a commercial unit including factory workers, truckers, warehousers, salesmen, installers, etc. A carpenter building an air heater from basic materials avoids all the middlemen.

However, the hydronic collectors have a lower heat loss coefficient U_L than the air collector for two reasons. First both hydronic units have selective surface absorbers, which reduces heat loss at high temperatures. Second, there is a dead air zone between the absorber and cover glass in the hydronic units (although there is natural convection between the absorber and glazing above), whereas flowing air in the forced air unit manifests higher heat loss in the air unit. The maximum temperature observed in the air unit was 185^{o}F at stagnation conditions, whereas either hydronic collector will stagnate above 200^{o}F in summer.

This means that the application must be fit to the collector. If the goal is winter space heating, then air temperatures above 125^{o}F are not required, so a high-performance collector designed to produce high temperatures loses its advantage. A solar air heater providing winter space heating takes cool air from the building, heats the air in the collector, and returns the heated air to the house without a heat exchanger. The hydronic collector generally requires heat exchangers to transfer heat from the liquid to air, with an attendant performance and cost penalty.

If the system task is domestic hot water heating, then again water temperatures above 125^{o}F are not required. The air heater approach can easily provide this heat but an air-to-water heat exchanger is required. Even with the heat exchanger cost penalty, the site-built air heater will do the same job for less cost than the Sunvelope unit, even though the Sunvelope system is ideally suited to directly heat the potable water without a HE. The Viessmann unit must have a double wall HE to keep the glycol separated from potable water, with attendant cost and performance penalties.

In the summer of 2012 the REEF Workshop solar air heater heated 240 gallons of water to over 160^{o}F at no load. If the system goal is to provide hot water at (say) above 170^{o}F then the single-glazed solar air heater cannot compete with the hydronic systems. However, if a second glazing is applied to the air system, then its low temperature efficiency is reduced but its high temperature efficiency is increased, in which case it can compete technically with the hydronic units, and outperform them economically as it does at lower temperatures.

The Solar Ratings and Certification Corporation (SRCC) is a standard clearing house for rating solar collectors, and nearly all commercial solar collectors sold in the United States have been SRCC performance tested and evaluated, including the Viessmann and Sunvelope collectors. The SRCC ratings indicate that both hydronic systems provide essentially the same performance; they both have selective surface absorbers and single glass covers. The SRCC does not evaluate site-built units because each of them is likely to be different.

APPENDIX III

Manual for Student-Completed Home Energy Audits

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Overview

The ultimate goal of a residential energy audit is to improve both the comfort of the living space within the home and the cost-effectiveness of its energy usage systems. A successfully implemented energy audit includes suggestions for changes to the occupants' lifestyles and energy usage patterns that will result in energy savings in both long and short-term.

Pre-Audit Analysis

Audit Goal for Homeowner

Before conducting the energy audit for the interested homeowner it is important to identify why the audit was deemed necessary. Have the homeowner fill out a pre-audit questionnaire to ascertain their motives for the audit and get a feel for the homeowner's demeanor. Once the goal of the audit has been identified, the process of the actual audit can focus in a more specialized manner on certain systems within the home. It is important to find out if there are any known areas of comfort issues in the house. Be sure to ask for the square footage of the home as this value is used when calculating the home's Energy Usage Index. A copy of the questionnaire can be found in the Appendix.

ACTION ITEMS:

- *Identify Energy Audit goal for Homeowner.*
- *Identify the number of bedrooms, square footage & ceiling height of home.*
- *Identify any comfort issues throughout the home (i.e. – draft, moisture, etc.)*

Energy Usage Analysis

The first component of the pre-audit survey is to look at a home's energy usage history. All of the data needed for this analysis is located on the homeowner's utility bill each month. Have the homeowner collect the power bills for the past 1-2 years for analysis prior to the physical audit. Note that the more data you have for this section the better as it gives a more normalized value to the energy usage trends over time.

An additional service that can be offered is to drop off an energy usage monitor (Kill-A-Watt) 24-48 hours before the on-site inspection to measure energy consumption of household appliances. The Kill-A-Watt can measure electrical energy used in kW-h and expand this data for a total annual estimate of energy usage. By multiplying this value by the price of energy, basic return-on-investment calculations can be made to determine the economic feasibility of replacing an inefficient appliance.

Three values can be obtained from looking at the energy usage: the Home Heating Index (HHI), Energy Usage Index (EUI), and the Cost of Energy per square foot ($\$/ft^2$) to the homeowner. A sample calculation of each can be found in the Appendix. Each of these items can signify improvements can be made to energy usage and management throughout the home. The finished audit will show an HHI rating for the home, with the EUI and cost of energy per square foot reserved for more specific audit goals identified by the homeowner.

ACTION ITEMS:

- *Obtain energy usage data (i.e. utility bills) for at least 1 year.*
- *Calculate Home Heating Index (HHI).*
- *Calculate Energy Usage Index (EUI).*
- *Calculate Cost of Energy per square foot.*

Home Audit

Homeowner On-Site Interview

Tools: Pre-audit questionnaire, Audit analysis workbook.

When arriving at the residence on the day of the audit your obvious point of contact is the homeowner. Before inspecting the residence, ask the homeowner questions that may not have been answered during the pre-audit questionnaire, such as:

- How old is the home?
- Where is the majority of time spent in the home?
- What is the O&M history on home heating/cooling systems?
- Are there any known problem areas throughout the home (i.e. – leaky windows, unsealed cracks, etc.)?

A fairly exhaustive list of on-site interview questions can be found in the Appendix; more important questions are outlined in the Action Items section below. Before moving to the next section of the audit, make sure each member of the audit team has a hand-drawn floor plan of the home to make their own notes on. Try to focus the questions on 7 main areas:

- Occupancy within the home
- Thermostat usage habits
- Moisture & humidity within home
- Comfort
- HVAC
- Air quality
- Known issues

ACTION ITEMS:

- *Identify home age/how long homeowner has been current occupant.*
- *Identify age of heating/cooling systems and maintenance history.*
- *Identify heating/cooling usage throughout the day on average (i.e.- times and duration system is on and thermostat temperature settings).*
- *Identify areas with known problems throughout the home.*
- *Identify home retrofits if applicable/any home improvement projects that have been undertaken by the current or previous homeowner(s).*

External Building Envelope

Tools: Ambient Carbon Monoxide (CO) Monitor, Combustible Gas Leak Detector, Thermometer.

After conducting the on-site interview, the audit team should begin the inspection process on the outside of the house. The team should be equipped with a tablet PC along with a notebook or clipboard to make their own notes about the property while conveying them to the rest of the team. The analysis spreadsheet is to be filled out on the tablet as the audit is preformed. Be sure to turn on the Combustion Analyzer while you are outside for a more accurate reading. Important things to look for while inspecting the building's exterior include:

- Earthquake/home settling damage (possible air infiltration/exfiltration points).
- Moisture damage.
- External shading of windows (Trees, vines, overhangs, window shades, etc.).
- Window locations and concentration (more windows on one side of home than others, etc.).
- If applicable, document type/location of cooling system (i.e. - shaded outdoors, roof mounted, etc.).
- External envelope material (wood, masonry, etc.) & insulation.
- Any exposed pipes or vents that lead to the interior of the home.
- Roof type and orientation.
- Location(s) of bathroom & kitchen exhaust vents.
- Location of Gas Meter.

Any and all issues found should be documented by describing the problem in the audit notebook and its physical location marked on the hand drawn floor plan. This procedure will be repeated throughout the entire audit process. As in the previous section, more important questions have been outlined in the Action Items section below.

ACTION ITEMS:

- *Identify external home damage.*
- *Identify window locations and external sources of shading.*
- *Identify external building envelope material.*
- *Document type/location of cooling system.*
- *Measure and record external wall temperature in various locations.*
- *Document weather conditions at time of audit.*
- *Identify number of exhaust vents on roof to ensure fans aren't venting to unconditioned attic space.*

Interior Building Walk Through

Tools: Ambient CO Monitor, Combustion Analyzer, Manometer, Infrared (IR) camera, Anemometer

After completing the inspection of the building's exterior, the interior of the home is examined. Start the internal inspection by documenting the known issues the homeowner pointed out in the on-site interview if applicable. Using an infrared (IR) camera, try to locate areas with large temperature differences to their surroundings and take photos of the incidences. Operation instructions for the use of the IR camera are included in the Appendix. Be sure to note where each photo was taken on the floor plan drawing for easier reference when writing the post-audit summary. Try to set the home in wintertime conditions as you are completing the walk through (meaning shut/lock all exterior doors/windows and open all interior doors). This is done to prepare the home for the Worst-case depressurization test. Go from room to room and document any findings, including:

- Lighting types & locations
- Combustion appliance location(s), age, and temperature setting.
- Heating furnace location and age.
- Thermostat location and type.
- Measure and record temperature of hot water from faucet.
- Location of HVAC registers throughout home.
- Age and type of windows throughout home.
- Measure and record refrigerator and freezer temperatures.
- Locate attic and crawlspace. Document whether or not any of the piping/ductwork are insulated (along with insulation type).
- Compare number of exhaust fans inside to vents to outside.

- Use IR camera to identify any areas with notable temperature differences to their surroundings. Take photographs to include in the audit summary.

A thorough list of items to look for is located in the Appendix; more important things to look for are located in the Action Items list below. The more data you are able to gather while you are conducting this part of the audit, the better; it prevents having to come back for something vital you may have missed during the initial inspection.

Part of the safety audit of the residence includes testing the gas oven & clothes dryer for CO leaks. Use the ambient CO monitor to sniff gas lines leading to the oven and the dryer. Make sure the interior of the oven has nothing blocking the bottom and turn it on to 500^{o}F. After 5 minutes of operation, place the combustion analyzer probe into the oven's undiluted flue gasses and record the CO level displayed. BPI recommended action levels for Gas Ovens are shown in Table (1).

Table 1: BPI Recommended Action Levels for Gas Ovens

Action Level	Recommendation
Level 1 – 100 ppm to 300 ppm	You must install a carbon monoxide detector and make recommendation for service
Level 2 – Greater than 300 ppm	The unit must be serviced prior to work. If greater than 300 ppm after servicing, exhaust ventilation must be provided with a capacity of 25 CFM continuous or 100 CFM intermittent.

After completing the interior walk through, again make sure the home is in wintertime conditions prior to the Combustion Safety Testing.

ACTION ITEMS:

- *Identify lighting types (incandescent, CFL, etc.) & locations.*
- *Test oven & dryer CO levels.*
- *Identify hot water heater location and age*
- *Identify thermostat location and type.*
- *Measure and record temperature of hot water from faucet.*
- *Identify location of HVAC registers throughout home.*
- *Measure and record refrigerator and freezer temperatures.*
- *Test refrigerator and freezer seal tightness.*
- *Measure and record temperatures at top and bottom of walls throughout home.*
- *Identify attic and crawlspace. Document whether or not any of the piping/ductwork are insulated (along with insulation type).*
- *Document any liquid damage to home interior if applicable.*
- *Document internal window shade type throughout home.*

Combustion Safety Testing

Tools: Ambient CO Monitor, Combustion Analyzer, Manometer, Smoke Stick

This section of the audit aims to ensure the safe operation of combustion appliances located within the residence's conditioned envelope. Begin the tests by visually inspecting the water heater and furnace for signs of rust or burns. Document the combustion appliance's nameplate specifications and fuel source in the audit workbook. If the water heater is commonly vented with a furnace, make sure the unit with the lower Btu output is connected to the shared flue above the higher Btu unit. This will improve the lower Btu unit's ability to exhaust appropriately. If the flue is not mounted completely vertical, make sure it has the proper slope (at least 1/4" rise per foot of flue length). The complete procedure for combustion appliance inspection can be found in the audit workbook. After visual inspection has been carried out, the house must be prepared further for worst case testing:

1. Turn water heater to pilot; turn furnace/boiler off; turn off all exhaust fans.
2. Record ambient CO level in combustion appliance zone (CAZ).
3. Record outdoor temperature.
4. Make sure house is in winter condition: close exterior doors, latch or lock windows, open interior doors.
5. Close all operable vents (i.e. – fireplace damper).
6. Remove furnace filter.
7. Install hose from combustion appliance zone (CAZ) to outdoors; plug into manometer, CAZ with respect to outside (red nipple of DM-2 manometer).

The idea of worst case depressurization testing is to determine if the exhaust fans can create enough competition for air to back draft the furnace or water heater, causing significant safety concerns. If the appliances vent sufficiently under worst case conditions, they should also vent under natural conditions. Once the above steps have been carried out, you are ready to create worst case conditions as described in the audit workbook.

After completing the worst case depressurization test, combustion appliance testing should be carried out. These tests will verify a combustion appliance's nameplate efficiency and ability to vent exhaust gasses appropriately. The guidelines for carrying out these tests are also described in the audit workbook in the appendix, along with BPI recommended action levels for CO test results.

ACTION ITEMS:

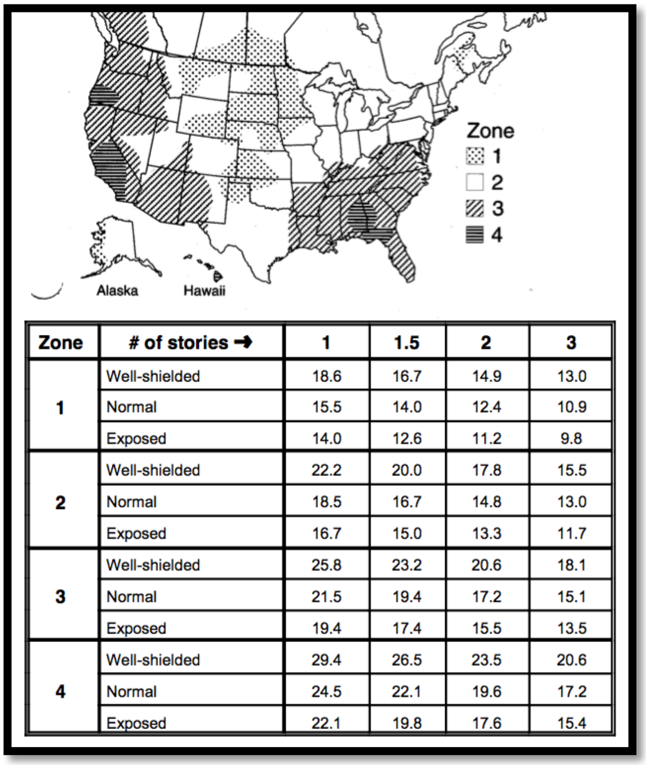
- Identify combustion appliance safety concerns.
- Conduct worst case depressurization testing.
- Conduct combustion appliance efficiency, CO, and spillage testing.

