Designing and Installing Solar Water Heating Systems

Tucson's Civano Community is a sustainable success —but its solar hot water systems could be better.

by Jennifer Kent and Bill Rittelmann

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In the Community of Civano, on top of garages and homes, dark, rectangular boxes bask in the Arizona sun. They are integral collector storage (ICS) panels, facing south and tilted at 35° up from horizontal to harness solar power to heat the home's domestic water supply. Homes in Civano's sustainable community, surrounded by the Southwest's signature wrinkled, brown mountains, are required by the community's energy standards to be energy and water efficient, and with a particular emphasis on the use of solar energy (see "Tucson Blooms with Less Water," *HE* May/June '04, p. 15). These solar water-heating systems are helping the homes they are perched on to meet the community's efficiency standards—most of the time. However, in some poorly designed systems the fraction of the total energy required for heating water that was provided by solar energy is almost zero.

To help meet its high-performance housing goals, The Community of Civano partnered with Integrated Building and Construction Solutions (IBACOS), through DOE's Building America program, and the local electric utility, Tucson Electric Power (TEP). IBACOS, where we work, contributed significantly to the design and optimization of some Civano homes—not the ones highlighted in this article—and assisted in construction quality control and home testing in many others to ensure compliance with the performance standards. As part of the postconstruction testing, IBACOS studied 18 solar domestic hot water (DHW) systems at Civano. The National Renewable Energy Laboratory (NREL) supported the testing in this project.

Solar Water Heating at Civano

Solar-assisted water-heating systems are either passive or active. Active systems incorporate a circulation pump with electronic or electromechanical controls. These systems require more complicated controls than passive systems, and they tend to be more costly. Component failures occur because of faulty products, improper installations, and improper maintenance.

To avoid the potential problems associated with active systems, the solar DHW systems installed in the homes at Civano are passive systems (see Figure 1). In these systems, the collector is also the storage tank, and water moves through the collector only when the homeowners use it. Passive systems are best suited to areas with moderate winter weather conditions, such as are found in Tucson, because freezing weather can cause the pipes to burst and damage the collector. Freeze tolerance specifications vary from product to product. The collectors used at Civano can only be used in climates with limited consecutive hours of subfreezing weather. With no pump and a reduced threat of freezing, these systems can contribute to the DHW energy requirements with little or no adjustment by the homeowners.

Of the 18 solar DHW systems that IBACOS studied at Civano, half have electric backup water heaters and half have gas backup water heaters. Four of the nine gas water heaters have an integrated heat exchanger that is used to supply space heating. System features include the following components:

- a 40-gallon ICS panel;
- a 40- or 50-gallon tank-type water heater, gas or electric;
- manual control valves with two modes: solar-preheat and solar-only;
- tempering valves with a temperature range of 110°F–170°F;
- pressure and temperature relief valves on the tank;
- a pressure only relief valve on the ICS panel; and in several systems
- a pumped hot water circulation loop within the house.

Each system is piped so that the incoming cold water goes directly to the ICS panel. The outlet of the ICS panel is piped into a three-way valve that can direct the water into the conventional water heater (solar-preheat mode) or bypass it directly to the tempering valve (solar-only mode). The solar-preheat mode is intended for use during the winter months, and the solar-only mode is sufficient to satisfy most households during the summer months. The installers opted not to follow the ICS manufacturer's installation guidelines and did not provide a third mode for conventional (nonsolar) water heating.

