Advantages of Integrated Control in Solar Combisystems

By Fredric Milder, Ph.D., Member ASHRAE

As discussed in the previous article, "Integrating Solar & Hydronic Heating in Residential and Small Commercial Systems," a primary/secondary loop plumbing design for a combisystem creates the unique advantage of being able to move heat from any place in the system to any other place at will. A typical, moderately complex system might include: three heat sources (boiler, solar, heat storage tank), a half-dozen zone loads (two manifolds: one with radiant floors, one with baseboards), and two tank loads (domestic hot water [DHW] and heat storage tank). Consequently, the user or installer is immediately faced with many conundrums and opportunities:

- Where to put the solar heat when it is available;
- When to use stored heat;
- When to store heat;
- When to boost solar or stored heat with the boiler;
- When or if to prioritize DHW production over space heating and up to what temperature in the DHW tank;
- When or if to prioritize one heating zone or group of zones over another;
- Whether the above prioritizations are the same regardless of the heat source; and
- When and where to distribute excess heat in the summer.

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The list of the plumbing possibilities is immediately followed by envisioning efficiency enhancements that would be possible if the controls were intelligent and adaptable:

• Can I capture stranded heat from the plumbing and put it to good use?

• Can I change my heat usage priorities with the season, or even time of day?

• Can I change my backup heat usage with the time of day (e.g., if electric rates change)?

• Can (or should) I use weather predictions to modify my response to heat calls (an Internet link would be necessary)?

• Should I modify when I use my boiler for space heating according to the fluid temperature required by the requesting zone?

Given the freedom to connect any heat source to any load, we are sure the reader can come up with additional questions and interesting possibilities.

The obvious way to implement the sophisticated control decisions that would be required to do any of the previous possibilities is to move away from arrays of interconnected controllers designed for specific tasks (the current approach in the residential market) to pure software algorithms operating in a central computer. Additionally, to support the decision-making process, one would need more information about the status of the system at a variety of physical locations in the plumbing. Fortunately, most of the needed additional information is temperature measurements, and thermistors are inexpensive and easy to deploy.

Complexity of Capability Built on Simplicity of Design

To take best advantage of the decision to centralize control, one would want software that is widely adaptive and yet not requiring reprogramming for each installation. The standardized primary/secondary loop approach discussed in the above-referenced companion article allows that. Since the variety of configurations is finite and well-defined, the software is written to accommodate the most complex system and software components are disabled if the particular system does not require them.

At our solar thermal laboratory in Santa Fe, N.M., we built a full combisystem and equipped it with a central computer and I/O and relay modules designed for measurement and control to test our control concepts. For our computer and interfacing, including relays, signal conditioning, measurement, and multiplex switching, we used a National Instruments PXI system with plug-in computer, multiplex, relay and DMM modules. The system was programmed in the National Instruments programming language Labview. For anyone wanting to build and program a system like ours by themselves, any Internet-ready computer with the ability to switch approximately 30 power switches for 120V AC pumps and 24V AC valve actuators, and to multiplex and measure approximately 70 resistor and low voltage DC inputs would be adequate. The programming language is arbitrary.

Every sensor in the system, every pump and every valve are "home-run" wired to the computer, which does all the decision making, control, and user interfacing, and logs more than 250 data items every five minutes continuously, keeping the data in perpetuity. Our laboratory system includes:

- Solar panels and heat exchanger;
- Natural gas-fired condensing, modulating boiler;
- One radiant floor distribution manifold feeding one, valved heating zone;
- One baseboard distribution manifold feeding one, valved heating zone;
- One manifold on the glycol side of the heat exchanger feeding:
  - One "spa" (in reality, a large insulated cooler);
  - One ice-melt zone;
  - DHW tank;
  - Heat storage tank;
  - Six pump stations (one solar, five distribution);
  - One primary loop pump; and
  - Multiple thermistors, thermostats and Btu meters.