Blower Door Test

Tools: Blower door, IR camera, Calculator

The Blower Door Test aims to remedy air quality issues and air leaks in the home. Once located, many of these areas can be serviced to improve air quality and help prevent energy losses from the residence. The Blower Door supplied by DRI is a Retro-Tec DoorFan-Q46. The blower door requires 1-2 people for on-site assembly and takes about 10 minutes to put together. The operation and installation instructions are included in the Appendix. Prior to turning the blower on, calculate the Minimum Building Airflow Standard (BAS):

1. Calculate ventilation required for building:
    a. Airflow (cfm) = 0.35 x Building Volume / 60
2. Calculate ventilation required for people:
    a. Airflow (cfm) = 15 x # of Occupants (occupants = bedrooms +1)
3. Using higher value of 1 & 2 above, convert to CFM50:
    a. BAS (Maximum CFM50) = Airflow (cfm) x N factor (Fig. 1)
4. Multiply Maximum CFM50 x 0.7 for acceptable range:
    a. BAS (Minimum CFM50) = Airflow (cfm) x 0.7



Zone	# of stories ➜	1	1.5	2	3
1	Well-shielded	18.6	16.7	14.9	13.0
	Normal	15.5	14.0	12.4	10.9
	Exposed	14.0	12.6	11.2	9.8
2	Well-shielded	22.2	20.0	17.8	15.5
	Normal	18.5	16.7	14.8	13.0
	Exposed	16.7	15.0	13.3	11.7
3	Well-shielded	25.8	23.2	20.6	18.1
	Normal	21.5	19.4	17.2	15.1
	Exposed	19.4	17.4	15.5	13.5
4	Well-shielded	29.4	26.5	23.5	20.6
	Normal	24.5	22.1	19.6	17.2
	Exposed	22.1	19.8	17.6	15.4

Fig. (1): LBL Factor zone map and conversion table. [Source: http://www.energystar.gov/ia/home_improvement/home_sealing/ES_HS_Spec_v1_0b.pdf]

The BAS range should be recorded and compared to the Before turning the blower on, ensure all registers, windows, and doors leading to the exterior throughout the home are closed to make an accurate measurement of the home's air-tightness. If the residence has a fireplace make sure the flue is closed and there aren't any leftover ashes left as they can scatter once the blower is running. The setting on the blower control unit should generally be set to range B for residential applications but may be adjusted as needed. If any combustion appliances (i.e. - heating system, water heater, etc.) are located inside the residence ensure they have been shut off prior to turning on the fan.

Once the blower door has been running for 10-15 minutes, make a note of the fan flow rate on the control unit connected to the blower. This will be used in the calculation of the amount of air changes per hour (ACH). The main idea behind the use of the blower door is to calculate the amount of ACH the house experiences with the applied suction of the blower door. The blower control unit maintains a fixed pressure difference between the inside and outside of the house by adjusting the fan’s flow rate (cfm). From this number the ACH for the home’s natural state can be derived using the LBL factor found in Figure (1) below. First the residence’s climate zone is identified using the map shown in the figure and the appropriate LBL Factor is selected from the table based on the home’s natural wind exposure and building height. The home’s ACH values can be calculated using the following formulae and conversion factors:

$$ACH_{50Pa} = \frac{Fan\ flow\ rate\ [cfm] \times 60 min/hr}{Area\ of\ House\ \ ft^2\ \times Ceiling\ height\ [ft]} \qquad (1)$$

$$ACH_{Natural} = \frac{ACH_{50\ Pa}}{LBL\ Factor} \qquad (2)$$

With the blower running, walk from room to room and feel for any areas that air seems to be escaping from. Document their location and severity on a copy of the hand drawn floor plan. Use the IR camera to photograph each occurrence, making sure to note the location for the post-audit summary. Common problem areas for energy loss and air leakage include:

- Doorframes leading to building exterior.
- Skylights.
- Home improvement project areas (i.e. - modified or added bedrooms and bathrooms, owner installed fixtures, etc.).
- Wall outlets.
- Fireplace enclosures.
- Ceiling-embedded lighting systems.
- Stove vent hood.
- Attic/crawlspace entrances.

A method of estimating how much air leakage there is in a specific room or area of the home (i.e. – attic or basement, etc.) is to bring a differential manometer to the audit. With the blower running, measure the pressure between two adjacent areas, such as between a bedroom and the attic. Since the blower door measures the total pressure difference across the conditioned envelope ($\Delta P_{in/out}$), this creates a partial pressure difference between the inside of the home and a "buffer" zone ($\Delta P_{in/buffer}$). Using these relationships:

$$\Delta P_{in/out} = \Delta P_{in/buffer} + \Delta P_{buffer/out} \tag{3}$$

Ideally, $\Delta P_{in/buffer}$ should be as close to 50 Pa as possible, as this indicates there aren't substantial leaks in the buffer zone. If $\Delta P_{in/buffer} < 40$ Pa, this is a clear indication that there are significant leaks that need to be sealed within the home.

ACTION ITEMS:

- *Assemble and install blower door.*
- *Ensure all registers/doors/windows/chimney flue are closed in home.*
- *If applicable, ensure all combustion appliances are turned off.*
- *Run blower for 10-15 minutes. Record fan flow rate (cfm).*
- *Calculate ACH for suction and no suction conditions.*
- *Identify and document leakage areas.*
- *Use IR camera to photograph any problem areas, documenting on floor plan where each photo was taken.*
- *Check common problem areas mentioned above and locations of known exfiltration stated in homeowner interview.*

Audit findings summary

After completing the audit, have one member of the team collect all of the team's data for the writing of the audit summary based on the final report template. It is best if the summary is written as soon after completion of the audit as possible to ensure that the details are still fresh in the author's mind. A complete audit should include:

- Description of the geographical location of the residence and weather conditions at time of audit.
- Information gathered in the Pre-Audit Energy Use analysis (i.e. - HHI, EUI, $/ft^2, etc.).
- Heating/cooling usage history (i.e. - heating schedule, thermostat settings, etc.).
- ACH calculations for blower door test.
- Recommendations for the homeowner(s) for energy usage improvements, also known as energy conservation measures (ECMs).
- Summary and documentation of issues found and IR photographs.

Send the completed audit out to the whole team for factual review and editing. Once the team gives the report the green light, the draft can be finalized and given to the homeowner. A list of common issues found and the ECMs that can reduce their impact can be found in the Appendix.

ACTION ITEMS:

- *Collect audit data from all team members; assign someone to write the audit summary report.*
- *Write report. Be sure to include the items listed above <u>at minimum</u>.*
- *Distribute completed report to rest of team for editing/comments.*
- *Submit finished draft of report to homeowner.*

Appendix

A. *Workbook*
   The following excel workbook contains the data collection and analysis tools necessary for a residential energy audit.

Docs - NBaker DRI Energy Audit Spreadsh

B. *Combustion Appliance Testing*

DRI has access to a Bacharach Fyrite Insight combustion gas analyzer, and its test results will be used to give educated recommendations to the building owner on O&M habits that should be implemented for the combustion appliance. The steps for testing combustion appliances are outlined below:

1. Pre-Audit interview
2. Nameplate specifications
3. Flame rollout
4. Unit security
5. Spillage testing
6. Combustion efficiency testing
7. CO monitoring
8. Observations

<u>1. Pre-Audit interview</u>

Interview the building owner/maintenance faculty to determine location of all combustion appliances. Take a note of all locations to ensure all appliances are tested during the site visit. Find out if there are any known issues with existing combustion appliances.

2. Nameplate specifications

Before testing each combustion appliance, visually inspect its exterior. Locate the appliance's nameplate and take a photo for documentation. This will be used to determine the efficiency per manufacturer specifications and age of the appliance. Document the efficiency in the workbook. If the appliance is a DHW heater take note as to whether or not it is wrapped in a blanket or other insulation, as this is a possible ECM recommendation to the site owner.

Fig. 1. DHW tank flame rollout [1].

3. Flame rollout

While inspecting the exterior of the appliance, be sure to note any signs of flame rollout. Figure 1 shows an example of flame rollout on a DHW tank. Document any abnormalities in the workbook along with a photo of the occurrence.

4. Unit security

Make sure that the unit is properly secured to the building and to its exhaust stack. For DHW tanks, the proper wrapping technique is shown in Fig. 2. This band will hold the tank in place in the event of earthquake or other natural disaster. The tank should have 2 bands, located at roughly 1/3 and 2/3 of the tank's total height. Document any abnormalities in the workbook along with a photo of the occurrence.

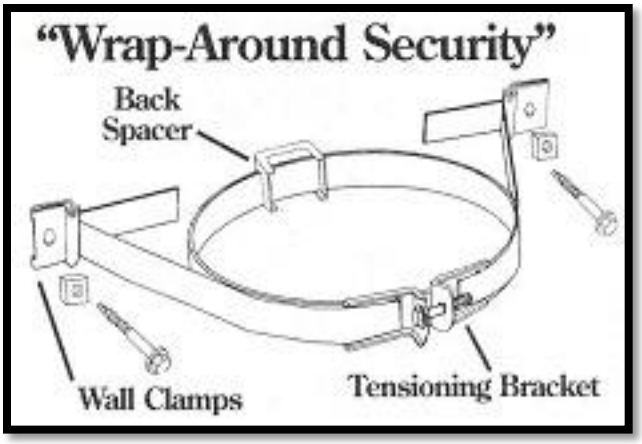


Fig. 2. DHW tank wrapping application [2].

NOTE: MAKE SURE APPLIANCE IS SET TO PILOT/OFF PRIOR TO ANY OF THE FOLLOWING TESTS. This is done to ensure the auditor's safety and to let the system stabilize before the test is conducted. The best practice for this is to turn the appliance to pilot and make sure the thermostat is turned off as well. Set your keys on top of the appliance to remind you to turn it back on before you leave the audit site. If there are any combustion hazards in the immediate testing area, alert the site owner and ask them to move them prior to testing as well.

Turn on Bacharach combustion gas analyzer outside prior to testing and allow 60 seconds for initial warm-up. Select gas type under options.

5. Spillage testing

The appliance's exhausting capabilities are verified through spillage testing. If the combustion appliance to be tested is commonly vented with another (i.e.- furnace & DHW, common in residences), make sure to test the unit with the lower BTU output first for more accurate results due to assisted drafting. This would generally be the DHW in residential combustion appliance testing.

Turn on the appliance, observing the flames as it turns on, and test for spillage with a smoke stick, ½" below and ½" outside lip of draft hood. Note the amount of time it takes to stop spilling in the workbook.

a) If the appliance stops spilling within 60 seconds, the unit passes. Leave unit on; proceed to combustion efficiency test.
b) If it takes more than 60 seconds to stop spilling, the unit fails. Leave unit on; proceed to combustion efficiency test.

6. Combustion efficiency testing

The testing procedures for both furnaces and DHW heaters are described in this section. The Bacharach Fyrite Insight combustion gas analyzer will be used for both tests.

a) Furnace testing

After 5 minutes, the combustion appliance is considered to be at steady state and combustion efficiency testing can be implemented. Press center button on the Bacharach to begin taking measurements. The unit will output CO ppm, 0_2 content %, and combustion efficiency. Record the highest CO reading measured through each of the exhaust ports (70% efficiency furnaces) and the measured efficiency in the workbook.

b) DHW testing

After 5 minutes, the combustion appliance is considered to be at steady state and combustion efficiency testing can be implemented. Press center button on the Bacharach to begin taking measurements. The unit will output CO ppm, 0_2 content %, and combustion efficiency. Record the highest CO reading measured on each side of the heat exchanger coil under the draft hood and the measured efficiency in the workbook.

Once testing is complete, be sure to turn the appliance back to pilot and turn the thermostat back to its previous setting.

7. CO monitoring

Based on the results of the combustion efficiency testing, describe any maintenance required based on the action level specified by the workbook. If during any of the tests the CO content rises above 400 ppm, stop testing immediately and let the site owner know the unit needs to be temporarily disabled until service is complete.

8. Observations

Document any notable observations made during the unit inspection and testing. If possible, include a photo for inclusion in the testing summary to be presented to the site owner. Possible observations include: combustibles in the area surrounding the appliance, signs of rust on equipment or exhaust stacks, "flickering" of flames during combustion, and anything that may serve to benefit the appliance's safe operation.

The workbook below allows for a streamlined data collection process, thus cutting down on time spent at the audit site. It is important to remember that the more data that is gathered the better; an auditor can lose his standing with a client if a follow up visit is needed due to an oversight in the initial audit. Take photos of everything that is done during the combustion appliance audit, as they tell the story of the environment the appliance is operated on and can provide further insight into O&M practices currently in use.

Microsoft Excel
Macro-Enabled Worksheet

Energy conservation measures that may be suggested to the site owner based on the results of the audit include:

- Compare energy usage (in BTUs and $/yr) of existing equipment to higher efficiency appliances.
- Calculate simple payback period (SPP) and return on investment (ROI) for unit replacement if need be.
- Suggest insulation of DHW tanks/combustion appliance zone (CAZ) as much as possible to minimize heat losses.
- Economic analysis of incorporating renewable technologies to supplement existing equipment (SPP, ROI, etc.).

