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Optimizing for High-Performance Solar Water-Heating Systems

In the first of a two-part series, **we examine ways to improve efficiency.**

By **GARY KLEIN**

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You have decided to install a solar water-heating system. There are many questions you need to answer, but for purposes of this two-part article we'll focus on four: What size does the solar-heating portion of the system need to be? Will you have a supplemental water heater? What size supplemental water heater do you need? What is the "best" supplemental heater to install? This article will focus on answering these questions for single-family residential applications, but the principles apply to all situations.

In the first article, we'll examine the first two questions. Specifically, we'll discuss how to squeeze the water and energy waste from your hot water distribution system, which might enable you to depend on smaller water heaters. Look for a discussion on sizing your supplemental heater and a recommendation for the best type in the November/December *SOLAR TODAY*.

Taking a Whole-System Approach

First, some background. I installed my first solar thermal system in 1974 and my first photovoltaic system in 1979. The thermosyphon solar thermal system that I installed in 1981 at my off-grid house in California is still working, although it is time to reapply the black absorber coating. That system has no integrated hot water backup. The few days a year when some combination of use and lack of sun causes us to run out, we heat water on the stove, do what I call "dry cleaning" — wash up using very little water — and wait for the sun to return the next day.

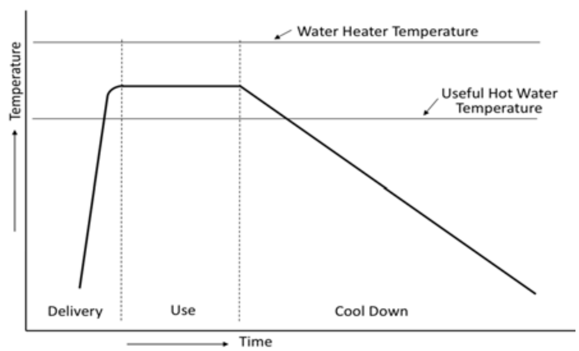
Since 1993, I have focused on hot water as a system, something building science has tended to ignore. I have interviewed more than 20,000 people nationwide and in several other countries to determine what people want and expect from their hot water systems. (For a discussion of these expectations, see Klein and McCabe, "The Future of Hot Water and Solar Thermal," presented at SOLAR 2010 and published in *Solar@Work*: tinyurl.com/28skedd.) The recommendations I present in this article come from this background and from my studies of how the components of a hot water system interact with each other and the desires of the people who use them.

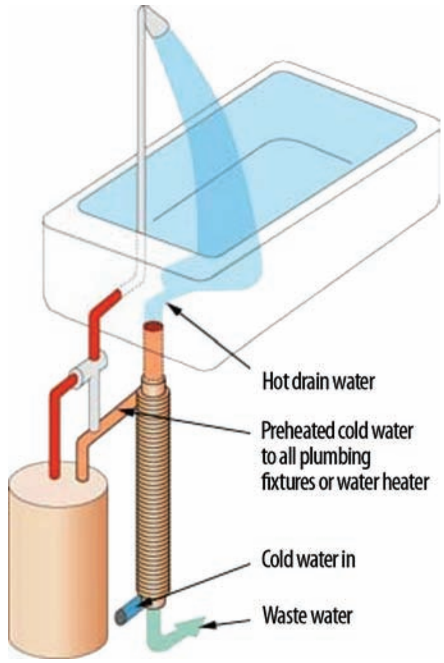
Figure 1, at right, shows a typical hot water event: There's a *delivery phase*, a *use phase* and a *cool-down phase*. People would like the delivery phase to be short. According to those interviewed, a few want hot water to arrive immediately after they open the tap, which is possible but rather expensive. Well over 90 percent say they want the time to tap to be between 2 and 3 seconds!

The speed of *delivery*, which can be stated in terms of volume-to-hot as well as time-to-tap, depends on the method of heating the water and the location of the water heater relative to the hot water outlets. If you want hot water to arrive "instantaneously" (say, in less than 3 seconds), two things must be true: You need hot water in the water heater before the start of each hot water event, and the water heater needs to be close to where it is needed. An instantaneous water heater is one in which hot water leaves the water heater immediately when one calls for hot water. Contrary to the definition in federal statutes, this describes a water heater that has some amount of storage that is hot. With only a couple of exceptions, tankless water heaters, which I would define as on-demand, continuous heaters, have no such storage and are therefore *not* instantaneous.

