A standard solar hot-water system,
for winter space heat and domestic hot water in rural northern New Mexico

My goals

- Convert 1984 two-bedroom, partly passive-solar house from electric-baseboard heat and electric DHW to all solar.
- Size the system so there will be no need for backup: enough collector area for all winter heat needs, and enough storage for a couple of cloudy days in mid-winter. (I have no natural gas.)
- Make it look good.
- Buy American, when possible.
- Do all the design and construction work myself, for fun, to learn, and to be able to afford a first-class, durable system. Guidance from Ramlow's book *Solar Water Heating*.
- Document the work well enough that a future owner of this house will maintain it.

Preliminaries

Insulation! This has been a twenty-year evolution---I've invested in insulation whenever some other repair, remodel, or improvement easily allowed it, plus I made some pure-insulation improvements.

- The attic now has about a foot of fiberglass bats, on top of what was originally a flat tar-and-gravel roof with a few inches of foam board.
- The outside of the house was sprayed with 3 inches of polyurethane foam before the most recent coat of exterior plaster was applied (and the north wall has extra foam). Sprayed-foam exterior wall insulation is a common retrofit for New Mexico adobe homes today. The same contractors spray it on flat roofs, too, for insulation and waterproofing in a single step. On walls, it's best to dig down at the base a little so the foam insulates part of the foundation, too. After the walls are foamed and trimmed, another contractor applies chicken wire and plaster (which I think would be called stucco in most of the US). With the thermal mass of the adobe walls inside such good insulation, the house barely responds to the day/night outdoor temperature changes.
- I put foam board on the garage side of the adobe wall between the kitchen and the garage.
- All doors and windows are now at least double-pane. Most also have one of the following in winter: insulating cellular shades with edge seals (Comfortex: ComforTrack Plus Sidetrack), home-made, interior storm-window inserts (as described elsewhere at BuildItSolar), or home-made foamboard-and-mylar door inserts for doors that I don't use in the winter.

After the insulation improvements, I assessed the remaining need for solar heat:

- I reviewed monthly electric bills for the past four years. I assumed 5 kW-h per day to be non-heating loads; the rest became my target for the solar collectors. (If you have gas heat, you could do the same kind of estimate from your gas bill if you know the efficiency of your boiler.)
- I used standard solar-energy tables and free calculational tools (I used RadOnCol) and collector efficiency to estimate total collector area and a collector tilt angle that would work well at my latitude and my ratio of winter/summer load needs.
- During a particularly cold spell, I read the electric meter daily to find out the heating load on typical coldest days. I chose the storage-tank volume to supply that much heat for two cloudy days while dropping only about 30 deg F. If the house had already had a normal natural-gas-fired hydronic system, I would not have been so extreme about the storage-tank volume, but, with electricity as my only choice, I wanted to try to eliminate any need for supplemental winter heat.

Overview of solar hot-water system

There are three distinct, connected water systems involved here (in addition to the house's ordinary potable water supply), which I'll call the solar system, the storage system, and the hydronic system. The solar system is filled with water-antifreeze mixture. It connects the solar collectors and the excess-heat dumper with the utility room. The storage system is filled with clean water that is exposed to air. It connects the big storage tank with the utility room. The hydronic system is filled with clean water not exposed to air. It is a traditional hydronic-heating setup that connects the utility room to all the heat loads in the house. In the utility room, heat exchangers interconnect these three systems without allowing their fluids to mix. There's a block diagram near the end of this report.

2000 gallon storage tank

This fiberglass tank from Design Tanks is officially rated at 180 degrees F. I am using it only to 160 degrees F. I was willing to spend a bit more for 20 degrees of safe headroom, since the tank will be difficult to access if there is ever a problem with it.

The soil here is very sandy and shifty, so I dug deep and made a thick concrete slab with plenty of rebar, smooth and flat to 1/16 inch. Atop that, 8 inches of polyisocyanurate foam board, which handles heat under load better than polystyrene. Atop that stands the tank. (It was fun putting the tank in place single-handedly with skids, ropes, earth anchors, a temporary wooden gantry, and a few chain hoists and come-alongs. I imagined that the builders of the Egyptian pyramids would have approved.)

Figure 1. Rebar ready for pouring concrete to make the foundation under the storage tank.

