COST, DESIGN AND PERFORMANCE OF SOLAR HOT WATER IN COLD-CLIMATE HOMES

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ABSTRACT

As part of the Department of Energy's Building America initiative to research home energy systems, Steven Winter Associates (SWA) has monitored long-term performance of two solar domestic water heating systems in northern climates. Both homes are occupied by 4-person families that consume 60-80 gallons of hot water daily. The prices of the systems were between $6,000 and $8,000.

The evaluation of both systems uncovered issues that seriously compromised performance. Once repaired and commissioned, both systems collected an average of 25,000 – 30,000 Btu of solar energy daily with solar fractions near 90% during summer months and over 60% year-round.

The evaluations resulted in better understanding of good design – and possible drawbacks – when incorporating auxiliary tankless water heaters. The evaluations also highlighted the cost effectiveness of such solar systems: even with rising energy prices, the cost of solar hot water in homes with efficient water heating can be hard to justify.

1. INTRODUCTION

SWA has monitored the performance of two solar domestic water heating systems. The first system, located in western Massachusetts, has been monitored since June 2004; the second system, located in Madison, WI, has been monitored since March 2005. Both systems are indirect, closed-loop systems each with two 32-ft^2 flat-plate collectors on the roof and an 80-gallon storage tank in the basement. Both homes are occupied by 4-person families that consume 60-80 gallons of hot water per day.

Fig. 1: Roof top solar collectors on the Massachusetts home.

2. SYSTEM DESCRIPTIONS

2.1 Hadley, MA

In 2003, Western Massachusetts Electric Company (WMECO) partnered with SWA to begin researching the benefits – both to the utility and to homeowners – of zero energy homes. As a preliminary effort, WMECO sponsored the construction of a solar home in Hadley, MA. The home features an efficient envelope, 100% fluorescent lighting, efficient appliances, and an efficient boiler fueled by an oil/biodiesel blend. The home also features active solar electric and water heating systems.

