

TRULY ZERO ENERGY HOME: GRID-TIED PV, SOLAR HYBRID COOKING, PLUS OTHER UNIQUE ENERGY CONSERVING FEATURES

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ABSTRACT

Two years ago, I moved into a home that produces more energy than it consumes. The first year I lived there, I burnt no fuels of any type and the grid-tied solar system produced substantially more energy than it consumed. These results were achieved by combining some unique energy saving features with a grid-tied PV system. The second year, an inline gas heater was used as a backup for space heating, and the electrical backup was still used for domestic hot water. I was then able to feed more electricity into the grid during the second year of occupancy, which further reduced the carbon produced by my utility.

Energy consumption was minimized by incorporating a number of additional energy saving features: an energy efficient shower, solar hybrid cooking, a composting toilet and a number of other unique applications.

1. INTRODUCTION

The design goal of this project was to build a house that produced more energy than it consumed, and burned no fossil fuels. This goal was achieved by incorporating a number of unique conservation strategies: energy efficient appliances, a sunspace, passive solar gain, a grid-tied PV system and a solar thermal system that provided hot water for space heating, domestic hot water, and cooking. The first year, the PV system fed more electricity into the grid than was consumed. The solar thermal system incorporated a tankless electric water heater as a backup.

During the second year of operation, I reconsidered my strategy and decided to incorporate a tankless gas water heater as a backup for space heating. I was then able to feed even more electricity into the grid to further reduce the utility's primary consumption and the amount of CO₂ put

into the air (about three units of heat energy produces one unit of electrical energy).



Fig. 1: Sun space on south wall

2. PRIMARY FEATURES

The 960 square foot (89m²), two-bedroom house is located in Arcata, California, a coastal town near Oregon. Arcata has a unique climate; winters are mild and rainy and summers are cool and often foggy. We have the fewest cooling degree-days of any city in the continental United States. As a result of the long heating season, we have a relatively high number of heating degree days – 4650 HDD. With our cool summers, overheating is not a major concern in passive solar design. A good assumption for sizing PV arrays is that as a yearly average, Arcata has about four sunlight hours/day.



Fig. 2: South and east walls

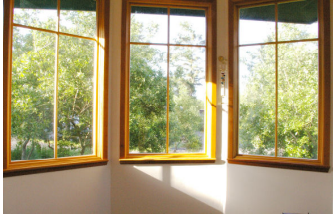


Fig. 3: Sun space

The house faces directly south and the bedrooms are located on the north side. The home's stud walls incorporate six inches (39 cm) of fiberglass insulation. An entry way sunspace contains about seventy square feet (6.5m²) of single glazed windows and the remainder of the south wall contains an additional seventy square feet (6.5m²) of double glazing. Low E glazing was not used on the south side of the house to maximize solar gain. Cellular shades are used on the interior south facing windows, approximately doubling the R-value of the windows. The windows are tall to provide good solar penetration for space heating and daylighting on a sunny day. The thermal mass of the sheet rock walls, fir floor, and furniture, on a typical winter day provides enough thermal mass to keep the house comfortable until about 11:00 pm. The temperature the next morning will generally be near 60° F (16°C) when the shades are closed overnight. Early morning winter temperatures are generally near 40°F (4.5°C).



Fig. 4: Solar thermal panels and PV power for pump

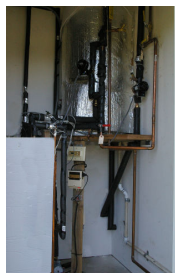


Fig. 5: Drain back tank (lower left), 40 gallon pressurized tank (upper right)

2.1 Solar Thermal Hot Water

The drain back solar thermal system incorporates eighty square feet (7m²) of selective surface single glazed solar panels. A small positive displacement PV powered pump circulates water from the 160-gallon (605L) drain back tank to the solar panels. The system originally was controlled by a differential thermostat, but after having some minor problems with the thermostat, I decided to eliminate it and

connected the circulation pump directly to the PV panel. Neither system offered perfect control; i.e., the PV controlled system would continue to circulate small quantities of water at the end of the solar day when the output of the solar collector was cooler than the water at the top of the storage tank. When the system was thermostatically controlled, the pump would be shut off while hot water was still being collected. In a practical sense, both systems were acceptable, however, I liked the simplicity of the direct PV system.



