IMPROVING THE BUILT ENVIRONMENT CARB

Solar Domestic Water Heating

A Roof-Integrated Evaluation

In 2005, CARB began work with Dawn Solar Systems Inc. on a project to evaluate the performance of Dawn's roof-integrated solar water heating system. The key benefit of the system is integration and aesthetic appeal; looking at the home evaluated (Figure 1), one does not notice any evidence of solar collectors.

Figure 1. The home in Litchfield, CT with roof-integrated solar thermal and electric systems.

The south-facing roof of the home in Litchfield, CT actually consists of three active solar systems. The main southern roof of the home (approximately 750 ft^2) incorporates a solar thermal system for space and water heating. The southern shed dormer (250 ft^2) supports both a thermal system (dedicated for domestic water heating) as well as a roof-integrated PV system using amorphous silicon laminates. Beneath the standing-seam metal roofs, the unglazed thermal collectors consist of cross-linked polyethylene (PEX) piping run in metal heat transfer plates. A propylene glycol solution is circulated through the collectors and through heat exchangers in storage tanks in the basement.

CARB did not participate in the design of the home or the energy systems, but as the home was nearing completion CARB seized an opportunity to install instrumentation to monitor performance of the solar systems. Over a 12-month period monitored (after all systems had been commissioned), the solar thermal systems provided 38% of the domestic water heating load and provided 2.0 MMBtu of space heating load (offsetting approximately 24 gallons of propane). The 1.4-kW solar electric system generated 1,809 kWh, providing 31% of the home's total electric load.

System Descriptions

The solar systems in this home are designed to be very well integrated into the home's roof system. From the outside, there is no visible evidence that solar thermal collectors exist on the south-facing roof, and the solar electric laminates (on the shed dormer) are very low-profile and difficult to detect.

Figure 2. The home during construction. Solar thermal and PV collectors have been installed on the shed dormer. Metal roofing has not yet been installed over PEX tubing and heat transfer purlins on the main roof area.

Above the roof deck and beneath the standing-seam metal roof, cross-linked polyethylene (PEX) tubing is plumbed through metal channels designed to hold the tubing in place while facilitating heat transfer. There are two separate solar thermal systems: the collector area for the small system is the 250-ft^2 area above the shed dormer on the southern roof; collection for the large system is installed in the 750 ft^2 of the main roof of the home (surrounding the dormer). The PEX pipes above the roof deck connect to manifolds in the conditioned attic of the home, and larger, insulated PEX pipes run from the attic manifolds to heat exchangers located in storage tanks in the basement.

The storage tank for the smaller system is a 120-gallon potable water tank; the larger system heats an unpressurized 300-gallon tank. Differential controllers sense the temperatures beneath the metal roofing as well as in the storage tanks; when the roof is substantially warmer, a 50% propylene glycol solution is circulated to transfer energy from the collectors to the tanks.

The smaller solar thermal system provides heat for domestic water heating only; the large system can provide heat to domestic water or to the radiant floors. Home occupants use manual valves to switch between the two uses of the larger system. On a domestic hot water draw, cold well water flows into the bottom of the smaller solar storage tank. From the top of the tank, preheated water exits and runs through a heat exchanger in the large solar tank (if enabled). From the solar tank(s), preheated water enters the auxiliary water heater – an indirect tank heated by a condensing, propane-fired boiler.

The roof of the shed dormer also supports UniSolar PV laminates. Each of the 12 standing-seam roof panels contains a 116-Watt collector (for a total of 1,392 Watts$_{DC,STC}$). The collectors are wired together in series (beneath the ridge cap of the home) and connected to an inverter located in the basement.

Monitoring Parameters

Performance of the solar thermal system was monitored by measuring several temperatures and fluid flow rates. CARB installed thermistors to measure the following temperatures:

- Outdoor air (in an aspirated radiation shield)
- Twenty collector temperatures (beneath the roof and above the roof deck where solar collector piping is run)
- Cold water from the well
- Preheated DHW leaving the small solar tank
- Preheated DWH leaving the heat exchanger in large solar tank
- DHW leaving the auxiliary heater (going to DHW loads)
- Solar tank temperatures (near the top of tanks)
- Glycol solution exiting each tank heat exchanger (running to the attic manifolds)
- Glycol solution at each attic manifold (running out to the roof collectors)
- Heated glycol solution at each attic manifold (coming in from the collectors)
- Heated glycol solution entering each tank heat exchanger (coming from attic manifolds)

Using turbine meters, three liquid flow rates in this system were measured:

- Domestic hot water
- Glycol solution in each solar collection loop

To monitor the electric systems, Watt-hour transducers were installed to measure PV generation and net electricity consumption for the home.