The water pipes go into the tank through flanges on top--- no worries about leaks there. One pipe vents the air space on top of the tank to atmospheric pressure inside the house; one pipe extracts water near the top of the tank; one pipe injects water a few inches from the bottom of the tank. Two 1/4-inch tubes go from near the top of the tank to the utility room. In the tank, one 1/4-inch tube ends a cm above the other, with the desired water level between them. Using a turkey baster in the utility room to see if one tube draws air and the other draws water lets me know if the water level is in the right place. I'll add distilled water annually, as evaporation takes its toll.

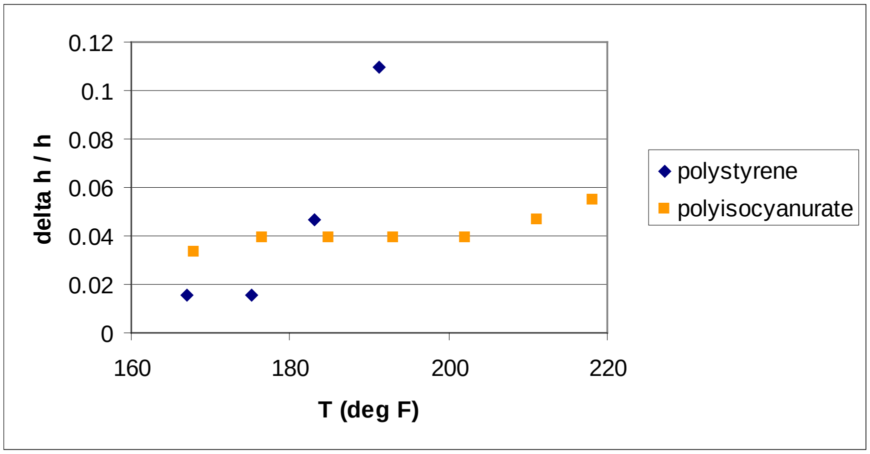


Figure 2. My tests of foam-board strength at high temperature. The polystyrene was rated at 165 deg F, 25 psi. The polyisocyanurate was rated at 200 deg F, 20 psi. Dow (blue polystyrene) recommends 3x safety factor for creep. I loaded 3 inch x 3 inch pieces of these foams with 40 pounds of steel, giving 4.4 psi, and heated them in my oven (approx 5 deg F per day), measuring height reduction as a function of temperature.

Figure 3. The tank in place atop the foam boards (which are out of sight below ground level), with pipes into the house and framing done.

After filling it with water so the tank would settle in to its final place, I hired a professional to spray 8 inches of polyurethane on top and all sides.

Then I finished the roof and walls to match the house. (Visible in collector photo, below.) (I hired a professional to do the plastering, because I know I can't do that well enough myself.)

All of the tank-shed framing is independent of the house, built up from the tank's slab. If the tank weight causes the tank slab to settle, the tank's shed will settle, too, independent of the house.

Figure 4. Details of pipe penetrations atop the storage tank. Thermistor wires also visible.

Figure 5. After the foam insulation was sprayed onto the tank.

Solar collectors

Four Radco 4 ft x 12 ft collectors, with the black chrome-oxide coating. The steep angle is so they will not get too much heat in summer. Ground mount, because putting them on my roof at this angle would've looked awful. Horizontal, so they don't block a nice view of distant trees from my back porch and windows. The bottom-right corner of the rightmost collector is the last to see morning sun in the winter, at 9 a.m.

The collectors came with nice support hardware intended for installing them on a flat roof. I mounted that hardware on threaded rod imbedded in concrete in the ground. The threaded rods for each collector were held in correct relative position by being bolted into boards while pouring and curing the concrete.

Figure 6. In the foreground, the two threaded rods for the right-front corner of collector number 2 are sticking out of concrete. The wood templates that temporarily hold the threaded rod in correct relative positions for collectors 3 and 4 are in the background.

Figure 7. In the distance, the storage-tank shed is complete with sheet-metal roof and exterior plaster. In the foreground, the four collectors are mounted. From left to right: Collectors 1 and 2 are in series; collectors 3 and 4 are in series. These two sets are in parallel. (I covered them with canvas tarps during the year I was finishing the plumbing, even though the manufacturer said that was completely unnecessary.)

The collector copper piping is insulated with 1-inch-wall foam-rubber insulation. (Armaflex UT Solaflex for the high-temperature runs, and ordinary Armaflex for the return runs.)

