TOHONO O’ODHAM SOLAR BATHROOM MODULE

Vivian Crespo Martínez, John Duffy, Ryan Burns, Ian Crabtree, Greg Pawlowski, Shawn Furey
University of Massachusetts Lowell
One University Ave
Lowell, MA 01854
Crespo@zapotecenergy.com, John_Duffy@uml.edu

George Miguel, John Bair
Tohono O’odham Community College, Sells, AZ
Lyvier Conss
Community College National Center for Community Engagement, Phoenix, AZ
lyvier.conss@mcmail.maricopa.edu

ABSTRACT

The Tohono O’Odham is an Indian reservation in the southwestern region of Arizona that borders Mexico. Its 2.8 million acres form an area that is comparable to the size of Connecticut, and houses a population of about 11,000 members. Many of the people in the reservation do not have access to electricity or running water; nevertheless, the students at the tribal college at the reservation (TOCC) have been working to provide better living conditions: they have constructed (with their carpentry, electrician and plumbing skills) modular bathrooms that contain sinks, showers and toilets. In the past, these bathroom modules have been created for older people that have access to electricity, potable water services and sewer services. Many of the people in the reservation live in remote places and do not receive these services, (and paying the utility company to extend the services would be too expensive). Therefore, a new version of the bathroom module was designed in collaboration with TOCC instructors that would address the energy and resource needs of the local people. The design includes green building features, a thermosiphon passive solar hot water system, a photovoltaic electrical system, an efficient evaporative cooler, and a composting toilet. In addition, the design focused on modularity and the possibility that the components would be built by the students at TOCC as part of a microenterprise.

1. INTRODUCTION

Energy: it has been the quest of civilizations throughout history. It has been linked with civilizations’ ability to progress and therefore conscientious engineers follow the calling to work with all peoples to obtain it, particularly those that do not have water, food, or comfortable shelter so that they can progress from their current situation and become self-reliant.

This paper describes the efforts of students from the University of Massachusetts Lowell partnered with the students from the Tohono O’odham tribal college in developing a heat loss/gain analysis, in designing and constructing an evaporative cooler, a solar hot water system, and a photovoltaic system.

2. NOMENCLATURE

Q: the needed air flow to remove H amount of heat, in cfm.
H: the indoor sensible heat to be removed (or the cooling load), in Btu per hour.
t1-t2: the increase in temperature of the air from the entrance to room to when discharged outdoors. This is assumed to be 8°F because this is a compromise between comfort and power consumption (and costs).
spht: specific heat of air, 0.24BTU/lb-ºF
m: mass flow rate,
Uc: collector's overall loss coefficient
F'= collector's efficiency factor
Ac= area of collector
Cp= specific heat of water
To= temperature at collector's outlet
Ti = temperature at collector's inlet
Ta= ambient temperature
S = radiation absorbed by collector
Ti+1 = temperature in tank at hour i+1,
Ti = tank temperature at hour i
V= Volume of water in tank
Cp= specific heat of water
ρ= density of water
Q = useful energy
Fhx = heat exchanger factor
Ic = solar irradiation on collector surface
Voll= water load
Tsr= surface reservoir water source temperature
Ut = loss coefficient of tank
At = Surface area of tank

3. PASSIVE SOLAR

Passive solar is a method of designing a building (its walls, windows, ceilings, etc.) in a way that increases the house's ability to collect and retain solar energy in the form of heat in the winter and keep out the heat in the summer. For the passive solar analysis, the heat loss of the building was determined, where "heat loss" is a function of various building parameters: the material with which the walls, roof and floor are made, the size and location of windows, the amount of insulation in the walls, basement and roof, and infiltration. The heat loss was then used in combination with the analysis of degree-days to calculate the auxiliary heat or cooling that would be needed throughout one year. This process of determining auxiliary heat and cooling was followed for different iterations of cases, each case representing a change in the construction of the building in order to determine which passive change would be most effective. For the bathroom, these cases were:

Case 1: The walls are made of plywood, R-13 insulation, wood framing and drywall with a 2ft x 2ft window assumed to face south; the roof having the same construction, but including a shingle on top of the bathroom; the floor has same construction of walls, but including linoleum. It measures 10 ft x 10 ft x 7 ft.
Case 2: Better Insulation on Walls
Case 3: Better Insulation on Roof
Case 4: Better Insulation on Roof and Walls
Case 5: Change Window from South to North
Case 6: Have Window on North and one in South
Case 7: Have window on North and Polyiso Insulation on Walls and Roof
Case 8: Change the assumed 100W light bulb to 20W
Case 9: Low-e Window on South
Case 10: Shaded Southern Window

TABLE 1: ENERGY SAVINGS VS. PASSIVE MEASURE - BATHROOM

Case	Aux.Heating (BTU/yr)	Aux.Cooling (BTU/yr)	Breakeven
1	1894400	3209800	-
2	1369800	2864900	29
3	1712300	3090400	27
4	1187800	2744600	28
5	2627300	2562800	Immediately
6	2022100	3293500	Never
7	1889700	2066500	23
8	1976800	3128000	0
9	1959400	3025800	4
10	1957100	2658300	1

Most situations decreased the auxiliary heat and cooling needed, but some actually increased it. For example, while the insulation measures all decreased the heating and cooling needed (with the case where both walls and roof were insulated being the best scenario), putting up a lower-power light bulb actually increased the heating needed, but decreased the cooling; changing the window from the south to the north also increased the heating needed but decreased the cooling because now not as much light would be coming in through the window.

But, in terms of money, Table 1 shows that most measures do not pay off very quickly (20 to 30 years to break even). This is due to the small size of the bathroom and that because it is used for such a short amount of time each day that it takes a longer time for the savings to accumulate. The only measures that are worthwhile are: having the window on the north side instead of the south, or, if one definitely wanted the window to be facing south, then having that window be a low-e window, and even better, have that window be shaded by an overhang that would be located 4 inches from the top of the window and protruding 9.2 inches from the wall. Also, having a 20W CFL light bulb instead of the 100W bulb is one of the best measures to implement since it takes less than a year for the investment to pay back for itself. This passive solar analysis was also performed for the hypothetical house of the people that would use the bathroom module. For the house, 10 cases were included:

Case 1: An assumed typical house measures 20 ft x 15 ft x 7 ft, and has a 2 ft x 2 ft window on the east and one to the west. It was assumed to be made of 12in.-thick adobe walls, and that the roof is made of a wood frame, topped with plywood and a metal shingle (based on site visits and personal communication).
Case 2: Polyisocyanurate Insulation on Walls
Case 3: Polyisocyanurate Insulation on Roof
Case 4: Polyisocyanurate Insulation on Roof and Walls
Case 5: 30ft2 of South Windows
Case 6: Polyisocyanurate Insulation on Roof and Walls and 30ft2 Window
Case 7: Low-e Windows on Sides
Case 8: 12ft2 Low-e Windows on South
Case 9: Cellulose Insulation on Walls
Case 10: Cellulose Insulation on Roof

TABLE 2: ENERGY SAVINGS VS. PASSIVE MEASURE - HOUSE

Case	Aux.Heating (BTU/yr)	Aux.Cooling (BTU/yr)	Breakeven
1	14033200	18499100	-
2	9025400	15013000	4
3	6307500	13103600	1
4	1554000	9617700	2
5	9566800	24189700	Never
6	0	18267700	5

7	13893400	18402000	6
8	12230700	20061600	Never
9	9009600	15001900	3
10	6295600	13095200	1

As the table shows, any of the proposed changes will decrease the auxiliary heating, while the auxiliary cooling was increased when southern windows were added. The third case, where the polyiso insulation was put on the roof alone, cut more of the heating and cooling than when the polyiso insulation on the walls alone was installed, but, when both walls and roof were insulated, the heating and cooling needs of the base case were cut by more than half. Installing more southern window area (even with the low-e window that has a lower loss factor) shows to be impractical, because the auxiliary heat and cooling continue to be high compared to the base case. It should be noted here that, for this climate, all the measures discussed here that include southern windows is not meant to be a design recommendation, but should serve as proof to the readers that it is not a good decision to have southern windows without having the proper overhang. It can also be noted that the two measures involving south-facing windows show to have created debt, while the measures that involve insulating the roof alone (either with the cellulose or the polyiso) are the most cost effective; they are also the measures that yield the quickest breakeven point (one year). It should also be noted that the 2 inches of polyisocyanurate thermally performs about the same as the thicker cellulose material, but because the cellulose is cheaper, it ended being more cost effective.

