Design, Installation, and Performance of Solar Hot Water Systems in New Homes

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ABSTRACT

The performance of solar water heating systems at three homes in cold climates is reported. The house located in Colorado utilized the solar thermal system for space heating and domestic hot water and produced savings of approximately 105 therms of natural gas and $93 over the course of the first year of operation. The solar fraction ranged between 7% in the winter and 100% in the summer months. A prototype house in Wisconsin exhibited solar domestic hot water savings of approximately 86 therms of natural gas and $58 for 10 months of operation, with solar fractions ranging between 16% in the winter to 93% in the summer. The solar domestic hot water system installed at a house built in Massachusetts offset 72 gallons of heating oil/biodiesel fuel worth $133 by offering solar fractions between 26% and 87%. Installation deviations from the designs which affected performance were experienced in two of the homes. In one house, the solar loop heat exchanger within the storage tank was piped backwards, discouraging tank stratification. In another case, a tempering valve was installed between the storage tank and the tankless water heater, forcing the heater to fire, even when the solar storage tank had the capability of supplying the draw of hot water. These issues and their solutions are discussed. These cases are used to highlight some of the challenges of incorporating solar thermal systems into production building.

Introduction

This study involves three builders in cold climates who have partnered with either IBACOS or Steven Winter Associates to participate in the US Department of Energy's (DOE) Building America (BA) program.[1] As part of a whole-house, systems approach to building more efficient, higher-quality homes, each builder included solar domestic hot water (SDHW) and space heating systems in a prototype house. The systems were instrumented and have been monitored for approximately a year.

Builder 1's Low-Energy Prototype House – Loveland, Colorado

In 2004, a builder in Colorado (Builder 1) worked with IBACOS, Inc., and the National Renewable Energy Laboratory (NREL) under the auspices of the Building America program to build a low-energy pilot home. Already exceeding code-based energy efficiency requirements, Builder 1's work with the BA program was taken as a step toward meeting their goal to build net zero energy homes on a production basis in the near future (IBACOS 2004a). Computer modeling of the pilot home determined that the as-built house exhibits total energy savings

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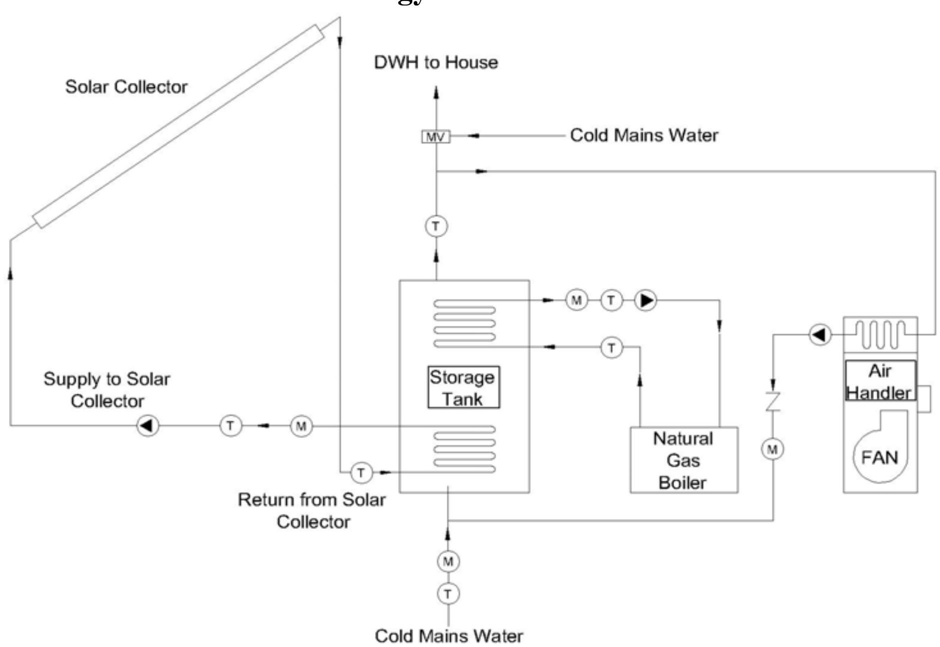
[1]For more information on the Building American program, visit the U.S. Department of Energy website at http://www.eere.energy.gov/buildings/building_america/.

greater than 50%, relative to the Building America benchmark[2] (IBACOS 2004b). The house is a one-story home with finished basement and is occupied by a family of three. It achieves its low-energy performance through a systems approach to thermal performance improvements, efficient mechanical systems and appliances, as well as on-site solar energy collection.