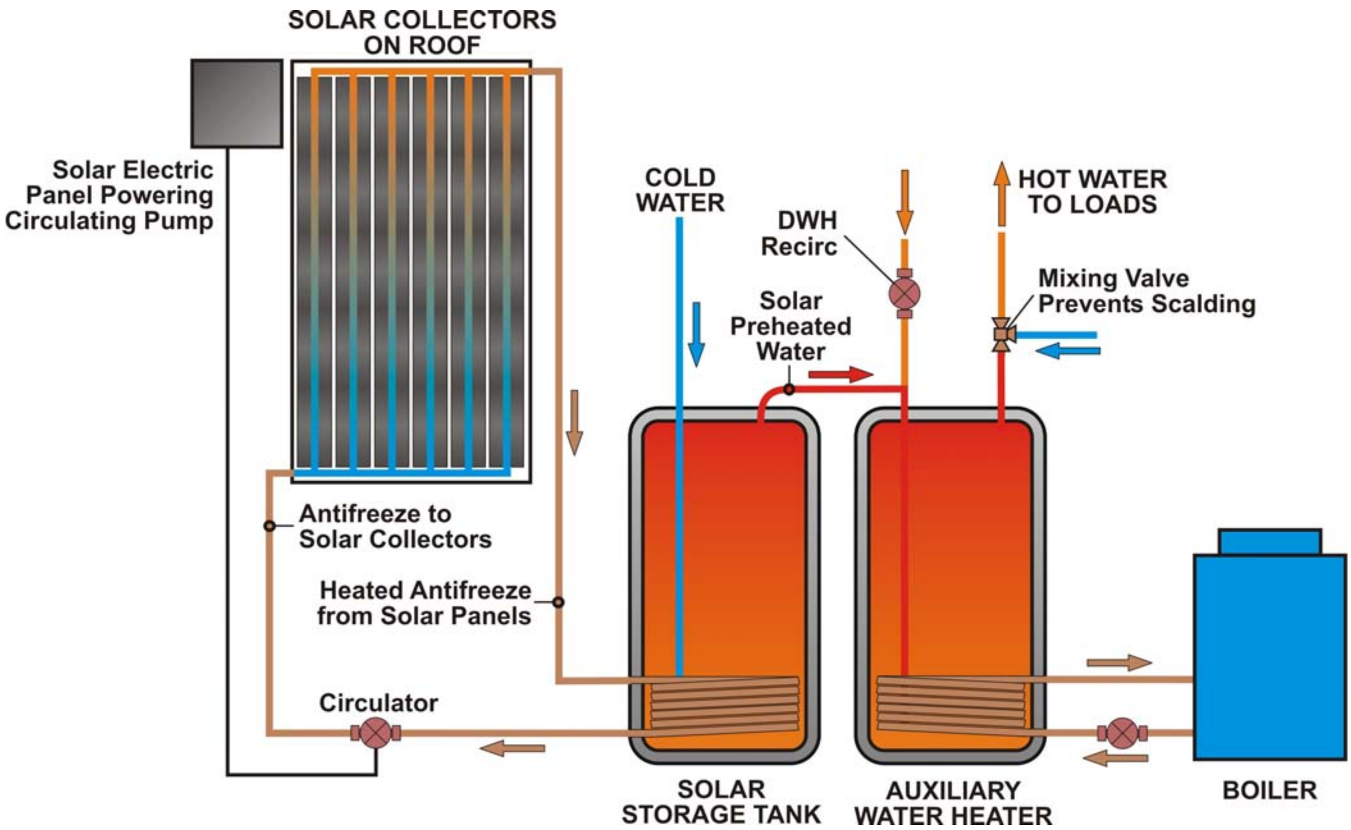

Fig. 2: Schematic of the Massachusetts solar system.

The solar hot water system installed in Western Massachusetts uses PV control, a single DC circulator, and a heat exchanger within the basement storage tank. Auxiliary hot water is provided by the boiler and a separate indirect water heater.

2.2 Madison, WI

In conjunction with the Wisconsin Focus on Energy program, SWA facilitated the installation of a solar thermal water heating system at a prototype home built by Veridian Homes in 2004. SWA reviewed the system design developed by the local solar contractor and installed instrumentation for a long-term evaluation of the system's performance.

The Wisconsin system is also an indirect system: two 4'x8' collectors are installed on the roof and water is heated in an 80 gallon storage tank in the basement. The system differs from the Massachusetts system in that it has differential temperature control and a heat exchanger outside of the solar storage tank. The system has two AC circulators: one circulates a blend of 55% glycol and 45% water through the collectors, the other circulates potable water from the storage tank to the external heat exchanger. A tankless, natural gas water heater provides auxiliary water heating.

Fig. 3: Auxiliary tankless gas water heater and solar storage tank in basement of Madison home.

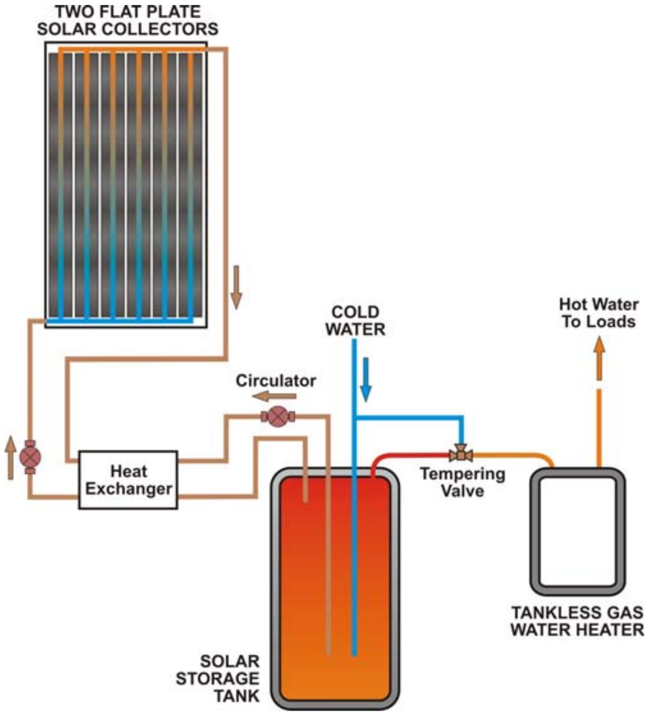

Fig. 4: Schematic of the Wisconsin solar system.

