SOLAR WATER HEATER
Final Presentation

CE 290 - 2009

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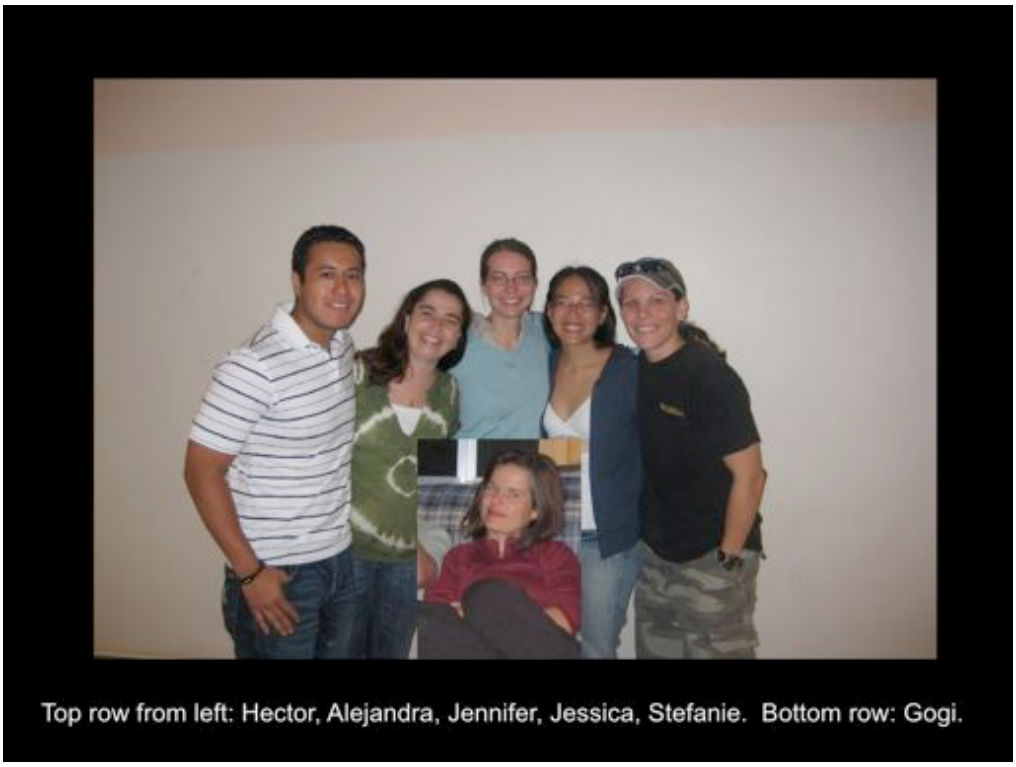


Top row from left: Hector, Alejandra, Jennifer, Jessica, Stefanie. Bottom row: Gogi.

Outline

- Background
- Minimal and optimal goals
- User needs assessment
- Prototype
- Hot water consumption profile
- Thermal model
- Financial Analysis
- Recommendations

Before us…

- Project started in Spring 2007 in Design for Sustainable Communities class
- Team of students designed a solar water heater for use in Xela, Guatemala
- Team members formed CalSolAgua and continued to work on design and eventually implemented it in Xela

Where we come in…

- Pinoleville Pomo Nation approached UC – Berkeley contacts about bringing solar water heater technology to their community
- CalSolAgua was asked if they could provide solar water heaters to meet the needs of the Pomo Nation
- In Spring 2009, CalSolAgua asked our team to help them decide if using their solar water heater in the Pomo Nation was feasible

The challenge…

Can the CalSolAgua solar water heater…

- Guatemala (Xela)
- US $150
- 100L at 40°C
- Shower at 4 pm
- No external storage
- Pressurized water system
- Gravity fed (passive)

Source: Google Maps

…be used here:

Pinoleville Pomo Nation

- California (Ukiah)
- 20 families in community
- Average High Temp 23°C
- Average Low Temp 8°C

Pyranometer measures solar insolation (energy received from solar radiation)

Optimal Goals

- User needs assessment of Pomo Nation community
- Compare CalSolAgua prototype performance with thermal model predictions
- Create hot water consumption profile

User Needs Assessment

Met with CalSolAgua members

- Adam Langston (surveys)
- Ernesto Rodriguez (interviews)
- Wanted to learn from previous team's experiences

Surveys

- Administered to 6 Pomo Nation residents
- Gathered information prior to follow up interviews
  - Family size and structure
  - Access to hot water
  - Hot water use

Trip to Pomo Nation

- Interviewed 7 residents
  - Followed up on survey information
  - More details on hot water use
  - Daily activities