The water heating system provides energy for both domestic hot water and space heating, as shown in Figure 1. The storage tank is a 79 gallon tank with two integral, immersed heat exchanger coils. The solar thermal collector loop is an active, closed loop system charged with a 50% propylene glycol mixture. The single collector is a 48 ft^2 flat plate collector from Radco Products and is oriented south. The solar loop adds heat to the bottom of the storage tank through the lower heat exchanger coil. The upper coil is connected to the closed boiler loop for auxiliary heating. The boiler is activated through thermostatic control based on the tank temperature, measured near the top of the storage tank. Domestic hot water and space heating demands are met by drawing potable hot water from the storage tank. When space heating is called for, a circulating pump is activated. Hot water from the storage tank is circulated from the top of the tank, through the heating coil in the air handler, and returned to the bottom of the storage tank. Similarly, when a draw is made on the domestic hot water system, hot water is drawn from the top of the storage tank, tempered by a tempering valve, and delivered to the fixture(s). Cold water from the mains is supplied to the bottom of the storage tank.

Figure 1. Schematic of the Installed Solar Water Heating Systems at Builder 1's Low-Energy House in Colorado



Builder 2's Prototype House – Madison, Wisconsin

Steven Winter Associates has worked with a builder in Madison, Wis. (Builder 2), for over four years. The latest prototype home, completed in 2004, features advanced envelope

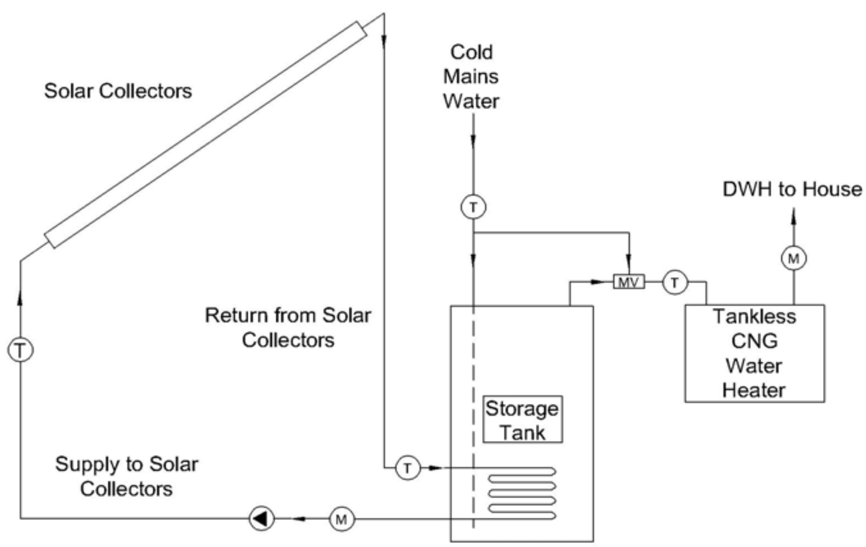
[2]The Building America research benchmark definition may be found at http://www.eere.energy.gov/buildings/building_america/pdfs/37529.pdf.

construction, energy efficient mechanical systems, 100% fluorescent lighting, and Energy Star® appliances, among other improvements over standard construction. In conjunction with the Wisconsin Focus on Energy program[3], Consortium for Advanced Residential Buildings (CARB)[4] facilitated the installation of a solar thermal water heating system at Builder 2's prototype home in 2004. CARB reviewed the system design developed by the local system installer and installed instrumentation for a long-term evaluation of the system's performance in conjunction with an auxiliary gas-fired tankless water heater. As standard practice, Builder 2 installs power-vented tank-type water heaters. Builder 2 was interested in evaluating the tankless technology, particularly in conjunction with the solar hot water system. The home was sold in the spring and was occupied by a family of four between March 2005 and January 2006.