Fig. 6: Parallel path heat exchanger for pressurized hot water system

The hot water is used for domestic hot water, cooking, and space heating. A custom designed heat exchanger at the top of the drain back tank provides hot water for cooking. For space heat and domestic hot water, a second custom designed heat exchanger thermosiphons water into a forty-gallon pressurized tank. The heat exchanger contains sixteen parallel paths for water circulation so that resistance to flow is minimized. The loop also contains a pump – at the time I designed the system I did not realize how well the thermosiphon loop would work. The pump circuit is shown below. The one-way valve, made by Zone Works, is parallel with the pump and contains a floating ball that provides minimum flow resistance in the thermosiphon loop.

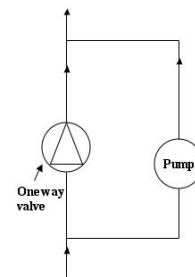


Fig. 7: Backup pump in thermal siphon loop.

I used an instantaneous heater as a backup to the solar thermal system. A primary advantage of an instantaneous heater is that it does not produce hot water when solar heated water is available. For example, in a system where a solar tank is in series with an actively heated tank, after a cloudy day, the solar tank will be cool at 7:00 am. After several early morning showers, the backup tank will be full of cool water from the solar tank. Gas or electricity will then heat the backup tank. If the sun then comes out from

10:00 am to 5:00 pm, the solar tank will be filled with hot water, however, the actively heated tank will have been unnecessarily heated by gas or electricity. If an instantaneous heater is in series with the solar tank, this problem will be alleviated.

The first year in my house, I did not want to burn any fossil fuels, so I used a 5kW instantaneous hot water heater for a backup. That year I produced more than I consumed. I recently installed an instantaneous gas heater as a backup for space heating, and still use the instantaneous electric heater as a backup for my domestic hot water needs. With this system, I am burning fossil fuels, however I am saving my utility fuel and reducing the net amount of carbon put into the air. It requires about three units of fossil fuel energy to produce one unit of electrical energy. My instantaneous gas heater is 83% efficient. If gas instead of electricity is used to produce one unit of backup heat, I will then be able to transfer an additional 2.5 units of electrical energy to the utility.

2.2 Proposed Rebate System

I am now saving the utility additional fuel, but my utility bill has increased. My utility sends a bill once per year for the net amount of electricity consumed. If you produce more than you consume, however, you are not paid for the additional kWh's you produce. Even though I am saving the utility additional fuel, I am now faced with a gas bill.

I would like to see a home rebate system based on the primary energy consumption of a home, where one unit of electrical energy would count as three units of energy derived from natural gas. The system could be revenue neutral; large consumers could pay for conservers. A home's energy consumption would be compared to the average consumption of a similarly sized home. A key feature of the system would be that the homeowner could take the most cost effective steps to save energy. To make a substantial dent in our country's energy consumption at an affordable cost, the most cost effective steps must be taken first. Conservation and solar orientation should be a prime consideration. As a homeowner's consumption approached zero, instead of paying they would receive a substantial rebate, for perhaps five years. On the other hand, energy hogs would have substantially increased utility rates. If a homeowner could not afford significant capital investment, they could participate by controlling lights and thermostat adjustments.

To encourage builders to build more efficient homes, the builder and the homeowner could share the rebate for about the first five years. This would encourage builders to incorporate effective low cost energy saving strategies, such as orientation.

3. SOLAR HYBRID COOKING

Conventional solar cooking is limited by weather conditions and the availability of sunlight. A system I call "solar hybrid cooking" offers more flexibility. The system consists of three elements: a solar thermal collector, a stove using renewable fuel, and insulated cooking implements.