3. MONITORING

At both sites, SWA installed these sensors on the water heating systems:

Temperatures

- Glycol to collectors
- Glycol from collectors
- Cold water (from main or well)
- Solar storage tank (near top of tank)
- Preheated potable water (from solar tank)
- Fully heated water (from auxiliary heater)
- Tempered water (after tempering valve)
- Outdoor air

Fluid Flow Rates

- Glycol solution to collectors
- Potable domestic hot water

From these readings, SWA was able to calculate solar energy collected, total water heating energy load, and the solar fraction of this load. Sensors were connected to a central datalogger and processor, and data were recorded at 15-minute intervals. SWA retrieved data weekly via telephone modems.

4. ENERGY PERFORMANCE

From the Massachusetts home, SWA has collected sixteen months of data. Over the 2005 calendar year, the solar thermal system provided 61% of the energy required to heat domestic water. The lowest solar fractions were reported in December (28%) and the highest in August (87%). In Wisconsin, only eleven months of data are currently available. On average, this solar thermal system provided 63% of domestic water heating energy. The lowest solar fractions were also reported in December (19%) and the highest in August (93%).

Figures 5 and 6 show the domestic water heating energy provided by solar and the respective auxiliary systems on a month-by-month basis.

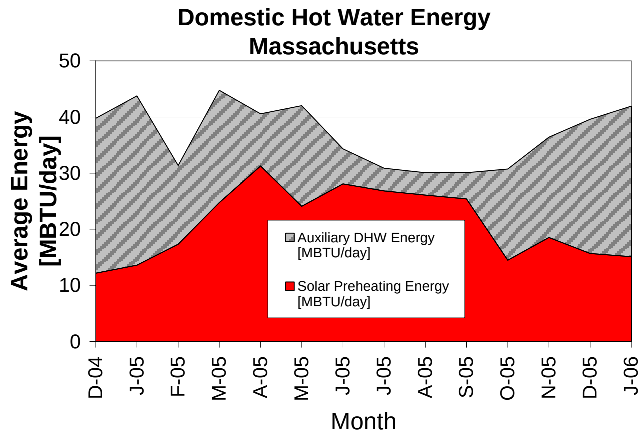

Fig. 5: Domestic water heating energy provided by solar and auxiliary oil/biodiesel boiler in the Massachusetts home.

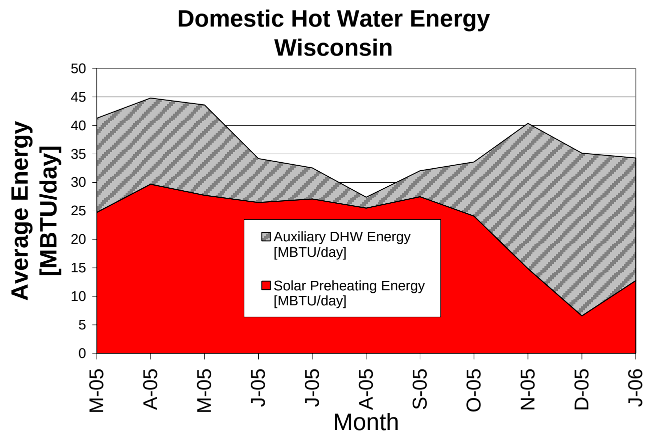

Fig. 6: Domestic water heating energy provided by solar and auxiliary tankless gas heater in Wisconsin home.