Figure 2 is a schematic of the domestic water heating system. The indirect, closed loop solar water heating system consists of two Heliodyne Gobi 4'x8' flat plate collectors (64 ft^2) installed on the main roof and an external heat exchanger assembly. The system circulates a 55% propylene glycol mixture through the collectors and into the heat exchanger within an 80 gallon domestic hot water storage tank located in the basement. Hot water back-up for the solar system is provided by a natural gas tankless water heater.

When a draw on the domestic hot water is made, the solar storage tank supplies preheated water to the tankless gas water heater. As per the installation instruction of the tankless water heater manufacturer, a tempering valve was installed between the solar storage tank and the tankless heater. Depending on the setpoint of the tempering valve and the solar preheated water temperature, the tankless water heater may or may not fire and add heat to the water being delivered to the domestic hot water fixtures.

Figure 2. Schematic of the Installed SDHW System at Builder 2's Wisconsin Prototype House



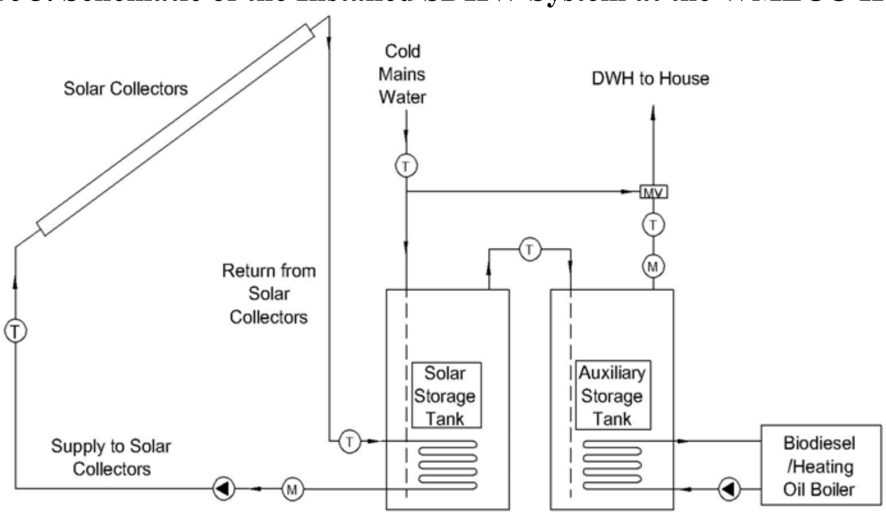
[3] Focus on Energy is a public-private partnership contracted by the Wisconsin Department of Administration's Division of Energy. More information may be found at http://www.wifocusonenergy.com/
[4] Consortium for Advanced Residential Buildings (CARB) is led by Steven Winter Associates, Inc.

WMECO – Hadley, Massachusetts

In 2003, Western Massachusetts Electric Company (WMECO) partnered with CARB 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, Mass. 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. The home was completed in the spring of 2004 and is currently occupied by a family of four. CARB provided design support and energy modeling early on and has been collecting data from monitoring equipment installed at the home since June 2004. Results of the study will be used to determine the viability of a program promoting "zero energy" homes in Western Massachusetts.

The domestic hot water heating system utilizing two 80 gallon storage tanks is shown in Figure 3. One is heated by the solar system. The second is preheated by the solar storage tank water, with auxiliary heating by the boiler. The Solar Works CL64-80 closed loop solar domestic water heating system consists of two flat plate solar collectors with a combined area of 64 ft^2 and charged with a 55% mixture of propylene glycol. The PV-powered pump circulates the collector fluid through an immersed heat exchanger, heating the water in the solar storage tank. When a draw on the domestic hot water is made, water preheated by the solar system is drawn from the solar storage tank into the bottom of the auxiliary hot water storage tank. When necessary, further heating of the water in the auxiliary storage tank is managed by the boiler via a coil in the tank. During a draw, cold mains water is supplied to the bottom of the solar storage tank.

