Solar Water Heater Project

"Design for Sustainable Communities"
Professor Ashok Gadgil

Final Report

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1. ABSTRACT

Solar water heaters (SWH) are becoming increasingly attractive in sustainable development. Efforts are continuously made to reduce their costs to make them more affordable. UC Berkeley's CalSolAgua (CSA) student team has designed a low cost SWH that can be manufactured and sold in Guatemala for US$150. As an extension of CSA's work, this project focused on a comprehensive feasibility analysis of extending the use of the same type of heater to the Pinoleville Pomo Nation (PPN), a local Native American Community located in Ukiah, CA. Our feasibility analysis for PPN consisted mainly of five sections: 1) conducting a user needs assessment, 2) prototyping and preliminary testing, 3) developing an analytical thermal model, 4) recording the hot water consumption of potential users, and 5) comparing the financial and energy costs and benefits.

Our user needs assessment revealed the showering habits and hot water needs of several households in the PPN. It further showed that most homes own a functional electric water heater, which could (and should) be used in conjunction with the SWH. We finished the construction of a CSA prototype. Preliminary testing in South Berkeley revealed two potentials: 1) potential for operating under similar conditions at PPN, and 2) potential for characterizing the SWH performance with the acquired equipment. We developed a thermal model that can estimate the performance of the SWH and can also be used to visualize water temperature behavior in response to design changes, thus aiding design optimization. For PPN, the model predicted yearly energy savings of about 930 kWh. A hot water consumption profile of a typical Pomo Nation family indicated that the SWH could not satisfy all hot water needs of a single household. Our financial analysis revealed that if the SWH is used only for showering (thus wasting most of its heat as most showers take place in the morning after the water cooled down over night) the payback period of 25 years for a simulated household of 2 adults and 2 children is too long to provide an economic incentive for acquiring a SWH. However, if the SWH is used for all daily hot water needs, the payback period is only 7 years. From the hot water consumption profile and financial assessment, we recommend that the SWH be used in conjunction with the existing electrical water heater for all hot water needs in order to

maximize its energy savings. Finally, further SWH design should consider freezing temperatures prevalent at the Pomo Nation during the winter months.

2. BACKGROUND

Two years ago a group of students from Ashok Gadgil's *Design for Sustainable Communities'* class –later to be known as the CalSolAgua Team (CSA), started to develop a solar water heating system that could be afforded by low income households in developing countries. With the support of the NGO Appropriate Infrastructure Development Group (AIDG) in Guatemala, the team managed to design and build up a solar water heater prototype (SWH) that could be manufactured with a retail cost of only $150. Currently, there are several prototypes installed in households in Guatemala's second largest city Xela. The CalSolAgua team continues to work in Guatemala on the design and implementation of additional SWH prototypes.

Figure 1: Previous CSA prototype at test site in Xela, Guatemala. Source: CSA

Building upon CalSolAgua's success in Guatemala, our group took on the challenge to expand the testing grounds for CalSolAgua's SWH prototype to the developed world, and work in more accessible territory, the US. To expand the SWH adoption in developing countries we looked for some opportunities in countries such as Panama and Colombia. However, we soon realized that communication with Central and South America during the course of the class would be very difficult and time consuming. We therefore decided to focus our attention on the Pinoleville Pomo Nation, a local Native American community located in Ukiah, California, who already had established contacts with the CSA team. The Pomo Nation was looking at the possibility of bringing solar water heater technology to their community and entered into an (informal) agreement with CSA to have three SWH installed at the Pomo Nation by the end of September 2009. As a result of this new project, the CSA team asked us as current students of the Design for Sustainable Communities class (spring 2009) to help them explore whether their SWH technology was feasible for the Pomo Nation.

Problem Statement

Our goal is to provide CSA with relevant information about the Pomo Nation (user needs, potential installation locations, and water use profile), create a thermal model to predict the prototype's performance, and recommend modifications to the SWH prototype in order to assist CSA in designing a SWH suitable for the Pomo Nation.

Pomo Nation Community in Ukiah, California

The Pinoleville Pomo Nation is a Native American tribe located in Ukiah, the largest city of Mendocino County, California. In 1996, it was ranked as the number 1 best small town to live in California and the sixth best place to live in the United States [1]. It has a Mediterranean climate with an average high temperature of 73.5°F (23.1°C) and an average low temperature of 46.1°F (7.8°C). Due to the frequent low humidity, summer temperatures normally drop into the fifties at night [1].

The land reserve of the Pinoleville Pomo Nation consists of ~106 acres on two sites. Approximately 100 acres are located on the outskirts of Ukiah city limits (see Figure 2) and the other six acres are located in Lakeport, CA. The site in Ukiah is typically referred to as "Pinoleville" and the site in Lakeport is typically referred to as "Lakeport". Both are considered to be a part of the Pinoleville Pomo Nation.

Figure 2: Ukiah, California [1]

The Pinoleville tribe is now governed by an elected council of seven members, and has its own constitutional tribal laws. The community we worked with consists of 20 large families, three of which will potentially serve as testing locations for the CalSolAgua prototypes. Currently only Pinoleville area residents are being considered for SWH, as decided by the Pomo Nation tribal council.

3. PROJECT GOALS WITH BRIEF JUSTIFICATIONS

Minimal Goals

- **Conduct a user needs assessment of SWH candidates at Pomo Nation** in order to understand the needs of the community and aid future CSA design.
- **Finish the CSA prototype** and test it in Berkeley before CSA installs it at the Pomo Nation to ensure that it works properly.
- **Create a basic thermal model of the SWH** to guide its optimization and design tradeoffs.
- **Obtain pyranometer data** in order to understand solar flux limitations and to aid in developing a more accurate thermal model.
- **Test the CSA prototype** to obtain updated performance data. This will be used in conjunction with the pyranometer data to validate the thermal model.
- **Complete financial analysis of energy savings on use of SWH** in order to assess its financial savings potential.

Optimal Goals

- **Conduct user needs assessment of the Pomo Nation community** to ensure that the SWH design can be applicable to the entire community, not just to SWH candidates.
- **Compare CSA prototype performance with thermal model predictions** to gauge its suitability for the Pomo Nation and aid modification suggestions and optimization.
- **Create a hot water consumption profile** to adequately address the hot water needs of the Pomo Nation and aid further design decisions of the CSA team.

4. RESEARCH AND FINDINGS

User Needs Assessment

We first met with two members of the CSA team, Adam Langston and Ernesto Rodriguez to discuss their methodology used for the surveys and interviews conducted in Guatemala and to learn from their experiences. This guided our survey and interview design and allowed for comparison between the data of the two different locations. We then developed and administered a user need survey to six residents at the Pomo Nation. We collected basic information about the family structure (number and relationship of household members), access to hot water, and methods of heating water, etc. Finally, we visited the Pomo Nation to interview seven people – the potential candidates for the SWH as well as additional members of the community. During the interviews, we followed up on the survey information as well as asked more detailed questions about daily routines and living conditions. In addition to the interviews, we inspected three homes and one building as potential installation sites. During the housing assessment, we took note of their current water heater, piping, roof suitability (can it hold the weight of a SWH, is the roof angled or flat), and sun exposure to the house.

Figure 3: Our team interviewing a Pomo Nation Resident

Figure 4: Electric water heater in the PPN

Figure 5: A home in the Pomo Nation

Figure 6: Potential installation site (not a very good one!)

Findings

The living conditions in the Pomo Nation are similar to those of any small town in northern California, with most modern amenities. A typical household consists of five to eight people (Numbers of residents per household are not fixed, as family members or guests from other Pomo Nation communities may visit for extended periods of time). The adults typically require hot water in the morning as it is the only time of the day that they feel clean and most residents like to shower before work and use it as a spiritual cleansing to start their day. In many households, the parents shower in the morning and the children at night. The community has pressurized water and is hooked up to municipal water lines. Most residents have a functioning electric water heater and they expect the SWH to function accordingly. The electric water heater could be used as a storage tank for the SWH or used in conjunction with it. The Pomo Nation experiences freezing temperatures overnight during the winter months (10-13% of the year). The residents of the Pomo Nation mainly want a SWH to reduce the cost of their electricity bill and to be more sustainable, meaning to live from nature and be self-sufficient (eventually they would like to be off the grid). The Pomo people have very strong spiritual and cultural beliefs, and feel very connected to their natural habitat.