TABLE 1 below summarizes and compares the performances of the two cold-climate solar systems. One entire year of data (January to December 2005) is used in the analysis for the Massachusetts home. For the Madison home, only 11 months of data were available (March 2005 to January 2006).

TABLE 1: SUMMARY OF SDHW PERFORMANCE

	Massachusetts (1 year)	Wisconsin (11 months)
Average Solar Fraction	61%	63%
Lowest Monthly Solar Fraction	28%	19%
Highest Monthly Solar Fraction	87%	93%
Average Hot Water Use	64 gal/day	71 gal/day

5. MONITORING AS COMMISSIONING

Using data collected from both systems, SWA discovered problems with the water heating systems that substantially compromised overall efficiency.

5.1 Hadley, MA

In the Massachusetts home, a timer-controlled recirculating pump was installed to provide more immediate hot water to bathrooms. Although convenient for the homeowners, SWA found that the recirculation of hot water resulted in significant cooling of the indirect water heater. Even when the solar tank was hot, the oil boiler was often needed to reheat the indirect water tank because of the excessive recirculating losses. SWA's instruments were not configured to accurately record the magnitude of these losses, but SWA explained the issue to the homeowners. While they still operate the recirculation pump, the schedule has been reduced.

5.2 Madison, WI

Most solar systems require a tempering valve to prevent scalding water from being delivered to taps. In most systems, the tempering valve is located after the auxiliary water heater as the hot water enters the distribution plumbing. In the Madison home, the tempering valve is located between the solar storage tank and the auxiliary, tankless water heater (see Fig. 4).

Before the system was installed, SWA contacted the manufacturer of the water heater to discuss their recommendations for solar applications. Their representative recommended that the tempering valve be located between the solar tank and auxiliary heater. Furthermore, the manufacturer recommended that the tempering valve be adjusted to deliver water at no more than 80°F to the tankless unit.

The rationale for this low setpoint was that under low load (e.g. a hot water draw near 0.5 gpm), if water entering the tankless heater was pre-heated by solar to 90-100°F, the minimum firing rate of the tankless burner would heat water above safe levels. As the heater's controls will not permit the unit to fire under these conditions, water would be distributed to the home at these lukewarm temperatures (90-100°F).

While the manufacturer's rationale is logical with regard to guaranteeing adequate water temperatures, it would result in a tremendous waste of useful solar energy. SWA recommended that the tempering valve be located after the tankless heater as is typical, but the solar contractor installed it before per the manufacturer's recommendations. A compromise, however, was to adjust the tempering valve to deliver water at approximately 125° to the tankless heater. This setting would prevent scalding and maximize use of solar energy.

Early evaluation of the Madison solar system under operation revealed a poorly configured tempering valve and significant overnight tank losses. The tempering valve was set too low; the valve tempered the water to near 100°F or cooler such that the auxiliary heater was required to fire during <u>every</u> hot water draw – even when solar tank water was well above 125ºF. Table 2 shows an example of this, where water leaves the solar tank at 136ºF, is tempered down to 105ºF, and then reheated by the gas heater to deliver water at 118ºF.

TABLE 2: IMPACT OF TEMPERING VALVE

Time, May 11	Solar Tank Temp, *ºF*	Tempered Water Temp *ºF*	Delivered DHW Temp *ºF*	Water Used *gallons*
6:30am	135.9	104.9	118.3	21.1

The valve was adjusted in mid-July to prevent unnecessary tempering (delivering approximately 125°F) and the solar tank was wrapped with insulation. Solar utilization increased substantially with these improvements (75% during the first half of the month, 91% in the second half and 93% during the month of August).

6. SYSTEM CONTROLS AND CONFIGURATION

While these two systems are located more than 1,000 miles from each other, the climate and weather conditions are similar in both locations. In addition, the systems are very similar in:

- Collector size (two 32-ft^2 collectors)
- Storage size (80 gallons)
- Heat transfer fluid (55% propylene glycol)
- Load (a family of 4 consuming 60-80 gallons/day)

Because of the many similarities, the evaluation of both systems provides an excellent opportunity to compare their key differences:

- The Wisconsin system uses differential temperature control, two AC circulators, and a heat exchanger external to the storage tank.
- The Massachusetts system uses PV control, a single DC circulator, and an internal heat exchanger.