Figure 3. Schematic of the Installed SDHW System at the WMECO House



Solar Hot Water System Performance Results

Builder 1's Low-Energy Prototype House – Loveland, Colorado

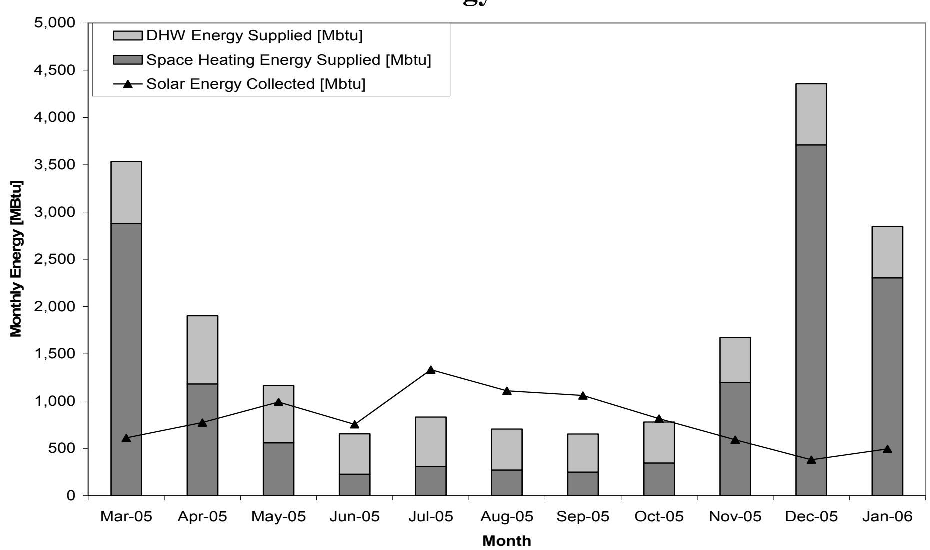
The performance data of the Builder 1's low-energy house are shown in Table 1 and Figure 4. Had there been no solar thermal system on this house, one can assume that the energy collected by the solar thermal system would have been provided by the 90% efficient boiler.

Table 1. Solar Domestic Water and Space Heating System Performance – Builder 1's Low-Energy House in Colorado

Month	Solar Energy Collected [MBtu]	Space Heating Energy Supplied [MBtu]	DHW Energy Supplied [MBtu]	Whole House Gas Usage[5] [MBtu]	Solar Fraction	Price of Natural Gas [$/MBtu]	Natural Gas Cost Savings[6]
Feb-05	495	1,726	601	4,400	11%	0.007479	$4.11
Mar-05	611	2,879	658	4,000	15%	0.007392	$5.02
Apr-05	774	1,182	721	2,300	27%	0.007504	$6.45
May-05	992	559	604	800	>58%	0.008026	$8.84
Jun-05	753	226	427	700	~100%	0.007805	$6.53
Jul-05	1,332	306	525	200	~100%	0.008032	$11.89
Aug-05	1,110	270	434	200	~100%	0.008884	$10.95
Sep-05	1,059	250	403	100	~100%	0.009362	$11.02
Oct-05	815	345	433	600	>60%	0.010681	$9.68
Nov-05	590	1,198	474	1,900	26%	0.011732	$7.70
Dec-05	381	3,709	648	5,900	7%	0.010332	$4.37
Jan-06	493	2,304	545	N/A	N/A	0.011923	$6.53
Average	784	1,246	539		55%		
12 Month Total	9,405	14,954	6,472				$93.09

With this caveat, the solar thermal system on the Builder 1's house has offset 105 therms of natural gas and saved the homeowner approximately $93.00 over the course of the first twelve months of operation. The solar fraction is defined as the ratio of the solar heating energy to the total heat addition to the water. This includes tank standby losses, but not the inefficiencies of the

Figure 4. Solar Collected and Hot Water Supplied Energy – Builder 1's Low-Energy House in Colorado