Centralizing the control and allocating it to software creates the array of opportunities we desire:

• Complex decision algorithms are completely flexible and any property of the system can be interactive with any other property because all system conditions are known in a single place;

• Algorithms can be optimized for the highest efficiency or user comfort, unrestricted by the hardware;

• The algorithms can be predictive, including using predicted weather data if so desired;

• The system has individual control of every component. This is particularly advantageous for doing diagnostics (discussed later);

• Logging of the complete system status continuously makes diagnostics and monitoring easy. The data can be used for component failure discovery or for analysis of performance;

• Adjustment can be system-wide (e.g., controlling groups of thermostats rather than programming individual ones) and can include memorized seasonal and diurnal settings;

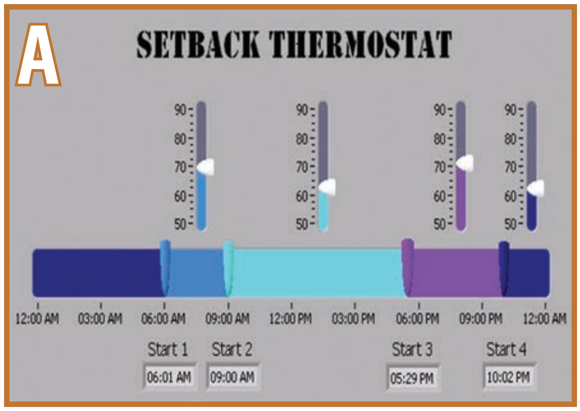
• Graphical User Interfaces become the natural, intuitive interaction of the user with the system. The user can get as little or as much information about the system as they desire. With LAN and web connections, the homeowner can access their system from anywhere in the world.

• With web connections, the installer or other service person can perform remote diagnostics and regular maintenance measurements without a local service call.

• Installation is greatly simplified because *all* other intermediary and control devices are eliminated. A central computer with digital I/O, an ADC, and relays replaces all of the following components: setpoint controllers, differential controllers, solar pump station controllers, thermistor interfaces, data logging devices, calculational devices (e.g., Btu monitoring units), web interfacing devices, valve control boxes, and pump control relay boxes. All components have wires that go only to one place (the computer) and with only a few exceptions, it is two wires from each device or sensor.

• Expensive, programmable thermostats are replaced by inexpensive, "dumb" thermostats because the central computer is more than capable of fulfilling all the requirements of a programmable thermostat.

For reliability reasons, the central control computer must be designed to operate unattended and reboot automatically after power failures, and to come up running the system with no further interaction. If it is web enabled, it must not be dependent on the web for proper functioning; similarly, it must not be dependent on the homeowner's LAN to function. Industrial control computers are ruggedized and designed to serve these purposes. Laptops and PCs are good for testing and development but are not reliable enough for continuous, real-time control applications.



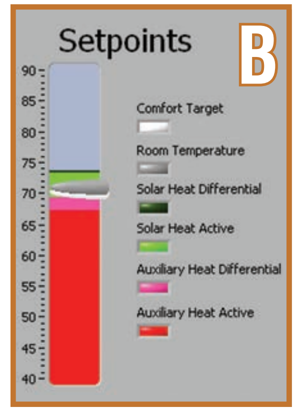


Figure 1a (left): User interface for controlling a setback thermostat in a non-mass heating zone. **Figure 1b (right):** Informational graphic showing the two-stage heating settings of an in-mass radiant zone.

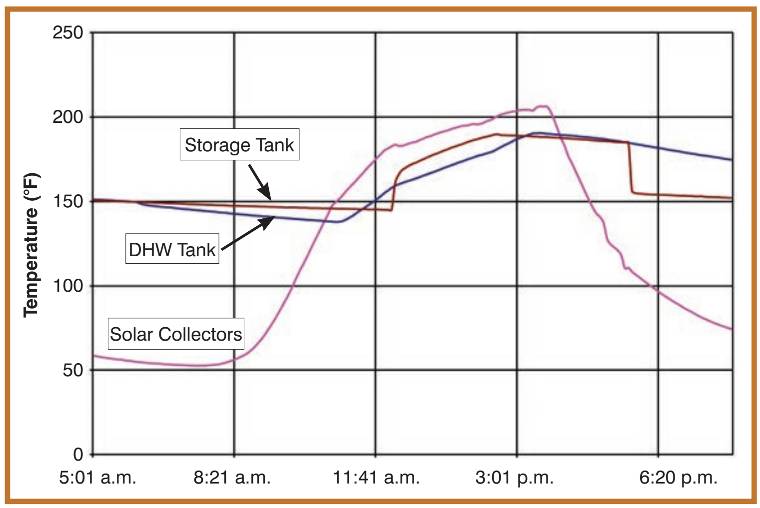


Figure 2: Logged data on heat storage, DHW use and night sky radiant cooling for a system in Virginia during the summer.