4. EVAPORATIVE COOLER

Evaporative coolers work by using a wetted material through which dry hot air flows through. Because the air has a high temperature, it evaporates the water in the wetted material, which in turn cools the flowing air. These devices are advantageous because they require less electricity than a conventional air conditioner; they were chosen to be part of this project because cooling is one of the main electrical loads in these hot climates and because these coolers are already a staple of buildings in Arizona due to the fact that they work efficiently only in dry hot areas. Nevertheless, most available systems are AC-powered and have a high running cost. Therefore, a cheaper and easy-to-assemble cooler was designed that would cool a regular sized adobe home. A prototype unit has already been built at the TOCC and has already performed to its desired capacity.

First, the size of the fan was determined. For this, the cooling load for the house was calculated using the heat loss calculated in the passive solar section and using ASHRAE's procedure for calculating cooling load called the "Cooling Load Temperature Differential". The cooling load was then used to calculate the capacity of the fan that would be needed for the house being studied.

$$Q=\frac{H}{(t_1-t_2)\cdot spht\cdot 60}$$

The fan capacity resulted in 10 different values (one for each passive solar case for the house). An average 1600 cfm was used for the initial steps in the design.

The next component selected was the recirculating pump. This component will lie in the sump section of the cooler where all the water that has dripped through the pads (i.e., did not evaporate) will fall into, and its purpose will be to pump all this water back to the top of the pads so that the water can be reused. To know the minimum required flow capacity of the pump, a thermodynamic analysis was done to determine the amount of water that is going to be evaporated during the process. The resulting flow is a function of the desired room temperature and the psychrometric parameters of the outside air.

The thermodynamic calculations were performed various times since the required cfm of the cooler was different for every passive solar case studied. This affects the workings of the evaporative cooler because, for example, a lower cooling load created by better insulation will then require less water from the cooler. The worst case yielded the need of, at least, a 6.4 gph pump.

TABLE 3: EVAPORATIVE COOLER REQUIREMENTS ACCORDING TO PASSIVE MEASUREMENTS

Case	Air Flow Rate (cfm)	Water Flow Rate (gph)	Relative Humidity
1	2088	6.136	72.8%
2	1749	6.139	72.8%
3	1177	3.458	72.8%
4	828	2.433	72.8%
5	2169	6.373	72.8%
6	940	2.763	72.8%
7	2084	6.123	72.8%
8	2055	6.040	72.8%
9	1749	5.139	72.8%
10	1177	3.458	72.8%

Table 3 shows that higher air flow rates are accompanied by higher water flow rates, meaning the cooler the house needs to be, the more water and the more air flow is needed. The table also shows results that are very similar as those obtained in the passive section: Southern-facing windows are not a good idea without an overhang for shading, insulation always decreases the cooling load, with the insulation on the roof alone being better than putting insulation on the walls alone.

The chosen fan was tested, both with and without an enclosure. As expected, the achieved air flows at different power levels of the fan with the enclosure were lower than in the test where no enclosure was set; this is because the enclosure and pads present an obstacle that creates a pressure drop that decreases the achieved air flow. The achieved flow at 12V was 1012cfm. From Table 3, it can be concluded that the as built cooler prototype is sufficient to cool the house modified with the more cost effective changes.