3.1 Energy Requirements for Cooking

Many cooking techniques are highly inefficient. Heating the kitchen while cooking is an indication that most of the heat is being wasted. The average person consumes about five pounds of hot food per day and the energy required to heat the food from room temperature to boiling would be about 700 Btu's (.2 kWh) (most food is cooked at 180°F/82°C). This is equivalent to one-fifth of a kWh, or the energy contained in one-tenth of a pound of wood, or .6% of the energy in a gallon of gasoline. If the cooking process was only 33% efficient in Arcata, California, the .6 kWh required for cooking one day's worth of food could be provided by a single 165 watt solar module. This single solar module could provide the energy required for nearly a lifetime.

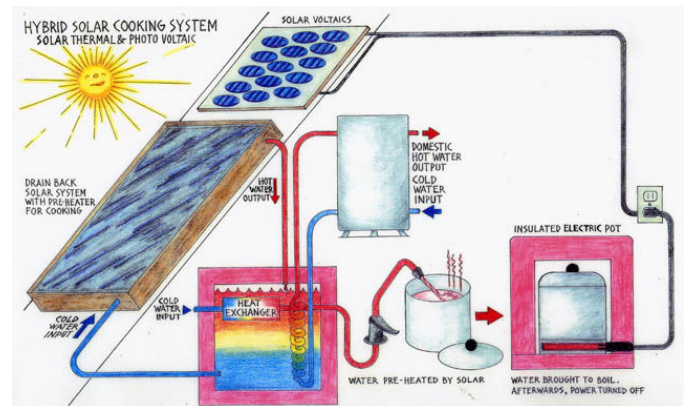


Fig. 8: Solar hybrid cooking system

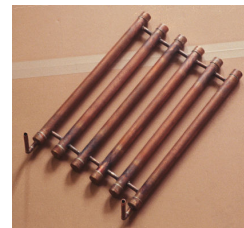


Fig. 9: Heat exchanger for solar hybrid cooking

With a solar hybrid cooking system this figure is further reduced because a solar thermal collector preheats hot water. The drain back system in my house incorporates a heat exchanger at the top of the drain back tank to provide hot water for cooking. The heat exchanger is composed of six 1.5 inch (3.8cm) copper pipes in series, and has about a 1.5-gallon capacity. Because of the location of the heat exchanger at the top of the tank, and its capacity, hot water

is provided at the kitchen sink at essentially the same temperature as the hottest water in the tank. When the 1.5 gallons of water are consumed, the temperature of the water substantially drops. A ¼ inch (6mm) tube runs from this heat exchanger to the kitchen sink. The small diameter tube minimizes wasted water and energy, and also reduces the time for hot water to travel to the kitchen sink. On a sunny day in the spring, summer, or fall, this preheated water is typically near 180° F (80°C), hot enough to brew a cup of tea.

The pots used are the types that have an attached heating element and an on/off thermostat. The attached heating element puts nearly all of the electrically generated heat into the pot. A teapot of this variety is over 90% efficient, while my microwave oven is only about 50% efficient. Although it requires three units of heat energy to produce one unit of electrical energy, when all aspects of the cooking process are considered, including the small quantity of energy needed for efficient cooking, I prefer a well designed electrical cooking system. For both pots and ovens it is easier to effectively transfer and control heat with electrically heated appliances. In addition, water vapor and pollutants produced by having an open flame inside a house are eliminated. The ideal pot would be insulated, have an attached thermostat with a remote probe to measure the temperature of the cooked food, and a variable output heating element. Heat would be distributed evenly over the bottom of the pot. A variable output heating element keeps food simmering with very little power. An insulated pot reduces the possibility of burning food because thermal gradients in the pot are minimized. For the pots I am using, two layers of towel draped over the pot provide insulation. For foods such as brown rice, 30 watts keeps the temperature near boiling. After the contents of the pot are initially heated, the 30 watt input could be totally eliminated by using heavier insulation. This is known as strawbox or retained heat cooking. I recently cooked a pot of rice and lentils consisting of ½ gallon (1.9L) of water and two pounds (.9kg) of rice and lentils, which, if eaten exclusively, contains enough calories for one and one half days. The process consumed only .2 kWh