For the above-ground sections of piping behind the collectors, I got some 12-inch galvanized and enameled sheet-metal strips (a standard width) bent into 4-inch-square "U"s by our local metal-roof and gutter supplier. I cut and folded this stock as needed to make color-matched insulation covers. Generally, one piece is screwed to the back of a collector, facing out, and the other is pop-riveted to the first, facing in. Practice with stiff paper let me plan the folds and overlaps for best rainfall shedding.

Figure 8. Above, the top-right corner of collector 4, showing the soldered copper piping, some insulation, a thermistor, and a piece of the square-U sheet metal attached to and facing out from the back of the collector. (This photo was taken before I added the air-release vent to this location.) Right, the mating piece of square-U sheet metal has been added. Folds and overlaps between the pieces of square-U shed rainfall from above and from the prevailing wind direction. Below, the transitions from sheet metal covers to underground PVC covers between collectors 2 and 3. (The yellow wire is the unluckily located TV cable.)

Also for good looks, I decided to bury all the lines between the collectors and the house. Four-inch S&D PVC pipe covers the insulated copper pipes below ground. I split PVC tees and elbows in half, and clamped them back together with hose clamps while the usual PVC cement set; finally sealing the little saw cuts with caulk and electrical tape and/or duct tape. I worked hard to tamp the backfill under and around these buried pipes so they won't settle through the years.

Waste-heat dumper

How to get rid of unwanted heat on sunny autumn days when the storage tank is at its maximum temperature? I figured that I wanted to be able to dump the entire incoming solar power, allowing for collector efficiency of 0.6, but also allowing a lot extra if I ever put reflectors on the ground in front of the collectors to get more heat in winter.

My solution? **Figure 9:** Eight finned-copper radiators (SlantFin C340) tucked behind one collector. Covered to prevent accidental dents, but to still allow cleaning with a garden hose. Mounted on four vertical stainless-steel square bars and two crosspieces, each vertical bar being anchored in a 4-inch-diam, 18-inch-deep concrete column.

I think another acceptable solution to this issue with ground-mounted collectors (or roof-mounted on an easily, safely accessible flat roof) is to put tarps on half the collectors for a few months of the year. A friend of mine happily adopted this approach. I did not, because I did not know if a future owner of my home would accept the hassle.

House penetration

So, going from the trench into the house, altogether there are five pipes (two, insulated, for the collectors; two, uninsulated, for the waste-heat dumper, and one, PVC, for a sump-pump ejection described below) and 4 thermistor wires (three for curiosity or spares!). These pass through the wall of the house in a green, 6-inch-diameter PVC penetration pipe that is poly-foamed into the house wall. It runs diagonally: below ground outdoors, yet above the floor indoors. Here is **Figure 10**, a photo of the underground end of that green pipe, with the foam-rubber pipe insulation in place on the collector pipes, their 4-inch PVC covers visible on the right, the naked copper pipes to the waste-heat dumper (though I insulated the hot one inside the green pipe and for a foot into the ground), and a cardboard mold that will contain the foam that I will apply to the entire elbow region to keep burrowing varmints out of the house. Also shown in this photo is the unluckily located telephone wire, which happened to be in the vicinity.

Utility room

A few Taco circulators, one expansion tank for the solar system and another for the hydronic system, and two brazed-plate heat exchangers ITT BP411-030MT: one for solar-to-storage (HX3 in the block diagram), the other for storage-to-hydronic (HX4).

I like having several pressure gauges and thermometers easily visible.

Hydronic subsystem

Most people who would undertake a solar project like this would probably be connecting it to an existing hydronic heating system, so I won't describe this in as much detail.

Potable water: A standard "indirect" hot-water tank (ST11 in the block diagram), with the hydronic heat-transfer coil at the bottom, and electric backup in the middle (which I have never turned on).

Living room and kitchen: Two big Beacon-Morris kick-space units (HX6 in the block diagram) are hidden behind the kitchen pantry shelves.