You can make the *use phase* — washing dishes, taking showers or whatever application — more efficient. This can be achieved through water-efficient equipment (aerators, showerheads, dishwashers and washing machines) and energy- and water-efficient behaviors (taking shorter showers or using cold water to wash clothes). However, making the use phase more water-efficient may result in unhappy customers if we ignore the impact of the other system components, such as the hot water-distribution system's effect on delivery times or the fact that tankless gas water heaters do not fire at low flow rates. By the way, the typical household generally has an observed peak hot water flow rate of less than 3 gallons per minute, or gpm (11.4 liters per minute); there is more diversity and less overlap of uses than one might suspect.

FIGURE 1: **TYPICAL HOT WATER EVENT**





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Installing a drain-water heat-recovery system on the showers can capture roughly half of the temperature rise from incoming cold water to the mix-point temperature of the shower. Showers represent 75 to 80 percent of a household's hot water use.

How much hot water do we use? While there is clearly a large standard deviation, we can reasonably estimate that an adult in the United States uses about 20 gallons (76 liters) of hot water per day. For a typical family of three, that means 60 gallons per day. Assuming that the temperature rise is 90°F (from 50°F to 140°F), it takes about 275 therms, or 5,750 kilowatt-hours, to heat this water every year, factoring in the efficiency of the water heater. Then there is the cost for the water itself. Nationally, the average cost is $0.006 per gallon for water and sewer combined, or $130 annually for this family's water. Assuming that natural gas costs $1 per therm and electricity costs $0.10 per kilowatt-hour, the total cost for hot water is about $400 per year for the family that heats with natural gas or about $650 per year for that family that heats with electricity. These numbers give us an idea of how much we can afford to spend on hot water systems for water and energy savings: We cannot save more than we spend!

PHOTOS BY DAVID SCHUMACHER, TAKEN DURING THE 2010 ANNUAL CONVENTION OF THE FLORIDA ASSOCIATION OF PLUMBING, HEATING AND COOLING CONTRACTORS.

Above, minimizing the volume in piping between the source of hot water and the hot water outlets reduces waste. Depending on diameter, pipes as small as 6 inches and as long as 25 feet can have the same volume. Each of these pipe lengths holds 1 cup of water. Right, in addition to reducing piping volume, we should also insulate pipes. For equal heat loss per foot, half-inch pipe gets half-inch wall thickness, three-quarter-inch pipe gets three-quarter-inch wall thickness and so on.

The *cool-down phase* begins when you turn off the tap, with the temperature of the water in the pipe cooling from the water heater all the way to the hot water outlet. It takes on the order of 10 to 15 minutes for the water in uninsulated pipes to cool from 120°F to 105°F when the pipes are located in air at a temperature between 65°F and 70°F. The water cools more quickly when the surrounding temperature is colder, such as in a basement or a crawl space or when the pipes are located in or under a concrete slab. Likewise, it cools more slowly when the pipes are insulated or in a hot attic.

> Wringing out the wastes and using water more efficiently can reduce overall hot water demand by 25 to 50 percent. It also reduces the size of a solar water-heating system required.

The water heater must be set to a higher temperature than the mix-point temperature, and the useful hot water temperature needs to be less than the point at which you mix it. Why? You need to have some headroom from the mixing point down to the useful hot water temperature point because of variations in desired temperature for any given application on any given day.

I would also observe that as solar practitioners, we can do very little to effect behaviors directly. What we can do is install systems that reduce the structural wastes so that we can encourage water- and energy-efficient behaviors.

Squeezing Out System Inefficiencies

What size does your solar water-heating system need to be? My take on it is that, in general, we can do more to wring out the wastes in the hot water distribution system and to install water-efficient faucets, showers, dishwashers and washing machines. We are after the most cost-effective, resource-efficient hot water system.