The electricity needed to operate two AC circulators is the obvious liability of the Wisconsin system. On the other hand, differential control can offer a better indicator of available solar energy, and the designer can be more certain that the system will operate only when there is sufficient energy to be captured. With the PV control, for example, it is possible that on a cold, bright, windy day, the PV module would power the DC circulator but that cold conditions at the collector would not provide significant gains; it's possible, in fact, that the system would lose energy under these conditions.

Monitoring showed, however, that this latter scenario did not result in a significant energy penalty. On rare occasions, heat transfer fluid did return from the collectors at temperatures lower than the supply to the collectors, but this energy loss was insignificant – 0.3% of the useful energy collected (see Table 3). Total collection for both systems is very similar, though weather and load differences do not allow for a straight comparison. Again, Table 3 includes twelve months of data from the Massachusetts system and eleven months from the Wisconsin home.

TABLE 3: SOLAR ENERGY COLLECTED

	Massachusetts (1 year)	Wisconsin (11 months)
Energy Collected	8,590 MBtu	8,180 MBtu
Control Losses	22 MBtu	NA

Concerns regarding electricity consumption of the Madison system, on the other hand, proved well founded. Table 4 shows useful solar energy collected and electric energy consumed by the solar circulators. While energy collected is similar to that in the Massachusetts home, Table 4 shows that the cost for operation the circulators is 24% of the fuel cost savings offered by the solar thermal system. This liability certainly does not help the already poor cost effectiveness of the system.

7. ECONOMIC ANALYSIS

Calculations showing favorable cost-effectiveness for solar thermal systems usually consider low-cost systems in non-freezing climates and/or inefficient or electric water heating as the reference. While this may be appropriate for some regions (in the Florida market, for example, electric water heating is standard and freeze protection is less critical), this is misleading in most of the country. In most U.S. households (61%, EIA 2001) water heating is provided by natural gas, fuel oil, or propane. In addition, tankless and other more efficient water heating technologies are becoming more common in American homes. Most parts of the country also require rigorous freeze protection for solar systems.

The two solar systems described here are fairly typical for northern climates. As Table 4 shows, the estimated net annual savings from these systems in homes with efficient auxiliary water heating is $135 and $86 each year.

TABLE 4: SYSTEM COST AND ANNUAL ENERGY SAVINGS

	Massachusetts	Wisconsin
Solar Energy Used	7,929 MBtu	7,870 MBtu
Aux. Energy Factor	0.78	0.82
Fuel Savings	73 gal. (oil)	96 therms (gas)
Fuel Savings, $	$135	$113
SDHW Electric Use	NA	247 kWh
SDHW Electricity,$	NA	$27
Net Annual Savings	$135	$86
Initial System Cost	$7,808	$6,493
Simple Payback	58 years	76 years
Incentives/Rebates	$1,500	$2,496
Payback w/rebates	47 years	46 years
IRR	no return	no return

Even without considering maintenance costs (none are included in Table 4), simple payback for these systems are 76 and 58 years. Tax credits and state and utility incentives can improve these values substantially, and increasing energy costs will also influence the economics, but the fact remains that these systems are not – in the purest economic sense – cost effective.

8. SUMMARY

The systems evaluated here work well, providing over 60% of the water heating load in each home. Commissioning of solar thermal systems is key for good operation, and without SWA's monitoring the homes would be consuming considerably more fossil fuel for water heating. The economics of the systems are far from favorable; costs of installed systems must come down to justify wide-scale implementation.

9. ACKNOWLEDGMENTS

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10. REFERENCES

(1) "Water-Heating Energy Consumption in U.S. Households by Climate Zone", 2001 Residential Energy Consumption Survey: Household Energy Consumption and Expenditures Tables, Energy Information Agency, 2001.