- Housing assessment
  - Current water heater
  - Roof suitability
  - Piping
  - Sun exposure

Findings

- Large family size (5-8 members)
- Modern living conditions
- Expect/require hot water in the morning
- Pressurized water system
- Storage tank available
  - electric water heater
- Freezing conditions
  - 10-13% of the year
- Save money and be sustainable
- Strong spiritual and cultural values
  - nature/water

Head Start Day Care

Warm water for 40 people to wash their hands

Exterior of Head Start Building

Head Start's staff in the classrooms

During our user needs assessment, the Pomo Nation identified their Head Start Day Care center as a potential candidate for a solar water heater (SWH). Head Start is supposed to provide warm water for washing hands for the 30 children and 10 staff members that use the building during the day.

Head Start Day Care

Head Start's facilities for hand-washing

Children in Head Start's playground

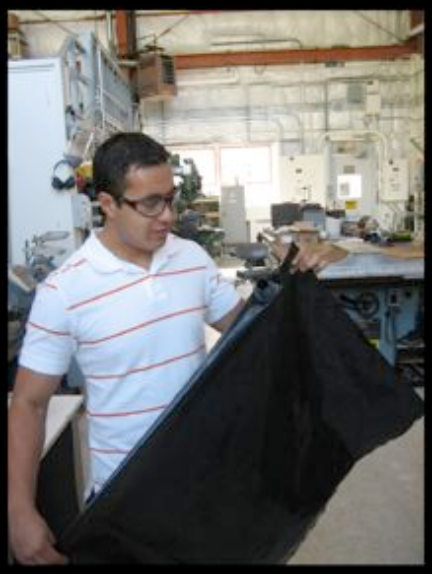
However Head Start does not have a water heater or tank to provide warm water in their bathrooms. The needs of the Head Start building are much different than those of the Pomo's homes. More people would be using smaller amounts of warm water frequently throughout the day, but the temperature would not have to be as hot as shower water. After consulting with Dr. Gadgil, our team decided that the CalSolAgua SWH would meet the needs of the Head Start building.

CalSolAgua Prototype

Our goal was to finish a CalSolAgua (CSA) SWH by the end of May 2009, so the CSA team could install it at the Head Start building over the summer. This picture was taken at the start of our prototyping process. The metal box is lined with insulating foam. The box and absorber were painted black. Fasteners were welded onto the frame to secure the glass.

Making the bladder

Jennifer and Hector worked on making a new water bladder at LBNL. The water bladder is a plastic bag that will contain the water inside the box on the previous slide.



Plumbing and Sensors

We made and attached a float valve in the 5 gallon bucket to regulate the amount of water in the bladder.

We patched leaky interfaces with caulk.

We installed 4 temperature sensors.

SWH Testing Location

We planned on testing the prototype on the 3rd floor balcony of a home in South Berkeley. The insolation and ambient temperature in Ukiah is supposed to be similar to the conditions in Berkeley, so the SWH should perform similarly in both locations.

Cold water enters the SWH from the bottom. The sun heats the water up and the warmer water rises to the top. The hot water leaves the SWH from the outlet at the top. The float valve regulates the amount of water in the bladder so the bladder cannot overfill and burst.

The float valve in the bucket works like the one in your toilet tank. Pressurized water from the house is connect to the float valve from the bottom of the bucket. The float valve allows the bucket to fill until the water level reaches the dashed line. Water will drain from the bucket into the SWH until the water level in the bladder is the same as the water level in the bucket (the blue dashed lines are at the same horizontal height but the angle of the picture is deceiving). 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.

Prototyping Future Work

CSA will be responsible for installing the prototype at Head Start. Before they install the SWH, we have the following recommendations:

1. Weld metal reinforcement bars on the frame to prevent the bladder from bulging and breaking the glass.

2. Caulk the interface between the pipes and the bladder or design another way to prevent leakage

3. Cover the float valve to prevent algae from growing in the water

Testing

- 2 Main Measurements
  - Water Temperature
    - Higher temperatures make SWH more appealing
  - Insolation
    - Needed to calculate SWH efficiency

Thermal Testing

2

3

1

4

Four locations for thermocouples
1) Water inlet
2) Water at middle
3) Water outlet
4) Ambient air temperature

HOBO data logger connected to thermocouple used for measuring water and air temperatures