Table 1. Installation and Operational Characteristics That Affect System Performance

House	Average annual hot water usage (gallons per day) (normalized for temperature)	Distance between collector and tank (feet)	Dominant time of use	Daily hot water recirculator use	Performance
4	70	20	PM	N/A	Good
7	35	120	AM	< 10 min	Bad
10	21	120	PM	5h, 40 min	Ugly
11	26	10	AM	N/A	Great

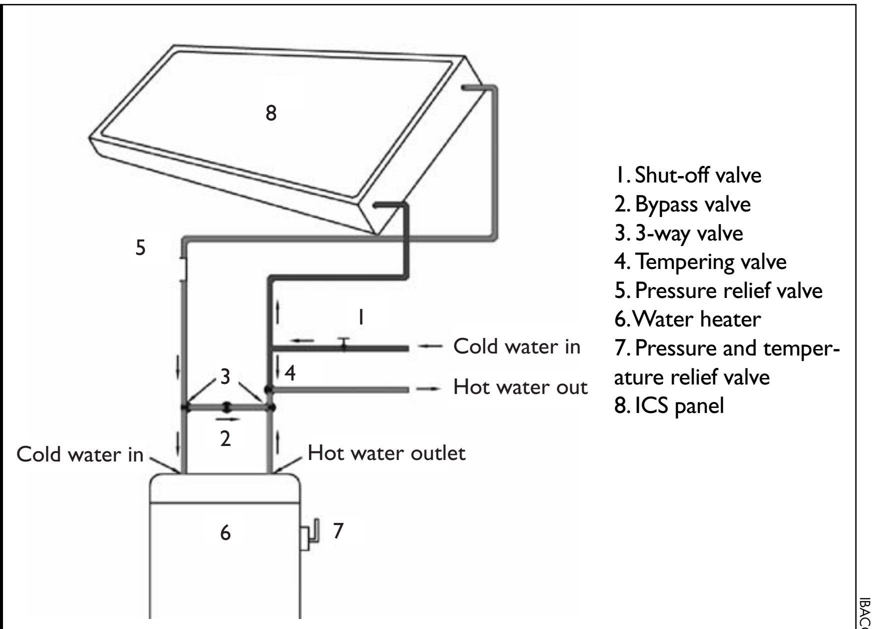

Figure 1. Passive solar-assisted water heating systems were piped to provide two modes of operation: solar preheat or solar only.

Six of the 18 systems have ICS panels mounted on the roof of a detached garage, with one-way pipe lengths of 120 ft.

Monitoring System Performance

We monitored the performance measurements of these 18 solar-assisted DHW systems for more than 36 months (August 2000 through August 2003). To determine the system's solar efficiency, we measured the annual amount of utility-provided energy consumed per household for DHW (Btu per gallon), and the fraction of the total required energy—including delivered hot water, tank heat losses, and piping heat losses—that can be attributed to the ICS panel. We refer to this fraction throughout this article as solar fraction. The solar fraction is 100% when all of the heated water is provided by solar energy. The higher the solar fraction, the better the efficiency.

To analyze the performance of each system, we recorded hourly measurements of temperatures, water volume, solar radiation, and input energy to the backup water heaters. We installed individual single-channel data loggers and retrieved data every three months during site visits. These site visits enabled us to inspect the systems on a regular basis and to also ask the homeowners about performance issues, use patterns, system failures, and changes to the system or its settings.

Even Simple Systems Suffer

During the course of our study, we found problems that severely affected the performance of the solar hot water systems. Out of the 18 homes that we studied, two had water heaters that were hooked up backward. The outlet from the solar collector had been mistakenly connected to the hot water outlet of the water heater. This causes poor mixing of the hot water coming from the collector and warm water in the tank, and reduced flow through the system due to the higher temperatures at the top of the tank. The main problem that we found was that the stratification caused by the reversal of the water heater piping connections resulted in the discharge of many gallons of hot water through the water heater's pressure and temperature valve.

Many Civano homes have hot water recirculation systems in addition to the solar water-heating system. These systems have a pump that recirculates water either when the homeowner turns it on, or by a timer. While the main purpose of the recirculation system is to move hot water from the water heater to the hot water fixture, it also starts the hot water moving from the collector to the water heater. Plumbers typically use the water heater drain or a tee fitting in the cold water inlet as the connection for the lukewarm water returned by the recirculation pump. This was the case for two out of six systems that had recirculation pumps. Although this plumbing configuration works during the winter solar-preheat mode, it does not work in the summer, when the solar-only mode is used, because it isolates the tank from the ICS panel, and the recirculation path becomes a dead end. For the recirculation system to work properly in all modes of operation, the hot water return must be connected upstream of the collector and the water heater. But be cautioned: With this piping configuration, the type of control on the pump can make or break the performance of the system.