References

[1] Image Source: http://www.tucsoninspection.com/sitebuildercontent/sitebuilderpictures/things9.jpg
[2] Image Source: http://www.americanhvacparts.com/Merchant2/graphics/00000001/WHSTKITA.jpg

Combustion appliance audit results/report flow chart

The responses below are to be included in the audit summary and serve as a template from which a report may be generated.

CA#	
Serial #	
Fuel type	
Efficiency	

1. **Flame rollout?**
   [YES] – Evidence of flame rollout was found with the appliance, indicating a need for service (Figure). Contact a service professional to have the unit inspected for any additional issues.

   [NO] – No evidence of flame rollout was found with the appliance.

2. **Secured properly?**
   [YES] – The appliance was properly mounted and affixed to the building.

   [NO] – The appliance was not properly secured to the building (Figure). Make sure all connections meet building requirements to ensure safe operation.

3. **Acceptable efficiency?**
   [YES] – The combustion efficiency of the appliance was within an acceptable range of the manufacturer's specifications.

   [NO] – The combustion efficiency of the appliance was not within an acceptable range of the manufacturer's specifications (Δ___%). This can be an indication of incomplete combustion in the appliance and energy savings can be gained through repair. Contact a service professional to have the unit inspected for any additional issues.

4. **CO Action level?**
   [Level 1] – The CO content of the exhaust gasses in the appliance was not within an acceptable range (____ ppm) and is a possible indication of incomplete combustion. Energy savings can be gained through repair. Contact a service professional to have the unit inspected for any additional issues.

   [Level 2] - The CO content of the exhaust gasses in the appliance was not within an acceptable range (____ ppm) and is an indication of incomplete combustion and poses a safety hazard. Energy savings can be gained through repair. Contact a service professional as soon as possible and install a CO detector in the building until service is complete.

   [NONE] – The CO content of the exhaust gasses in the appliance was within an acceptable range (____ ppm).

5. **Pass spillage?**
   [YES] – The appliance evacuated combustion byproducts safely, indicating a properly sized exhaust stack.

   [NO] – The appliance did not evacuate combustion byproducts safely, indicating an improperly sized exhaust stack or the need for service. Install a CO detector in the building and contact a service professional to have the unit inspected for any additional issues.

6. **Observations**
   [YES] – ____ should be examined as a possible source of safety/operational concern (Figure).
   [NONE] – ____.

Pass Audit:

If [NO, YES, YES, NO, YES, NONE]
– The appliance passed both the combustion and safety audits successfully.

If [NO, YES/NO, YES, NO, YES, YES/NONE]
– The appliance passed the combustion audit but safety concerns were found: ____

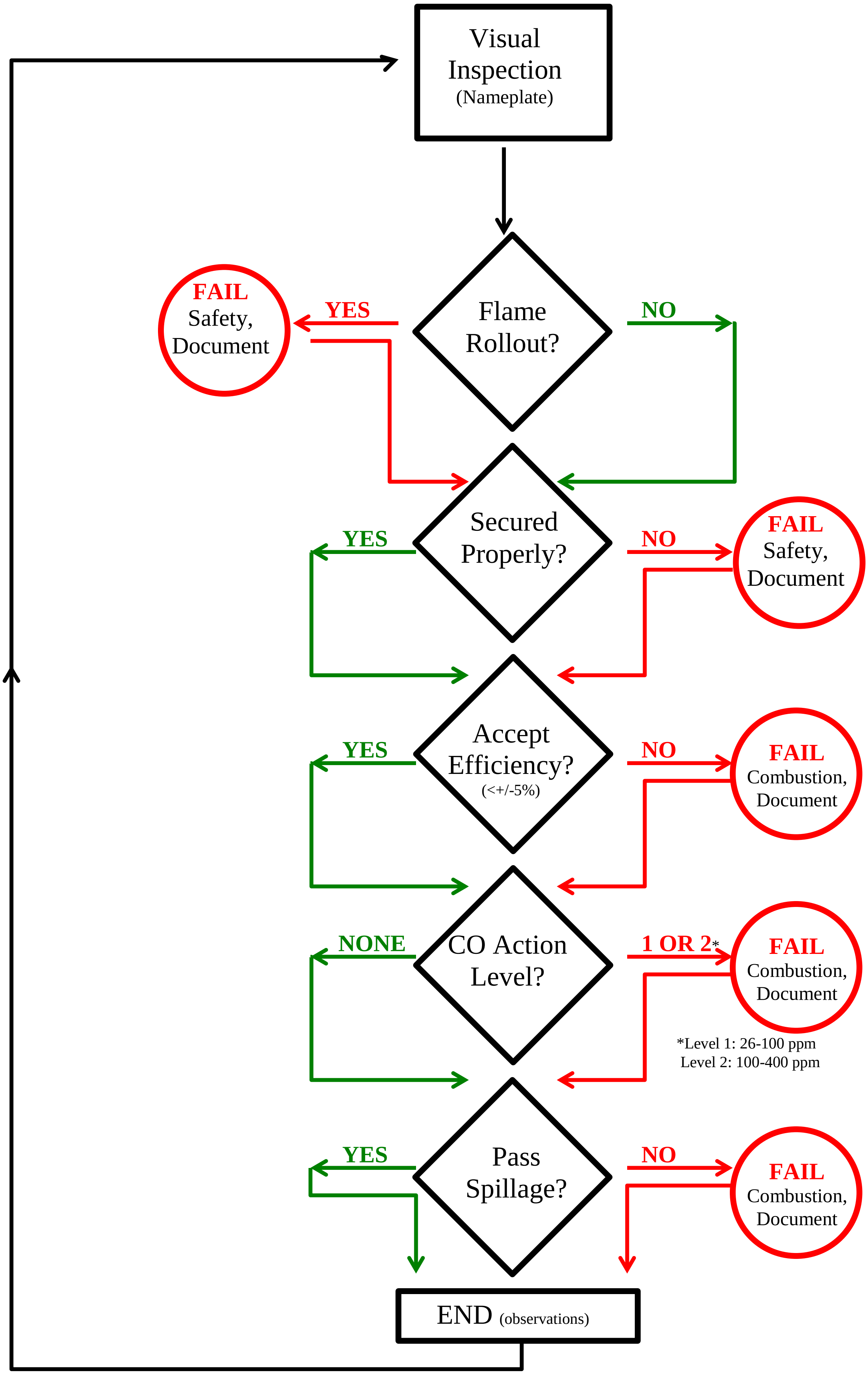
Else

Fail Audit:

– The appliance did not pass the combustion audit.

Energy Conservation Measures

- Calculate annual energy savings with higher efficiency appliance
- Calculate SPP and ROI for unit replacement
- Incorporation of renewable technologies (SPP, ROI, etc.)


Visual Inspection (Nameplate)
Flame Rollout?
YES
FAIL Safety, Document
NO
Secured Properly?
YES
NO
FAIL Safety, Document
Accept Efficiency? (<+/-5%)
YES
NO
FAIL Combustion, Document
CO Action Level?
NONE
1 OR 2*
FAIL Combustion, Document
*Level 1: 26-100 ppm
Level 2: 100-400 ppm
Pass Spillage?
YES
NO
FAIL Combustion, Document
END (observations)

APPENDIX IV

Home Energy Efficiency Reports

1. Economics of Residential PV Power Systems in Northern Nevada
2. Weatherstrip Doors
3. Insulate Garage Doors
4. Save Money on Your Lights
5. Shade Windows in the Summer

ECONOMICS OF RESIDENTIAL PV POWER SYSTEMS IN NORTHERN NEVADA

By

Nicholas Baker
Desert Research Institute

Introduction

Homeowners looking to make a residential energy investment can find financial incentives to installing a simple solar power system. With the emergence of reputable Internet wholesalers and an increased demand for renewable energy, many of the components of the system are now readily available for installation by the homeowner. Rather than hiring contractors, some homeowners are installing their own solar power systems, driving the net cost of their solar project down and making the technology somewhat more financially attractive.

This article describes the economics of installing a residential solar power system. The system will be described in the nomenclature of the solar power industry to make the homeowner well versed in the terminology when speaking to reputable contractors who conduct the installation process for them. The information contained within this report is the end result of reviewing solar energy websites, journals, textbooks, and telephone interviews conducted with contractors and homeowners who utilize solar power. This report enables homeowners to make informed decisions about utilizing household solar power.

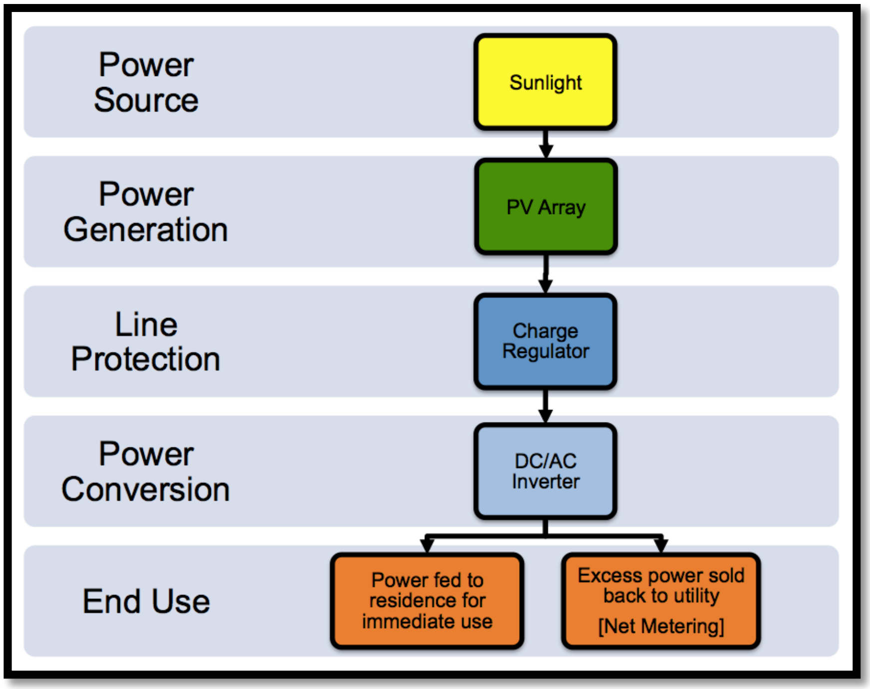


Figure (1): Components and description of a grid-tied residential photovoltaic (PV) power system.

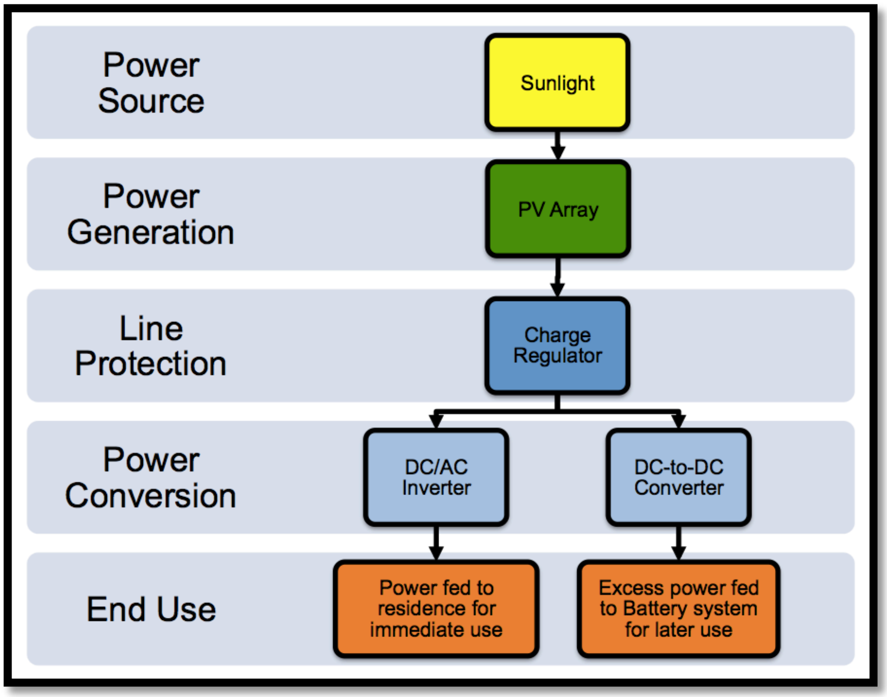


Figure (2): Components and description of an off-grid residential photovoltaic (PV) power system.

Residential Solar Power System Overview

I. Direct Sunlight

Figures (1) and (2) depict sunlight falling on silicon photovoltaic (PV) cells. This creates a reaction within the solar panel (also known as a “PV array”) that can generate the useful direct current (DC) that will either directly supply or supplement the power needs of a residence. The amount of sunlight that reaches the system determines how much power the system is able to create. Abundant year-round insolation (incoming sunlight) makes Northern Nevada an ideal location for solar power [1].

II. PV Array

The PV array consists of thousands of individual cells wired in series to generate enough current to be useful. The solar panels themselves are generally mounted on roofs of existing buildings or designed to be an integrated part of the roof itself, depending on the application. PV ground arrays are also installed. This facilitates system cleaning and seasonal adjustment. Since the power generated by the system is directly related to the amount of light the array gets during daytime hours, the placement and orientation of the PV array affects the amount of power it is capable of producing [2]. If possible, the array should be adjusted seasonally to the appropriate angle to receive the largest amount of direct sunlight from month to month or season to season. If the angle of the roof or location on which the system is mounted is too low or too high the homeowner will notice a substantial difference between the power generated during summer and winter months. There are many resources available online to determine the optimum angular orientation of the array, one of which is listed in Appendix B.

The optimum location for a solar power system is an area that receives the maximum amount of sunlight throughout the year. Factors that can decrease power output include surrounding temperatures in the extremes (either exceptionally cold or hot climates), dust/dirt accumulation, and inconsistent wiring of the arrays. These losses associated with the functionality of the array are typically called the system’s “derating factor” [3]. It is important to note that many PV products are rated in DC power output, while the useful alternating AC power that the residence will actually be able to use after the DC power conversion process to AC will be roughly 77% of the DC value.