CalSolAgua Prototype

Our user needs assessment suggests that the CSA SWH may satisfy the needs of the Head Start Day Care Center. Head Start is required to provide enough warm water for 30 children and 10 staff members to wash their hands during the day. There is currently no hot water supply for the bathrooms in the Head Start building. David Edmunds, the Pomo Nation’s environmental director, commented that the Head Start building is in more urgent need of a SWH than residential homes.

Figure 7: Head Start building

Figure 8: Indoor dining and play area

Figure 9: Children's washroom

Figure 10: Outdoor playground

Figure 11: Bladder Construction

One of our goals was to finish a CalSolAgua SWH by the end of term so the CSA can install it at the Head Start building over the summer. We welded fasteners onto the frame to secure the glass, and painted the main frame and absorber black. We produced a new bladder, and also attached plumbing and sensors. We added a float valve, similar to the ones in toilet tanks, (mounted within a 5-gallon bucket) in order to reduce the pressure of the water entering the bladder. As hot water is being used, and the amount of water in the bladder decreases, the float valve will allow cold water to enter the SWH from the bottom. When the bladder is full, the float valve shuts off the inlet of cold water.

We had planned on testing the prototype on the 3rd floor balcony of Jessica's co-op in South Berkeley. The insolation and ambient temperature in Ukiah is thought to be similar to Berkeley, so we figured the SWH will perform similarly in both locations.

We needed to minimize modifications to the CSA design so that data collected using our prototype could be used to verify a thermal model designed to predict the performance of the CSA solar water heater. Without a detailed construction plan for the SHW, we encountered a few setbacks as we were only relying on a CSA member for information about finishing and testing the prototype. Unfortunately, we were not instructed by CSA that there should be reinforcement bars on the front and back of the box. We were also misinformed that the angle of the SWH should be 45 degrees from the horizon. As a result of these errors, when we started filling the SWH with water, the bulging bladder pressed the sheet metal upwards and cracked the glass. We drained the SWH and repaired the PVC fitting that had pulled out of the bladder by caulking around the seam (see Figure 13). We also cut some spare pieces of wood to use as reinforcements on the frame and to protect the glass from the bulging bladder. We calculated that the SWH should be at an angle of 22.9 degrees (Berkeley's latitude 37.9 degrees minus 15 degrees) from the horizon, as opposed to 45 degrees as stated by CSA.

Figure 12: Attaching float valve

Figure 13: Caulk between bladder and fitting

Figure 14: Sensors in inlet and outlet

Figure 15: SWH front view

Figure 16: SWH angled view

Testing

After the prototyping was finished, we intended to measure its performance. Two main measurements were of particular interest: 1) Water temperature variation throughout the day, and 2) Solar insolation. The former is of interest as a higher maximum temperature reached implies that the SWH becomes more and more financially appealing. The solar insolation is needed for the calculation of the water heater efficiency.

Water Temperature Measurement

Because temperature variation within the SWH is not uniform, we decided to measure water temperature at least in three strategic locations within the water heater. Figure 17 displays how the temperature measurements within the heater are taken at the inlet, center and the outlet of the heater. This helps us visualize the temperature stratification within the heater. Furthermore, heat losses vary with ambient air temperature, which we consequentially included as a fourth measurement. Temperature measurements were taken with Onset temperature sensors and logged into HOBO data loggers as shown in Figure 18.

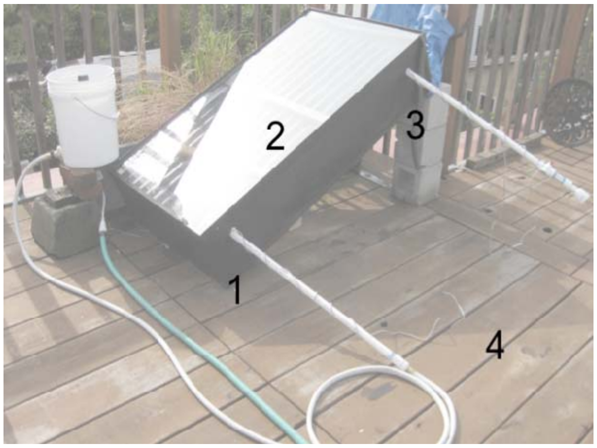


Figure 17: Temperature sensor locations

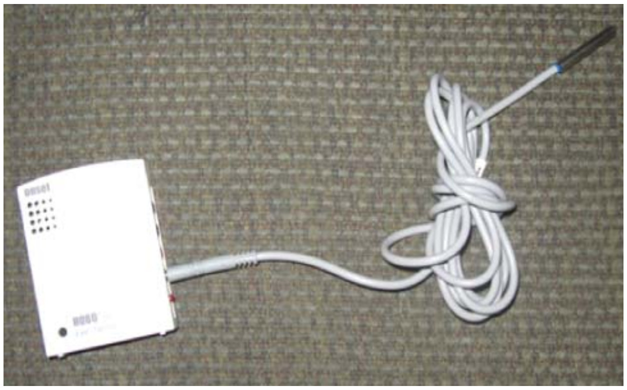


Figure 18: Onset temperature sensor connected to HOBO data logger

Solar Insolation Measurement

To measure solar insolation, a Li-cor pyranometer type Li-200 was used as shown in Figure 19. In order to be able to read and record the small current that is outputted by the pyranometer in response to solar insolation, the signal has to be amplified. As shown in Figures 20 and 21, a Universal Transconductance Amplifier (UTA), manufactured by EME Systems from Berkeley, CA, was used in conjunction with the same type of HOBO data loggers used for the temperature recordings.

Figure 19: Li-Cor pyranometer

Figure 20: EME Systems Universal Transconductance Amplifier

Figure 21: Li-Cor pyranometer connected to amplifier and data logger

The advantage of using equipment compatible with HOBO data loggers is that the loggers can be left at the test site without having to be connected to a computer. They operate on battery power and they are preprogrammed via HOBOware on a computer to record data at a desired sampling rate which then determines the total sampling time, as the data storage is limited. As soon as the loggers finish recording, the data can then be downloaded and analyzed with HOBOware. We used a pyranometer to measure the insolation and install temperature sensors in the SWH to measure the change in water temperature with respect to time. We then compared the experimental data to the analytical predictions of the thermal model.

Sample of Testing Results

We successfully set up the testing equipment for taking temperature and solar insolation measurements to be able to visualize the performance of the solar water heater.