In addition, a pyranometer was installed on the roof to measure global horizontal radiation. All sensors were connected to a Campbell Scientific CR10X datalogger, and the datalogger was connected to a modem that allowed data to be collected remotely.

System Performance

Because the plumbing systems and controls were fairly complicated, the system was not operating as designed until approximately 18 months after installation. The integration of space heating performance was especially complicated. Before the controls were repaired and the system was fully commissioned, it was rare for there to be any solar contribution to space heating. The system was fully operational in April of 2007, so data from the first twelve months of full operation are presented here (May 2007 – April 2008).

Domestic Water Heating

Over this 12-month period, the solar thermal systems provided 38% of domestic water heating energy (with an average consumption of 35.7 gallons of hot water per day). The total energy contributed to water heating over this period was 2.95 MMBtu. Using a simple effective efficiency of the indirect water heater of 80% (CARB did not measure performance of the indirect water heater), the solar system offset approximately 40 gallons of propane. Figure 3 shows that the solar contribution is much greater in the summer months than in winter months – as expected. It's also worth noting that the smaller solar system (250 ft^2 vs. 750 ft^2) provides 85% of the total solar contribution.

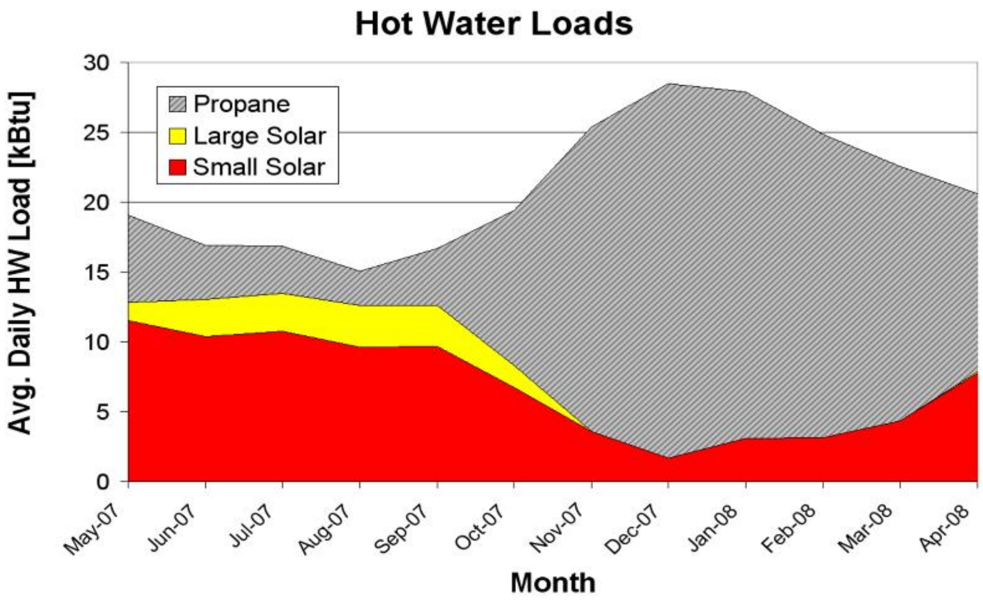

Figure 3. Average daily domestic water heating energy by month for the first full year monitored where all systems were operational.

Space Heating

The primary function of the larger solar thermal system (the steeper, main part of the home's roof covering approximately 750 ft^2) is to provide space heating through the radiant floor heating system. The system is designed and installed so that the home owner must manually adjust valves to direct heat either to the domestic water stream or to the radiant floor. Since April of 2007 – when the system became fully operational – it appears that the owner has made the appropriate changes (near the equinoxes) to the valves. Figure 4 shows the monthly solar contributions to space heating.