III. Charge Regulator/Power Conditioning

As the amount of sunlight that hits the PV array is prone to variations throughout the day and year (i.e. shade from passing clouds, overcast days, etc.), the charge regulator and power conditioner are vital components of the system. Any inconsistencies in the lighting can cause individual cells to act as diodes and discharge any current generated by neighboring cells. The charge regulator can detect these discrepancies and correct them using a series of blocking diodes to temporarily reroute the current flowing through the system. It is a necessary component to make sure the power is safely distributed from the entire PV system.

IV. DC/AC Inverter

The direct current (DC) power generated by the PV array is not useful for most residential appliances. At this point in the system, the direct current is fed through a power inverter that converts it to the alternating current required by most appliances and wall outlets within the residence. The DC-to-AC inverter is an essential component in both on-grid and off-grid applications since a vast majority of household appliances use AC. Inverters operate under high stress due to variations in the load that is being applied through them. They require periodic conditioning to ensure optimal operation, but can last for almost the lifetime of the entire system if maintained properly. Losses in power are also associated with the inversion process, again contributing to the system's derate factor [3].

For grid-tied PV systems, the DC-to-AC inverter also feeds excess power generated back to the power utility, essentially running the homeowner's energy meter backwards. This is where the financial savings manifest themselves in the form of generating power credit to the homeowner, thus lowering the monthly power bill. This practice is known as "Net Metering," and is commonly practiced within urban/suburban residential PV systems. The effectiveness of Net Metering is discussed in further detail in the Financial Impact to Homeowner section.

V. Battery System for Off-Grid Applications

A battery system for energy storage is an optimum choice for residences that are remotely located and thus required to operate independent of the traditional power grid. Power not immediately used within the residence is fed to a DC-to-DC converter and is in turn used to charge a lead-acid battery system. Although not required in every PV application, the battery system ensures all energy harvested from the sun's rays are converted to some useful form of power, storing enough power to accommodate night time demands. The batteries can also be used for power if the PV array is damaged or out of service temporarily. It is important to note that the batteries have a shelf life, as do the other components of the residential PV system, and require periodic maintenance and discharge to ensure proper power distribution to the rest of the system.

VI. End Use

The end result of the PV system is to power fixtures and appliances throughout the household. Since there are no waste byproducts created during the PV power generation, PV energy is arguably one of the most ecologically benign sources of electrical power. Despite this fact, the technology required to harness solar power remains fairly expensive and not yet cost effective, but costs are declining as newer PV techniques, materials, and financial incentives become available.

To estimate how large a system should be, review the residence power usage over the past year(s), and then decide how much of this power the homeowner wants to have generated by a PV system. It is a good idea to build a solar power system above estimated demands, as there are power losses that occur during the power conversion process and through normal use. Table (1) shows sample calculations on the sizing of a PV system based on energy usage. Data and assumptions for these calculations can be found in the spreadsheet located in Appendix A and in the Financial Impact to Homeowner section below.

Table (1): Sample PV system size estimator for Northern Nevada

Season	Power Usage by Season [kW-h]	% of Power to be supplied by PV System	System Output Demand [kW]	System Size Needed for % Power Specified
April-September	2255	50%	1.4	50%: 1.6-2.0 kW
		75%	2.1	
		90%	2.6	75%: 2.3-2.8 kW
October-March	2594	50%	1.7	
		75%	2.5	90%: 2.8-3.3 kW
		90%	3.0	

Once installed, the PV array requires little periodic maintenance, generally a semi-annual cleaning of the array to remove any debris from the cells that can cause performance losses is generally sufficient for the majority of residential applications [1]. Many PV cells can have a life longer than 25 years, but damage to cells can occur at any time. The warranty period for the majority of the PV arrays available on the market is 25 years as well [2]. It important for the homeowner to check the system at least once a month to make sure all components are operating at peak capacity.

VII. Financial Impact to Homeowner

a.Tax Incentives

The bottom line to homeowners is how much the switch to solar power will cost them out of pocket and what they can expect for a normal payback period. Tax rebates are offered by the Federal Government to help offset the capital needed to install the system. In many instances, these rebates can be up to a third of the system's entire cost. Although currently inactive in Nevada (early 2012), many states offer incentives for renewable energy as well. Contractors interviewed for this report suggested homeowners view the cost of the solar power systems as a long-term investment in their home and suggested a simple payback period for an average size solar system in Northern Nevada as 16 years when external financial incentives are applied; see Table (2).

For this report, contractors were asked to supply a cost per Watt quote for an average residential system. Estimates for how large an average solar power system should be ranged from 1.8-3 kW (kW = 1000 Watts) capacity, and the cost of installation per Watt ranged from $6.00-7.50, brining the final bill to the range $10,000-20,000. NV Energy offers an incentive once a year that is available to homeowners who install a PV system to help offset the up front (capital) costs. NV Energy will reimburse the homeowner $2.30 per AC Watt that the system can generate up to $23,000 (NV Energy SolarGen). Homeowners can get a crude estimate of how much they can expect to receive by multiplying their system size (i.e.-1,800 Watts) by the common output derating value (roughly 0.77), and then multiplying this number by the incentive value. Adding to this, the Federal Government offers a tax credit of 30% of the system cost after NV Energy's incentive to reduce the final cost of the system to the homeowner.

To verify contractor claims, these figures were tabulated along with the amount of solar radiation available in Northern Nevada. Table (2) contains estimates for the cost and payback period of a simple PV system for energy usage outlined in Table (1). The assumptions made for the calculations of this data are: the cost of installation is $6.00/Watt, the panels produce around 10W/ft^2, and an annual increase in energy prices of 1% to determine the value of the power generated by the system. Alternative uses of money are not considered in Table (2). Figure (3) shows the net cash flow over the average warrantied lifetime of the PV systems outlined in Table (2).

Table (2): Estimates of a contractor-installed PV system cost and payback period in Northern Nevada.

System Size [kW]	Estimated up-front cost to homeowner	NV Energy SolarGen Incentive	30% Federal Tax Credit	Net Cost to Homeowner	Simple Payback Period
1.8	$10,800	$3,188	$2,284	$5,329	17 years
2.5	$15,000	$4,428	$3,172	$7,401	15.8 years
3	$18,000	$5,313	$3,806	$8,881	15.8 years

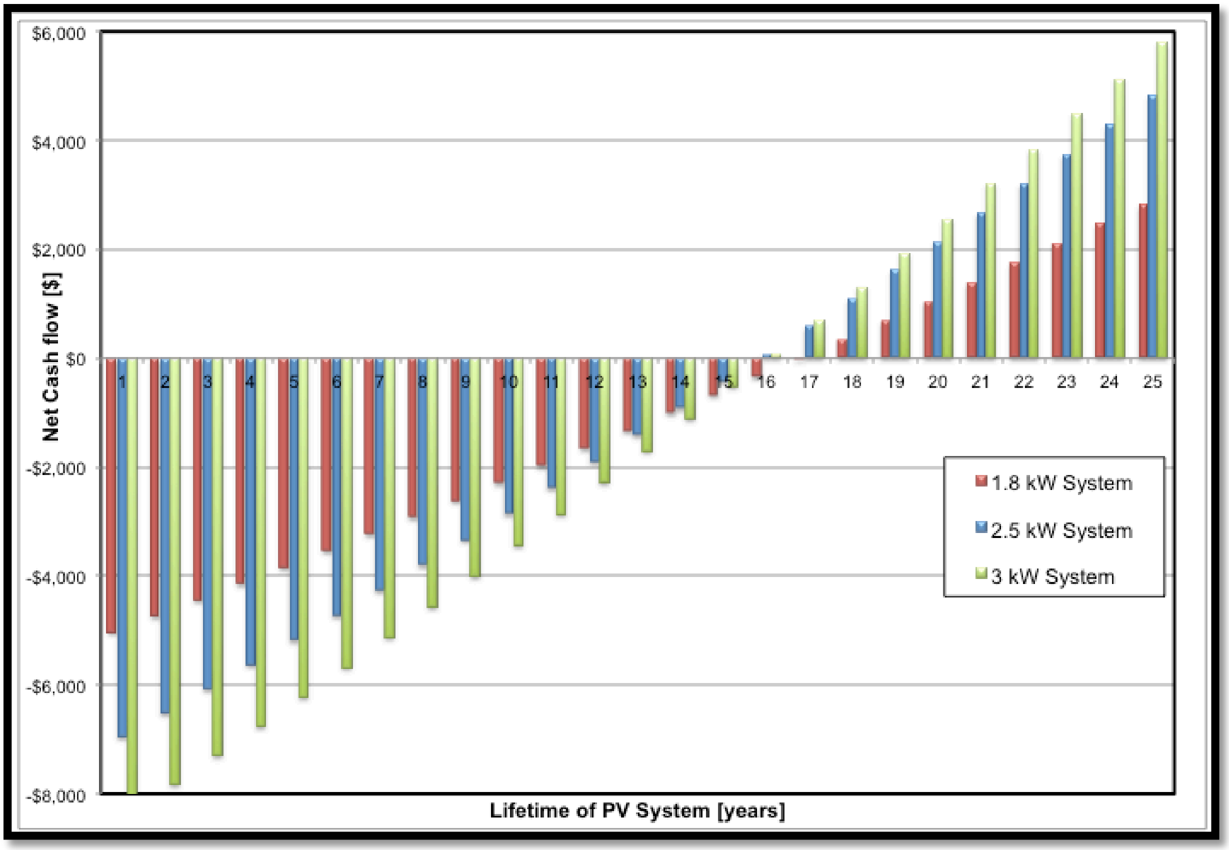


Fig. (3): Net Cash flow for sample contractor-installed PV system in Northern Nevada with a 1% annual increase in energy prices.

Due to the high availability of online PV kits and many homeowners interested in performing a majority of the installation on their own, this was self-installation scenario is outlined in Table (3) below. The assumptions made for the calculation of Table (3) is that the homeowner will do about 25% of the system installation. Figure (4) visualizes the net cash flow for the average warrantied lifetime of a PV system. Complete calculations of this data can be found in Appendix A at the end of this article.

Table (3): Estimates of a homeowner and contractor-installed PV system cost and payback period in Northern Nevada.

System Size [kW]	Estimated up-front cost to homeowner	NV Energy SolarGen Incentive	30% Federal Tax Credit	Net Cost to Homeowner	Payback Period
1.8	$8,100	$3,188	$1,474	$3,429	12.3 years
2.5	$11,250	$4,428	$2,047	$4,776	11.3 years
3	$13,500	$5,313	$2,456	$5,731	11.3 years

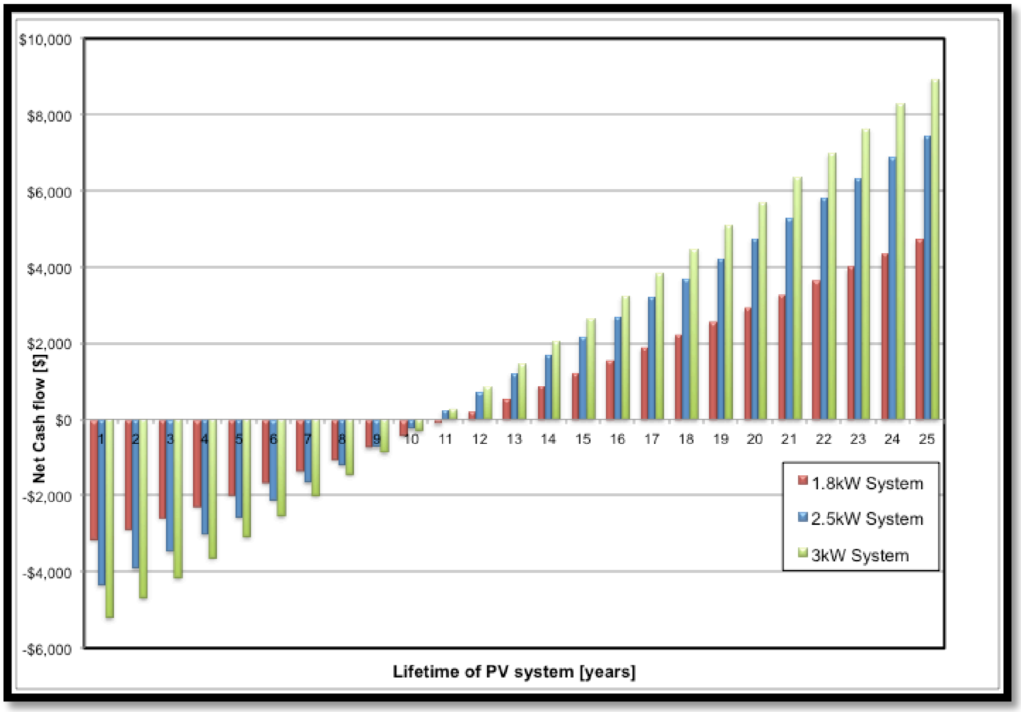


Fig. (4): Net Cash flow for sample homeowner and contractor-installed PV system in Northern Nevada.

A reasonable methodology to evaluate the pros and cons of installing a PV power system is to use the same decision criteria used by major companies: by looking at the return on the initial investment. By comparing this value to things like the amount of interest a similar amount of money may generate in an alternative investment, the homeowner is able to get a better concept of the economic attractiveness of PV power. Sample returns on initial investments can be found in Table (4) for both types of systems described above; information on how to calculate these values can be found in Appendix A.

Table (4): Return on investment in Northern Nevada for various system sizes from sample calculations, which include rate-payer and tax-payer support.

System Size	Installation Type	First year Return on investment	Average Return on investment over 25 years
1.8 kW	Contractor only	5.41%	6.12%
2.5 kW	Contractor only	5.85%	6.61%
3 kW	Contractor only	5.85%	6.61%
1.8 kW	Contractor & Homeowner	8.39%	9.48%
2.5 kW	Contractor & Homeowner	9.06%	10.24%
3 kW	Contractor & Homeowner	9.06%	10.24%

It is important for homeowners to understand all that installing a PV system entails to ensure optimum performance at a fair price. As such, many helpful links and resources for the interested consumer have been compiled and can be found in Appendix B.