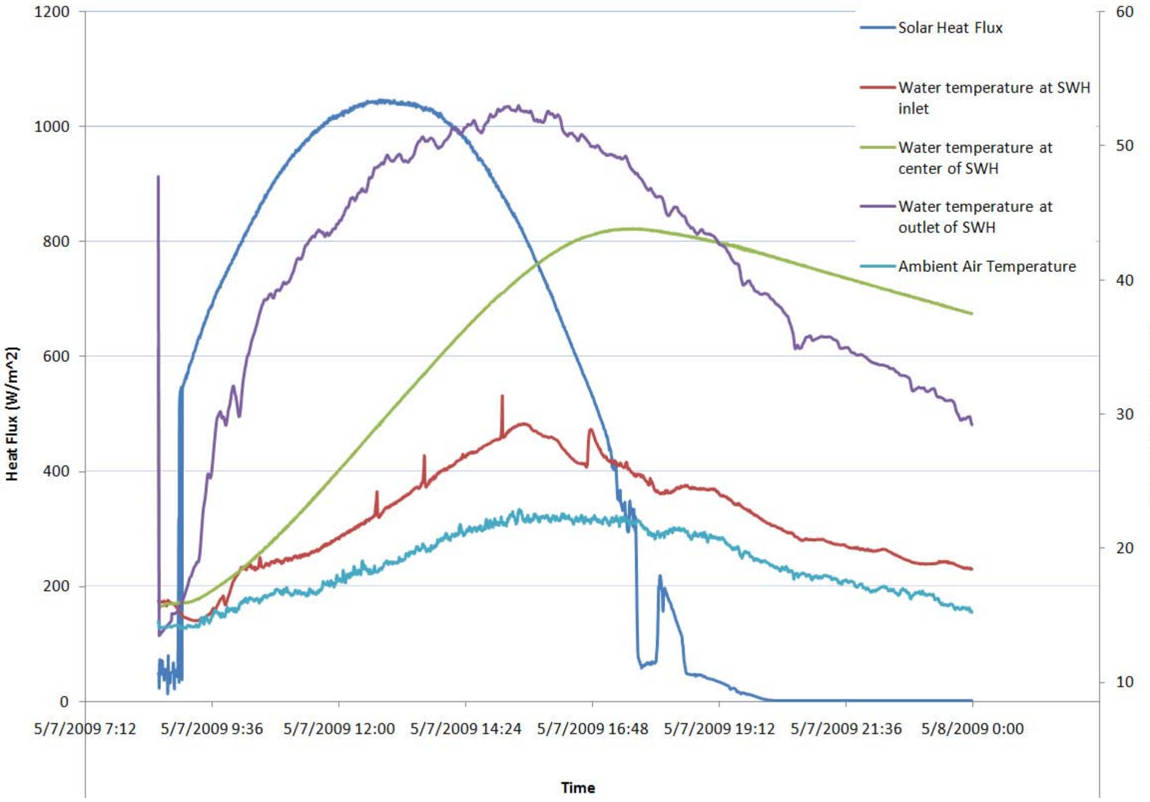


Figure 22: Measured solar insolation and Measured Water Temperature

Figure 22 exemplifies the type of data that can be recorded when looking at the behavior of the solar water heater. The temperature measurements correspond to the locations suggested above (figure 17), while the secondary y-axis on the figure corresponds to the solar insolation.

Aside from simply looking at the water temperature in the design of the water heater, it is key to be able to quantify performance in a way that can be compared to other water heaters. One way to quantify the performance of the water heater is to be able to calculate its efficiency. The efficiency of any type of energy conversion is usually defined as the desired output divided by the invested input. In our case, the desired output is hot water, while the invested input is solar energy. A suggested method to calculate the water heater off of measured data is the following:

$$efficiency = \frac{m \cdot C \cdot (T_{i+1} - T_i)}{A \cdot Solar\ Energy}$$

where:

m=mass of water

C=specific heat of water

T_{i+1}=Average water temperature at a time t_{i+1}

T_i= Average water temperature at a time ti

A= Area of solar incidence

Solar Energy= total solar energy delivered between time ti and time t*i+1*

$$Solar\ Energy = \int_{t_i}^{t_{i+1}} (Solar\ Power)\, dt$$

Solar Power= Solar heat flux measured by the pyranometer in W/m2.

Since the solar power varies as a function of time, the integral for solar energy can easily be calculated using the data from the pyranometer and integrating with a numerical method such as trapezoidal integration. This type of analysis will give the solar water heater efficiency as a function of temperature/time.

Unfortunately, the data recorded was not adequate for performing this calculation for multiple reasons: 1) The time step on the pyranometer logger was different than that of the thermocouple logger, 2) we were not able to measure the exact amount of water that went into the water heater for testing purposes, 3) a minor undetected leak caused a changing water volume/mass that could not be quantified in the remaining time.

Thermal Analysis

An initial thermal analysis was performed to determine the performance of the solar water heater and aid in decisions regarding design modifications.

Nomenclature

A = collector area, m^2

C_p = specific heat capacity, J kg^{-1} K^{-1}

E = equation of time, minutes

h_a = convective heat transfer coefficient to the ambient, W m^{-2} K^{-1}

h_{agap} = convective heat transfer coefficient in the air gap between absorber and tank, W m^{-2} K^{-1}

h_r = radiation heat transfer coefficient, W m^{-2} K^{-1}

$I_{sol,net}$ = net solar radiation, W m^{-2}

l = location latitude, °N

k_{abs} = thermal conductivity of the absorber, W m^{-2} K^{-1}

L_{Loc} = location longitude, °W

L_{st} = standard meridian for local time zone, °W

m = mass of the water, kg

$\dot{m}$ = mass flow rate of the water, kg s^{-1}

n = day of the year, #

t = time, s

R = thermal resistance, K W^{-1}

T = temperature of the water, K

T_a = ambient temperature, K

T_{ave} = withdraw temperature, K

T_c = supply water temperature, K

U = overall heat loss coefficient, W m^{-2} K^{-1}

w_{abs} = width of the absorber, m

α = hour angle, radians

$(\alpha\tau)$ = absorptance-transmittance product, dimensionless

χ = solar zenith angle, radians

δ = declination, radians

ε = emittance of the glazing, dimensionless

σ = Stefan-Boltzmann constant, W m^{-2} K^{-4}

ϑ = angle of inclination of the SWH from the horizontal, degrees

ξ = solar azimuth angle, radians

ζ = surface azimuth angle, degrees

Assumptions

Assumptions used in deriving the governing equation include:

1. Temperature stratification of the water within the tank is neglected as a first approximation.
2. Diffuse radiation is neglected.
3. Adiabatic side and bottom surfaces of the SWH.
4. Constant ambient temperature.
5. The (cold) supply water temperature is 20°C.

Governing Equation

The thermal analysis assumes a lumped capacitance model for fluid in the tank (bladder). An energy balance on the system yields

$$mC_p\frac{dT}{dt} = I_{sol,net}A - UA(T - T_a) + \dot{m}C_p(T_c - T)$$

where the energy stored in the water is equal to the net solar irradiation (insolation), minus thermal losses through the SWH, minus the flow of water out of the SWH which is replenished at the same rate by cooler water supplied to the SWH. The net insolation is determined by

$$I_{sol,net} = (\alpha\tau)I_{tot}$$

The governing equation was converted to finite difference form and numerically implemented in Matlab to obtain the transient temperature profile of water in the tank.

Insolation

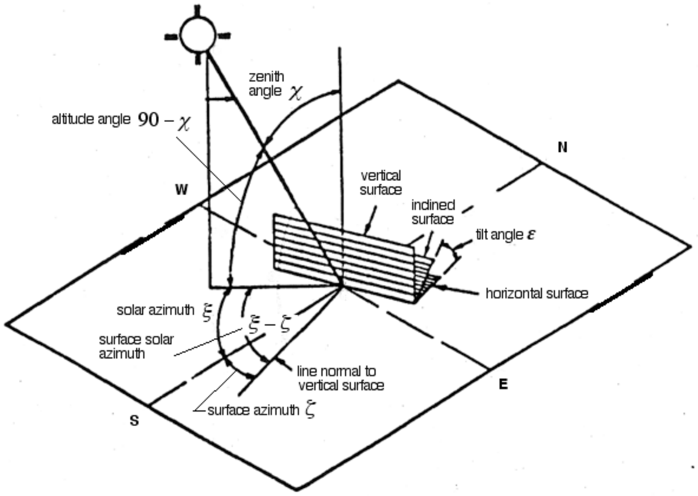


Figure 23: Solar position and geometry [3]

The direct incident solar energy flux I_D was calculated as a function of latitude l, day of the year n, time of day t, hour angle α, declination δ, solar zenith angle χ, solar azimuth angle ξ, surface azimuth angle ζ, and angle of inclination of the SWH from the horizontal ϑ. Figure 23 shows this geometry.