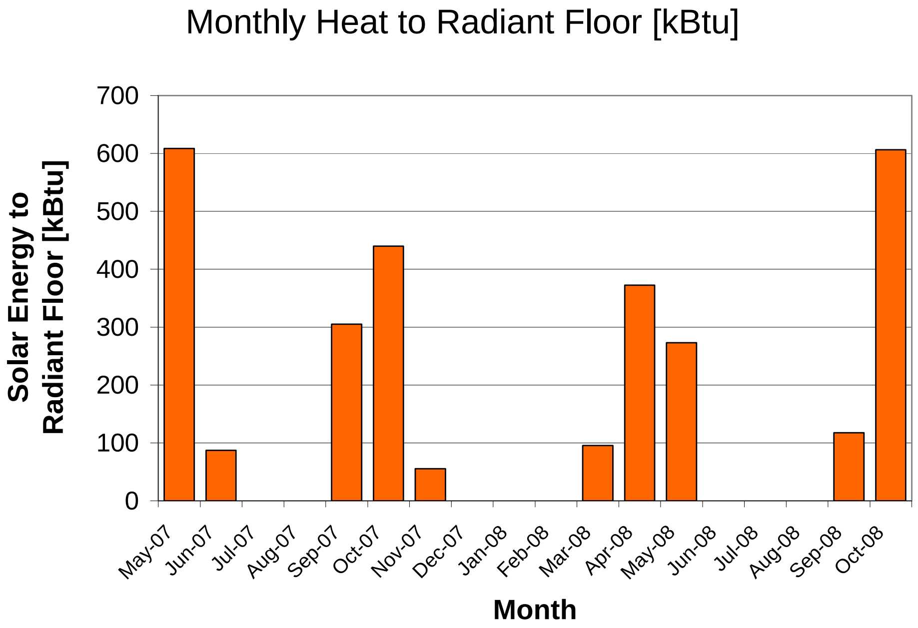

Figure 4. Summary of monthly solar contributions to radiant floor heating. Effective heating only occurs during swing seasons – there is no solar space heating from December - February.

PV Generation

The solar electric system on the home worked quite well. The roof faces within 10° of due south, and there is virtually no shading of the collectors. Over the twelve months from May 2007 through April 2008, the system generated 1,809 kWh. This equates to normalized annual generation of 1,299 $kWh_{AC}/kW_{DC,STC}$. This is excellent performance for New England. From SWA's experience monitoring and evaluating PV systems in the northeast, generation above 1,100 $kWh_{AC}/kW_{DC,STC}$ is above the average for typical residential PV systems. Figure 5 shows the average daily generation of the system by month.

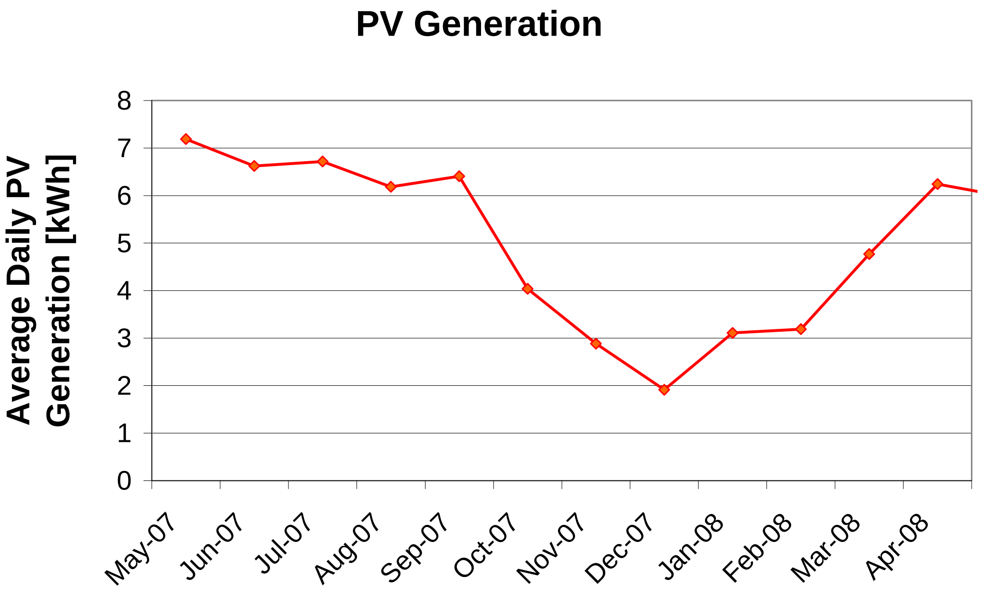

Figure 5. Average daily PV generation by month of the 1.4-kW PV system.

System Benefits

From CARB's monitoring and research, a "typical" solar domestic water heating system (e.g. 80 ft^2 of flat-plate collector with 110 gallons of storage) will provide solar fractions of 60-80% in a residence with average hot water consumption. This system provided only 38% of the domestic water heating load. This is discussed more in the "Gaps and Lessons Learned" section below.