Beyond the capital costs of installing a PV system, homeowners need to be licensed on a local, state, and Federal level to operate a solar power system. The utility company also needs to set up the appropriate accommodations for the power to be fed back to the energy grid in order for the system's Net Metering to work properly. All of these bureaucratic items can take weeks or even months to be in effect for the homeowner so it is important the homeowner understands the length of the process before investing in a PV system [4].

b. No-incentive cost

To demonstrate the large effect of federal, state and utility incentives when offsetting the capital needed to purchase the PV system, a brief analysis was conducted without including these discounts in the net system cost to homeowner for the same system sizes discussed previously. The assumptions made for these iterative calculations are the same as those listed in the previous section. Table (5) can also be considered the total system societal cost, since costs defrayed to the homeowner must be assumed by the taxpayer and ratepayer. The payback periods in Table 5 exceed the 25 year warrantee offered by vendors.

Table (5): Estimates of a contractor-installed PV system cost and payback period in Northern Nevada, less incentives.

System Size [kW]	Net Cost to Homeowner	Payback period
1.8	$10,800	31 years
2.5	$15,000	29.1 years
3.0	$18,000	29.1 years

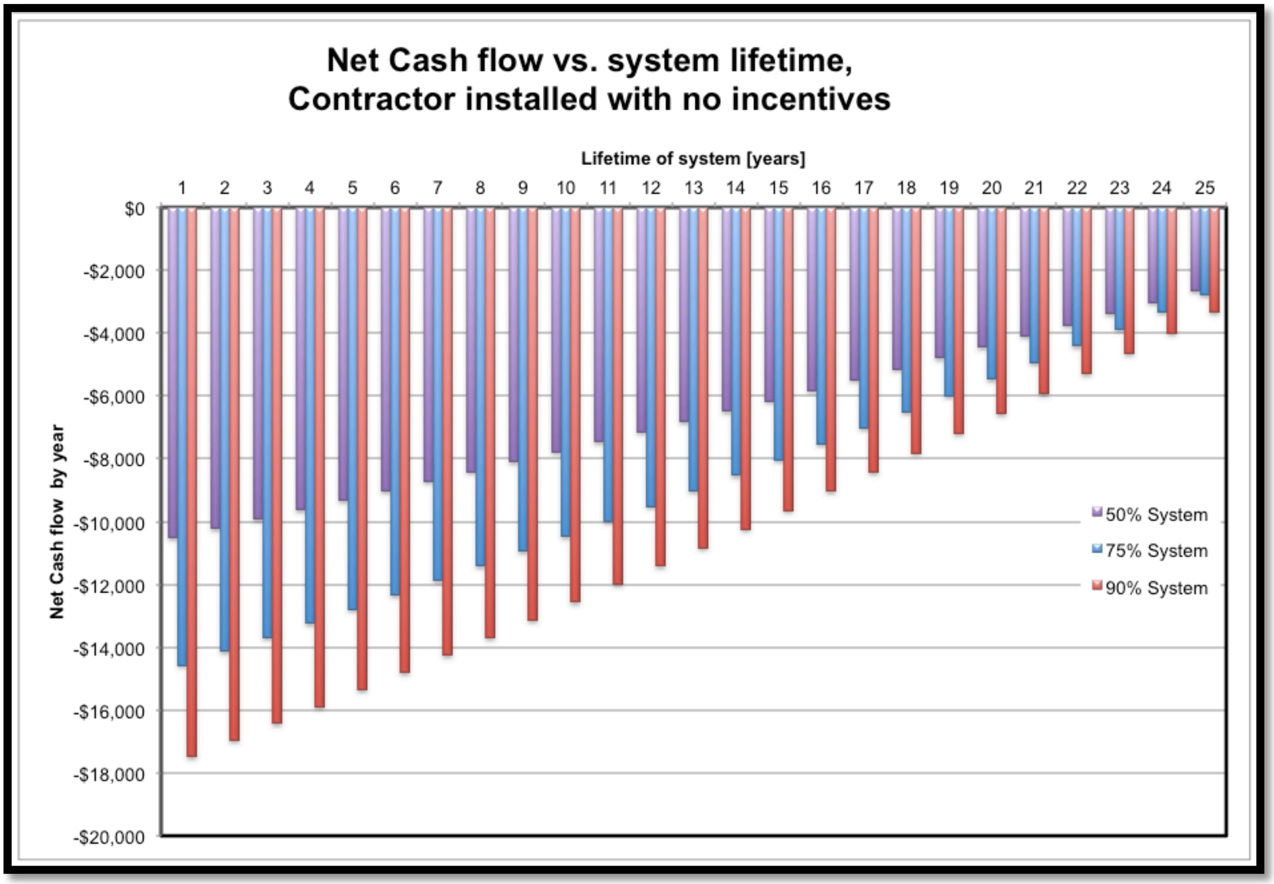


Fig. (5): Net Cash flow for sample contractor-installed PV system in Northern Nevada with a 1% annual increase in energy prices, less incentives.

The payback period for systems purchased with no incentives increases by nearly a factor of two for all three considered system sizes, thus diminishing the value of installing PV (Fig. 5 & Table 5). Even if homeowners are able to do part of the installation themselves the payback period is still almost 25 years (Fig. 6 & Table 6):

Table (6): Estimates of a homeowner and contractor-installed PV system cost and payback period in Northern Nevada, less incentives.

System Size [kW]	Net Cost to Homeowner	Payback Period
1.8	$8,100	24.1 years
2.5	$11,250	23.8 years
3	$13,500	23.8 years

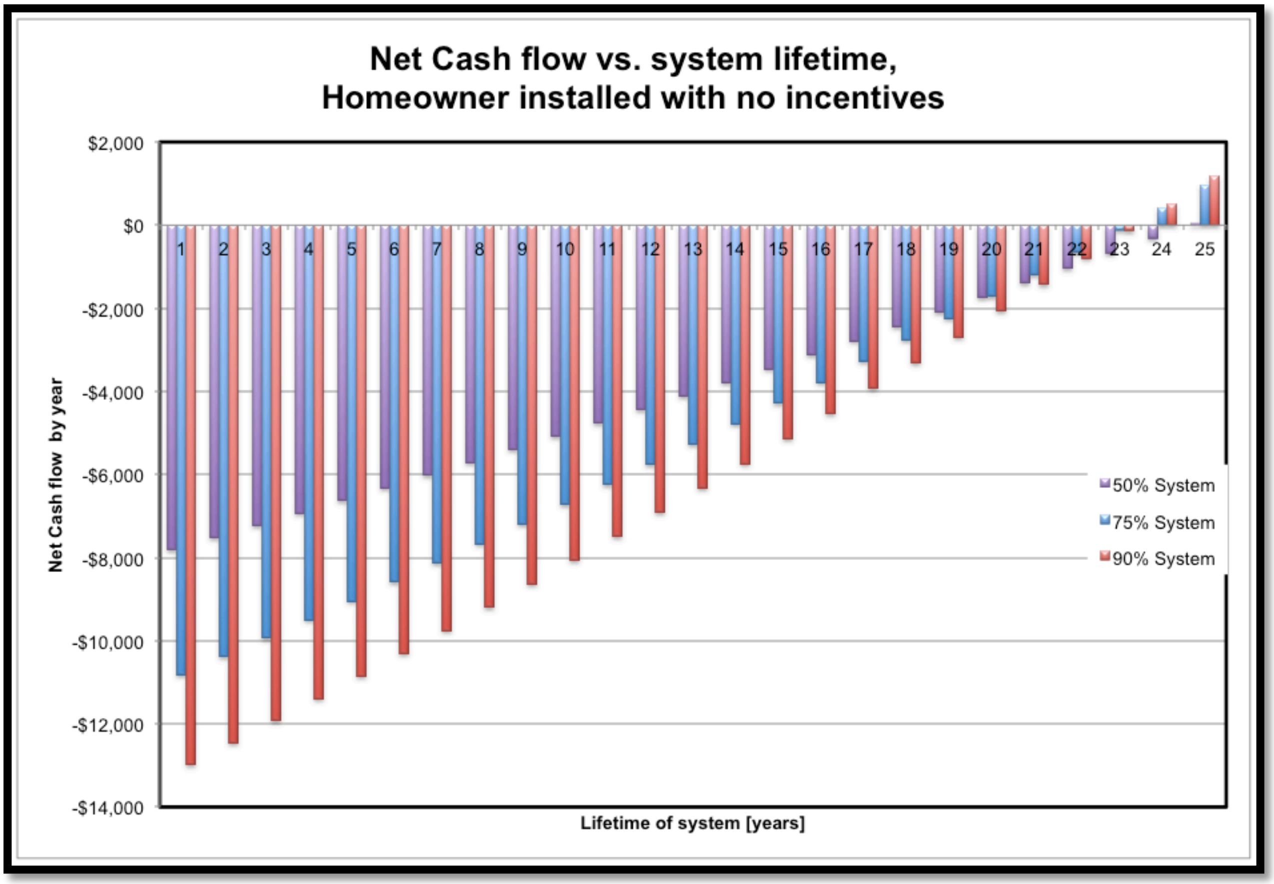


Fig. (6): Net Cash flow for sample homeowner and contractor-installed PV system in Northern Nevada, less incentives.

The return on investment decreases by roughly 55% for both the first year and over the first 25 years of the system's ownership as well (Table 7). This further demonstrates how PV technology still needs to develop methods to decrease the cost to the end user in order for PV to assume a strong foothold in the energy market.

Table (7): Return on investment in Northern Nevada for various system sizes from sample calculations.

System Size	Installation Type	First year Return on investment	Average Return on investment over 25 years
1.8 kW	Contractor only	2.67%	3.02%
2.5 kW	Contractor only	2.89%	3.26%
3 kW	Contractor only	2.89%	3.26%
1.8 kW	Contractor & Homeowner	3.56%	4.02%
2.5 kW	Contractor & Homeowner	3.85%	4.35%
3 kW	Contractor & Homeowner	3.85%	4.35%

Homeowner Statement

An interview was conducted with a Northern Nevada homeowner about his family's decision to install a residential solar power system through a contractor. The homeowner started his PV project by sourcing a contractor through a home improvement store's list of contacts. The initial contact from the contracting company assured the homeowner that the installation would be straightforward and that they would walk the family through the system's operation and maintenance procedures prior to installation. They would also explain how the system would be integrated to the residence's current power needs. The contact estimated a 1.4 kW system with a price tag of $15,000 but stated the payback period would be 7-8 years. The homeowner said that the contact acted pushy during the consultation process and seemed to be out for a fast sale. When it came time to arrange for the contracting company to actually install the system, the homeowner was told his initial contact at the company had been let go, but that the contractors would still be able to describe the system's functionality to the family.

The homeowner felt wary about his decision but decided to go ahead. When the contractor came to the residence for the system installation, the workers were less than professional and failed to show the homeowner how the system would operate. After the installation was completed, the homeowner found he had to spend considerable time acquiring the appropriate licenses and permits to use the system. The contractor failed to mention the licensing requirement to the homeowner prior to the system's installation. The system has been operational for over 6 months (at the time of this interview) and the utility company is yet to come make the appropriate accommodations for the system to net meter and begin to recoup the capital cost. As a whole, the homeowner felt he was oversold a solar power system that costs his family money to use each day. This negative experience demonstrates the importance of finding a reliable contractor and ensuring well-informed decisions prior to purchasing PV systems.

Conclusions & Recommendations

With current trends in energy prices and technologies, PV power is approaching financially viability. The ease of operation and maintenance, rebates and incentives available to homeowners, and the ecological implications make PV power increasingly attractive to some people. The value of the system will increase as energy prices increase each year, and advances in PV technology continue to make for more efficient panels with longer lifespans. However, it is a ponderous process to integrate the PV system to the residence and power grid with all the required licensing and contacts. But by shifting financial responsibility from the homeowner to taxpayer and ratepayer, in some cases the system can pay for itself from the standpoint of the homeowner in the long term if the system lasts its warranted lifetime.

In any case, when solar photovoltaic electric power generation approaches financial competiveness with other fuel sources, electric utility companies will be able to deploy this technology much less expensively than homeowners because they enjoy economy of scale, scheduled maintenance by experts, thoroughly understand every phase of electrical production and integration, and can avoid interminable licensing permits for net metering.

Questions for Contractors

The questions presented below represent a short list of the few key items any legitimate PV system contractor should be able to answer without hesitation. The list is by no means exhaustive and should be used as a guide for homeowner decisions about installing a PV power system. As with any home project, it is suggested that several competitive estimates be obtained. [5].

- What is the warranty period for each component of the PV system?
- Do you offer a warranty on the installation workmanship?
- Are you registered with the Nevada State Board of Contractors? Are you licensed to perform installations of PV systems?
- What is the derate factor of each type of system configuration you offer?
- Do you have any performance curve charts that display the performance of the system under different load conditions (i.e. operation through all four seasons)?
- Can you explain how each component in the system works alongside the others to generate power?
- What is the cost of each component? Do you offer custom system configurations based on desired performance (i.e. offer a choice between expensive vs. cheaper components)?
- What is the payback period offered by installing your particular type of PV system?
- Do you have any type of data to back up payback period assertion (i.e. net metering capacity of a typical system along with a projected cost of energy in the future)?
- What types of State, Federal, or other rebates are offered by installing a PV system in Northern Nevada?

- Are any types of permits required for me to operate the PV system? What is the general turnaround time and cost for applying for these permits?
- Do you have any references from previous clients that can attest to your quality of workmanship?
- Can I do part of the installation?

References

[1] Hamilton, Reid. "PV Energy Contractor Interview: Hamilton Solar." Telephone interview. Jan. 2011.

[2] The German Energy Society. *Planning and Installing Photovoltaic Systems: a Guide for Installers, Architects and Engineers*. London [u.a.]: Earthscan, 2009. Print.