Frying can be done most efficiently with a “George Foreman” type cooker. This device has two electrically heated hot surfaces, one above the food and one below. This configuration minimizes heat loss and cooks quickly. These cookers typically have no insulation between the electrically heated plates and the outer covering. I disassembled the cooker I am using and added some high temperature batting type insulation. I also use an electrically heated frying pan. The pan is covered with a terrycloth towel when appropriate.

Baking can be done efficiently in a well-insulated oven; minimizing the ovens’ thermal mass and not over sizing the oven will help minimize consumption. I constructed an oven

which is twenty-one inches long, ten inches high, and eight inches wide. The oven is an insulated box that is placed over an electrical heating element. Cooking three loaves of bread consumes only .3 kWh. However, I do most of my baking in a small commercially purchased convection oven. Before installing the oven, I disassembled it and added additional insulation to the innards – all of its double walls were not initially insulated.

3.2 Solar Hybrid Cooking in Developing Countries

A simple form of “solar hybrid cooking” could make the cooking more efficient and flexible in developing countries. The solar thermal element of the system could merely consist of a black pot placed in the sun. An efficient wood stove could bring the pot to a boil. This cooking process would then be completed without expending any additional energy by covering the pot with an insulated cover. The advantage of putting an insulated cover over the pot is that rising hot air will not escape through the seals. This process will maintain higher temperatures longer with larger pots because of the reduced surface to volume ratio.

3.3 Other Appliances



Fig. 10: Sun Frost refrigerator, pedal controlled faucets and solar hybrid cooking system



Fig. 11: Sun Frost composter

On the cooling side, the kitchen incorporates a Sun Frost RF-12 refrigerator which consumes only .27kWh per day. Food is composted in a Sun Frost “Scrap Eater.” With one inhabitant, the composter only needs to be emptied every few years. Composting is more energy efficient than using a garbage disposal and also allows nutrients to be recycled. The high south facing windows provide good natural light. In addition, there are several high clearstory windows on the east and west walls to provide additional light in the rear of the kitchen and living room. Light bulbs are primarily

screw-in fluorescents. The exterior lighting fixture was placed to provide light where needed with a minimally sized light bulb.

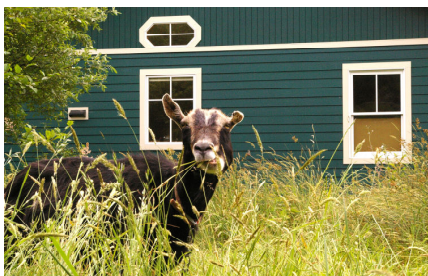


Fig. 12: Grass is cut by a grass-powered mower

4. DOMESTIC HOT WATER SYSTEM

With solar hot water panels and an energy efficient shower, the power required to boost the temperature of the water supplied to the shower is typically small. If $\frac{1}{2}$ gallon /minute (1.9L/minute) is required for a shower and the solar heated water is at 90°F , only about 3500 Btu/hours (1kWh) would be required from the backup heating system. Instantaneous gas hot water heaters only modulate down to about 16,000 Btu/hour (4.7kWh). However, an instantaneous electric heater would provide the 3500 Btu/hour required. Using an instantaneous electric heater rather than gas consumes half as much primary energy and also reduces my water consumption. Also, with an oversized gas heater, the cold water supply must be increased to reduce the water temperature to 105°F (40°C).