Graphical Interfaces

By shifting to a single control computer, one immediately moves from a plethora of miniature, cryptic, alphanumeric displays only available in the mechanical room to full graphical displays of a computer screen available anywhere on the Internet. Our goal in designing the computer screens is to make the information on the screen immediately understood and any interaction with the screen as friendly and intuitive as possible.

As examples, *Figure 1* comprises the graphical parts of two screens: a) the setup and control of a classic setback thermostat; and b) the settings of an in-mass radiant floor heating zone with two-stage heating. We gave the setback thermostat control screen (*Figure 1a*) to users with no instructions on how to use it. All users were able to figure out on their own what it represented and how to adjust it. (You click and drag on the thermometer indicators to control the desired temperature setting of each time block. You click and drag on the time block separators to change the start and end times of the blocks.) The setback thermostat is used in our system for heating a non-mass zone in the usual fashion.

In contrast to a non-mass heating zone, for in-mass radiant floors we use two-stage heating. When solar heat is available we store heat directly in the mass floor in anticipation of it coming out slowly and uniformly as the room cools at night. The alternative would be to put the heat into a storage tank during the day when it is often not needed and then take it out later. Storing heat directly in the floors results in as much as 25% higher use of the solar Btus.[1] The control settings allow for a warmer room if heated by the solar source and conserve fuel by only turning on the boiler if the room drops below a defined comfort setpoint. *Figure 1b* clearly displays the temperatures at which the solar heat is put into the floors (green) and at which boiler heat is put into the floors (red). It also shows that once the boiler is turned on (67°F [19°C]) it remains on until the room is brought up to 69°F (21°C) (pink region). Above 69°F (21°C), the boiler will not be used to heat the room, but solar heat will be put into the floors until the room is 73°F (23°C).

After building our laboratory, installing the system described and programming it, we built another four systems and placed them in actual homes around the country (three in New Mexico, one in Virginia). All systems were remotely monitored approximately daily and log files have been collected covering the entire test period. In-home testing began with the first system in October 2009, and continues to this day. The last system in the test program was brought online in

May 2010. The remainder of this article comprises case studies of actual events and experiments with these five systems.

Examples from the Field

Heat from Anywhere to Anywhere

Figure 2 (Page 36) is logged data from our system in Virginia from 5 a.m. through 8 p.m. on a single day in the summer. The system has two in-mass radiant floor zones and one baseboard zone and thus the need for a heat storage tank for the baseboard zone. At this time of year, the only use for the solar heat is making DHW but the storage tank is used to buffer heat so the collectors do not overheat during the day. With primary/secondary plumbing and intelligent, centralized control, Btus are moved throughout the system at will.

The sun rises just after 8 a.m. and by 11 a.m. the fluid from the collectors is hot enough to be useful. At this point, the heat storage tank is 145°F (63°C) and the DHW tank is 140°F (60°C). For this family, the size of the DHW tank is small, so the system parameters are set to prioritize solar heat into the DHW tank first. The target DHW temperature is 160°F (71°C). With this amount of heat in the DHW tank, the family can be reasonably assured that there is enough hot water (mixed down) to meet their needs until the next day's sun.

After the DHW tank reaches its target at noon, heat is simultaneously put into the storage tank and the DHW tank. (The storage tank heats up quickly because it is directly filled with the circulating boiler fluid.) The two tanks continue to absorb the unneeded solar heat for most of the rest of the day. Just before 3 p.m., the storage tank is at the highest temperature we allow for safety reasons and the system stops sending heat to that tank. The DHW tank continues to absorb heat until it reaches its maximum at about 3:30 p.m.