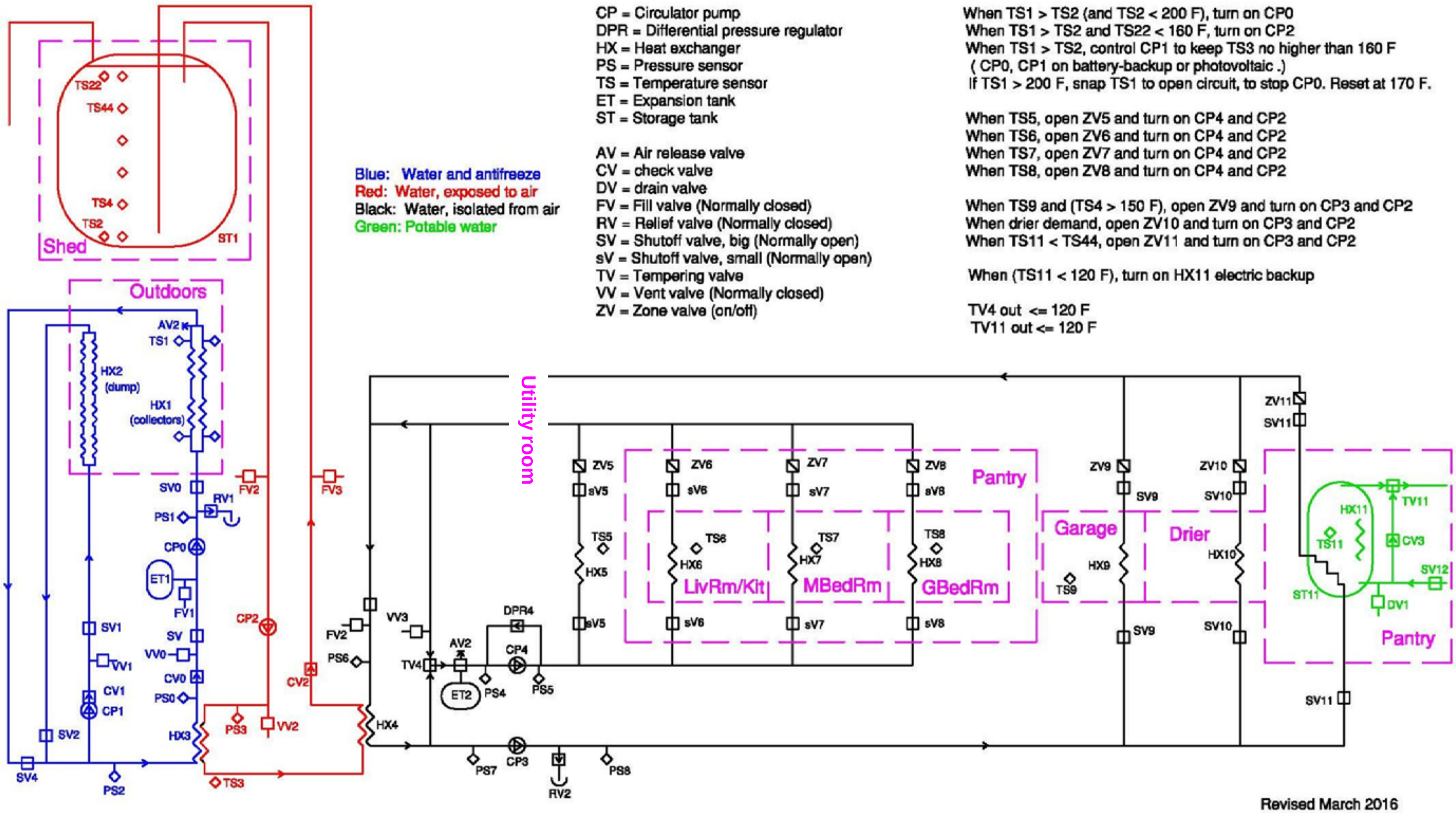
Master bedroom and bathroom: Handsome cast-iron radiators (HX7 in the block diagram).

Guest bedroom: PEX under a new wood floor (HX8 in the block diagram). Guest bath: no exterior walls, so no need for its own heat.

Utility room: The smallest Beacon-Morris kick-space heater (HX5 in the block diagram), in the wall in a cabinet.

Garage: I installed the valves and pipes, but have not yet installed any heating unit.

Modern programmable thermostats in each room, much nicer than the dumb baseboard-electric thermostats I had before.