5. SPACE HEAT

I opted not to put any additional thermal mass into the house. In Arcata, we often get prolonged periods of rainy weather during the winter months. Considering the climate and my lifestyle, additional thermal mass would be a detriment. When the house is unoccupied during the day, heat is not necessary. On rainy days, I want the house to warm up quickly - in the morning and when I arrive home at night. With additional thermal mass, the house would not heat up as rapidly, but would stay warmer later into the night when I am sleeping. It is seldom cold enough to need this additional heat. When the house is heated in the morning, it would also stay warmer later into the morning when the house is no longer occupied. Keeping the house warm when it is not necessary would increase heat loss and energy consumption, even if the heat was provided by thermal mass. Without any additional thermal mass, on sunny days during the winter the house stays at a comfortable temperature until I go to sleep. Indoor temperatures are typically near 60°F (16°C) by the next morning, when the temperature outside is near 40°F (16°C). The house also incorporates 80 square feet (7m^2) of solar thermal panels, which heat up 160 gallons (605L) of water. This water is used for domestic hot water, cooking, and

space heat. The 160 gallons of hot water can be thought of as thermal mass that is isolated but can be called upon to heat the living space when desired. If I need heat in the morning and it was sunny the previous day, the heat stored in the hot water tank will heat the house. But when the rains began in November, my solar thermal system was not always producing an adequate amount of heat. I then turned on a 5,500-watt instantaneous electric heater to boost the water temperature.



Fig. 13: Fan coil heating.
Air enters upper right
and exits lower left



Fig. 14: Hydronically
heated towel rack

For space heating, fan coil heaters distribute the hot water. These devices look like car radiators. To heat the bathroom, I constructed a combination radiator/towel warmer. The fan coils were oversized so that comfortable conditions could be attained with relatively low temperature hot water—an advantage with solar hot water because the solar collectors become less efficient as the water gets hotter.

5.1 Convective vs. Radiant Heat

Radiant heating is an excellent way to provide comfortable, uniform temperatures, but convective heat also has its place. In convective heating, air is heated more than surrounding surfaces. The fan coils I use are convective heaters. The advantage is that they can rapidly warm up a space without keeping the space warm long after heating is needed. It would take about twenty times more energy to heat the thermal mass in my house than to heat the air. Typically, the air will get about 70°F (4°C) warmer than the surrounding thermal mass when the system is initially turned on; thermal comfort is dependent on both the air temperature and the mean radiant temperature (the temperature of surrounding surfaces).

6. WATER CONSERVATION

The house also incorporates a number of water conserving features. In the kitchen and bathroom, either a conventional faucet or a foot pedal can control flow. These devices save water when washing dishes or brushing your teeth and are quite convenient.