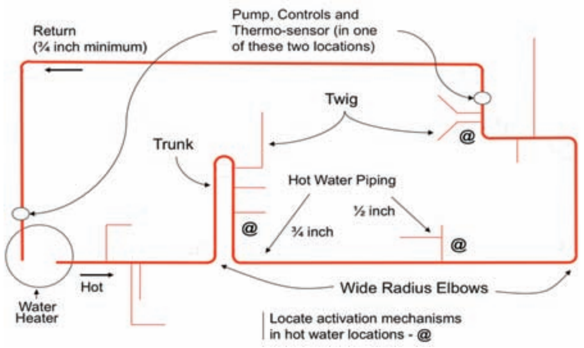
In addition to the size of the solar collectors, we need to consider how close to hot water outlets the storage tank for the solar water heater is located. If storage is far from the outlets (volume in the pipe is what matters), what will you do to minimize wasted water, energy and time for hot water to arrive after you turn on the tap? Can the hot water distribution pipes be insulated? Is it possible to install a drain-water heat-recovery system to capture waste heat from showers as water runs down the drain?

Water wasted during the delivery phase of a hot water event — that is, the volume of water that comes through the pipe from the water heater to the hot water outlet before hot water arrives — can represent 10 to 30 percent of the total hot water consumed. The amount of water wasted is larger than the volume in the pipe. This additional waste of water is on the order of 1.3 times the volume in the pipe for flow rates around 2 gpm; in general, the extra waste goes down as flow rate goes up, and it goes up as flow rate goes down. At flow rates less than 1 gpm, the volume of water delivered before hot water arrives can be double the actual volume in the pipes.

All of this water came through the water heater, so there is energy attached to it. Don't believe that the energy is free because we have installed a solar water heater! We had to pay for this waste in the cost of a larger-than-necessary system and whenever the supplemental heater is operating, right? It makes sense to minimize the waste, because if it is small enough, we may be able to install a somewhat smaller solar system and get more useful value from the solar-heated water it produces.

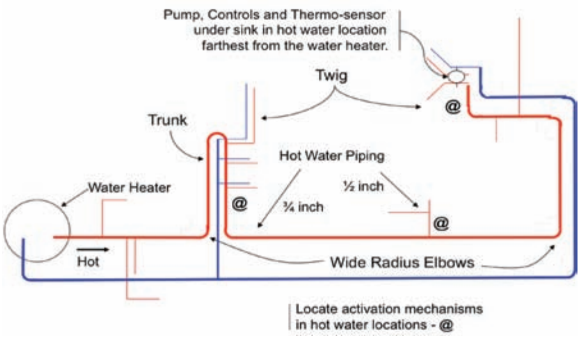
The amount of energy wasted due to the volume of hot water in the piping is larger than one might have thought. There are three kinds of waste: that lost in the delivery phase, that lost

FIGURE 2: **STRUCTURED PLUMBING WITH A DEDICATED RETURN LINE**



in the use phase and that lost in the cool-down phase. Minimizing the volume in the piping between the source of hot water and the hot water outlets reduces all three of these wastes.

FIGURE 3: **STRUCTURED PLUMBING USING THE COLD WATER LINE AS A TEMPORARY RETURN**



It reduces the time-to-tap and volume-to-hot during the delivery phase. It reduces the temperature drop during the use phase, which means that hotter water will arrive at the outlets, so less will be used when it is mixed to meet the desired temperature. It could also enable us to reduce the set-point temperature of the supplemental water heater. Reducing the volume in the piping saves energy during the cool-down phase because there is a smaller mass of water to cool down, which it will eventually do if the time between hot water events is long enough.

When we reduce piping volume, we should also insulate pipes. Pipe insulation helps in all three phases of a hot water event. If the piping goes through a thermally adverse environment, such as a vented crawl space, the insulation makes it possible for hot water to maintain heat to delivery without an abnormally high set-point on the water heater. During the use phase, insulation on pipes surrounded by room-temperature air will, for a given flow rate, reduce the temperature drop over a given distance by roughly half. During cool-down, pipe insulation extends the time during which the water in the pipes remains hot enough to use. On half-inch nominal piping, R-4 insulation roughly doubles the cool-down time, and on three-quarter-inch nominal piping it triples it. In terms of the amount of insulation, I like to aim for an equal heat loss per foot of pipe regardless of pipe diameter. That means for a given k-factor of pipe insulation, the wall thickness of the insulation should be equal to the nominal pipe diameter for all piping greater than a quarter-inch nominal.