CP = Circulator pump
DPR = Differential pressure regulator
HX = Heat exchanger
PS = Pressure sensor
TS = Temperature sensor
ET = Expansion tank
ST = Storage tank
AV = Air release valve
CV = check valve
DV = drain valve
FV = Fill valve (Normally closed)
RV = Relief valve (Normally closed)
SV = Shutoff valve, big (Normally open)
sV = Shutoff valve, small (Normally open)
TV = Tempering valve
VV = Vent valve (Normally closed)
ZV = Zone valve (on/off)
When TS1 > TS2 (and TS2 < 200 F), turn on CP0
When TS1 > TS2 and TS22 < 160 F, turn on CP2
When TS1 > TS2, control CP1 to keep TS3 no higher than 160 F
(CP0, CP1 on battery-backup or photovoltaic .)
If TS1 > 200 F, snap TS1 to open circuit, to stop CP0. Reset at 170 F.
When TS5, open ZV5 and turn on CP4 and CP2
When TS6, open ZV6 and turn on CP4 and CP2
When TS7, open ZV7 and turn on CP4 and CP2
When TS8, open ZV8 and turn on CP4 and CP2
When TS9 and (TS4 > 150 F), open ZV9 and turn on CP3 and CP2
When drier demand, open ZV10 and turn on CP3 and CP2
When TS11 < TS44, open ZV11 and turn on CP3 and CP2
When (TS11 < 120 F), turn on HX11 electric backup
TV4 out <= 120 F
TV11 out <= 120 F
Blue: Water and antifreeze
Red: Water, exposed to air
Black: Water, isolated from air
Green: Potable water
Shed
ST1
TS22
TS44
TS4
TS2
Outdoors
AV2
TS1
HX2 (dump)
HX1 (collectors)
SV0
RV1
PS1
CP0
ET1
FV1
SV
VV0
CV0
PS0
HX3
SV1
VV1
CV1
CP1
SV2
SV4
PS2
FV2
FV3
CP2
CV2
PS3
VV2
TS3
HX4
PS6
VV3
TV4
AV2
ET2
PS4
DPR4
CP4
PS5
PS7
CP3
RV2
PS8
Utility room
ZV5
sV5
TS5
HX5
ZV6
sV6
TS6
HX6
LivRm/Kit
ZV7
sV7
TS7
HX7
MBedRm
ZV8
sV8
TS8
HX8
GBedRm
Pantry
ZV9
SV9
Garage
HX9
TS9
ZV10
SV10
Drier
HX10
ZV11
SV11
HX11
TS11
ST11
TV11
CV3
SV12
DV1
Revised March 2016

Features for disaster prevention

The antifreeze-loop circulators and controls are plugged into a backup power unit, to prevent the collectors from overheating when the electricity goes down (more frequent here than in cities). The batteries should last about 5 hours. I hope that is enough for our typical power outage, and/or to get us through the hottest part of the day. This has been working fine for several years now.

The antifreeze expansion tank should be big enough to handle complete boilout of the collectors if the circulator fails, but I've put in a 75-psi relief valve whose discharge is routed to a plastic bucket just in case. This is the first thing the county building inspector looked for when he came to approve my installation. (Warning story: A friend's President-Carter-vintage solar system was "fixed" by a professional recently, who failed to diagnose a ruptured expansion-tank bladder and thus overfilled the antifreeze loop. Without a pressure-relief valve, this misdiagnosis would have led to a catastrophe on the next sunny-day power failure or circulator failure. Don't think you can get by without a relief valve!)

Water damage is a serious threat in my house, because it is slab-on-grade with the adobes stacked right on top of the stem wall, which sticks up only 1 inch above the top of the slab in the utility room --- thus, more than an inch of water standing in that room will begin to dissolve the adobes. I can imagine either a slow leak or a catastrophic leak near the tank-loop circulator, which could siphon much of the 2000-gallon storage tank into the house. To reduce the potential volume of such a leak, there is a swing check valve that will prevent siphoning from the pipe that goes to the *bottom* of the tank, so siphoning can only take place until the pipe at the *top* of the tank starts sucking air --- so only about 100 gallons could come quickly into the house. To handle that possibility, I cut a shallow sump in the utility-room floor, with a water sensor (plumbingsupply.com, Electronic Utility Pump Switch, HC6000) and "floorsucker" pump (Utilitech PPSU25, 1/3 hp, 1500 gpm). This ejects water outdoors, through a small PVC pipe mentioned in Figure 10. The pump is only rated to 100 deg F, but water from a slow leak should cool down ok as it spreads across the floor.