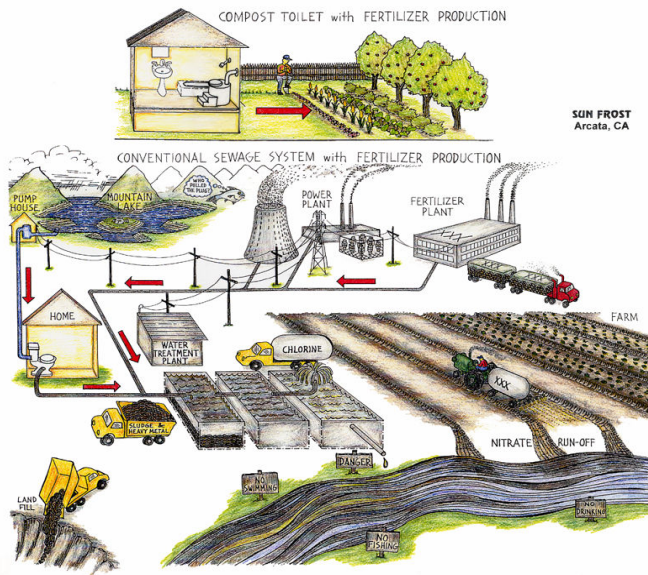


Fig. 15: System Comparison – composting toilet versus conventional sewage system

I have also unofficially incorporated a Sun Frost composting toilet. The toilet is self-contained and requires no drain field. A composting toilet conserves water and energy, and if used on a community-wide basis, would greatly simplify a city's infrastructure. It also turns a potential pollutant into a valuable soil amendment. The only energy consumed by the composting toilet is for a four-watt exhaust fan. The fan exhausts air from the composting chamber so there is always airflow into the toilet. This eliminates the need for an exhaust fan when the toilet is being used, since fumes are directly exhausted to the outside. The toilet is located in a utility room behind the house. To meet building codes the house also contains a conventional toilet. The conventional toilet also contains a similar "task ventilation system"; a small vent located between the bolts holding the toilet seat down exhausts air to the crawl space under the house. This system is highly efficient at controlling odors and also conserves electricity and reduces unwanted infiltration.

In developing countries or war torn countries such as Iraq, composting toilets would be highly effective since they would eliminate the need for the complicated infrastructure of a sewage treatment system. A well-designed toilet effectively controls pathogens so that the compost can be safely used as a soil amendment, eliminating many water-borne diseases associated with untreated sewage.



Fig. 16: Task ventilation

7. ENERGY EFFICIENT SHOWER

7.1 The Problem

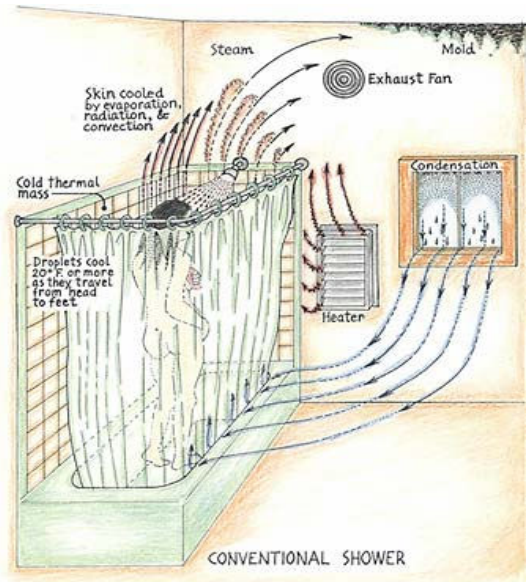


Fig. 17: Moisture and energy flow in a conventional shower

The design features of a conventional shower minimize thermal comfort, maximize energy use and water consumption while exacerbating moisture problems. Most of these negative effects are caused by evaporation. As small droplets of water fall from the showerhead, the high surface area and velocity of the particles of hot water maximize evaporative cooling of the droplets. Water saving showerheads that produce exceptionally small water particles can actually further increase evaporation. Water particles can be cooled by as much as 30°F (-1°C) as they fall from the showerhead to the ground. Convective air currents and low humidity also accelerate evaporation. With the shower curtain in place, a shower area can act as a thermal chimney; cold air enters from below the curtain, then rises as it is heated. The humidity of the moving air is kept low by condensing its moisture load on cold surfaces in the bathroom. This often results in mold growth, rotting walls or ceilings, and wet insulation; a problem that can be particularly acute in straw bale construction.

Bathroom moisture is often controlled by the use of an exhaust fan. The fan sucks out the moisture-laden air, which is then replaced by drier outside air. During the winter, the moisture level in outside air is particularly low, further accelerating the rate of evaporation. In addition, the exhaust fan increases infiltration and the heat load.

Evaporation is also the main source of heat loss from our skin. Lower humidity will result in increased heat loss from the shower's occupant and require turning up the hot water to maintain comfortable conditions. If a window is opened to control moisture, the temperature of the bathroom will be lowered. The shower's occupant will have to then turn up the hot water to stay comfortable, causing the bathroom to turn into a steam room as moisture in the humid air leaving the shower condenses in the cooler room air.