What configuration of plumbing we should use depends on the layout of the hot water outlets in relation to the water heater location. Because installing a solar water-heating system is relatively expensive, we'll probably have one primary location for the storage and controls to keep costs in check. Our system is also likely to have one backup system, although it is worth considering installing remote heaters near the points of use. Unless we keep the volume very small, say to 1 quart, in

Water wasted during the *delivery phase* of a hot water event — that is, the volume of water that comes through the pipe before hot water arrives — can represent 10 to 30 percent of the total hot water consumed.

each path of the hot water-distribution system from the water heater to the hot water outlets, it makes sense to consider zoning the distribution system. A typical house is likely to have one or two hot water zones; larger and more complex layouts could easily have three or more.

Home-run plumbing systems, which feed hot and cold water separately through small-diameter piping to each fixture from a central location, may make sense from the perspective of minimizing water, energy and time when the volume of hot water in each pathway is very small (less than 1 quart). They are best suited to situations where it is unlikely that hot water events will occur often enough that the temperature of the water in the pipes would still be useful at the same outlet or at outlets on what would have been the same branch line. Over the life of most households, that is unlikely to be the case, although it may be true in some commercial installations.

A concept called Structured Plumbing (a proprietary concept of ACT Inc. Metlund Systems) is a better choice in most applications. Figure 2, at top left, shows a diagram of a structured plumbing system with a dedicated return line. This system includes an on-demand pump, the controls and the activation mechanisms in each hot water location (except those very close to the water heater). The on-demand pump primes the hot water line with hot water after being activated by the user, on demand, shortly before it is needed. In addition, the supply portion of the circulation loop is located close to each hot water

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outlet, so that the volume of water that must be cleared out of the pipe at the beginning of the draw is very small.

Figure 3, on page 63, shows a structured plumbing system that uses the cold water line as a temporary return. This is the most common configuration in retrofit applications, where you are unlikely to improve the layout of the plumbing.

Why on-demand pumps? They are the most energy-efficient way to have the benefits of a hot water circulation system.

Once we have improved the hot water-distribution system, it is possible to make the way we use hot water significantly more efficient as described above. There are several interactions that we need to account for. If the hot water delivery is not improved first, the time-to-tap could easily double, triple or even quadruple! Likewise, if we install a low-flow-rate showerhead (less than 1.75 gpm) or reduce the hot water temperature, the hot water flow rate will drop below that needed to trigger the typical gas tankless water heater. In addition, installing a drain-water heat-recovery system on the showers can capture roughly half of the temperature rise from incoming cold water to the mix-point temperature of the shower. Showers represent 75 to 80 percent of a household's hot water use, so this is a good strategy. However, a drain-water heat-recovery system will reduce our demand for hot water, so we must consider that effect in our distribution system strategy, as well as on the choice of supplemental water heater — will it work properly with low flow rates?

> Don't believe that the energy is free because we have installed a solar water heater! It makes sense to minimize the waste, because if it is small enough, we may be able to install a smaller solar system and get more value from the water it produces.

Wringing out the wastes and using water more efficiently as we've described can reduce overall hot water demand by 25 to 50 percent. That means the actual amount of hot water desired for use by the typical household of three could be 30 to 45 gallons (114 to 170 liters) per day. Sure, we're likely to see some take-back effect when people have a "free" source to heat their water. But reducing the amount of hot water needed also reduces the size of a solar water-heating system required for the facility or home.

Living With — or Without — Backup

Will you have a supplemental heater, or will you live within the means the sun can supply? Imagine that you have a hot date Saturday night. It involves the big tub, soft candlelight and a special meal. You awake Saturday morning and realize that you barely had enough hot water for your shower. You remember that it has been partly cloudy all week, and it looks like it will be overcast all day. Are you keeping the date, or will you postpone it until the sun is more accommodating?

If you answered, "I am keeping that date!" you need a supplemental heater.

In the November/December issue, we look at what type of supplemental heater is the best technical match for your solar water heating system and how to size it. **ST**