Natural ventilation was selected to address the cooling needs of the bathroom module. Three different cases of natural ventilation were studied: a case where only one 2 ft by 2 ft opening will be assumed, a case where a windward and a leeward opening will be assumed (both 4 ft2), and a case where the leeward and the windward windows would measure 3 ft by 2 ft. The ventilation needs of the bathroom were only fulfilled by the third case, in which the bigger windows are separated by 4 feet; no forced ventilation would be needed. For this reason it is suggested that the bathroom is placed with the slope of the roof facing south, one window should be placed facing east on the bottom of the wall (for the windward window) and the other window should be placed on the west wall 4 ft higher. Proper shading should be provided over this window to prevent the afternoon sun from overheating the bathroom module.

5. SOLAR THERMAL

The solar hot water heating project was also designed so that it could be constructed from readily available products, like wood and copper. Therefore, a thermosiphon system was chosen: no circulation pump would be needed (which would be an added expense), it would be easier to construct, and also the weather at the site allows for water to be the primary fluid (no antifreeze and accompanying heat exchanger would be needed). The estimated payback time for the solar hot water system is 3.5 years.

First, the size of the collectors needed to be determined so that the array would provide enough hot water for a 9-person household, using an estimated 110 gallons per day and have an outlet temperature of 110°F. A program called RETScreen (http://www.retscreen.net/ang/home.php) was used to calculate an approximate estimate of how much collector area would be needed. It was found that having 6m2 of collector would be needed to achieve an 85% solar fraction, where the solar fraction is the amount of energy provided by the solar system as a fraction of the amount of energy needed to cover the load. Therefore the system was broken down into being composed of 2 panels, each one being 3m2 in area (or a 4ft by 8ft collector). This setup of 2 55-gallon drums with 2 3m2 collectors could then be scaled down to system of 1 tank and 1 3m2 panel for a 4-person family.

The next factor that had to be determined was the optimal tilt at which the collectors should be placed. The monthly f-Chart method equations (Duffie and Beckman, 1991)were used to calculate the solar fraction of the system, taking into account the effects of location, tilt, storage, collector size, and other parameters. Twelve worksheets with the same procedure were used (one for each month and each one calculating the results for four different tilt angles). The solar fraction profile for the entire year was obtained for the different tilt angles (Fig. 1).

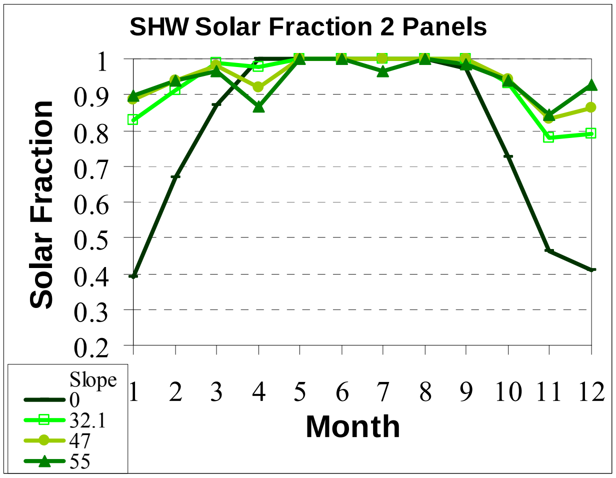


Fig. 1: Solar Hot Water Solar Fraction

The selection of a tilt angle of 47° was made (latitude plus 15°) because it provided the most even solar fraction distribution over the course of the year, while 32.1° and 55° tilt angles provided more energy during the warmer and colder months respectively. Also, the total useful energy from the solar hot water system was estimated: 11.3MWh, for a tilt angle of 47°.