[3] Coughlin, Jason, and Karlynn Cory. "Solar Photovoltaic Financing: Residential Sector Deployment." *National Renewable Energy Laboratory*. U.S. Department of Energy, Mar. 2009. Web. Feb. 2011. <http://www.nrel.gov/docs/fy09osti/44853.pdf>

[4] Caldwell, Grace. "PV Energy Contractor Interview: Independent Power Corporation." Telephone interview. Feb. 2011.

[5] Rader, Bryce. "PV Interviews: Homeowner Statement" Telephone interview. Feb. 2011.

APPENDIX

Section A: Financial Analysis of Residential PV System Value

Worksheet in

The above spreadsheet allows users to input their energy usage data and calculates the payback period and return on investment. Fields that are yellow and orange represent cells that the user can change the values in to vary the inputs (energy usage, solar radiation, annual energy price increase, etc.) and see how each can affect the output data. There are three pages in the spreadsheet: the first page offers a breakdown of the sizing guidelines, the second calculates the payback period of the system, and the third visualizes the information into a bar graph showing the net cash flow over the years.

How to use Excel workbook:
Table

Sheet 1 – Sizing guidelines

1. Obtain residences' electrical utility bills for 12-month period.
(Available electronically at http://www.nvenergy.com/)

2. Input monthly electrical usage (in kW-h) into spreadsheet fields marked in yellow.

3. Input annual solar radiation (in kW-h/m^2, http://www.nrel.gov/eis/imby/) and cost per kW-h of electricity (found on utility bill) into spreadsheet fields marked in orange.

4. The spreadsheet will calculate the size of system needed to provide 50, 75, and 90% of usage specified in step 2 (Cells F4-F10), the estimated footprint of the specified system (Cells H4-H10), and the annual expected power output of the system (Cells I4-I10).

5. The capital financial impacts of the PV system before incentives and rebates are marked in light green (Cells G4-G10 and J4-J10). Click to the next sheet on the bottom of workbook screen.

Sheet 2 – Payback and ROI

6. Sheet 2 of the workbook performs cash flow calculations based on systems specified in steps 1-5. The net cost to homeowner after incentives is calculated for both contractor installed and homeowner/contractor installation types and marked in dark green (Cells F4-F10 and F15-F21).

7. If desired, the annual increase in future energy prices can be varied for comparison (Cell B23, marked in orange).

8. The cash flow and return on investment over an assumed 25-year life is shown towards the bottom of this sheet (Rows 30-90). Click to the next sheet on the bottom of the workbook screen.

Sheet 3 – Net Cash Flow Graph

9. The net cash flow is visualized in this graph over the assumed life of the system. The system has paid for itself when the net cash flow (y-axis) is equal to zero.

The next steps after carrying out the directions listed above would be to start looking at the useful links listed below and begin planning the installation of a residential PV system. It is important to consult as many sources as possible to ensure well-informed decisions are made with confidence.

Section B: Useful links for Homeowners

This is a shortlist of helpful resources and articles available to consumers about the application of PV energy.

- NV State Office of Energy – Miscellaneous information on energy policies and practices in Nevada:
  http://energy.state.nv.us/

- NV Energy's Solar Generations Program – Information on NV Energy’s rebate program:
  http://www.nvenergy.com/renewablesenvironment/renewablegenerations/solargen/

- Nevada Tracks Renewable Energy Credits - Register renewable energy system with the Public Utilities Commission of Nevada, allowing homeowners to track credits for renewable energy:
  https://www.nvtrec.com/

- Nevada State Contractors Board - Ensure proper installation of PV system by a licensed and bonded contractor:
  http://www.nvcontractorsboard.com/

- NREL “In My Backyard” PV electricity generation calculator:
  http://www.nrel.gov/eis/imby/

- PV Tilt Angle Calculator:
  http://www.alternate-energy.net/angle_calc05.html

- Kyocera Solar PV Calculator – 3rd Party Solar Power cost/benefit calculator, including payback period information:
  http://www.kyocerasolar.com/buy/pv_calculator.html

- Federal Renewable Energy Tax Credit Form – Form used for Federal Income Tax credit for utilizing renewable energy:
  http://www.irs.gov/pub/irs-pdf/f5695.pdf

- NREL PVWatts Calculator – Outputs PV system performance based on geographical location, system derating value, and energy costs: http://mapserve3.nrel.gov/PVWatts_Viewer/index.html

- NREL PVWatts Interpretation Guidelines – Guidelines on how the results from the PVWatts application may be interpreted correctly: http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/interp.html

- California Energy Commission's Consumer Guide to Buying a Photovoltaic Solar Electric System: http://www.energy.ca.gov/reports/2003-03-11_500-03-014F.PDF

WEATHERSTRIP DOORS

by

Robert H. Turner, PhD, P.E.
James R. Ross
Desert Research Institute, Reno, NV

Exchange of ambient and interior house air (called infiltration or exfiltration) is a major contribution to heating and cooling costs, as well as discomfort. Doors are sources of air exchange with the ambient. Fortunately, cracks are readily detectable and repairs can generally be made inexpensively with minimal skill requirement.

A homeowner can visually check exterior doors, including the door to the garage. Figure 1 shows a slit over a front door that requires weather-stripping. Rubber or felt strips with glue on one side are inexpensively available from hardware stores; the products are made exactly for this purpose. In some cases small wide-head nails may help keep the strips in place, either on the door top or on vertical jambs.

FIGURE 1 The crack above this front door will be filled in with rubber or felt weather stripping applied to the frame, or the door top, or both.

If there is a noticeable crack under the exterior door, of if the homeowner can feel a draft during a wind, then either a rubber threshold can be installed on the floor, or a sweep can be installed on the door itself. The semi-circular rubber threshold is mounted in an aluminum frame, which is cut to the width of the door. It is then screwed to the floor, so the door when closing gently rubs against the raised rubber, forming a good air seal. The threshold is designed so people can walk on it without tripping. The second device is a rubber sweep that screws on to the door and sweeps along the floor when the door is opened. When the door is closed the sweep makes a secure air seal against the ambient.

The above two devices also work for an interior door to a garage or unheated laundry room.   But for an interior door a Styrofoam and cloth sliding draft reducer may be practical, as shown in Figure 2, which might be easier to use than a towel to block under-door drafts.

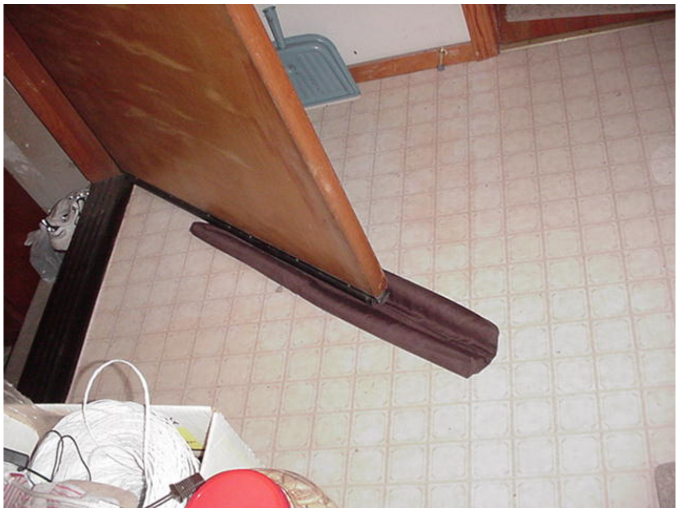


FIGURE 2   The sliding draft reducer is made from two flexible Styrofoam tubes sewed in cloth. It easily slips under the door. When the door moves the unit slides along the floor, and when the door is closed the system provides an effective seal.

INSULATE GARAGE DOORS

by

Robert H. Turner, PhD, P.E.
James R. Ross
Desert Research Institute, Reno, NV

Uninsulated garage doors allow a garage to become very cold in winter, and if the garage is attached to the house it fails to serve as an efficient buffer against ambient cold. Also, cold can be hard on a car battery, and entering a cold car in winter is miserable.

Furthermore, if the door(s) faces east or west the garage can become very hot during summer. Instead of buffering the house from exterior heat, the garage without insulated east or west doors heats the house in summer.

Figure 1 is an infrared photograph of an uninsulated east facing door taken from inside a Reno garage on an August morning (10 am). The door temperature (red area) is 145^{o}F and the air temperature inside the garage is above 90^{o}F (higher than outside) and rising.

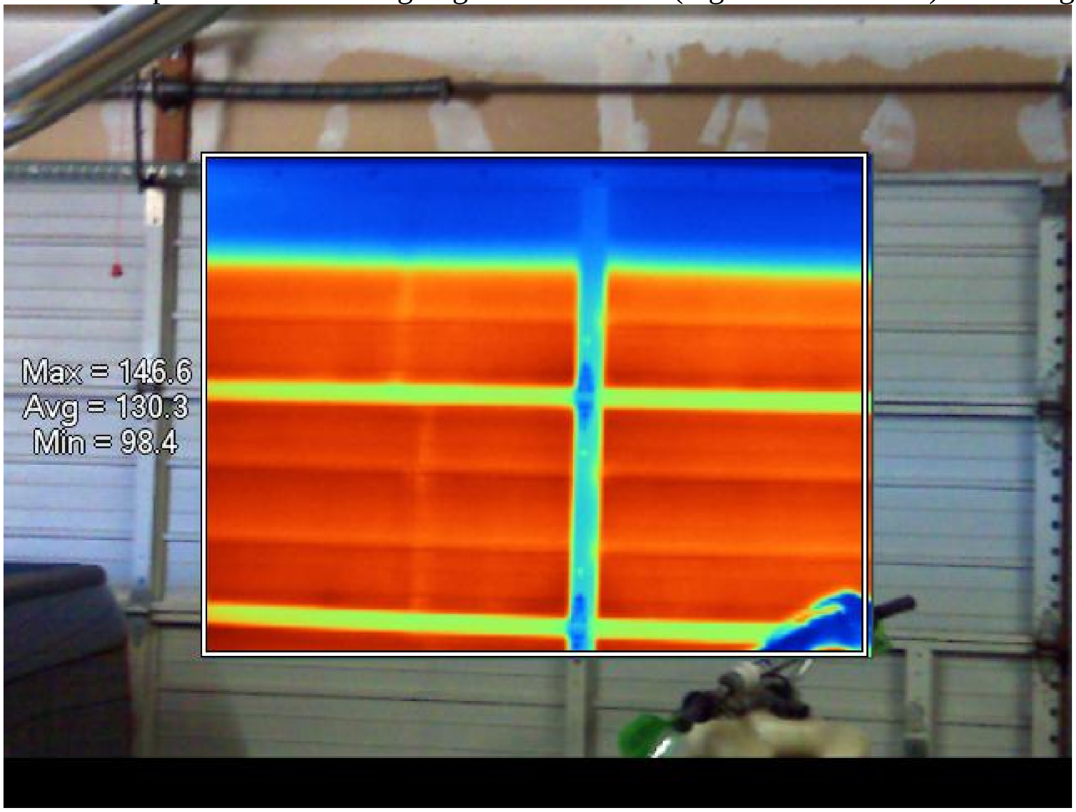


FIGURE 1 This uninsulated east facing garage door heats the garage to 100^{o}F every sunny morning in summer, which in turn heats the attached house. The freezer in the garage also works harder and consumes more electricity as the temperature rises.

The solution for both winter and summer conditions is to insulate the garage door. This is within the skill capabilitiy of most homeowners The first step is to measure the thickness of the garage door ribs, since the rigid insulation slabs will be cut to size and forced between the ribs and outer door. Rigid insulation is available from home improvement hardware stores, and it is important to buy the proper thickness such that the door ribs will hold it with a tight squeeze.

Figure 2 shows a garage door in Reno that was insulated by the owner, who used mostly foil backed insulation   Prior to insulation, every sunny summer afternoon the air temperature inside the garage would reach 105-110^{o}F. After insulation the garage high temperature reaches 85^{o}F.   The insulation cost for the three car garage was about $60 for materials ~ the homeowner required about 3 hours total labor.   An ancillary benefit is the garage door opens more quietly because the insulation absorbs rattle.

FIGURE 2   The foil-backed insulation cuts cleanly with a razor knife, whereas the compressed (white) styrofoam tended to crumble into messy electrostatic crumbs. The insulated garage is much more comfortable both winter and summer, and helps moderate the temperature of the attached living space.

However, for garage door insulation to be effective, the garage roof must also be insulated. If roof insulation is missing then the summer sun shining on the roof will heat the garage regardless of door insulation (just as an attic gets hot in summer), and in winter the heat loss through the roof will bypass the effect of door insulation. At a minimum R-19 (R-30 is better) fiberglass blanket insulation should be applied between the roof joists.