Aside from energy savings, the key whole-building benefit of the system was the integration. Aesthetics is always subjective, but this system truly is integrated. There is no outward, visible evidence that the home contains a solar thermal system.

Cost Advantage

The costs of these solar thermal systems were not made public. One estimate from the manufacturer, however, is that a "typical" roof-integrated solar thermal system used for domestic water heating only will cost 50% more than a "conventional" solar thermal system. In this comparison, a "typical" Dawn Solar system would include approximately 400 ft^2 of collector and 110 gallons of storage; a "conventional" solar thermal system would feature approximately 80 ft^2 of flat plate collector with 110 gallons of storage.

As the system evaluated here contained two solar thermal systems as well as complex controls and plumbing for integration with both domestic water and space heating systems, this 50% incremental cost estimate does not apply.

In return for the cost premium, purchasers of these systems get integration and aesthetic benefits. In situations where conventional solar thermal collectors are not acceptable for aesthetic reasons – and at least some solar thermal contributions are desired – this integrated system can certainly be appropriate.

Reliability Advantage

Because these roof-integrated collectors are unglazed, they always operate at much lower temperatures than flat-plate or evacuated tube collectors. As a result of this, the highest glycol temperature recorded in the solar collector loop was 131°F (55°C). The solar tanks reached 120°F (49°C) only once during the twelve months monitored. While this obviously limits how solar heat can be used effectively, there is a silver lining with respect to maintenance and durability.

With the maximum antifreeze temperature recorded at 131°F, there is no need for high-temperature protection for these solar systems during summer months. In addition, the propylene glycol in this system will probably last substantially longer than glycol in higher temperature systems. System reliability may improve, and operation and maintenance costs may be substantially reduced when compared to flat-plate and evacuated tube systems.

Gaps and Lessons Learned

Temperature and Available Heat

Because of the low temperatures generated by this unglazed thermal system, it can only provide DHW preheating; i.e. temperatures in the solar tank are rarely sufficient to meet domestic temperature requirements without supplemental heating (DHW was delivered to loads between 120°F and 130°F). During July, the month with the highest solar fraction, the water temperature at the top of the small solar storage tank never fell below 75°F and reached a maximum of 121°F. In January, by contrast, tank temperatures ranged from 57°F to a maximum of only 73°F.

These low tank temperatures are a result of the relatively low collector temperatures (i.e., relative to temperatures reached in glazed collectors). The effectiveness of the system is truly limited by the low operating temperatures; when collectors cannot generate temperatures necessary to heat domestic water, the system can only function as a pre-heating system. Even much larger areas and storage volume will not significantly improve the solar fraction if higher temperatures are not achieved.

One lesson from this finding is that large areas are not necessarily warranted. It's noteworthy in looking at Figure 3 that the small solar thermal system on this home (approximately 250 ft^2 of collector) provided 32% of the water heating load. The large system (approximately 750 ft^2) provided only an additional 6%. While it's true that the large system was used to provide some space heating during the swing seasons, the additional contribution to domestic water heating would have been trivial. From these results, it appears that a small, roof-integrated solar water heating system may be nearly as effective, and certainly much less costly, than larger systems. While more investigation is needed, it's possible that installation costs of such a small system would be similar to costs of flat-plate or evacuated tube systems, though the total energy savings would be less.

Performance in Warmer Climates

As the solar collectors are so closely tied to ambient temperatures, it's logical that performance during warmer weather is dramatically better than performance in colder weather (certainly the amount of sunlight contributes to this as well).

This effect is demonstrated by examining the two equinox months. In September 2007, for example, average daytime temperatures were 69°F, and the solar thermal systems provided 75% of the water heating load. In March of 2007, average daytime temperatures were 39°F, and the solar systems provided only 19% of the water heating load. Other weather factors (especially snow) certainly came into play, but all the data show that effect of ambient temperature on system performance is consistently pronounced. CARB believes that this unglazed, roof-integrated solar system may provide much higher, more consistent, year-round benefits in warmer climates. CARB has not had the opportunity to evaluate any systems in warmer climates.

Operation and Maintenance

With indirect, glycol-based solar water heating systems, high-temperature protection and ensuring proper maintenance are consistent challenges. Propylene glycol breaks down at high temperatures, and the antifreeze needs to be checked periodically and replaced when necessary. As discussed above, these roof-integrated systems, with much lower operating temperatures, do not require high-temperature protection and glycol will likely last much longer than in higher-temperature systems. Because of this, maintenance costs, durability, and reliability of these roof-integrated systems may be greatly improved when compared to glazed collector systems. It is impossible to predict without investigating performance over much longer periods of time.