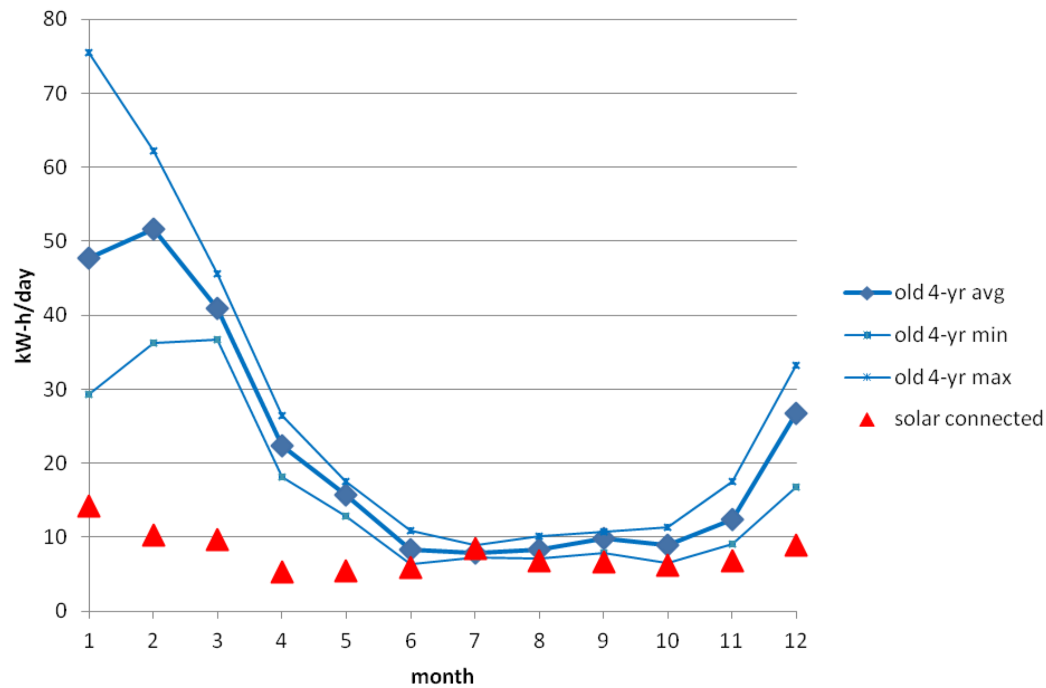
If there is ever a problem in my big storage tank, I'll have to take the roof off its shed, carve through the foam insulation, and get into the tank itself through the hatch shown in Fig. 4.

Performance thus far

There was a winter in which the insulated storage tank was full of water but nothing was hooked up. The tank never got colder than 43 deg F, despite being on the north side of the house where old snow typically hangs around for months. So the insulation seems fine.

Here is a graph showing electricity usage vs month. Vertical axis is energy use shown on my electric bill. Horizontal axis is month receiving the bill (e.g., 1 = January's bill, covering part December, part January).

The blue lines show monthly average, minimum, and maximum during the 48 months before I started the solar system. The red symbols show what happened the first 12 months after I got it all hooked up.



What's responsible for my remaining electricity usage?

- The circulators, controllers, and pantry fans for all this new stuff use around 5 kW-h/day in the winter, half of that in the summer.
- The kitchen refrigerator is 1.5 kW-h/day.
- Well-water pumping is roughly 0.1 to 0.3 kW-h/day during winter, but as high as 3 kW-h/day in summer, depending on rainfall and irrigation-ditch availability. This accounts for the high July bill last year.
- The clothes drier is another very roughly 1 or 2 kW-h/day, on average, I think.
- The rest must be cooking, lights, and computer.

During that first year, the storage tank was usually around 120 deg F in the winter, 135 deg F in the spring and early summer, and 155-160 deg F in late summer and fall (with the waste-heat dumper running very frequently during mid fall).

Cost--benefit considerations

Cost of solar and storage equipment: $27,977. This does not include my own labor, nor the hydronic components (roughly $6,000) which I did not think I should claim for renewable-energy tax rebates.

Federal and state tax rebates (40% of equipment cost but not including sales taxes): $10,909.

Net cost: $27,977 – $10,909 = $17,068.

Savings in utility bill, first 12 months: $620. (Plus I enjoyed the house being more comfortable all winter than ever before.)

Tax-free, risk-free annual return on investment: $620/$17,068 = 3.6% if we include only my net cost for the equipment I claimed for the tax rebates. Including also the $6,000 cost of the hydronic parts reduces this to 2.7%, which I think is still good for a guaranteed, tax-free return. If energy costs go up in the future, this rate of return on investment will rise.