Save Money on Your Lights

by

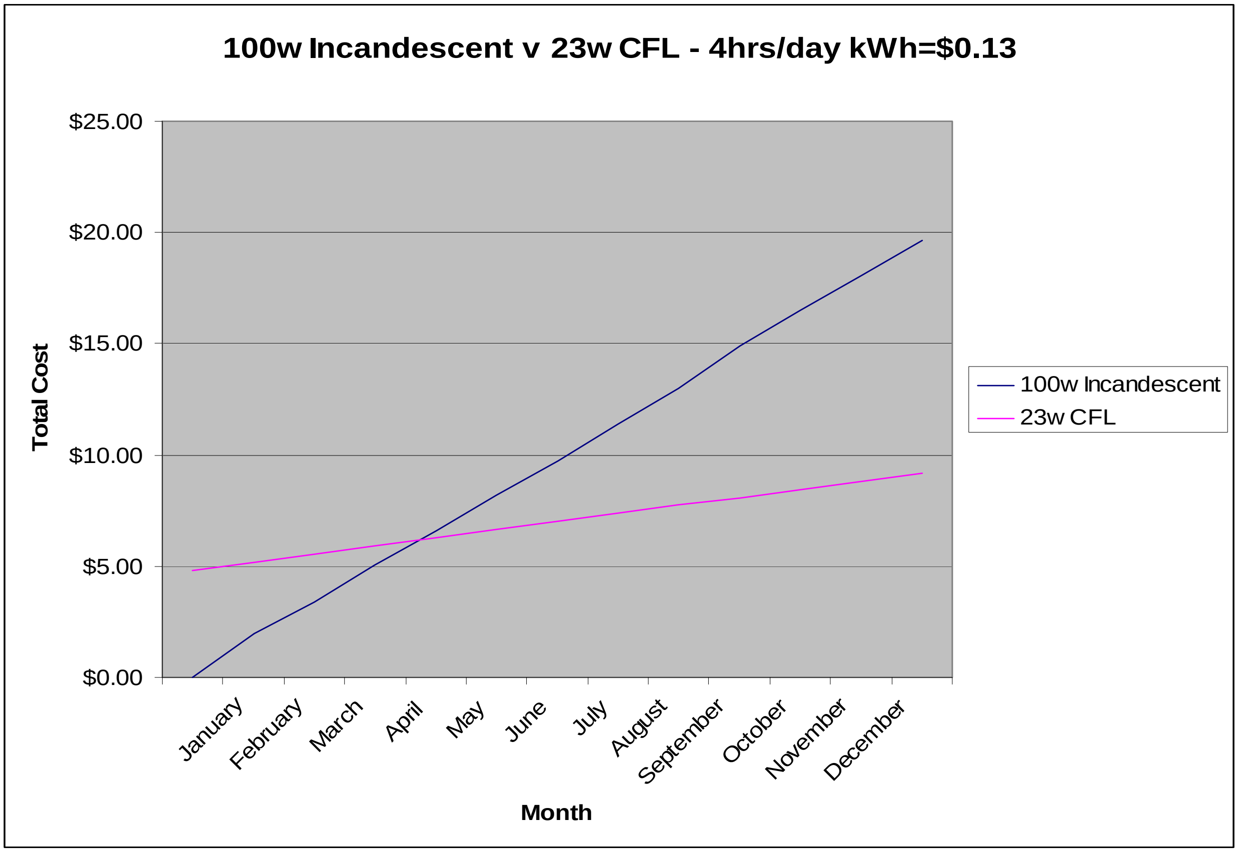
James R. Ross

Robert H. Turner, PhD, P.E.

Desert Research Institute, Reno, NV

There is a simple way for homeowners and others to reduce electric bills. Change out frequently used light bulbs! Compact Fluorescent Light (CFL) bulbs use a fraction of the electric power to generate the same illumination as an incandescent light bulb, so they cost less to operate. And since they consume less power, they also produce less space heating. CFL light bulbs are rated to last 10,000 hours (that's 4 hours every day for 7 years), which is much longer than incandescent bulbs.

Now $5 for a light bulb may sound high, but the electricity saving will quickly pay back the initial expense. For example, consider replacing a 100-watt filament light bulb with a 23-watt CFL, both of which produce similar illumination. The CFL costs around $4.85, and the cost of electricity is around $0.13/kW-hr (in Reno in 2009). If the light is burned 4 hours/day, then the graph below shows that the simple payback period is around 4 months and by the end of the first year the saving is over $10! Over the 7 year life of the CFL the saving is just over $100!



Shade Windows in the Summer

by
James R. Ross
Robert H. Turner, PhD, P.E.
Desert Research Institute, Reno, NV

Figure 1 – Two west facing windows with bamboo blinds rolled up

On a sunny July day in Reno a 5-ft by 4-ft unshaded east or west facing window admits as much solar heat into your house as 64 100-watt light bulbs burning for an hour, or the total output of an 80,000 BTU/hr furnace running for 15 minutes. Drawing the curtains is better than leaving them open because part of the sunlight can be reflected back outside. However, the solar energy not reflected is absorbed by the curtains and converted to heat (just like in a solar collector!) and heats the house.

A much better solution is to shade the window, so the solar radiation does not reach the window. In some cases a large tree or building shades the window. But generally an external shutter or blind is necessary, which requires daily opening and closing outside the house.

Figures 1, 2 and 3 show a bamboo blind on a west window in Reno. In Figure 1 the blinds are rolled up for the night and morning. Figure 2 shows the blind being manually deployed, and Figure 3 shows the blind down, ready for the afternoon. It literally takes only a minute to conduct this twice-a-day chore. From the house interior one can see outside shapes with the blind down. Such a blind costs about $13 from a home improvement hardware store and will pay for itself in reduced energy cost in just a few weeks; if there is no air conditioning it will pay for itself the first sunny day via a cooler house. In Autumn the shades are removed and stored for the winter, and installed in late Spring when necessary.

Figure 4 depicts an even less expensive way to provide exterior window sun block. The window shade is porous shade cloth or ground cloth, available from hardware or gardening stores, at a cost of approximately \$0.10/ft^2. The porous fabric is stapled onto two pieces of 1” by 2” support wood for easy deployment and removal. The wood ends have a hook which hangs on a nail. With a single thickness of porous fabric, most of the sunlight is captured outside the window, but it is still possible to see outside. Figure 5 shows the external shade cloth affixed to a door using magnets.

Figure 2 – Takes only a minute to lower or raise the bamboo curtains

Figure 3 – Bamboo Blind rolled down

Figure 4 – Large Window Shade held up by hooks on nails

Figure 5 – External Shade Cloth affixed to door using magnets

APPENDIX V

REEF Presentations

1. Sunrise Sustainable Resources Group – May 16, 2012
2. DRI Faculty and Staff – September 21, 2012

Sunrise
Sustainable Resources Group

EMPOWERING NEVADANS TO A BRIGHTER ENERGY FUTURE
A Chapter of the American Solar Energy Society

2012 Lecture Series #5 :

Desert Research Institute's (DRI)
Net Zero Building

Discussion and TOUR of the Renewable Energy Experimental Facility (REEF) Building.

Wednesday, May 16th 6:30 - 8:30 pm
Desert Research Institute (DRI) Stout Conference Room A

The REEF consists of 2 structures and incorporates numerous renewable energy technologies and demonstrates computer control of the entire system.

The goals of the REEF are to have equal energy input and output on the grid, or to be completely off the power grid. Come join the discussion/tour lead by several DRI professional staff members to learn how these goals can be accomplished by new and existing technologies. For more information: www.dri.edu

Light refreshments will be served at 6:30 pm and Discussion/Tours begins at 7 pm

Sunrise members FREE, non-members $5 donation requested

DIRECTIONS: To get to DRI, take 395 North to the Parr/Dandini exit. Turn right and follow the signs to DRI. Park in the lower parking lot, and the conference room is upstairs.

Please e-mail president@sunrisenevada.org with any questions.

DRI’s Renewable Energy Experimental Facility (REEF)

Presentation to Sunrise Sustainable Resources Group

May 16, 2012

S. Kent Hoekman, Roger Jacobson, Curt Robins, Peter Ross, and Bob Turner

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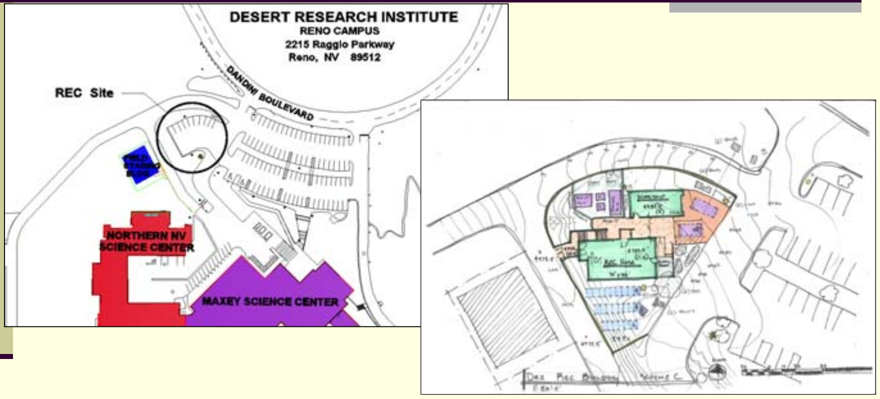
Motivation and Goals for REEF

- Need for REEF was defined in earlier Nevada Southwest Energy Partnership (NSWEP) Program
- Primary Goal: Help grow DRI’s capabilities and expertise in areas of RE research, development, demonstration, and deployment (RDD&D)
- Provide separate facility to support:
  - 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

REEF Location and Layout



REEF consists of two separate buildings:

- 1400 ft^2 House
- 600 ft^2 Workshop

Construction of REEF House

September 2010

January 2011

February 2011

April, 2011

Moving Day (June 30, 2011)

Construction of REEF Workshop

Solar Collector on REEF Workshop

Special Features of the REEF

- Renewable power generation
  - PV, wind, and H_2 genset
  - Off-grid capabilities and controls

More info from Roger

- Solar thermal heating system in REEF Workshop
  - Design and construction
  - Operation and controls

More info from Bob

- Solar thermal HVAC system in REEF House
  - Different collector systems
  - Heating/cooling operations and controls

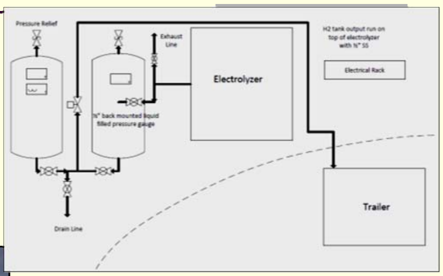
More info from Curt

Renewable Power Generation in the REEF

- Two 1.5 kW Bergey BWC1500 wind turbines
- Two 1.0 kW tracking PV arrays
- Two 1.8 kW fixed PV arrays
- Stuart SunFuel 5 electrolyzer (generate 1m^3 H_2/hr)
- Two 2.5 m^3 H_2 storage tanks
- 3-cyl. Daihatsu gas engine and generator
- Battery bank
- Power interface, inverters, and monitoring/control equipment
- Control logic and software

Renewable Hydrogen System

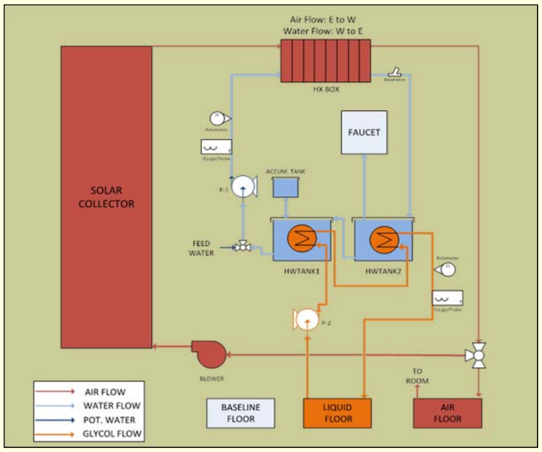
Excess renewable power (from solar PV and wind turbines) is used to produce H_2 by electrolysis.



When additional power is required, stored H_2 is burned in an internal combustion engine to drive an electrical generator.

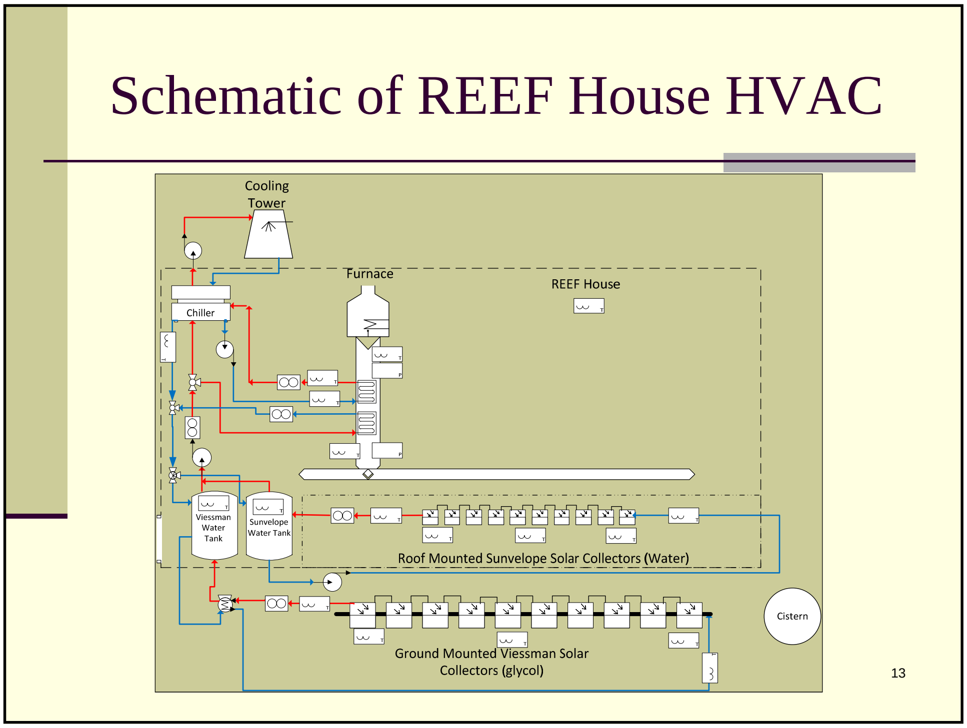
Solar Thermal Heating System in REEF Workshop

- Roof-integrated solar air collector of 578 ft^2
- Blower-driven hot air used to heat floor and/or room space in winter
- Heat exchanger used to heat water for floor heating and domestic water use
- Hot air also used to heat drying oven in Workshop



Solar Thermal HVAC System in REEF House

- Two different types of solar thermal collectors used; each heating a separate 120-gal water tank:
  - 200-ft^2 of Veissmann Vitosol 100-F (standard glycol-based system; ground mounted)
  - 200-ft^2 of Sunvelope collectors (potable water system; roof mounted)
- Stored hot water used for heating and cooling house
- Yazaki WFC-FC5 absorption chiller used to generate cool water
- Heat exchangers within conventional furnace ducting system used to heat/cool house air



Schematic of REEF House HVAC

Current Uses of the REEF

- Home base for USDA Energy Audit Project
- Comparative evaluation of solar thermal collector systems
- On-going integration and optimization of renewable energy components
- On-going monitoring of system performance
- REEF Workshop houses a process development unit (PDU) for Biomass-to-biofuels project
    - Converting wood chips to bio-coal

Future Uses of the REEF

- Home base for DRI Energy Audit Service
- Home base for DRI’s Green Power Program
- Comparative evaluation of various solar components and systems
- Site for seminars, public meetings, and other outreach activities
- On-going monitoring and improvement of system performance
- Additional biomass conversion projects

Desert Research Institute DRI
Nevada System of Higher Education

Visit DRI-REEF at
http://www.dri.edu/ctrec

DRI ENVIRONMENTAL SEMINAR & OPEN HOUSE*
FRIDAY SEPTEMBER 21ST, 12:00 – 1:00 pm

DRI's Renewable Energy Experimental Facility (REEF)

Presented by:

S. Kent Hoekman, Peter Ross, Roger Jacobson, Bob Turner,
and Curt Robbins

What is the REEF?