Another type of analysis used on this system was an hour-by-hour modeling of the tank's temperature throughout one year. In order to do this, the data from NREL was used (2008): the hourly data for radiation and ambient temperature was used to determine the incident radiation on the collector according to the orientation and tilt of the collectors. This was then used to determine the temperature of the water in the tank and also the useful energy that can be harnessed by the collectors. This useful energy can be determined for a thermosiphon system by calculating the mass flow rate of the water through the collectors. The equation was taken from Duffie and Beckman (1991), which states that this equation is used for thermosiphon systems, and that according to various studies, the difference between the outlet and inlet temperatures of thermosiphon collectors is usually 10°C, regardless of the conditions [p.501]:

$$\dot{m}=\frac{U_c F' A_c}{C_p \ln\left[1-U_c\frac{(T_o-T_i)}{S-U_c(T_i-T_a)}\right]}$$

where the difference between the outlet and inlet temperature is set to 10°C. Then, the useful energy absorbed by the water in the collector(s) can be determined by the following:

$$Q=\dot{m}C_p\Delta T$$

where the ΔT is the outlet/inlet temperature difference of 10°C. Finally, the temperature in the thermosiphon tank can be determined as a function of the absorbed energy (Q), minus the energy lost due to the load, and the losses from the tank due to convection:

$$T_{i+1}=T_i+\frac{1}{V\cdot Cp\cdot\rho}\cdot\left[[Q]\cdot Fhx\cdot\left(I_c\cdot Ac\right)-\frac{\rho\cdot Cp\cdot Voll\cdot(T_i-Tsr)}{24}-Ut\cdot At\cdot(T_i-T_a)\right]$$

In our case it was then modeled that there would be no temperature increase if there was no irradiation (i.e., at night); during these hours, only the losses through the tank would affect the temperature: the losses through the collector would be considered negligible because no flow would occur during the night (since no hot fluid could rise and promote circulation), and, also considering that no losses due to the load would occur at night. Also, the mass flow rate was modeled so that it could not be negative at night.

As the Figure 2 shows, having the collectors tilted at 0° yields a water temperature profile that is hot during the summer, and colder during the winter, when the goal is to have a constant source of hot water throughout the year. Having a tilt of 32° or 47° both yield temperatures that are higher during the winter months, and both provide for a more constant source of hot water, nevertheless, the 47° tilt produces slightly hotter temperatures during the winter months. For this reason, the 47° tilt was selected as the best, which was the same conclusion that was made from the f-Chart Solar Fraction calculations. It can also be seen that the water temperature in the tank will rise to a maximum of about 205°F, which is very close to the boiling point of 212°F, and therefore it is recommended that an air vent be installed in the panels at the bottom and top which could be opened in the summer to allow air flow to keep the collector temperatures from being too high.

The stagnation temperature is the temperature that the collector will experience if let to sit under the sun without the water carrying away the absorbed heat, which means conditions of high radiation, high ambient temperature and no water circulation. This temperature is important to know because the collector should be designed to be made of materials that can withstand this temperature. Because there is no flow, then the total absorbed radiation should equal the energy loss through the collector (due to convection):

$$I_c\tau\alpha=U_c(T_{p,m}-T_a)$$

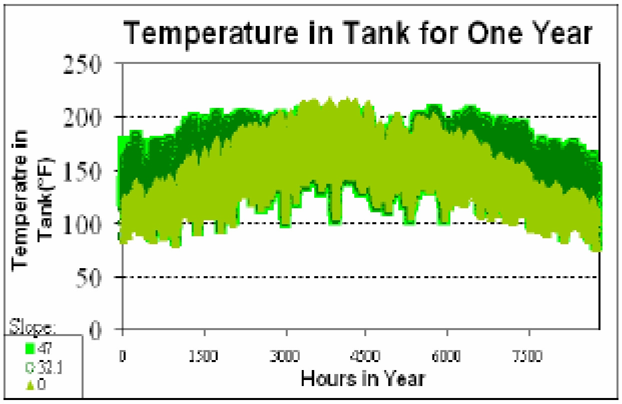


Fig. 2: Temperature in tank for one year

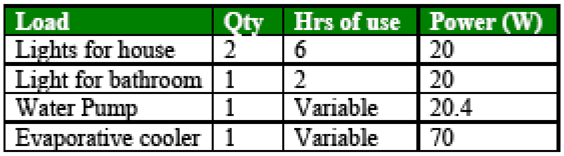
5. PV

The PV system was then designed to power some lights for the bathroom module and for an adjacent house, and would also power a DC evaporative cooler (which ended up being the main load of the system because of how long it would be used during the summer). The payback time for this system was 13 years.