Regrets, doubts, etc.

What I was stuck with: I wish the slab under the house was insulated. I wish the foam wall insulation extended farther underground. I wish there was an easy way to insulate the tops of the adobe walls, where the roof rests on them. I wish the windows were low-e. But no one was thinking of expensive energy when this house was built.

I wish I had paid more attention to the electricity consumption of different brands and sizes of circulators---maybe I could have designed for lower electricity usage. Maybe the collector and waste-dump circulators (and their controllers) should have been photovoltaic powered, to save utility electricity and to avoid the battery-backup hassle.

I should have thought more carefully about the 120 Vac / 24 Vac interfaces, to avoid some relays. I should have thought more carefully about controllers, instead of choosing to use the same controllers and circulators as a friend of mine has so we can share spare parts.

I should not have bothered installing a hydronic heater in the utility room. That room is now perfectly comfortable all winter from heat leak through the insulation on all the piping.

I should not have bothered installing hydronic pipes to the garage. I'll probably never install a heater there.

I should not have bothered with differential pressure regulator DPR4 and tempering valve TV4 in the hydronic system. I don't think they are ever doing anything. Maybe I should also have skipped the potable tempering valve TV11, although that might protect residents from scalding in the fall when the water is hottest.

I should have done a better job of color-matching the piping covers on the backs of the collectors to the collectors themselves. Don't trust memory to "recognize" a color!

The tank and its shed were expensive. Maybe 1500 gallons would have been a better choice. Or, a completely new approach, suggested by the foam-spraying guy: Dig a hole, pour a concrete floor in the hole, add foam boards, with the tank up on the ground spray-insulate the top and sides of the tank, adjusting the foam mix for good insulation near the inside and durable hardness near the outside, set the tank into the hole, bury everything, and install all plumbing and circulators through a single, central hatch on top. He says there's no worries about crushing the foam if they tune the mix properly, and no worries about varmints burrowing into it. Or, consider a welded stainless-steel tank instead of fiberglass, if you are a good welder---it would be more expensive, but would eliminate some overheating-prevention hardware and controls.

The most unexpectedly unpleasant and time-consuming part of the project was the underground installation of the piping between the collectors and the house. I had to hand-dig all of it, because of many buried utilities in the area. Even with large sub-assemblies made comfortably, I had to finish many joints lying on my stomach and reaching into the trenches. So, I wish I had kept a lot of that piping above ground, tucked up against the backs of the collectors. I wish I had thought about disguising the rest of that piping as something attractive above-ground, like a trellis attached to the house.

Further notes, four years later…

Ramlow's book *Solar Water Heating* advises that an air-release valve should be unnecessary in the antifreeze loop if the air is purged well enough when filling the system. That advice did not work well for me. With no air-release vent, I found that gas accumulated in the antifreeze loop after a few years of operation, impeding flow. So, I added an air-release vent. It is shown above, in the plumbing diagram on page 9, and in the second (right) part of Fig. 8.

I ended up using my old baseboard-electric heaters in one bedroom for 12 cold nights in the first winter. That was most of the remaining winter peak in the electricity usage. To try to fix this, I added slick white-tarp reflectors stretched flat on the ground in front of the collectors during the coldest months, but was disappointed that they only added about 7% more heat into the collectors during winter and early spring. I had expected them to be as reflective as fresh snow, but they quickly get dirty. Maybe I should've used five or six collectors instead of four!

For windows without the Comfortex +ComforTrack/Siderack insulating shades, I made some double-mylar "storm windows" as described at http://www.builditsolar.com/Projects/Conservation/MylarStorms.htm to use in the coldest months, hoping that improves the windows from about R2 to about R4. Aluminum frame kits from Lowes; 2 mil mylar; Scotch permanent double-sided tape (yellow box, cat 665). For three doors that I never use in winter, I made similar inserts to go between the existing inner and outer doors. These door inserts are made of 2 inch foam board, painted with white Latex, with "windows" cut through and covered on both sides with clear plastic film.

Finally, I got 2 kW of photovoltaic installed on the roof, net metered. The roof angle was perfect for this. Averaged over a full year, the "net" is slightly in my favor. So, finally, I have a zero-energy home. Here are photos in 1985 (from southeast) and 2014 (from south-southwest):

Future improvements

I plan to make a hydronically boosted clothes drier.

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