[5] Winter gas usage is solely the boiler use. Summer is almost entirely gas grill use. Swing months include both.
[6] Calculated using a boiler efficiency of 90%.

auxiliary boiler. The monthly solar fraction for February through December ranges between 7% and 100%, with an average of 55%. The summer solar fraction is assumed to be near or at 100%, because the homeowner shuts the auxiliary heating system off May or June through September (Builder 1 2006). The solar fractions for the remaining months are calculated by the ratio of solar input energy to the sum of solar and gas input energy. The gas input energy is obtained by multiplying monthly gas usage multiplied by the boiler efficiency. The boiler is the only piece of gas equipment in use during the winter. During the summer, the homeowners use a natural gas grill frequently for cooking. The average daily domestic hot water usage for each month ranged from 28 to 39 gallons per day, with an average of 32 gallons/day over the course of the year.

Builder 2's Prototype House – Madison, Wisconsin

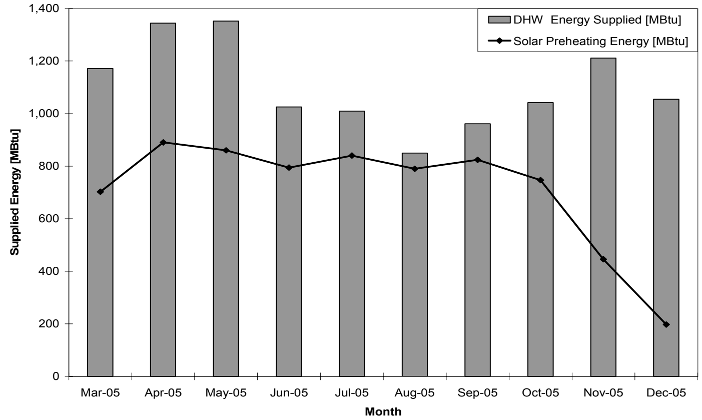
A summary of data collected from the Builder 2's prototype house between March and December 2005 may be found in Table 2. The solar thermal and tankless gas water heating contributions to the domestic hot water load for the house can be seen in Figure 5. Analysis of the energy data for these months shows that the solar thermal system is able to provide an average of 66% of the energy needed to meet the home's hot water demand. The breakdown into seasons is 63% in the spring, 85% in the summer, 65% in the fall, and 19% in December (as the only winter month of data[7]). The solar thermal system has offset 86 therms of natural gas and saved the homeowner approximately $59.00 in gas during the first 10 months of operation.

Table 2. Solar Domestic Water Heating Performance – Builder 2's Wisconsin Prototype House

Month	Solar Preheating Energy [MBtu]	Auxiliary DHW Energy [MBTU]	DHW Energy Supplied [MBtu]	Daily DHW Used [Gal/day]	Solar Fraction [%]	Price of Natural Gas [$/MBtu]	Natural Gas Cost Savings[8]
Mar-05	703	469	1,171	74	60%	0.008987	$5.14
Apr-05	890	454	1,344	80	66%	0.0097095	$5.37
May-05	860	492	1,352	83	64%	0.0097833	$5.87
Jun-05	794	231	1,026	71	77%	0.0090141	$2.54
Jul-05	840	169	1,010	69	83%	0.0095535	$1.97
Aug-05	790	60	850	58	93%	0.0098624	$0.72
Sep-05	824	137	962	70	86%	0.012225	$2.05
Oct-05	747	294	1,042	72	72%	0.015044	$5.40
Nov-05	446	766	1,211	79	37%	0.014948	$13.95
Dec-05	197	857	1,054	63	19%	0.014948	$15.62
Average	709	393	1,102	72	66%	0.0114075	$5.86
10 Month Total	7,092	3,929	11,022				$58.64

[7] The house has been unoccupied since January 2006.
[8] The tankless water heater is estimated to be 82% efficient.