The 150 Watt panels were first tested to assess if the panels were still performing at the rated capacity. The short circuit current and the open circuit voltage were measured in order to determine the panel's I-V curve. Nevertheless, with a thermometer and a pyranometer, the voltage and current measurements were corrected to filter out the effects of temperature and irradiation and therefore make these corrected measurements more comparable with the standard test condition parameters. It was concluded that the panels were performing at the rated capacity.

For the PV sizing analysis, the first parameter that was determined was the irradiation. The monthly average daily radiation (Duffie and Beckman, 1991) was used in conjunction with the latitude of the site, the reflectance of the ground, the tilt angle and the calculation of the declination angle, and various other parameters in order to calculate the total radiation absorbed on the tilted panel. Then, the load on the system was tabulated:

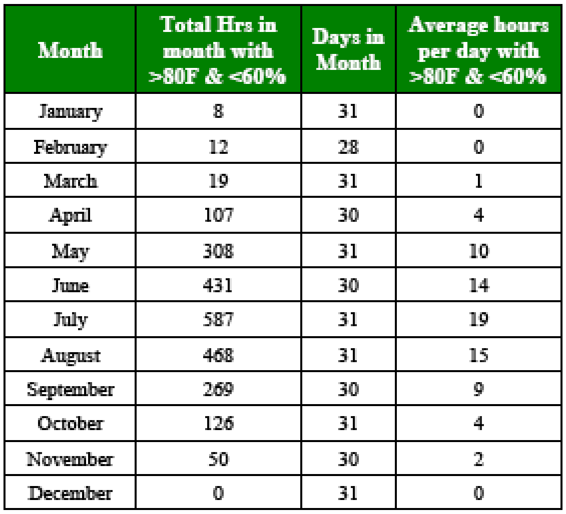
TABLE 4: LOADS OF PV SYSTEM



Load	Qty	Hrs of use	Power (W)
Lights for house	2	6	20
Light for bathroom	1	2	20
Water Pump	1	Variable	20.4
Evaporative cooler	1	Variable	70

The time of use for the evaporative cooler is variable, because as can be imagined, the evaporative cooler is going to be used more during the summer than during the colder winter. To determine an approximation of how much the evaporative cooler is going to be used during the year, the temperature data obtained from NREL was used once again. First, the data was screened to determine how many hours per month was the ambient temperature (dry-bulb) more than 80F. This point of 80F was chosen as the cutoff point because as seen in a psychrometric chart, this is approximately where the ASHRAE comfort zone begins, meaning that below 80F the air begins being comfortable, so the evaporative cooler would not be considered necessary at those points. Then, because humidity also affects the use of the cooler, the data was filtered again to screen out those hours when the air was also 60% humid, or more, because at 60% the air can still be humidified by 20% more before being utterly humid. After the data was screened for these two conditions, the total hours per month that the cooler would be used was then counted. This total amount of hours per month was then divided by the number of days in each month to calculate the average hours per day that the cooler would be turned on. Table 5 summarizes the results.

TABLE 5: USE OF EVAPORATIVE COOLER



Month	Total Hrs in month with >80F & <60%	Days in Month	Average hours per day with >80F & <60%
January	8	31	0
February	12	28	0
March	19	31	1
April	107	30	4
May	308	31	10
June	431	30	14
July	587	31	19
August	468	31	15
September	269	30	9
October	126	31	4
November	50	30	2
December	0	31	0

The load was determined to be 2760 Wh per day for the month of July. Then, the final parameter for the PV sizing analysis was studied: what power will the panels provide? To determine this, first it should be noted that since all the loads are DC it was better to not have converted them to an AC system due to the losses and costs associated with an inverter and also because these systems are to be connected in very remote places where there is no electrical grid to connect to. Nevertheless, batteries were needed in order to provide for storage, and for this, a charge controller is necessary: it is a device that regulates how much or how little current is added or drawn from batteries. They provide a safety device that prevents overcharging, prevents deep discharge of the batteries and also guards against overvoltage, all of which deteriorate the battery, its performance, and its lifespan (Komp, 1995).