In the following case studies, we investigated two homes with similar systems that differed primarily in the type of pump control that was installed. An on-demand hot water recirculation pump controller was installed in House 7, and the occupants used the pump on a daily basis. The system in House 10 used a 24-hour timer to control the hot water recirculation pump, which was set to operate for several hours per day. The on-demand pump control is greatly preferable to the 24-hour timer. An on-demand system may run less than 2 minutes for each demand, so half a dozen uses a day would amount to only 12 minutes of run time. At the other end of the spectrum, we have come across systems with timers that were set to run 24 hours a day, seven days a week.

Many of the tempering valves were difficult for homeowners to reach, let alone adjust. These valves need to be installed so that the homeowner can see the range limits that are stamped on the face of the valve. It's critical that homeowners see the range limits on the valves, and that they be able to reach them, because not being able to set the tempering valve is a safety problem that can lead to scalding.

Only 1 of the 18 homeowners understood how to operate the valves to change the mode of the system. No written instructions had been left with the homeowners, and most homeowners never received verbal instructions or forgot them if they did. (IBACOS later provided laminated instruction cards for the homeowners in the study, and the Civano homeowners association distributed cards to the other homeowners in the community.) Variations in time-of-use trends among individual households suggest that some homeowners may not understand how to optimize the performance of the ICS panel by adjusting the valves when they use hot water the most. Or they may not care enough to change their lifestyles. When asked, many of the homeowners didn't know that the system had a tempering valve, what its function was, or how to set it.

Long pipe lengths between the collector and the water heater reduce the efficiency of the solar collector due to heat loss from the pipe. During the planning of the Civano homes, the installer of the collectors advised the builders to mount the collectors as close to the water heaters as possible. However, the installer was unable to estimate the efficiency lost if the collectors were mounted at some distance from the water heaters. Consequently, six of the homes in the study have collectors that are mounted on detached garages, resulting in pipe lengths

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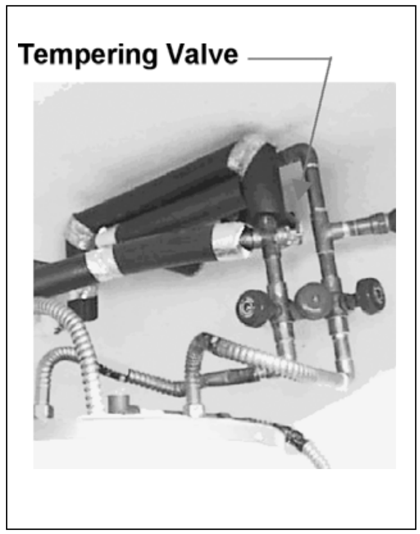

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(left) Without instructions, most homeowners didn't understand how to operate the system. *(middle)* The range limits on this tempering valve on this system were impossible to see, so the homeowners didn't know how to adjust them. *(above right)* Pre-assembled valve trees save time and reduce problems on site.

between the collector and the water heater of approximately 120 ft. Approximately 40 ft of this pipe is below grade, and it is unclear how it is insulated. Another 40 ft is exposed on the roof or concealed in unconditioned spaces. The length of pipe for the other 12 homes that we studied varies from as little as 8 ft up to 45 ft, although none of these homes has piping below grade, and exposed piping on the roof is limited.

All of the piping between the collectors and the water heaters is 1/2-inch copper with 1/2-inch neoprene insulation (with an approximate R-value of 2.5). The resulting UA value for a 120-ft section of pipe is 9.4 Btu/hr°F, approximately 4 times the UA value of an electric water heater and 0.75 times that of a gas water heater. The calculated heat loss during a typical steady-state flow is negligible. At a collector temperature of 150°F, surrounding ambient temperatures of 70°F, and a flow of 1.75 gallons per minute, the water would only cool to 149°F. When the nonsolar energy intensity of the delivered hot water is in the neighborhood of 200 Btu per gallon, a 1°F loss in temperature represents only 8.33 Btu per gallon. A typical household with a nonrecirculating system may use only 30 gallons per day, resulting in a loss of 250 Btu per day. On the other hand, a recirculation pump can easily move 5 gallons per minute, or 7,200 gallons per day. If each gallon pumped around the system loses 1°F in temperature, the additional load on the water heater is 60,000 Btu per day.