Figure 5. Solar Preheating and Domestic Hot Water Supplied Energy – Builder 2's Wisconsin Prototype House



WMECO – Hadley, Massachusetts

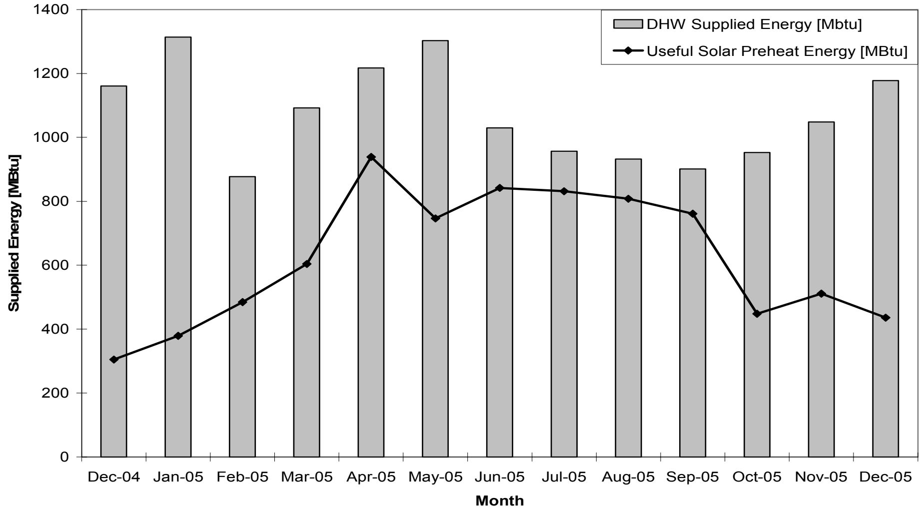
Thirteen months of performance data for the solar domestic hot water system in the WMECO house is tabulated in Table 3, and the solar and domestic hot water energy use is shown in Figure 6. During 2005, the solar thermal system provided an average of 62% of the energy delivered to the domestic hot water demand. The winter contribution averaged 40%, spring 63%, summer 85%, and fall 60%. If the thermal energy for hot water were to be provided completely by the biodiesel fuel (~$1.85/gal), the year's solar thermal savings are approximately 72 gallons of fuel and $133.

Table 3. Solar Domestic Water Heating Performance for 2005 – WMECO House

Month	Solar Thermal Energy Collected [MBtu]	Useful Solar Preheat Energy [MBtu]	DHW Supplied Energy [MBtu]	Hot Water Consumed [Gal/day]	Solar Fraction[9]	Price of Oil/ Biodiesel [$/gal]	Oil/ Biodiesel Cost Savings[10]
Dec-04	305	305	1161	68	26%	1.85	$5.22
Jan-05	379	379	1314	71	29%	1.85	$6.48
Feb-05	493	485	877	50	55%	1.85	$8.29
Mar-05	610	604	1093	71	55%	1.85	$10.33
Apr-05	1021	939	1217	68	77%	1.85	$16.05
May-05	787	747	1303	73	57%	1.85	$12.77
Jun-05	957	842	1030	65	82%	1.85	$14.40
Jul-05	997	832	957	63	87%	1.85	$14.22
Aug-05	949	808	932	62	87%	1.85	$13.82
Sep-05	994	761	901	62	84%	1.85	$13.02
Oct-05	455	448	953	60	47%	1.85	$7.66
Nov-05	511	511	1048	66	49%	1.85	$8.74
Dec-05	436	436	1178	67	37%	1.85	$7.46
Average	684	623	1074	65	59%	1.85	$10.65
2005 Total	8590	7791	12803	65 (average)	62% (average)		$133.23

[9] See the discussion section regarding the calculation of solar fraction for this house.
[10] Calculation of heating oil/biodiesel offset and solar savings assumes boiler efficiency of 78%.

Figure 6. Solar Preheating and Domestic Hot Water Supplied Energy - WMECO House



Discussion

The solar thermal systems in the three houses involved in this study offset significant usage of fossil fuels. The financial benefit to the homeowners is modest, with long payback times at current energy prices. With the potential for increasing energy prices and the development of the "Green Building" markets, the current financial savings may not be representative of the marketability of this technology.