The walls of a bathroom are often covered with high thermal mass materials, such as ceramic tiles. The tiles will typically be below skin temperature resulting in additional heat loss via radiation and convection. The shower's occupant will then again compensate for this heat loss by turning up the hot water even further.

7.2 The Solution

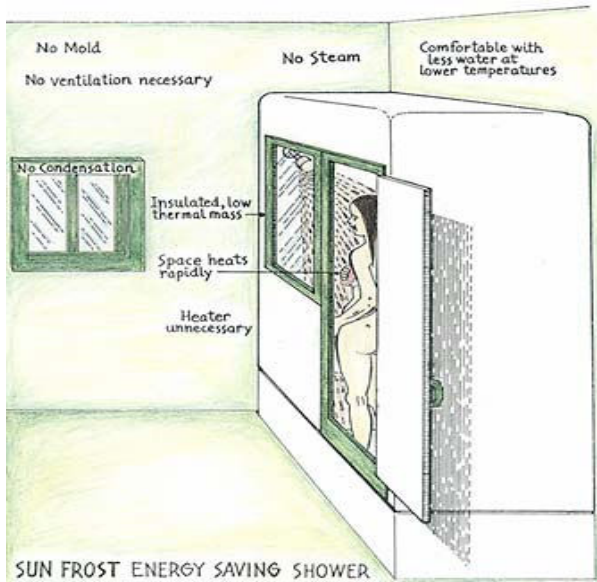


Fig. 18: Moisture and energy flow in a sealed shower

There is a simple solution to this myriad of related problems; preventing airflow to and from the showering area. Additional benefits can be obtained by the incorporation of insulated low thermal mass walls that heat up rapidly. The result is a shower stall where air currents are minimized, humidity is increased and the air is warmer. All these effects will increase thermal comfort and reduce energy and water consumption.

If the walls of the shower have a fairly low thermal mass, the shower stall will heat up rapidly so a comfortable shower can be taken even in an unheated bathroom. We constructed a shower stall for Home Power magazine. The stall has very low thermal mass; the walls are covered with "Reflectics" (aluminized bubble wrap). The top of the shower is covered with a clear plastic bubble. The shower is located in an unheated greenhouse. During the winter, when greenhouse temperatures dip to 38°F(3.3°C), a comfortable shower can still be taken.



Fig. 19: Sealed low thermal mass shower stall

A fiberglass tub/shower combination in my home was sealed with plywood and Plexiglas. This configuration allows for a comfortable shower even if the air in my bathroom dips to 50°F (10°C). After showering, I can dry off in the warmed up shower. A vent is opened in the ceiling to dry off the interior. This arrangement allows me to take a comfortable shower in a cold bathroom while using only ½ gallon (1.9L) of water per minute. Many showers use as much as 3 gallons (11L) of water per minute.



Fig. 20: Shower enclosed by curtain and acrylic glazing. Glazing extends horizontally over the shower curtain

7.3 Application in Solar Homes and Developing Countries

This energy efficient shower combines effectively with solar heating, since it allows for a fairly comfortable shower when water temperatures dip to 90°F(32°C) (typical water temperature for a shower is 105°F(40.5°C)). In tropical countries showers are often unheated. The water is generally not quite warm enough for a comfortable shower.

To boost the temperature of the water, an electrical heater located at the showerhead is often used. The sealed shower could move the water into the comfort zone eliminating electrical heating.

8. PV POWER

My 1,670-watt solar-electric system consists of ten 167-watt PV modules. During the darker part of the year, from September 21, 2004 to April 13, 2005, my net production equaled my consumption, and my PV system and solar thermal system supplied all my energy—no additional backups were required. During the summer months I contributed quite a few kWh to Pacific Gas and Electric (PG&E), my local utility company.