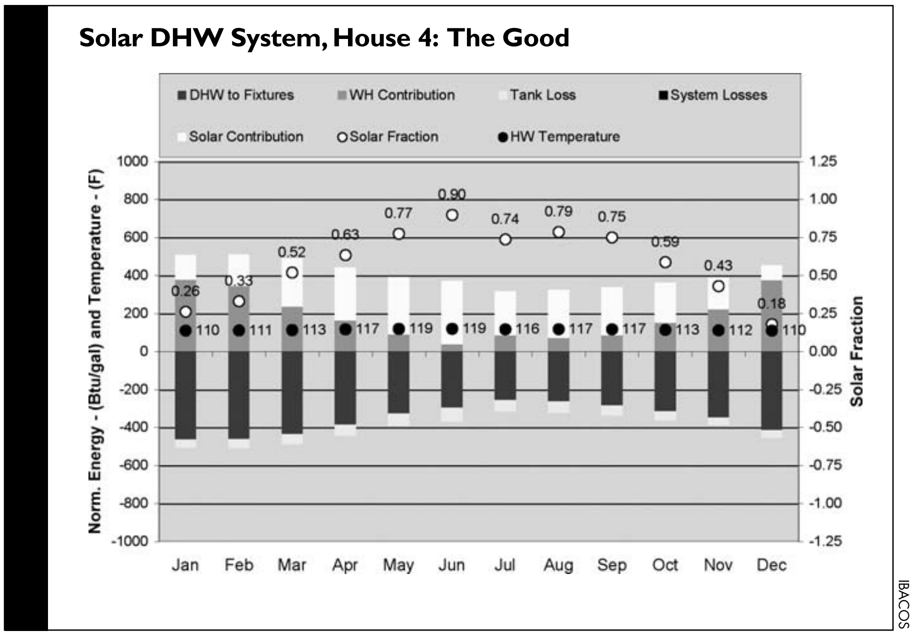

Figure 2. Despite average monthly hot water demands that reached 86 gal./day in January, the ICS panel provided 26% of the energy requirement for that month.

The Good, the Great, the Bad, and the Ugly

To get a clearer idea of how pipe length, hot water recirculation, and occupant behavior affect the performance of a system, we took an in-depth look at four Civano houses. Each of the houses is equipped with the same basic system: a 40-gallon ICS solar collector with a conventional 40-gallon electric-resistance water heater for backup. The differences between the systems include pipe length between the collector and backup water heater, type of hot water recirculation system, occupant behavior, and mode of summer operation (solar-preheat or solar-only). The characteristics that affected system performance are shown in Table 1.

The data presented in the figures for monthly DHW performance for each house (Figures 2, 3, 4, and 5) have been normalized by gallons of hot water used and temperature rise to compare energy use by gallon in households with different hot water volume demands and temperatures. For example, the homeowners in House 4 use a lot of hot water, and

Integral Collector Storage (ICS) panels on Civano homes are part of solar-assisted water heating systems.

therefore a lot of energy, whereas the homeowners in House 10 use very little water, so we normalized the data by dividing the measured energy totals by the total volume of hot water used. Temperature normalization accounts for the fact that not all houses have the same hot water delivery temperature. The average annual and monthly hot water temperature increases of all 18 homes was used as a reference to adjust gallons and Btu per gallon values for individual houses up or down for a more equitable comparison.