The hour angle α, declination δ, solar zenith angle χ, and solar azimuth angle ξ are determined by the following equations:

$$\alpha = \frac{(t-12)}{24}\frac{360\pi}{180}$$

$$\delta = \mathrm{asin}(-\sin(23.45\frac{\pi}{180})\cos(\frac{(n+10)}{365.25}\frac{360\pi}{180}))$$

$$\cos(\chi) = \sin(l\frac{\pi}{180})\sin\delta + \cos(l\frac{\pi}{180})\cos\delta\cos\alpha$$

$$\tan\xi = \frac{\sin\alpha}{\sin(l\frac{\pi}{180})\cos\alpha - \cos(l\frac{\pi}{180})\tan\delta}$$

where the solar azimuth angle is $2\pi + \arctan(\tan\xi)$ if the sign of α is positive and the sign of $\tan\xi$ is negative, $\pi + \arctan(\tan\xi)$ if the signs of α and $\tan\xi$ are the same, and $\arctan(\tan\xi)$ if the sign of α is negative and the sign of tanξ is positive. The direct normal radiation incident upon the SWH surface is calculated using

$$I_{DN} = 1310\ \exp(\frac{-0.18}{\sin(\frac{\pi}{2} - \chi)})$$

and the direct (beam) insolation is determined by

$$I_D = I_{DN}[\cos\chi\cos\theta + \sin\theta\sin\chi\cos(\xi - \zeta)]$$

Since the analysis only accounts for beam radiation, and doesn't include diffuse radiation, I_{tot} = I_D. Figure 24 shows the total insolation used in the model for Ukiah, CA (39°N) on a "typical" day near the spring equinox (April 28th).

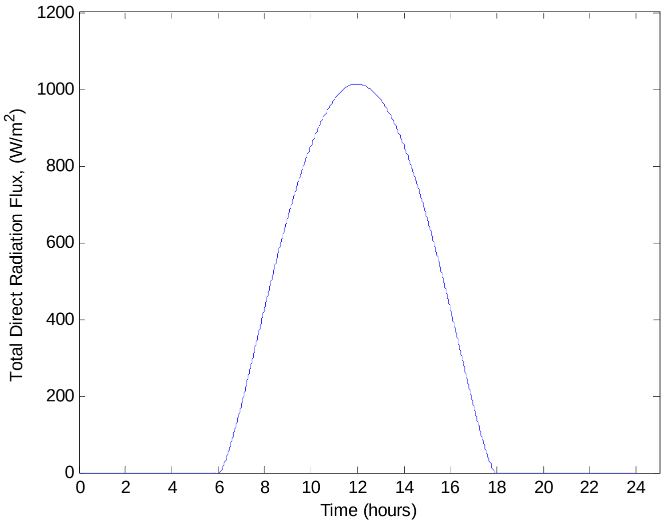


Figure 24: Direct Insolation throughout the Day

Thermal Losses

Thermal losses are accounted for from the top glazing (single-paned glass cover) of the SWH. A resistance analogy for these losses yields

$$UA = \frac{1}{R_{top}} + \frac{1}{R_{bot}} + 4\frac{1}{R_{side}}$$

The model accounts for the thermal losses through the top only, and assumes adiabatic side and bottom surfaces of the SWH so that the equation reduces to

$$UA = \frac{1}{R_{top}}$$

where the resistance through the top surface is

$$R_{top} = \frac{1}{h_a A + h_r A} + \frac{1}{h_{ag\,ap} A} + \frac{w_{abs}}{k_{abs} A}$$

and the radiation heat transfer coefficient h_r, is given by

$$h_r = \epsilon\sigma(T_a^4 - T_{ave}^4)/(T_a - T_{ave})$$

Thermal Model Results

A plot of the transient temperature profile is shown in Figure 25 for Ukiah, CA (Latitude 39°N, Longitude 123°W) and compared with experimental data obtained from CalSolAgua for April 28th, 2007. The experimental data (dotted lines) are from data loggers placed in three locations along the water tank: bottom, center, and top.

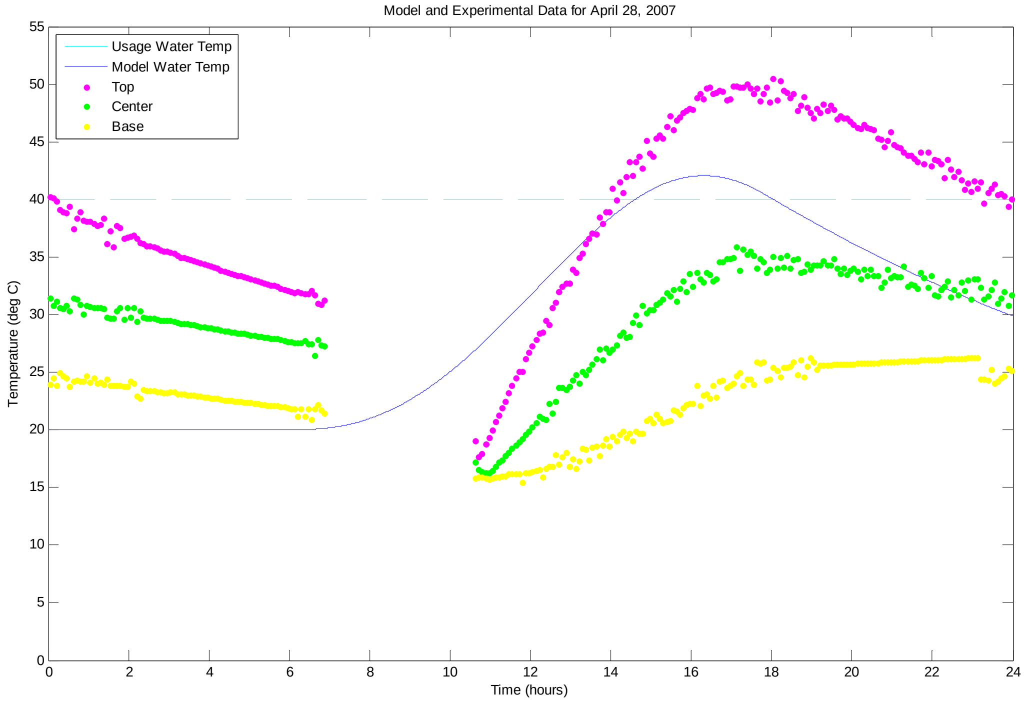


Figure 25: Predicted and Actual Water Temperature throughout the Day

Since the thermal model assumes all of the water within the tank to be at one uniform temperature, the actual water temperature being withdrawn from the top of the tank will be greater, due to natural circulation and the effect of buoyancy.

The potential energy savings that could be achieved by using the SWH is determined using

$$Q_{day} = mC_p(T_{max} - T_c)$$

where daily kilowatt-hour energy savings are calculated from

$$kWh_{day} = \frac{1}{1000}\frac{1}{3600}mC_p(T_{max} - T_c)$$

From the conditions modeled, with 100 Liters of water and a maximum water temperature of 42 deg at about 4 pm, the daily energy savings are 2.5 kWh. A rough estimate ideally predicts the yearly (365 days) energy savings to be about 930 kWh. The initial model compares relatively well with experimental data, and could be refined further to better predict thermal performance.

The initial thermal model was created to predict water temperature and energy savings, and aid design modifications of the SWH. This analysis provides the ability to adjust different parameters (materials, etc.) to achieve desired results and could be used to efficiently obtain a trade-off between performance and cost. Further prototyping and testing of the SWH is needed to refine the thermal analysis and determine the performance of the SWH. The thermal model may be used to assist in the design of a SWH to meet the needs of the PPN.

Hot water consumption profile

In order to understand the hot water needs of the Pomo Nation residents, we compiled a hot water consumption profile for two selected residential houses in the community. First, we measured the average water flow rate during a hot shower with a flow rate measuring bag (as available from EBMUD). In order to monitor showering times and durations, we attached thermocouple sensors to the metal pipe leading into the shower head of two residential houses, and recorded changes in temperature for four consecutive days with Hobo data loggers. We then assessed the amount of hot water used by the residents at a given time by simply multiplying the duration of hot water flow with the average flow rate of the shower. (We realize that this is a slight overestimation of the daily hot water use for showering, as hot water is usually mixed with cold water, which is neglected in our analysis. However, we believe that our estimate still gives us a useful approximation of daily hot water use).

Figure 26 shows a hot water consumption profile for showering of a typical Pomo Nation house with five residents (two adults and three children).