Why do we have a REEF?

What's going in those funny-looking buildings?

These questions, and more, will be answered

***For all those interested, an Open House of the REEF will follow the presentation**

DRI
Desert Research Institute

DRI’s Renewable Energy Experimental Facility (REEF)

Presentation to DRI Faculty and Staff

September 21, 2012

S. Kent Hoekman, Peter Ross, Roger Jacobson, Bob Turner, and Curt Robbins

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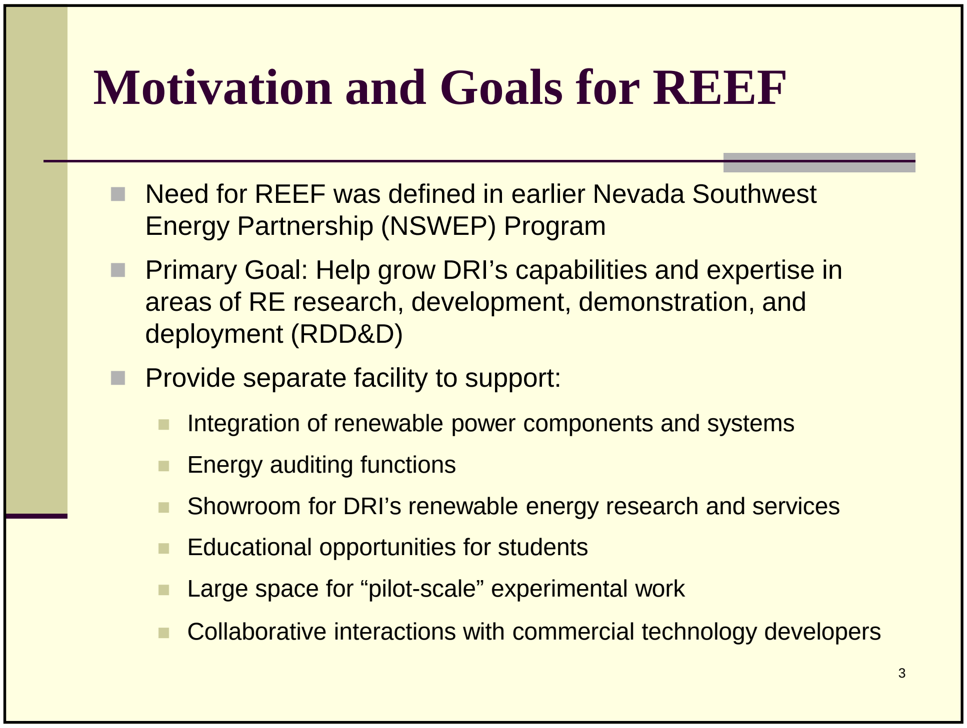
Outline:

- Motivation and Goals
- Funding Sources and History
- Project Tasks:
  - REEF-1
  - REEF-2
- Special Features of the REEF
- Current Uses
- Future Plans



Motivation and Goals for REEF

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- Provide separate facility to support:
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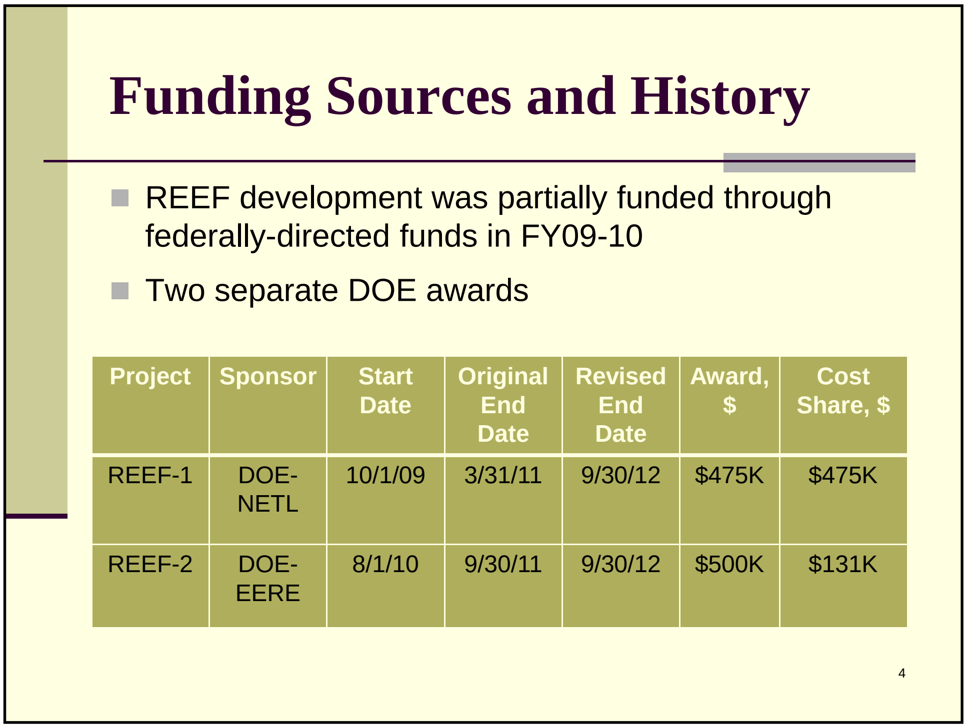
  - Showroom for DRI's renewable energy research and services
  - Educational opportunities for students
  - Large space for "pilot-scale" experimental work
  - Collaborative interactions with commercial technology developers



Funding Sources and History

- REEF development was partially funded through federally-directed funds in FY09-10
- Two separate DOE awards

Project	Sponsor	Start Date	Original End Date	Revised End Date	Award, $	Cost Share, $
REEF-1	DOE-NETL	10/1/09	3/31/11	9/30/12	$475K	$475K
REEF-2	DOE-EERE	8/1/10	9/30/11	9/30/12	$500K	$131K

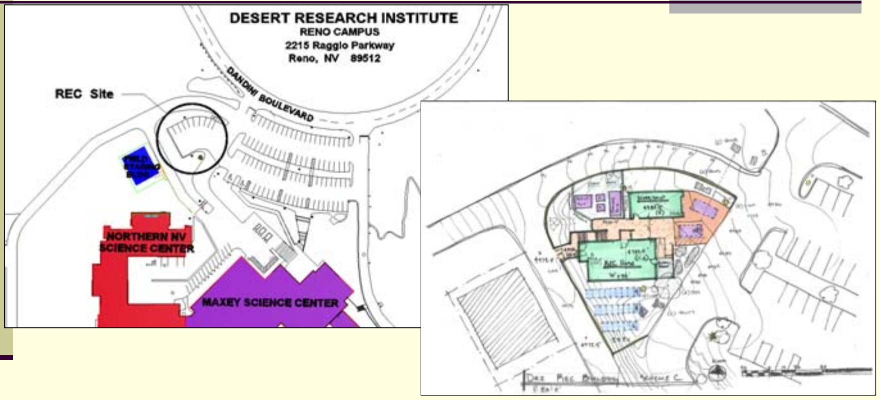
REEF-1 Project Tasks (PI: Ross)

- Task 1: Design REEF structures
  - Permitting
  - Design
  - Bid
- Task 2: Assemble/Install structures
- Task 3: Integration of renewable systems
- Task 4: Evaluation and education/outreach
- Task 5: Management and reporting

REEF-2 Project Tasks (PI: Hoekman)

- Task 1: Optimize off-grid operation
  - Move/install equipment
  - Test system as entire unit
  - Optimize off-grid performance
- Task 2: Develop gas-fueled engine R&D Platform
- Task 3: Biomass pre-treatment R&D
- Task 4: Education and outreach
- Task 5: Project management and reporting

REEF Location and Construction



REEF consists of two separate buildings:

- 1200 ft^2 House
- 600 ft^2 Workshop

Construction of REEF House


September 2010


January 2011


February 2011


April, 2011

Moving Day (June 30, 2011)

Construction of REEF Workshop

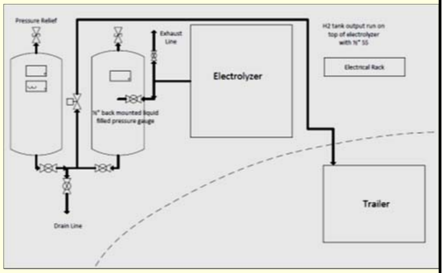
Special Features of the REEF

- Renewable power generation **(Roger)**
  - PV, wind turbines, electrolyzer, and H_2 genset
  - Off-grid capabilities and controls
- Solar thermal system in REEF Workshop **(Bob)**
  - Design and construction
  - Operation and controls
- Solar thermal HVAC system in REEF House **(Curt)**
  - Different collector systems
  - Heating/cooling operations and controls

Renewable Power Generation

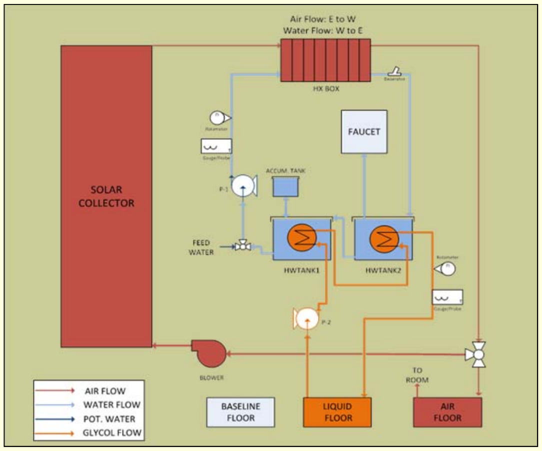
- Two 1.5 kW Bergey BWC1500 wind turbines
- Two 1.0 kW tracking PV arrays
- Two 1.8 kW fixed PV arrays
- Stuart SunFuel 5 electrolyzer (generate 1m^3 H_2/hr)
- Two 2.5 m^3 H_2 storage tanks
- 3-cyl. Daihatsu gas engine and generator
- Battery bank
- Power interface, inverters, and monitoring/control equipment
- Control logic and software

Renewable Hydrogen System



Solar Thermal Heating System in REEF Workshop

- Roof-integrated solar air collector of 578 ft^2
- Blower-driven hot air used to heat floor and/or room space in winter
- Heat exchanger used to heat water for floor heating and domestic water use
- Hot air also used to heat drying oven in Workshop

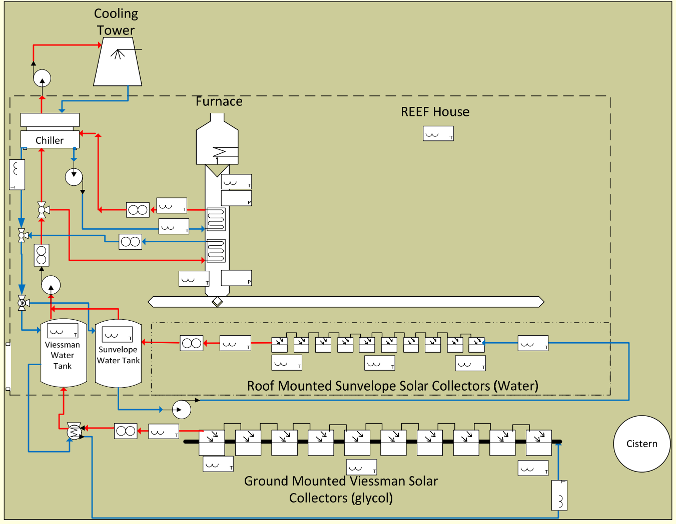


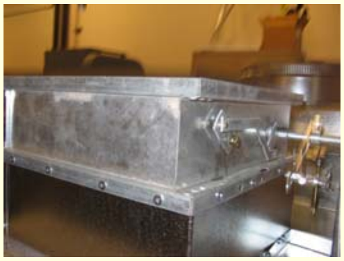
Solar Collector on REEF Workshop

Solar Thermal HVAC System in REEF House

- Two different types of solar thermal collectors used; each heating a separate 80-gal water tank:
  - 200-ft^2 of Veissmann Vitosol 100-F (standard glycol-based system; ground mounted)
  - 200-ft^2 of Sunvelope collectors (potable water system; roof mounted)
- Stored hot water used for heating and cooling house
- Yazaki WFC-FC5 absorption chiller used to generate cool water
- Heat exchangers within conventional furnace ducting system used to heat/cool house air
- Addition of economizer in attic to aid in cooling the house

Schematic of REEF House HVAC





Current Uses of the REEF

- Home base for USDA Energy Audit Project
- Comparative evaluation of solar thermal collector systems
- On-going integration and optimization of renewable energy components
- On-going monitoring of system performance
- REEF Workshop houses process development unit (PDU) for Biomass-to-biofuels project

Biomass R&D in REEF Workshop

Process Development Unit (PDU) for converting raw biomass to bio-coal

Apparatus for sorting wood chips

Future Uses of the REEF

- Home base for DRI Energy Audit Service
- Home base for DRI's Green Power Program
- Comparative evaluation of various solar components and systems
- Site for seminars, public meetings, and other outreach activities
- On-going monitoring and improvement of system performance
- Additional biomass conversion projects

Q&A and Tour/Open House

- Additional information is available in the REEF buildings
- Roger, Bob, and Curt will be there to answer more questions