House 4: The Good

The DHW system in House 4 has relatively short pipe lengths (20 ft) and no recirculation system. These factors help to make the system design and installation good; however, occupant behavior isn't ideal. The homeowners use a relatively large amount of hot water, 55–86 gallons per day, which tends to reduce the solar fraction (remember, the higher the solar fraction, the better the system efficiency). One good aspect of occupant behavior, though, is that they make an effort to do laundry later in the day to allow the water in the collector to heat up. This behavior helps to achieve an annual solar fraction of 52%, despite the large demands on the system (see Figure 2).

The system was operated in the solar-preheat mode in summer. The energy requirement per gallon of the hot water delivered to the fixtures tends to decrease during the summer months as the main water temperature rises and the tank temperature remains relatively constant. This, combined with more abundant sunshine, increases the average monthly solar fraction to 90% in June, which means that the system is performing near optimally. The average annual water heater energy contribution was 202 Btu per gallon of water used. On an annual basis, 1,512 kWh of electricity is used to help heat 24,493 gallons of water. The efficiency of this house is very similar to that of House 11, whose occupants didn't use a lot of hot water.

House 7: The Bad

The DHW system in House 7 has relatively long pipe lengths (120 ft) between the collector and the backup water heater. The system features an on-demand hot water recirculation system; the homeowners turn the system on when they need it, and it automatically shuts off. The system was operated in the solar-preheat mode in summer. The homeowners are a typical working couple who use hot water mostly in the morning, with a daily volume of 31–45 gallons per day, depending on the time of year. Due to the long pipe runs in this system, the average annual solar fraction is only 36%.

Using an on-demand recirculation system, the occupants were able to conserve water while minimizing energy use. The on-demand controller is activated every morning before the first shower. This is because the average temperature of the water heated by solar energy entering the water heater is actually warmer than the average temperature of the water leaving the collector during the morning hours. We believe this is happening because water in the collector stratifies during the night—that is, warmer water rises to the top. With almost 3 gallons of water in the pipes between the collector and the water heater, part of which is warm, it is quite possible that the temperature at the collector will be cooler than the water that is just arriving at the water heater, since the warmer water in the pipes will arrive first. During the rest of the day, the temperature of the water heated by solar energy at the collector is noticeably lower at the water heater than it is just leaving the collector. This is primarily due to heat loss from the pipe, as the water from the solar collector reaches an average of 175°F by 5 pm each day. The warmer the water, the more heat loss there will be.

The average annual water heater energy contribution was 379 Btu per gallon of water used (see Figure 3). This is approximately 200% of the average of the systems with shorter pipe lengths

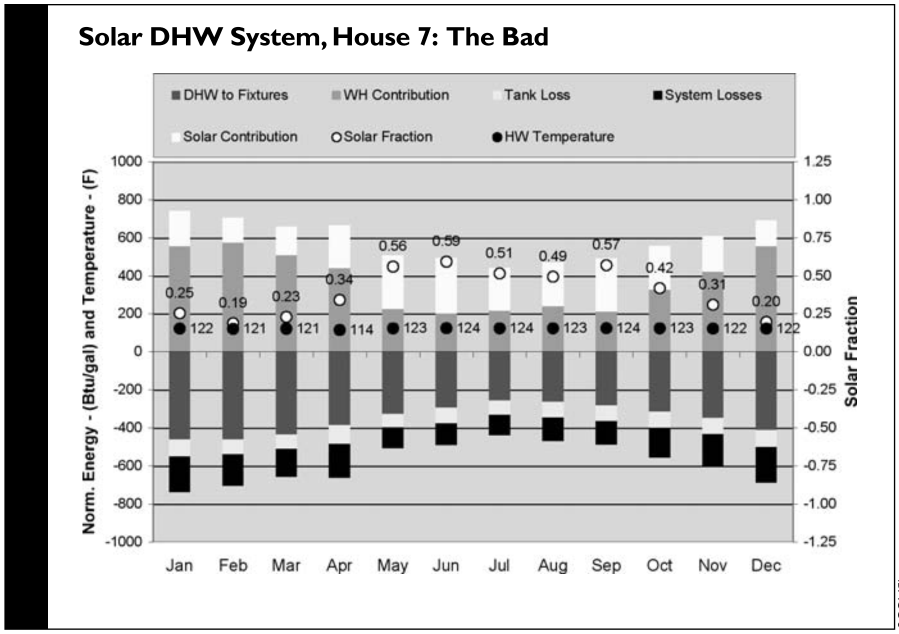

Figure 3. A plateau of the solar fraction in the summer months is believed to be the result of a less-than-optimal hot water usage schedule combined with heat loss from collector piping buried in the ground.