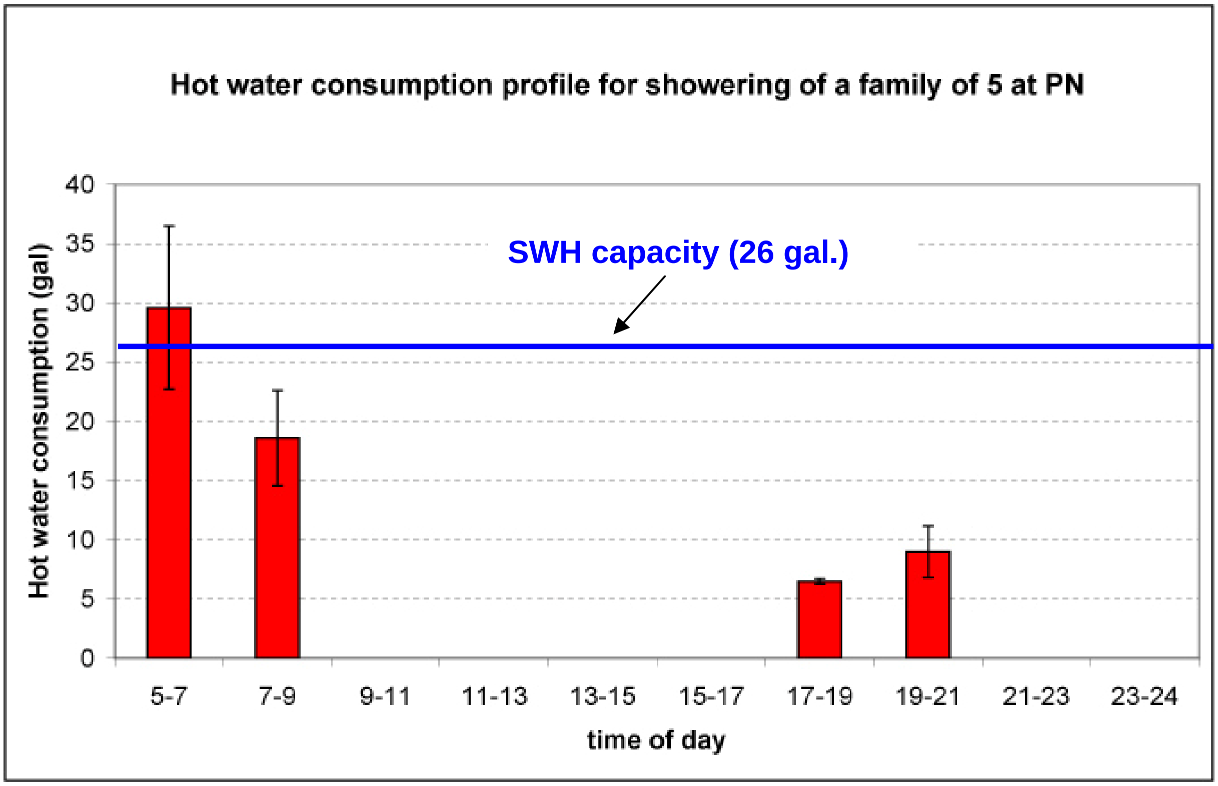


Figure 26: Showering Hot water consumption of Pomo Nation home with 5 residents

On average, family members took a total of four showers a day, resulting in a per capita shower rate of one shower per day, (as one small child showered together with one adult). Shower duration ranged from 3-14 min, with an average of 9 min, at a water flow rate of two gallons per minute. The water consumption profile clearly indicates that CalSolAgua's solar water heater will not satisfy the family's needs for showering. In fact, the daily hot water consumption for showering alone amounts to roughly 2.5 times the 26 gallon capacity of the solar water heater (about 67 gallons). However, due to two children regularly showering in the late afternoon or early evening, there is a hot water demand for showering of about 16 gallons later in the day, when the water in the water heater had its maximal exposure to sun radiation.

Financial assessment solar water heater

Assumptions

For the financial assessment, we made the following assumptions according to the parameters found in the bibliography and the user needs assessment we conducted in the Pomo Nation community:

1. According to the US Energy Department:
    - Water heater accounts for 15-20% of the total energy bill.
    - Shower and bath represent about 37% of the hot water usage
    - The average retail price of electricity to ultimate consumers in California at December 2008 was 14.36 cents/kWh

2. According to Smart Energy [2]:
    - A shower of 5 minutes uses 24 gallons of water
    - The average temperature for a hot water shower is 105°F or 40.6°C

3. According to CalSolAgua parameters for Guatemala:
    - The SWH holds 100 Liters of water, or 26.4 Gallons
    - The SWH maximum temperature is 40°C

- The maximum temperature is reached at around 4:00 pm
- No maintenance necessary for the first 5 years
- Social discount rate is 6%
- The SWH is in use 12 months per year

4. According to our thermal model (for a ‘typical’ spring day):
    - The SWH reaches its maximum temperature at around 4:00 pm
    - Maximum temperature produced is 42°C
    - SWH produces 2.5 kWh energy savings per day

5. According to users assessment at the Pomo Nation:
    - Pomo Nation’s Community is not willing to change their shower habits
    - Adults shower in the morning, children shower at night
    - The SWH will complement their electric heater, and the SWH will be in use nine months per year (not used during winter months during freezing conditions)
    - Financial savings are important to the Pomo Nation residents

6. Pomo Nation’s hot water consumption profile:
    - Average duration of showers: 9 minutes
    - Flow rate: 2 Gallons/minute
    - Average Hot water temperature: 93° F (34°C)

7. Other assumptions:

   - Unlike CSA, we included the cost of the float valve and plumping in our financial assessment. This results in an increase in the price of the SWH
   - SWH maintenance after 5 year, resulting in 10% of the total price per year

Production Cost

CalSolAgua's SWH production cost was US $156 and they determined a price of US $350 per unit, 224% the cost per unit, taking into account some additional costs for maintaining the SWH, including operating costs, in Guatemala. We realized that the float valve and its plumbing is an essential part of the SWH, and thus need to be included in the production cost, raising it by US $83. In order to maintain the same structure on costs and prices defined by the previous group we decided to apply the same proportion to our own cost. We arrived at a final price of US $536.

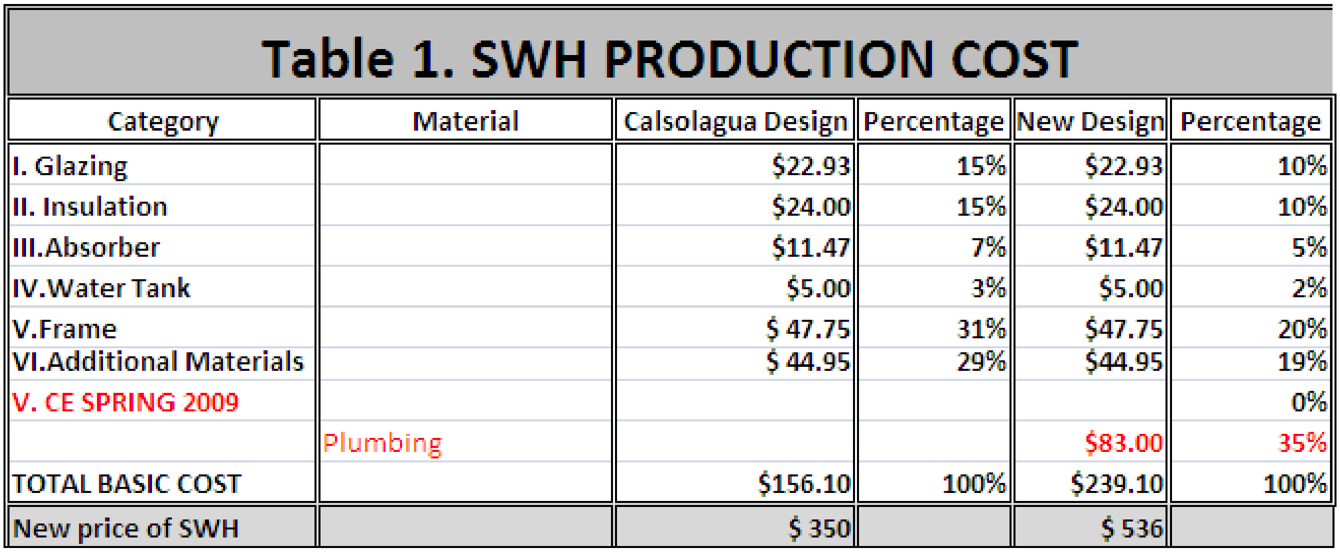


Table 1. SWH PRODUCTION COST

Category	Material	Calsolagua Design	Percentage	New Design	Percentage
I. Glazing		$22.93	15%	$22.93	10%
II. Insulation		$24.00	15%	$24.00	10%
III.Absorber		$11.47	7%	$11.47	5%
IV.Water Tank		$5.00	3%	$5.00	2%
V.Frame		$ 47.75	31%	$47.75	20%
VI.Additional Materials		$ 44.95	29%	$44.95	19%
V. CE SPRING 2009					0%
	Plumbing			$83.00	35%
TOTAL BASIC COST		$156.10	100%	$239.10	100%
New price of SWH		$ 350		$ 536	

Financial assessment

The financial assessment was based on the energy bills (2008) we received from two families belonging to Pomo Nation's community, who show similar energy consumption patterns.