Integration of Solar Space Heating

CARB does not generally advocate active solar space heating. The primary challenge with the technology is the obvious one: solar energy is least when space heating loads are greatest. In addition to this, however, CARB has consistently encountered challenges with the integration of solar and auxiliary heating systems.

To reach zero energy goals, addressing space heating loads is critical, especially in cold climates. CARB currently recommends that *if* solar thermal space heating is used, heat should be delivered to the space through a small, simple system separate from the auxiliary distribution system. This may present a controls challenge, but CARB feels that this will be more easily solved than challenges of integrating the two heat sources with one delivery system.

Piping Heat Loss

In several recent projects where CARB has monitored performance of solar thermal systems, CARB has expanded monitoring to include the heat loss from piping between the collectors and storage. In this system, as with others, CARB found that a large amount of energy was lost from pipes running between the solar tank (in the basement) and the collector manifolds (in the attic). The pipe runs are rather long (approximately 50-70 feet each way). CARB was informed by the installers that each PEX pipe was insulated with ½" closed-cell foam. In addition, all pipes were run together in an insulated flexible duct (typically used for forced-air distribution).

Over the 12-month period, 21.3 MMBtu were collected from the two collector areas on the roof (measured using the temperature differentials at the attic manifolds). Only 8.2 MMBtu, or 38%, were transferred to the solar tanks. The balance was lost through convection and conduction from fluid in the piping.

When heated glycol reached temperatures of 100°F or more (as measured in the attic manifolds), the fluid was between 5°F and 10°F cooler when it reached the solar tanks in the basement. In a low-temperature system, this results in a significant overall energy loss. This problem is not at all specific to this system, however, though it is rather pronounced because of the long piping runs and low operating temperatures. CARB now recommends at least R-5 $ft^2hr°F/Btu$ pipe insulation (typically Armaflex or equivalent closed-cell foam with thicknesses of at least 1-1/4").

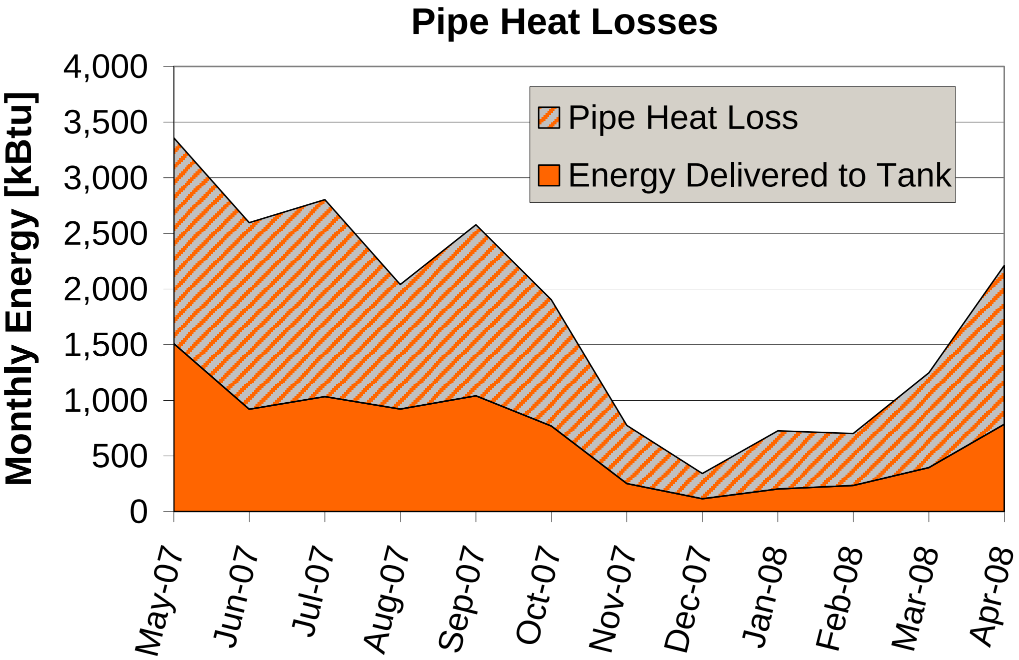

Figure 6. Chart showing total solar energy collected divided between useful energy delivered to solar tanks and heat lost in piping between the attic manifolds and the solar tanks.

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