The sun begins to set and we have successfully absorbed all of the unneeded heat into the two tanks. At 6 p.m. the collectors are used to radiate heat from the storage tank into the night sky[2] and within one-half hour we have cooled the tank enough to have adequate heat storage capacity for the next day's buffering. The DHW tank is left untouched. Both tanks will cool overnight 5°F to 10°F (2.8°C to 5.5°C) further and DHW will be available at all times, with no fuel usage. The system is also set to take heat out of the storage tank and put it into the DHW tank overnight if the DHW usage happens to be large that evening.

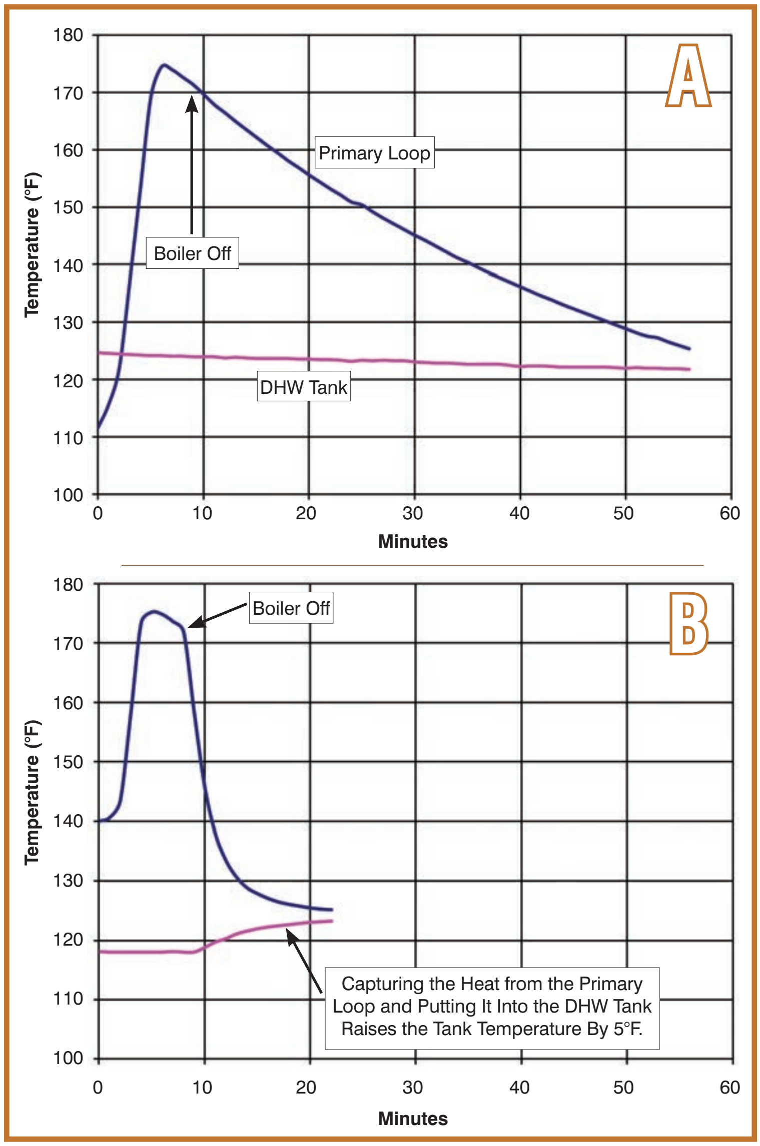


Figure 3a (top): With normal controls, after the boiler is turned off, the stranded heat is slowly lost to the mechanical room. **Figure 3b (bottom):** With central control and integrated logic, the system can keep pumps running to capture the stranded heat in the primary loop and move it to the DHW tank.

Heat Capture from the Primary Loop

Figures 3a and *3b* show how a centrally controlled system can perform efficiency tasks impossible with ordinary controls. *Figure 3a* shows the temperatures in the primary loop and the DHW tank when controlled in a normal fashion after a brief period of running the boiler for space heating. After the boiler turns off, the primary loop dissipates its heat to the mechanical room over a period of an hour. For this system, the primary loop plumbing is particularly spread out and we estimate that there are 2,000 Btus (2.11 MJ) of heat stranded in the primary loop after the boiler turns off that are eventually released to the mechanical room. Meanwhile, the DHW tank continues its normal slow loss of heat.