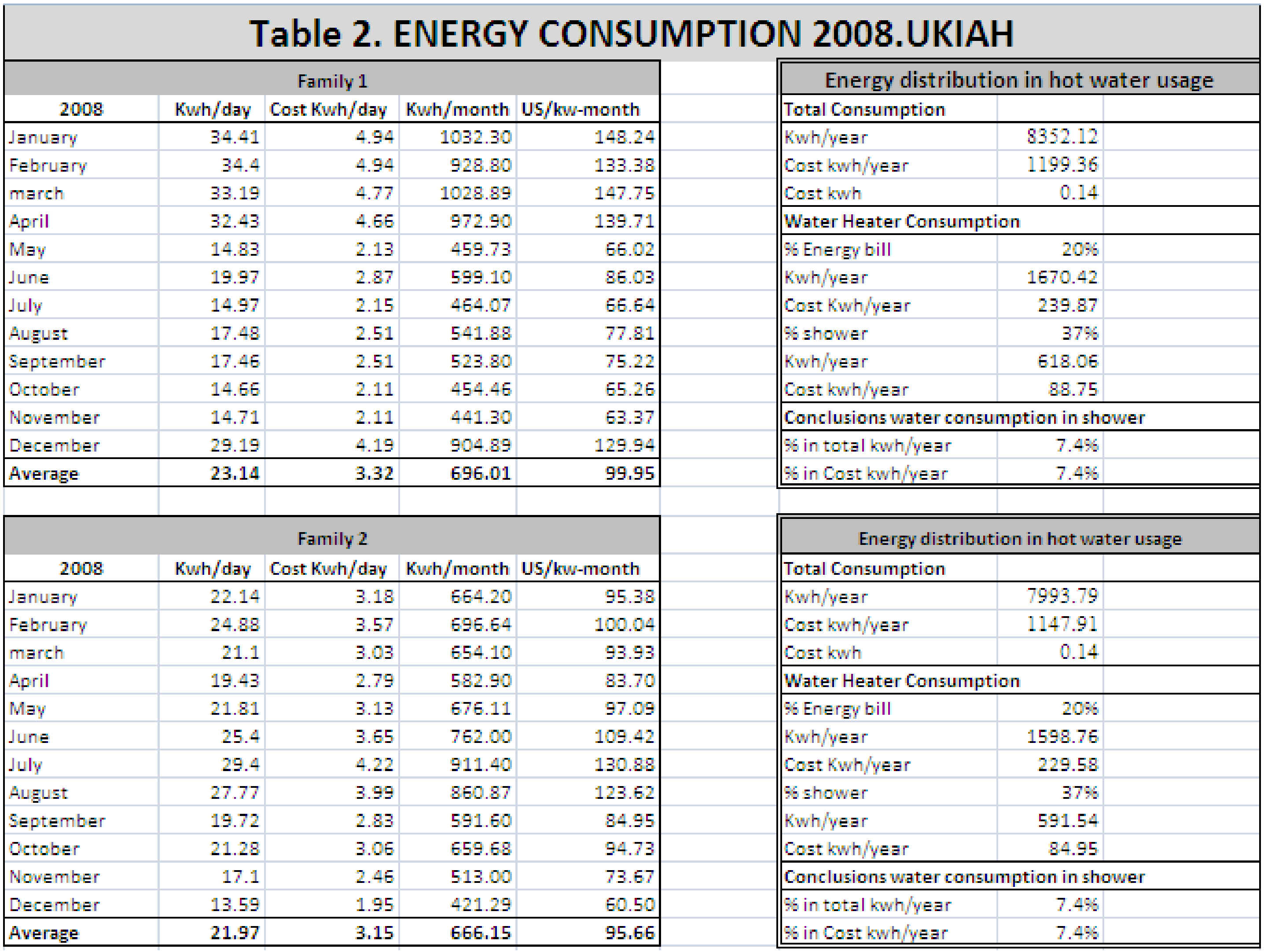


Table 2. ENERGY CONSUMPTION 2008.UKIAH

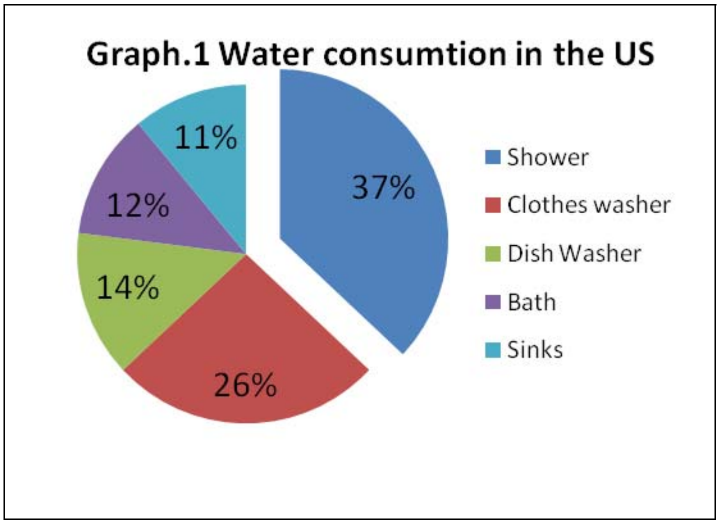
Family 1				
2008	**Kwh/day**	**Cost Kwh/day**	**Kwh/month**	**US/kw-month**
January	34.41	4.94	1032.30	148.24
February	34.4	4.94	928.80	133.38
march	33.19	4.77	1028.89	147.75
April	32.43	4.66	972.90	139.71
May	14.83	2.13	459.73	66.02
June	19.97	2.87	599.10	86.03
July	14.97	2.15	464.07	66.64
August	17.48	2.51	541.88	77.81
September	17.46	2.51	523.80	75.22
October	14.66	2.11	454.46	65.26
November	14.71	2.11	441.30	63.37
December	29.19	4.19	904.89	129.94
Average	**23.14**	**3.32**	**696.01**	**99.95**

Energy distribution in hot water usage	
Total Consumption	
Kwh/year	8352.12
Cost kwh/year	1199.36
Cost kwh	0.14
Water Heater Consumption	
% Energy bill	20%
Kwh/year	1670.42
Cost Kwh/year	239.87
% shower	37%
Kwh/year	618.06
Cost kwh/year	88.75
Conclusions water consumption in shower	
% in total kwh/year	7.4%
% in Cost kwh/year	7.4%

Family 2				
2008	**Kwh/day**	**Cost Kwh/day**	**Kwh/month**	**US/kw-month**
January	22.14	3.18	664.20	95.38
February	24.88	3.57	696.64	100.04
march	21.1	3.03	654.10	93.93
April	19.43	2.79	582.90	83.70
May	21.81	3.13	676.11	97.09
June	25.4	3.65	762.00	109.42
July	29.4	4.22	911.40	130.88
August	27.77	3.99	860.87	123.62
September	19.72	2.83	591.60	84.95
October	21.28	3.06	659.68	94.73
November	17.1	2.46	513.00	73.67
December	13.59	1.95	421.29	60.50
Average	**21.97**	**3.15**	**666.15**	**95.66**

Energy distribution in hot water usage	
Total Consumption	
Kwh/year	7993.79
Cost kwh/year	1147.91
Cost kwh	0.14
Water Heater Consumption	
% Energy bill	20%
Kwh/year	1598.76
Cost Kwh/year	229.58
% shower	37%
Kwh/year	591.54
Cost kwh/year	84.95
Conclusions water consumption in shower	
% in total kwh/year	7.4%
% in Cost kwh/year	7.4%

Family one was composed of two adults and two children while family two consisted of two adults and three children; for our financial assessment we will assume a family of two adults and two children.