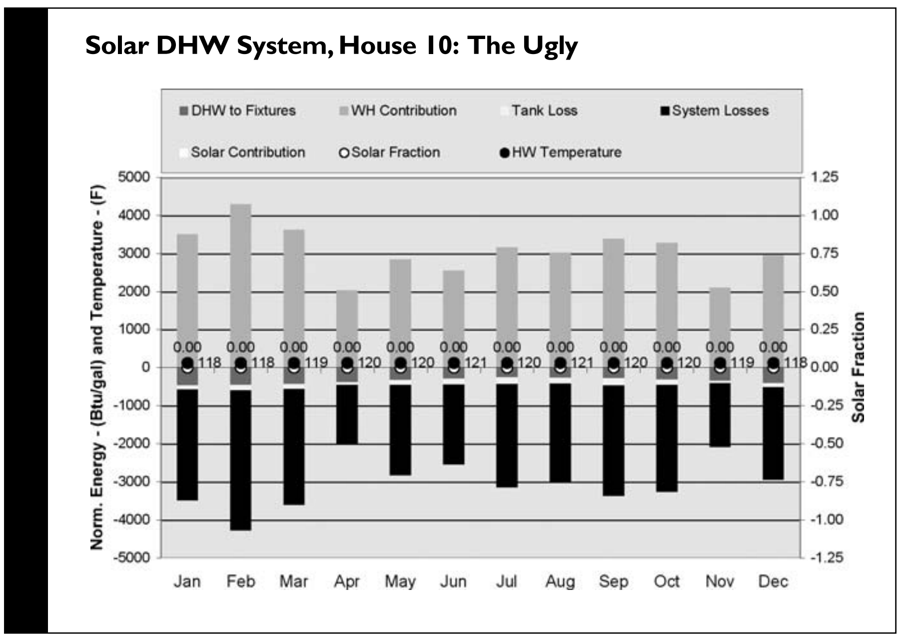

Figure 4. Energy required for DHW delivered to the plumbing fixtures is dwarfed by energy lost due to a hot water circulation pump using a simple clock timer for control. Incidentally, the scale of the Y-axis is five times greater than that of the graphs for the other three homes.

(Houses 4 and 11). On an annual basis, 1,447 kWh of electricity is used to help heat 13,019 gallons of water.

House 10: The Ugly

The DHW system in House 10 has relatively long pipe lengths (120 ft) between the collector and the backup water heater. The system was operated in the solar-preheat mode in summer. The Achilles heel of this system is the hot water recirculation pump, which is controlled by a 24-hour timer. The timer was originally set to operate 12 hours and 40 minutes a day, but we set it back to 5 hours and 40 minutes a day during a data collection site visit. We notified the homeowners shortly thereafter that this saved a significant amount of energy and asked them to set the timer to less than 30 minutes per day, but apparently this was never done.

The homeowners use only about 22 gallons of water per day, mostly in the morning. This low volume, combined with extremely high heat loss, resulted in a very high energy contribution per gallon of water used (see Figure 4). It reached 4,239 Btu per gallon in February, when city water temperatures are at their annual minimum and solar resources are low. The average annual water heater energy contribution was 2,949 Btu per gallon of water used, approximately 1,500% of the average of systems with shorter pipe lengths. Pipe length, system operation and control, and R-value of the pipe insulation all affect efficiency. The losses can be minimized by better pump operation, but the homes with longer pipes and no recirculation used almost twice as much nonsolar energy per gallon of hot water as the systems with shorter pipe lengths. On an annual basis, House 10 used 6,530 kWh of electricity to heat only 7,331 gallons of water. This home was by far the worst performing of the four homes in this case study.