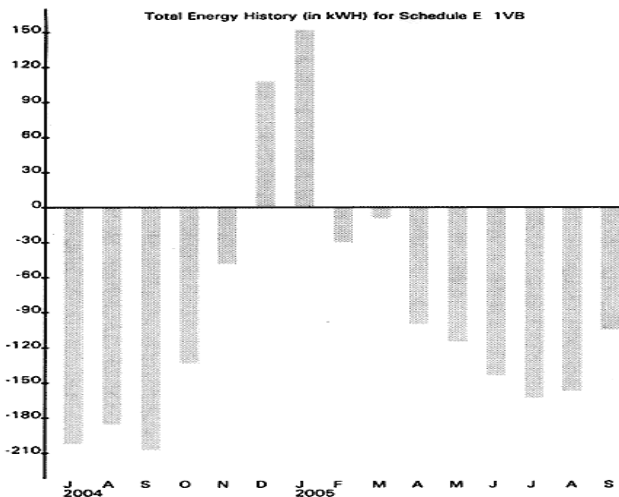


Fig. 21: Utility bill for first year of occupancy

In Arcata, the average yearly insolation is a maximum on a surface tilted 26°. This is the same as the angle of my roof, which has a 6-in-12 pitch. The average number of hours of full sun hitting my roof is approximately 4.4 hours per day. To calculate the daily output of my PV array, both inverter losses and the losses of my PV panels were estimated. The inverter is about 92% efficient. (I located my inverter in an interior space so I could readily keep track of its performance, and also capture the 8% waste heat it generates.)

The losses in the PV panels are primarily due to solar heating. For each degree Fahrenheit the panel temperature rises above 77°F (25°C), the output decreases 0.27%. A pole-mounted array will typically be about 40°F (22°C) above the ambient temperature. A roof-mounted array with a small clearance between the roof and the array could heat up to 65°F (36°C) or more above the ambient temperature. In inland California where temperatures climb above 90°F (32°C), this loss alone could be more than 22%.

For aesthetics, I used a mount that placed the panels fairly close to the roof's surface (3 in/8 cm). The mount has a skirt

in front of the panels that is only 1 3/4 inches (4.4 cm) from the roof surface. Using an infrared thermometer, I estimated that the cells were about 62°F (34°C) above the ambient temperature. With a mean daytime ambient temperature of 60°F (16°C), the average loss is then 12 %. Because increasing panel temperature can decrease efficiency, both PV panel and mount manufacturers should include information on how mounting configurations affect efficiency. However, this information is not available.

My calculations showed an overall efficiency of 81%. At this efficiency, and 4.4 peak sunlight hours per day, the output of my system should be 5.95 kWh per day, or 2,172 kWh per year. My measured output over twelve months was actually 2,130 kWh or 5.8 kWh per day. This was in excellent agreement with the calculated value; I was actually surprised these figures were so similar.

On a yearly basis, my solar-electric system produces 3.5 kWh per day for each kW of solar array. This ratio is useful to see how large an array is needed to run an appliance. For example, my Sun Frost refrigerator consumes 0.27 kWh per day. Seventy-seven watts or a little less than half of one of my 167-watt modules can run the refrigerator.

The installed cost of a grid-tied system can range from US\$6,500 to \$11,000 per kW, depending on the ease of the installation, the cost of the equipment and labor, and the size of the system. Assuming the cost per kW is US\$8,500 in Arcata with an average production of 3.5 kWh per kW of solar array, an investment of US\$2,444 is required to produce one kWh per day. In a stand-alone system, the investment required to produce 1 kWh per day is roughly double that, or US\$5,000.

Conservation is a good investment if you can reduce your energy consumption 1 kWh for less than the cost of generating 1 kWh. For example, in a grid-tied system, if you purchase a product that consumes a kWh less than a competing product and its additional cost is less than US\$2,444, it would be a good investment. The product should have the same life expectancy as the PV system. In an off-the-grid system, an investment up to US\$5,000 would be worthwhile to save a kWh per day.

9. CONCLUSION

Numerous strategies are available for reducing a home's energy consumption. If we are going to make a significant impact on the nations' energy consumption, the most cost effective strategies must be emphasized.