To better understand the share that hot water and showering have in the total energy bill, we developed a financial model with the data given by the US Energy department on the typical U.S. homeowners' water consumption (Graph 1). According to the Energy Department water heating is the third largest residential energy expense, accounting for 15-20% of the energy bill. In our case we will account for 20%.

For water usage and temperature, we found the following data on US consumption [2]: average high temperature for a hot shower is 105°F or 40°C, average water consumption 5 gallons per minute, and the average American time per shower is 5 minutes per person.

However, according to our thermal model the maximum temperature that the SWH can produce is 42°C, and the Pomo Nation's hot water profile defined the maximum average temperature used is 34°C, so in that sense our SWH should work well there.

For the financial analysis we first compared differences between the features on the CSA prototype for Guatemala and the needs assessed for the Pomo Nation in the US as shown in Table 3. The main differences are the time during the year that the SWH is going to be used, 9 months in Pomo Nation due to its freezing temperatures during the winter as opposed to 12 months in Guatemala. Even though there is not much difference between the showering durations between the two communities, it is important to note the difference in the water flow of 1.06 gallons/minute in Guatemala, as compared to 2 gallons/minute in Pomo Nation. That divergence allows the SWH to provide hot water for three showers in Guatemala and just one in Pomo Nation.

Taking these differences into account, we developed our financial assessment with two scenarios: The first where the SWH is used only for showering and a second where the water heated by the SHW is used for showering AND other hot water daily needs, such as cleaning dishes, washing hands, etc. According to Smart Energy, an average person uses 4 gallons of hot water during the day.

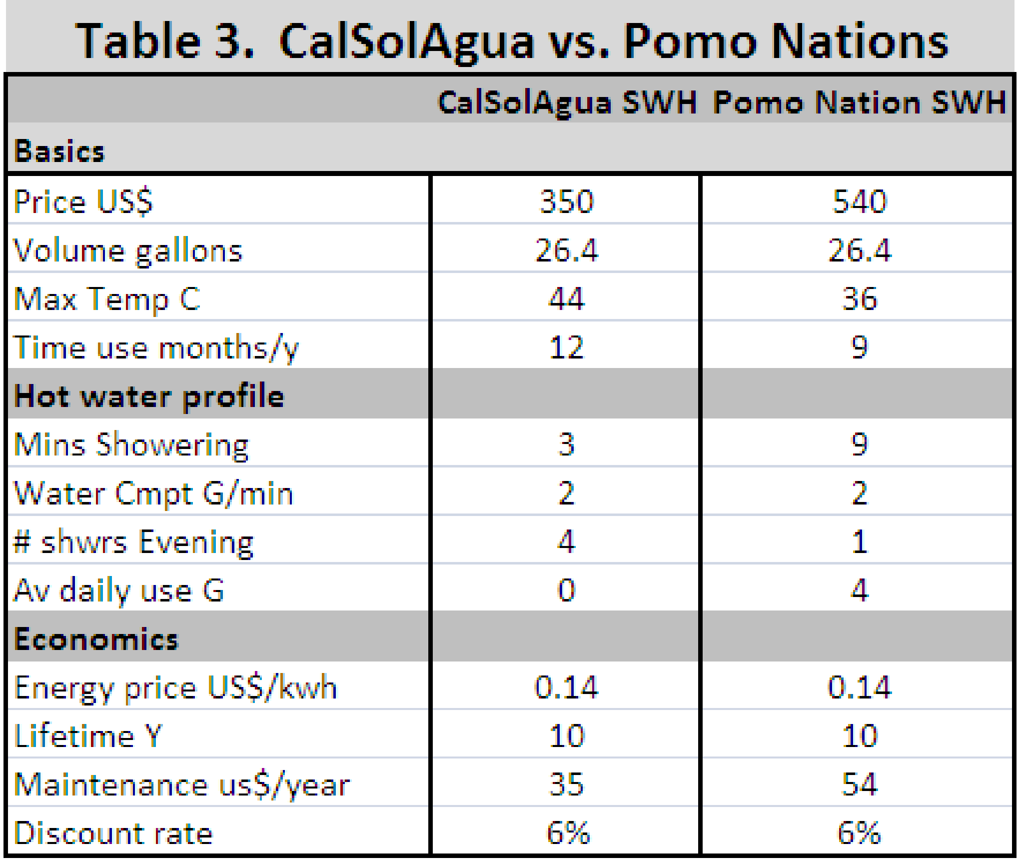


Table 3. CalSolAgua vs. Pomo Nations

	CalSolAgua SWH	Pomo Nation SWH
Basics		
Price US$	350	540
Volume gallons	26.4	26.4
Max Temp C	44	36
Time use months/y	12	9
Hot water profile		
Mins Showering	3	9
Water Cmpt G/min	2	2
# shwrs Evening	4	1
Av daily use G	0	4
Economics		
Energy price US$/kwh	0.14	0.14
Lifetime Y	10	10
Maintenance us$/year	35	54
Discount rate	6%	6%

For the financial assessment, we ran both scenarios assuming a price for the SWH of US $540. According to the results on Table 4 and assuming the SWH will produce about 1.9 kWh per day (as calculated by the thermal model for a ‘typical’ summer day) we have a total production of 521 kWh per year and hot water demand for shower of only 155 kWh per year. Thus, if the SWH is only used for showering, 366 kWh of potential energy savings will be lost annually.

Scenario 1: Hot water from SWH only used for showering

The SWH produces an energy equivalent of 521 kWh/year, but only 155 kWh/year will be used for showering. The rest will be lost. Thus, there is no financial incentive to invest in the SWH as the payback of 25 years will be longer than the lifetime of the device, and the energy cost per kWh produced is one cent higher than the 14 cents/kWh Pomo Nation already pays. That means that from the financial perspective, it would not make sense for the Pomo Nation residents to acquire the SWH.