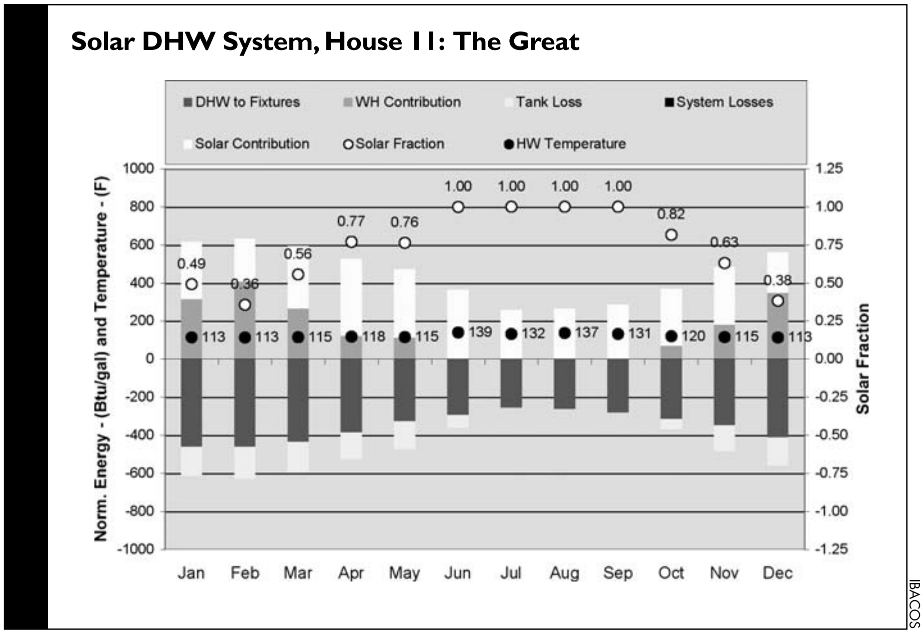

Figure 5. Tank losses are eliminated, solar fraction reaches 1.0 and delivered hot water temperatures soar in the summer months when this system is operated in the "solar only" mode.

House 11: The Great

The DHW system in House 11 has very short pipe lengths (10 ft) and no recirculation system. The two occupants are very energy conscious, using an average of only 27 gallons per day. The system was the only one of the four that was operated in the solar only mode from June to mid-October, which eliminates tank loss and reduces pipe heat loss (see Figure 5). The reduction of both tank losses and pipe heat losses also reduces heat gain to the cooling system. The result is a high annual solar fraction of 66 % and an average annual water heater energy contribution of only 159 Btu per gallon of water used. On an annual basis, House 11 used 443 kWh of electricity to help heat 9,008 gallons of water. This was the best-performing system of the four in terms both of solar fraction and of total energy use.

Incredible Inefficiencies

The solar-assisted hot water systems IBACOS researched at Civano differed in several respects. These were

- pipe length between the collector and the backup water heater;
- whether or not the house had a hot water recirculation system;
- occupant behavior; and
- of summer operation (solar-preheat or solar-only).

While each of these factors contributed to the performance of the system, perhaps the most significant was whether the house had a hot water recirculation system. Houses 7 and 10 had recirculation systems; Houses 4 and 11 did not. The system in House 10 used 15 times as much energy as the properly designed and operated solar system in Houses 4, and approximately 6 times as much energy as a conventional water heater with no solar-preheat. The system efficiencies for House 7 and House 10 were decreased even more by the long pipe lengths. (For general recommendations about installing solar hot water systems, see "Recommendations for Best Practices.")