Figure 3b shows how the central control can capture that stranded heat and put it to good use. The control knows that the boiler was just turned off and that there are no other calls

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for heat in the system. It knows that the primary loop is hotter than the DHW tank. So why not run the primary loop pump and the DHW heat exchanger pump to pull those 2,000 Btus (2.11 MJ) out of the primary loop and put them into the DHW tank? *Figure 3b* shows just that: over a period of 10 minutes, the primary loop is cooled and the DHW tank temperature is raised by 5°F (2.8°C). To do this type of integrated, multi-level logic with differential controllers and relays would be nigh impossible. We estimate that just this one algorithm can save a homeowner $50 to $100 per year in fuel costs for a home using fuel oil or propane for backup heating.

Failure Diagnostics and Alerts

With significant amounts of data from around the system coming into the control computer, it is easy to set up alerts and diagnose a problem when something goes wrong. Over the cumulative system time of eight years, our systems have experienced valve failures, pump failures and a boiler lockout from water leaking onto the burner.

Valve failures are identified by knowing when a valve is asked to open and then knowing that an end switch signal has not been received within a fixed time. There are two possibilities: either the valve is not responding or the end switch is not working. Because we can control every component in the system over the Internet, when we suspect that a valve is malfunctioning, we log on to the system remotely, ask the valve to open *and* send heat to that zone by turning on the appropriate pumps and the boiler. This last aspect allows us to test which of the two possible failures we are dealing with. If the valve is indeed opening but the end switch is not reacting, then we will see a temperature rise in that manifold even though the end switch is telling us that the valve is closed.

Pump failures are identified in a similar fashion. One opens a zone valve of choice and turns on the pump in question along with the boiler and looks for a temperature change on an appropriate thermistor.

We were alerted to another failure by the homeowner that although the system was clearly calling for the boiler to be making DHW, in fact, the water temperature in the DHW tank was not going up. *Figure 4* from the log files shows clearly what happened. Shortly after midnight the boiler, the primary loop pump and the DHW heat exchanger pump were turned on for making DHW. The primary loop temperature goes up to 110°F (43°C) indicating that everything is normal but then plateaus at 110°F (43°C). After that, the DHW temperature is going *down* slowly as the primary loop temperature is going *up* slowly; they are in fact coming to equilibrium because the boiler is no longer on. When the homeowner went to the mechanical room after our over-the-Internet analysis, he found that a pressure and temperature relief valve had leaked water into the boiler and caused a boiler safety lockout. In this case, no service call was required. The owner was able to replace the faulty P&T valve himself and powering the boiler on and off reset the lockout.

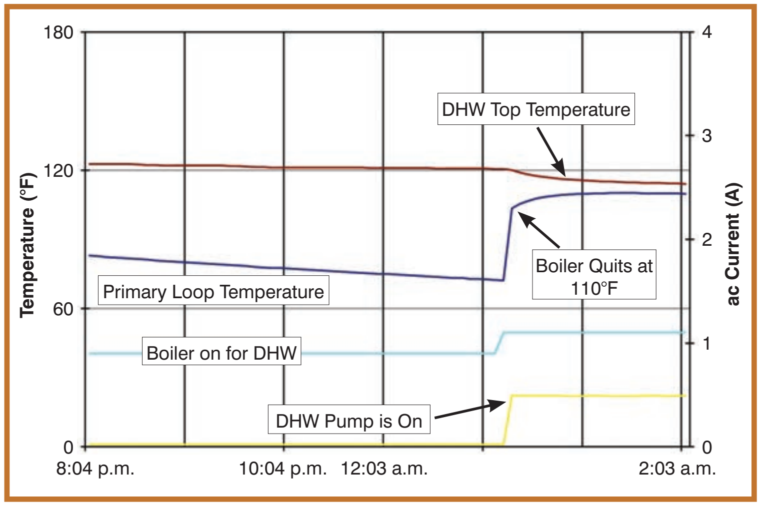

Figure 4: A boiler failure (safety lockout) is the cause of a lack of DHW.