Solar Insolation Testing

Pyranometer

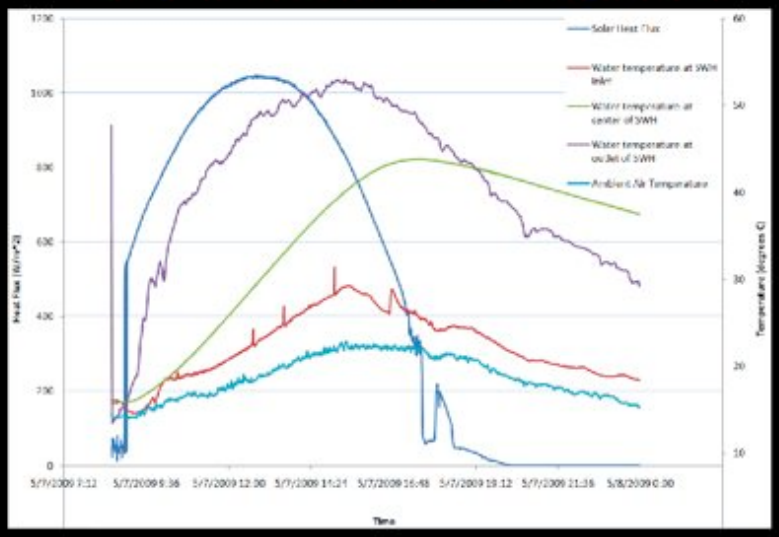
Pyranometer Amplifier

The pyranometer converts incident solar radiation into a current output. The current output then needs to be converted into a voltage so that it can be read by computer software. The pyranometer amplifier accepts the current input and outputs an amplified voltage that can be read by conventional loggers.

Solar Insolation Testing

The amplifier is compatible with HOBO data loggers that were acquired for temperature sensing. The loggers can be conveniently left at the test site without the need of a laptop computer. The recorded data can then be downloaded and analyzed via HOBOware. Data can also be exported into Microsoft Excel.

Sample Data Collection



Solar insolation and temperature data collection for SWH in South Berkeley on May 7, 2009 from 8:35am till Midnight

Suggested Analysis with Data

- Measure SWH performance by calculating efficiency:
  Efficiency = desired output/ invested input

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

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 t_i

A= Area of solar incidence

Solar Energy= total solar energy delivered between time t_i 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/m^2.

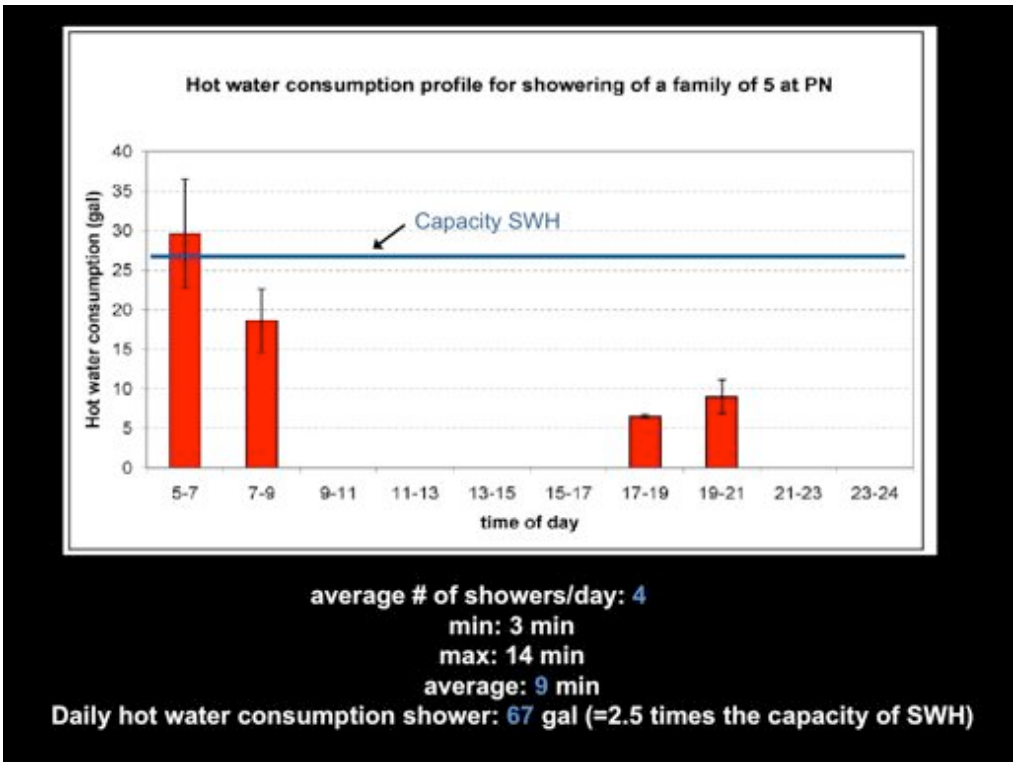
- Couple experimental data to thermal model for successful design optimization