We compared our research findings with research that the Solar Rating and Certification Council (SRCC) conducted on systems that had the same collector and a similar tank. Although the assumptions used in the SRCC annual simulations for these systems are somewhat different from system configurations and measured data in our study, the SRCC estimated performance appears to agree well with our calculated performance from the measured data. The SRCC results are based on a comparison to the energy use of a conventional electric water heater under the same load con-

Recommendations for Best Practices

The pipe run between the solar collector and the water heater should be limited to a maximum of 30 ft to keep heat loss due to piping within the 10% range, and also so that the piping can be insulated better. Short pipe runs can use 1-inch instead of 1/2-inch insulation, for example. The temperature drop of flowing water is small in longer runs, energy is lost during periods of no flow when water stranded in the pipes loses all of its heat through the pipe walls. On longer runs, an on-demand recirculation system can be used to increase the amount of hot water that reaches the tank, which will help offset some of the heat loss due to the piping. However, if the hot water fixtures are close to the water heater, but the solar collector is not, this approach may not do much to improve system performance. When this is the case, a timer with a manual start could circulate the water longer than is necessary to reach the fixture in order to bring hot water from the collector to the water heater.

A 24-hour timer should never be installed to control a hot water recirculation pump, because the more the pump runs, the greater the heat loss. This is because the pump will keep hot water flowing through the pipe, and a hot pipe loses heat. An on-demand controller with a manual start and an automatic shutoff that limits pump operation to no more than two minutes per occurrence should be used instead.

For the recirculation system to work properly in all modes of operation, the hot water return must be connected upstream of the collector and the water heater. While on-demand systems typically don't use a return per se, in new construction we would still recommend a dedicated hot water return pipe to minimize the mixing of hot water with cold water. This helps to prevent any conflicts when there are simultaneous uses of cold water.

Although ICS systems do not require routine drain-down, most installations will be drained at some point, due to the inevitable failures of the water heater, heating elements, expansion tank, collector, and so on. When this happens, the system must be easy to refill without trapping air in the collector. This means that an air vent/vacuum breaker must be installed at the highest point in the system—the outlet of the collector. Some collector manufacturers give installers the option of eliminating this device by filling the collector before they connect the pipe to the collector outlet. But this works only once. If the system is drained and filled after the piping is complete, it is nearly impossible to get all the air out of the collector. In addition, the supply and return pipes should each have a boiler drain just above the water heater, so that the collector can be drained independently of the water heater. These drains should be specified to withstand the system pressure, and they should have an external hose thread so that a hose can be connected to direct the water to a nearby drain.

As a rule of thumb, collectors should be tilted above horizontal by 10° more than the latitude of the location for optimum annual performance. This translates into a range of 35° in Key West, Florida, to 59° along the northern border of the continental United States. This should be done to favor lower winter sun angles, to compensate for colder outdoor air temperatures and inlet water temperatures. For climates with extremely cold or cloudy winter conditions, a system simulation should be performed to determine the optimal angle. The Solar Rating & Certification Council (SRCC) will perform site-specific analysis on certified systems for a fee.

Homeowners need to understand the system if it is to perform optimally. It is a good idea to leave behind an instruction card and manual. In addition, pipes and valves should be installed so that homeowners can see the labels and reach the valves.

For more information:
To get a rating of a solar hot water system, contact the SRCC at (321)638-1537 or srcc@fsec.ucf.edu.

dition. This load is an annual energy requirement of 3,600 kWh. One of the largest differences concerns the tilt of the collectors; the SRCC simulation assumes a 23° tilt, while the tilt of the collectors in Civano is 35°. The SRCC assumption for daily hot water volume is also relatively high (64.3 gallons per day) compared to Civano measured use, and it is not varied throughout the year in response to changing municipal water temperature.

Despite these differences, the normalized water heater energy use from the SRCC simulation is 183 Btu per gallon, which is within 4% of the average value of 190 Btu per gallon for House 4 and House 11. Modification of the collector tilt in the simulation would probably bring the SRCC estimate more closely in line with the performance we measured. A comparison between different-size collectors using the SRCC estimates reveals an additional saving of 100 kWh per year when the size of the collector is increased from 40 to 50 gallons. This amounts to an additional 7% reduction in annual DHW energy use and can offset additional PV capacity, which generally costs $5/kWh per year to install.

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For more information:

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