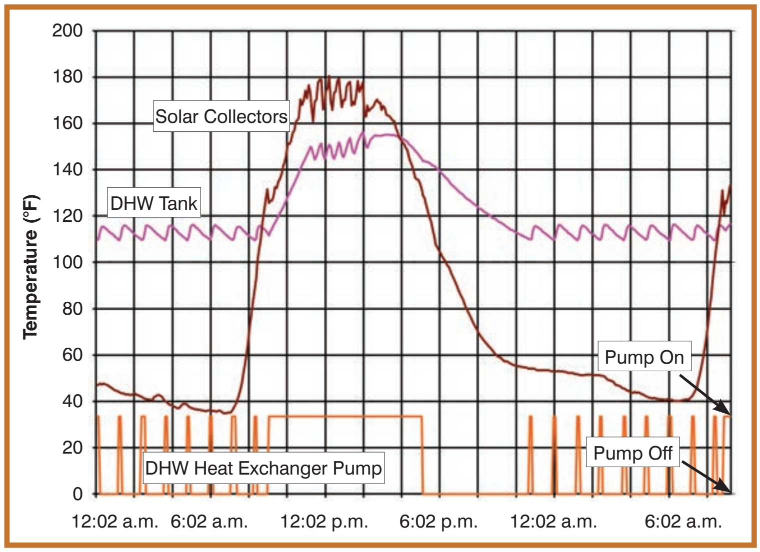

Figure 5: In this home, the DHW recirculator is on continuously and manages to waste all of the solar heat stored in the DHW tank within six hours after sunset.

Performance Analysis

Having a history of more than 250 data values taken every five minutes allows for a performance review of the system on a routine basis. *Figure 5* shows how this analysis informed a user decision and saved significant money on a system near Santa Fe.[3] The chart shows one day's cycle of solar heat into the DHW tank and what happens to that heat overnight. During the day (summertime) solar heat is put into the DHW tank, heating it up to 155°F (68°C) by the end of the afternoon; The DHW heat exchanger pump is on

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continuously 9:30 a.m. through 5:30 p.m. In this house, the DHW recirculators are on continuously so the homeowner can have "instant" hot water. However, as was discovered by this analysis, at least some parts of the DHW recirculation loop are uninsulated and circulating hot water through those pipes all night long sheds an enormous amount of heat, assumedly into the floors and walls somewhere in the house or underground.

By midnight, with only minor DHW use, the DHW tank is at its minimum setpoint and the boiler turns on and off periodically for the rest of the night and early morning keeping the temperature at that minimum level. This is a large DHW tank and the estimated cost to the homeowner for the *convenience* of instant hot water is $700 in fuel (natural gas) plus the electricity cost of keeping the pump running. Not surprisingly, after the homeowners were shown this data, they chose to alter the scheme for running the recirculators. Currently, the recirculators are on timers and the homeowners are considering changing it further to an on-demand system only.

Summary

Switching from an array of interconnected, decentralized hardware controllers to a central computer making all control decisions in software, coupled to the appropriate I/O and relay functions brings the control of solar combisystems into the 21st century. Our approach takes advantage of standardized plumbing in a primary/secondary loop structure. Our guiding principle is "Sophisticated on the inside; Simple on the outside." The benefits are many and can be summarized as:

- Plumbing design is streamlined;
- Installation is simplified, particularly in the wiring and control setup;
- The homeowner gets easy-to-understand-and-operate graphical interfaces;
- Numerous sensors provide for performance analysis and troubleshooting;
- The inside (the algorithms) can be sophisticated without that complexity showing through to the user;
- Logging functions are included routinely; and
- Web interfacing enables remote control, diagnostics, and monitoring.

References

1. Soifer, B. and B. Stickney. 2010. "Solar Heating Systems—Storage Mediums and Temperature-Control Strategies for Predictable and Consistent Performance." *SolarPro* (Apr./May):79–88.

2. Stickney, B. 2009. "Solar Solutions—Bristol's six principles of good solar hydronic design, Part 7: Cooling with Flat-Plate Solar Panels." *Plumbing Engineer* (1):60, 96–98.

3. Stickney, B. 2011. "Quality Assurance—Solar Hot Water Recirculation Considerations: Avoidable Energy Waste." *SolarPro* (Feb./Mar.):20, 22, 24. ■