There are many types of charge controllers, but for the system being analyzed here, 24 volt nominal panels were going to be used to power 12 volt loads. Therefore, a maximum power point tracker was used that would be able to take this 24 volt input and be able to admit the use of 12 volt batteries to power 12 volt loads.

Now, with a MPPT controller, it can be inferred that the panels would always be performing at the current and voltage at which they produce the maximum power (which is the power at which the panels are rated, which in our case is the 150 Watts). With this, it was calculated that in the worst case scenario, the irradiation on the tilted panels would be 7.3 kiloWatt hours per square meters per day (or 7.3 hours at 1000 Watts per square meter per day), that the power at which the panels would perform would be at 150 Watts, and that the worst-case scenario for the load would be 2760 Watt hours, then the number of panels needed would be 3 panels:

$$No.\ of\ Modules = \frac{Load}{Power\ per\ module \cdot Irradiation}$$

Where the irradiation is in kWh/m2, or equivalent sun hours at 1000 W/m2 and the load takes into account the battery efficiency. The next component of the system that was analyzed was the batteries. They provide the storage for the energy that is absorbed through the panels, so that when there is no sun (as when the sky is cloudy for several days or as in the nighttime) you could still use the different electrical loads (the lights, the evaporative cooler, etc.).

To know the capacity of the batteries that we will need for our system (and how many batteries will be needed) the following equation is used:

$$Storage = \frac{Load}{System\ Voltage} \cdot \frac{No.\ Storage\ Days}{Depth\ of\ Discharge}$$

For a 1.4-day storage and 80% DoD and system voltage of 12 Volts, the Storage needed was 402 Amp-hours. The load is the same as that used when calculating the number of panels needed. Multiplying by the number of days that one would want the system to work without the sun, and then dividing that by the depth of discharge (which is usually 80%, but can be found as a parameter on the datasheet of the battery), one can calculate the storage needed.

Various batteries were considered, but, after taking into account their price, the quantity that would be needed and the amount of traveling that would be required in order to purchase them, the 6 Volt – 225 Amp-hour Trojan T-105-Plus was selected. With this battery, the PV system would then need only 4 batteries: two strings of two batteries. Finally, the other components needed for the system were selected, like the DC-lightning arrestor, and the fuses.

To support the results obtained for the PV sizing performed with the equations above as programmed in MathCad, the RETScreen PV sizing worksheet was used. Although RETScreen uses what is called the “utilizability” method for its calculations, it arrived at the same result that about 3 PV modules would be needed, which would provide for 94% of the load for the year. It should be noted though that the panel parameters used in this worksheet were not exactly from our panel (since the database in RETScreen does not include it), the most similar panel was chosen. Also, the results showed that only 314Ah are recommended for storage of 1.4 days (instead of the 466.3Ah calculated through the MathCad calculations).

Another aspect of this analysis was the need for optimization of the number of panels that would make the system cost effective. Usually such an optimal point can be calculated for systems that are stand-alone using methods like the PVXTOOL, the graphic method and the LOLP method. These methods usually conclude that covering 100% of the load with solar panels is not usually as cost effective as only covering, for example, 70% of the load with solar. The PVXTOOL, is a PV sizing program (Duffy and Frye, 1989) based on random autocorrelated daily irradiation and random loads (Bloom and Duffy, 1988) that strives for minimum cost and that uses the concept of loss of load probability (LOLP), i.e., the expected fraction of the demand that will probably not be satisfied on average during the life of the PV/storage system. The method predicts the size of PV array, the capacity of storage, and optimal tilt of PV array to meet the target LOLP for the lowest cost. This process was followed twelve times: once for every month. It was found that the worst case scenario was the month of July where 416W of PV and 592Ah of batteries are needed. This agrees with the results obtained above, where it was concluded that 3 panels would be needed (453W) combined with four 225Ah 6V batteries (or 450Ah). But, after concluding that July was the critical month, a more in-depth analysis was made for the month of July. First, how do the results change if the cost of the batteries is changed radically, or what if the LOLP is changed from 5% to 1%? The results were nearly the same and did not notably change.