Hot water consumption profile

Shower head flow rate

Shower length and frequency

We compiled two hot water consumption profiles of Pomo Nation residents by recording hot water flow to the shower heads with a thermocouple and Hobo data loggers and multiplying it with the hot water flow rate during a hot shower.



average # of showers/day: 4
min: 3 min
max: 14 min
average: 9 min
Daily hot water consumption shower: 67 gal (=2.5 times the capacity of SWH)

Thermal Model Development

- Assumptions for Initial Analysis
  - Lumped capacitance model for fluid in tank (neglect temp. stratification as first approximation)
  - Direct solar radiation flux
  - Adiabatic side and bottom surfaces of the SWH
  - Cold water supply temperature 20 deg C
  - Constant ambient temperature
  - Ukiah, CA (Latitude 39 deg, Longitude 123 deg)
- Energy balance on SWH:

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

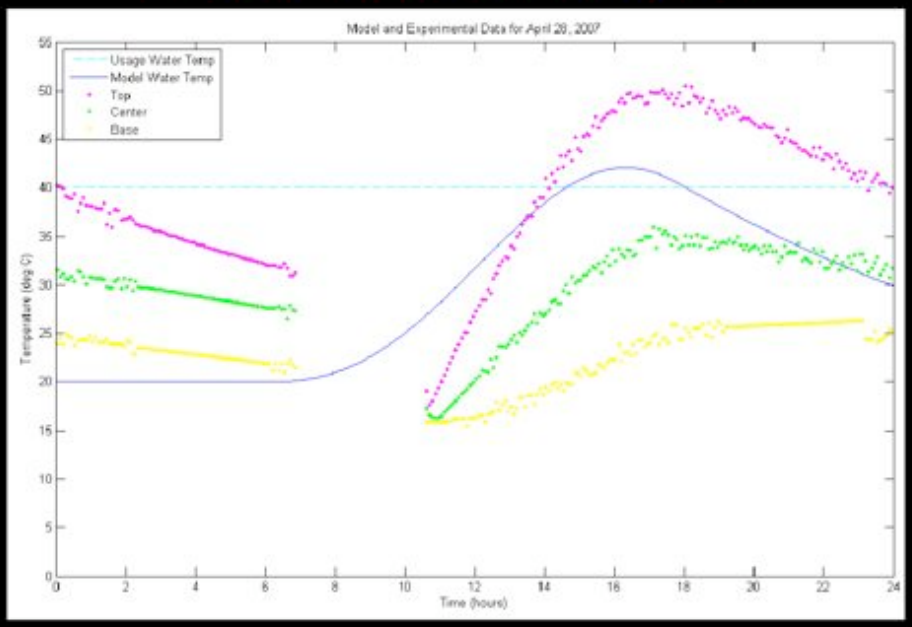
- Finite difference model implemented numerically

Thermal Model Development…

The direct solar irradiation was calculated as a function of latitude, day of the year, time of day, hour angle, declination, solar zenith angle, solar azimuth angle, surface azimuth angle, and angle of inclination of the SWH from the horizontal. The net insolation is the direct solar irradiation multiplied by the absorptance-transmittance product.

A plot of the transient temperature profile is shown on the next slide for Ukiah, CA 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.

Thermal Model Results



Thermal Model Results…

- 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.
- For a “typical” spring day (4/28/07)
  - Max. water temperature 42 °C about 4 pm
  - Daily energy savings 2.5 kWh
  - Yearly energy savings (365 days) about 930 kWh
- The thermal model may be used to assist in the design of a SWH to meet the needs of the PPN
  - Ability to adjust parameters (materials, etc.) to achieve desired results
  - Ability to calculate heat loss and energy savings
  - Could be used to obtain trade-off between performance and cost

Thermal Model:

Recommendations for Further Work

1. Account for the angular-dependence of solar transmittance through the glazing.
2. Model ambient temperature as a polynomial function of time of day, using a curve fit from experimental data.
3. Include thermal losses through the bottom and sides of the SWH.
4. Convert model 'time' from solar time to standard time to better fit the experimental data
5. Validate the thermal model with experimental data of solar radiation and water temperature to accurately determine the thermal losses within the SWH.
6. Calculate the effect various design modifications have on performance and cost by adjusting parameters and coefficients in the thermal model.
7. Include a diffusive radiation term.
8. Possibly account for temperature stratification of the water within the tank.