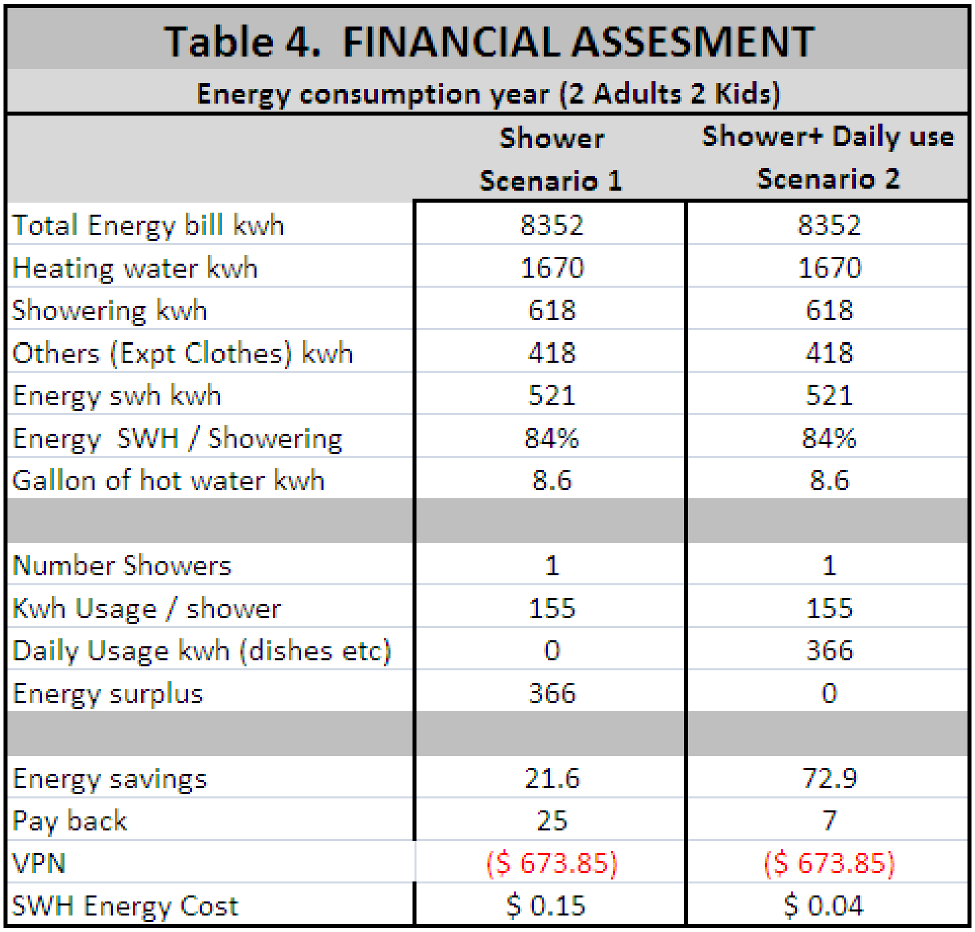


Table 4. FINANCIAL ASSESMENT

Energy consumption year (2 Adults 2 Kids)

	Shower Scenario 1	**Shower+ Daily use Scenario 2**
Total Energy bill kwh	8352	8352
Heating water kwh	1670	1670
Showering kwh	618	618
Others (Expt Clothes) kwh	418	418
Energy swh kwh	521	521
Energy SWH / Showering	84%	84%
Gallon of hot water kwh	8.6	8.6
Number Showers	1	1
Kwh Usage / shower	155	155
Daily Usage kwh (dishes etc)	0	366
Energy surplus	366	0
Energy savings	21.6	72.9
Pay back	25	7
VPN	($ 673.85)	($ 673.85)
SWH Energy Cost	$ 0.15	$ 0.04

Scenario 2: Hot water from SHW used for Shower + other hot water uses

In the second scenario, we assume that the Pomo Nation will use the 366 kWh per year for other hot water needs such as washing dishes, hands or even clothes. In that case, a household will save US $73 per year, and the payback period will be 7 years. On the other hand, after calculating the annual levelized cost (US $22.58) and the Net Present Value (NPV) (US $673.85) we arrive at a price for the kWh produced by the SWH of US $0.04 per kWh, 10 cents less than the price the Pomo Nation currently pays. In this scenario, there clearly is an economic incentive for acquiring the SWH.

5. SUMMARY AND CONCLUSIONS

Our team has conducted a preliminary analysis regarding the suitability of CalSolAgua's solar water heater for use in Pinoleville Pomo Nation, a Native American Community located in Ukiah, CA. The analysis for Pomo Nation consisted mainly of five sections: 1) conducting a user needs assessment, 2) prototyping and preliminary testing, 3) developing an analytical thermal model, 4) recording the hot water consumption of potential users, and 5) comparing the financial and energy costs and benefits. From our analysis, we determined that the CSA SWH will need some design modifications to be able to meet the needs of PPN residents.

Our user needs assessment and water consumption profile revealed that some PPN members prefer to shower in the morning, but CSA SWH is not able to provide hot water in the morning because it is not very well insulated. The PPN members preferred not to change their showering habits to shower in the afternoon because most of their homes already have an electric or propane water heater that provides hot water in the morning. Therefore, the CSA SWH should be used as a pre-heater for the electric or propane water heater. Our assessment also revealed that Ukiah reaches freezing temperatures, which the CSA SWH was not initially designed to withstand. The CSA SWH should be modified with adequate insulation not to freeze, or it may need to be drained and covered during the winter months to prevent damage.

The CSA prototype construction was finished and preliminary testing in south Berkeley yielded a sample set of solar insolation and temperature data that could be used to verify the thermal model. Based on the assumptions of the thermal model, its predictions deviated as expected from the data collected. The thermal model can be used to aid in the optimization of the SWH, since it predicts water temperature behavior in response to design changes. For Pomo Nation, the model predicted a yearly energy savings of about 930 kWh (based on a ‘typical’ spring day).

The hot water consumption profile shows that the CSA SWH would not satisfy all hot water needs of a single household. If the SWH is used only for showering, the financial analysis predicted that the payback period is 25 years, since some of the hot water from the SWH will remain unused. If the SWH is used for showering and other daily hot water uses, the payback period is only 7 years since all of the hot water from the SWH will be used. For the SWH to be financially viable for the PPN, it should be used for showering and other daily uses, or serve as a preheating device so that all the energy provided by the heater is used.

6. RECOMMENDATIONS FOR NEXT STEPS

Our team’s work and findings will be handed off to CalSolAgua, who will continue to work on solar water heaters for the Pinoleville Pomo Nation. Our recommendations to CalSolAgua are outlined below for the main topic areas.

Regarding the thermal model, recommendations for further work include:

- Account for the angular-dependence of solar transmittance through the glazing.
- Model ambient temperature as a polynomial function of time of day, using a curve fit from experimental data.
- Include thermal losses through the bottom and sides of the SWH.
- Convert within the thermal model ,‘time’, from solar time to standard time to better fit the experimental data, using the following equations [4]:

$$\text{solar time - standard time} = 4(L_{st} - L_{Loc}) + E$$

$$E = 229.2(0.000075 + 0.001868\ \cos B - 0.032077\ \sin B - 0.014615\ \cos(2B) - 0.04089\ \sin(2B))$$

$$B = (n-1)\frac{360}{365}$$

- Calculate the effect various design modifications have on performance and cost by adjusting parameters and coefficients in the thermal model.
- Include a diffusive radiation term.
- Possibly account for temperature stratification of the water within the tank.

Based on the user needs assessment, we suggest that the initial summer pilot test involve two solar water heaters. The prototype we have fabricated may be installed at the Head Start Day Care Center. Another prototype with significant design modifications can be installed at Vaughn Pena’s house for the family of five. To facilitate the construction and maintenance of the CSA SWH in the future, we recommend that CSA write up a brief document or photo manual about how to construct their SWH, including specifications for all the parts used and contact information for suppliers of obscure parts. Recipients of the SWH should receive training on the operation, maintenance, and repair of the SWH.

Before CSA installs the SWH on the Head Start building, we recommend the following:

- Weld metal reinforcement bars on the frame to prevent the bladder from bulging and breaking the glass.
- Cover the float valve to prevent algae from growing in the water.
- Check all hose connections for leakages and address the leakage issues before installation.
- If the maximum temperature obtained by the SWH is hot enough to cause burns, install a tempering valve to mix the hot water with cold water so the warm water exiting the faucets will not cause burn injuries.

Regarding installation of the CSA SWH on residential homes, we recommend the following:

- Install the solar water heater in-line with the existing electric water heater. The SWH could preheat the water before it enters the electric heater, in order to reduce the electricity consumption.

- Since the Pomo Nation community is not willing to change their showering habits, and because the SWH can provide hot water just for one average shower in the evening due to its limited capacity, the SWH should be used for activities, such as dish washing, clothes washing, hands washing, and so on.

- Revisit the findings of the user needs assessment when re-designing the SWH for the PPN.

- Monitor electricity consumption of the electric water heater to account for energy savings provided by the SWH.

For continued testing of the prototype, we recommend the following:

- Quantify the efficiency based upon the suggested analysis, where the average water temperature is to be taken as the temperature at the center of the SWH.

- The measured data should be coupled to the thermal model for successful design optimization. CSA could validate the thermal model with experimental data of solar radiation measured by pyranometer, and water temperature obtained by thermocouple data loggers at various locations along the tank to accurately determine the thermal losses within the SWH.

7. ACKNOWLEDGEMENTS

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