Finally, the load standard deviation portion of the PVXTOOL program was used. Here it is acknowledged that the load is not constant every day (one day people use 3 lights and the next day they might just use one). This variability is certainly true in this case, since the hours used to calculate the load created by the evaporative cooler each month was an averaged value for each month. As explained before, it was estimated that the evaporative cooler would be turned on when the temperature outside would go higher than 80F with a relative humidity lower than 60%. This yielded an average use of 19 hours per day in the month of July, with a standard deviation of 333Wh, which is 17%. Using this standard deviation in the PVXTOOL then gave a new estimate of how many PV watts would be needed for the system: 516W, which is 3.4 panels; nevertheless, the charge controller selected can only work with 3 panels. Therefore, for the prototype design only 3 panels in parallel along with the 4 batteries were chosen.

6. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to develop bathroom modules for remote hot, dry areas that are energy efficient and solar-powered to provide the bathroom and adjoining house with hot water and cooling as well as sanitary facilities. A prototype solar bathroom module is in the process of being built and tested at TOCC (Fig. 3). The conclusions reached after the analysis and design of the different projects are:

- The best single passive solar measure that could be taken to make the house energy efficient and save money is to insulate the roof with either polyisocyanurate or cellulose insulation. Wall insulation and air leak sealing are also recommended. Also, no south-facing windows should be used (without an overhang) because although it does provide for some heat during the winter, the cooling necessary during the summer is far greater.
- For the bathroom, it is best to use compact fluorescent light bulbs that consume only 20 Watts instead of the incandescent 100 Watt bulbs. Another cost-effective measure is to install an overhang on a south-facing window which would provide shade in the summer and light during the winter. Changing the currently used insulation to polyisocyanurate insulation is not a cost-effective measure for the bathroom though, because the room is so small that the benefits take a long time to accumulate.
- For a roof-insulated house that is 2100 ft3, an evaporative cooler that could cool incoming hot air to a comfortable temperature would need a fan with a capacity of about

1200cfm at a pressure drop of 0.1 inches H_2O (about 20 Pa). The recirculating pump for the evaporative cooler should be able to pump at least 5 to 6 gph.

- Ventilation: have one 3 feet by 2 feet closable vent or window on east and one same-sized vent or window on the west (properly shaded) offset by 4 feet (with the lower one on the east) to fulfill all ventilation needs.
- The solar hot water heating system will provide for about 98% of the annual hot water load for a 9-person home. It will need a water filter to remove sediments from the hard water, in addition to the need of a safety mixing valve and two 55 gallon drums that will have to be located at least 1 foot above the top of the solar collectors.
- The two 4 feet by 8 feet collectors would need to be tilted to 47° to obtain the best performance, and all the materials used for making the collectors should be able to withstand the stagnation temperature of the system, estimated at 358°F.
- To be able to power the evaporative cooler and three lights, the PV system needs to consist of 3 150 Watt PV panels (connected in parallel), 4 225Ah batteries (connected as 2 strings of 2 batteries) and a maximum power point tracker (MPPT). The sizing of this system accounts for a 5% LOLP (loss-of-load probability).
- The MPPT is needed for this system because the donated panels have a nominal voltage of 24 Volts, whereas the loads are going to work at 12 Volts; the MPPT allows the user to get the maximum power from the panels while being able to use the 12 Volt loads.

Future research and development should include:

- Use a proportional controller for the evaporative cooler that, using a thermostat and a humidistat, would vary the water and power consumption of the cooler according to the temperature changes.
- Design and test SDHW collector air ventilation measures to avoid boiling water in the summer.
- Design an indirect evaporative cooler to test the difference in cooling capabilities between it and the direct evaporative cooler.

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Fig. 3. CAD Drawing of Design (Burns et al., 2008) and Prototype Construction at TOCC, Sells, AZ.