Financial analysis

Assumptions	CalSolAgua SWH	Pomo Nation SWH
Basics		
Price (US $)	350	540
Volume (gallons)	26.4	26.4
Max temp (°C)	44	36
Time use (months/year)	12	9
Hot water profile		
Time showering (mins)	7.5	9
Water flow rate (gal/min)	1.06	2
Showers in evening (# of)	3	1
Avg. daily use (gallons)	0	4
Economics		
Energy price (US $/kWh)	0.14	0.14
Lifetime (years)	10	10
Maintenance (US $/year)	35	54
Discount rate	6%	6%

Financial analysis

- The SWH price increased mainly because we included the plumbing for the float valve in the total cost. The price was defined maintaining the proportions that CalSolAgua previously established between prices and cost.

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 analysis

- We assume the SWH is going to be used for 9 months per year because of freezing temperatures in the winter months.
- Even though the duration of an average shower does not differ much between Guatemala and Pomo Nation, there is a big difference in water flow. That difference allows the SWH to provide 3 hot showers in Guatemala and just one in the Pomo Nation.
- We assume that hot water provided by the SWH could be used for hot water needs other than showering at Pomo Nation.

Financial analysis

- Our analysis is based on the price of electricity in California in 2008, as given by the Energy Information administration.

Average Retail Price of Electricity to Ultimate Customers (Cents per kWh)				
State	Residential		Commercial	
	Dec-08	Dec-07	Dec-08	Dec-07
California	14.36	14.46	11.49	11.24
U.S. Total	**10.99**	**10.33**	**9.95**	**9.42**

Source: Energy Information Administration, Form EIA-826, "Monthly Electric Sales and Revenue Report with State Distributions Report."

ENERGY BILLS 2008

Family 1

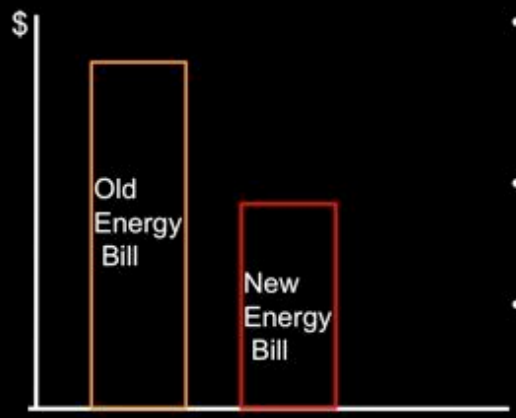
2008	Kwh/day	Cost Kwh/day	Kwh/month	US/kw-month
January	34,41	4,94	1032,30	148,24
February	34,4	4,94	928,80	133,38
march	33,19	4,77	1028,89	147,75
April	32,43	4,66	972,90	139,71
May	14,83	2,13	459,73	66,02
June	19,97	2,87	599,10	86,03
July	14,97	2,15	464,07	66,64
August	17,48	2,51	541,88	77,81
September	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**

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**

The backbone of the financial analysis

Financial analysis



- Water heating is the third largest energy expense at home
- It accounts for 15% to 20% of the energy bill
- Showers and baths represent about 37% of the hot water usage

Energy consumption year (2 Adults 2 Kids)		
	Shower	Shower + Daily use
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
Showers (# of)	1	1
kWh usage / shower	155	155
Daily usage (dishes etc.) (kWh)	0	366
Energy surplus (kWh)	366	0
Energy savings (US $)	21.6	72.9
Payback (years)	25	7
Net Present Value (US $)	($ 673.85)	($ 673.85)
SWH Energy Cost (US $/kWh)	$ 0.15	$ 0.04

Financial analysis

Scenario 1: SWH Only for shower

- The SWH produces 521 kWh/year but just 155 kWh/ year will be used for showering. The rest will be lost in this scenario.
- There is no incentive to invest in the SWH as the payback will be longer than the lifetime of the device and the energy cost per kWh produced is higher than the price of electricity.

Scenario 2: SWH for Shower + other uses

- The total production of kWh/ year of the SWH is going to be used.
- There are savings of US $73 /kWh-year and the payback time is 7 years. The cost of energy produced by the SWH is US $0.04/kWh, ten cents less than the price of electricity from the utility.

Conclusions

- The CSA SWH should be used as a pre heater for the electric or propane water heater.
- 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.
- To be financially viable for the PPN, the SWH should be used for showering and other daily uses.

Recommendations

- Analyze the solar water heater efficiency
- Couple experimental data to thermal model for successful design optimization
- Install two solar water heaters and collect data
  - Vaughn's house (family of 5)
  - Head Start building
- Install the solar water heater in-line with the existing electric water heater
  - Solar preheating of water saves energy
  - Supply hot water for all uses, not just showering
- Be culturally sensitive, as water has high spiritual significance for the Pomo Nation.

Acknowledgements

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