Builder 1's Low-Energy House – Loveland, Colorado

As mentioned in the results section for this house, the solar fraction was estimated to be near or at 100% during the summer based on homeowner assurances that the boiler is turned off during the warmer months, except when large groups of people are visiting (Builder 1 2006). This is supported by the monitored data for solar energy collected compared to the combined demand on the heated water, as shown in Figure 4. The solar fraction is calculated from gas usage data during winter months and swing seasons. Also, during the warmer months, the homeowners use a natural gas grill for cooking. This leads to some uncertainty of the exact solar fraction during the swing seasons, in particular May and October. The solar fraction for these two months may be higher than shown in Table 1 due to uncertainty in boiler on/off dates and gas grill usage.

In regards to the solar fraction and gas cost savings calculations, the boiler is rated to have a 90% efficiency. However, given the small temperature difference across the boiler, it is likely that it performs at a lower efficiency for most of its operation. Because this was not measured directly and that an arbitrary derating factor would increase the solar fraction and apparent gas cost savings, the boiler efficiency of 90% was retained for calculations in order to provide a conservative estimate of gas cost savings and solar fraction.

It should be noted that monetary savings of gas offset by the solar thermal system do not account for added electrical costs of running the solar loop circulation pump. As noted below in the Builder 2's prototype house discussion, this can consume a significant portion of the financial savings offered by reduced gas usage.

As indicated in Figure 4, the space heating load did not drop to zero during the summer months. This is a drawback to the overall design of the heating system in this house, but not the solar thermal system itself. This undesired load is due to the space heating loop design. To avoid issues with potable water sitting undisturbed in the space heating loop for long periods of time during the warmer months, the space heating loop circulating pump is activated for a short while every four hours. The impact of this is twofold. Drawing water from the storage tank through the heating coil removes heat from the storage tank. It also adds to the cooling load during the warmer months. During the four summer months of 2005, the total energy delivered to the heating coil and associated piping was equal to 1,050 MBtu. More heat is removed from the tank when the cycle coincides with operation of the air conditioning system, because of the forced convection of heat from the space heating coil in the air handler.

Another issue that was found to degrade the performance of this solar water heating system is that the solar loop was plumbed to the heat exchanger coil in the storage tank backwards. The system was designed so that the hot solar fluid returning from the collector enters the top inlet to the lower coil and exits at the very bottom of the tank. However, the as-installed system is set up so that the hot solar fluid enters the bottom end of the coil and exits at the upper. The as-installed path discourages stratification within the storage tank by subjecting the coolest portion of the tank to the highest temperature solar fluid. Stratification typically allows for the hottest water in the storage tank to be delivered to the load. It also reduces the runtime of the auxiliary heating system when the tank temperature for the control is measured near the top of the tank. TRNSYS simulations (Barker 2004) of the original design and the as-installed design predict that the system is capable of collecting up to 11% more energy were it installed as the original design.

Despite these complications, the homeowners are very satisfied with the temperature and quantity of hot water provided solely by the solar water heating system during the summer months (Builder 1 2006). Improvements in performance for the swing and winter seasons would be seen were the solar heat exchanger piping to be corrected and the space heating coil isolated from the storage tank during the summer. A simpler solution to the space heating issue would be to rely on the boiler as the exclusive heat source for space heating and remove the storage tank from that loop.

Builder 2's Prototype House – Madison, Wisconsin

The higher solar fraction during the summer months is attributed not only to the increase in insolation, but also to a slight decrease in demand for hot water, higher entering water temperatures, higher outdoor air temperatures, and optimization of the tempering valve.

The reported cost savings of the solar-displaced natural gas do not address the cost of the electric pumping energy required to run the solar loop. The electrical energy consumption of the circulating pumps was on average 24 kWh per month or about 4% of the home's total electrical energy consumption.[11] This electric load effectively reduces the daily solar savings by 16-40%, depending on the month.

Early evaluation of the system exposed issues compromising its performance. The tempering valve was installed between the solar storage tank and the tankless gas water heater and set fairly low, per the tankless water heater manufacturer's recommendations. The tempering valve was originally designed to be installed after the tankless heater. The preheated water

[11] The home's Energy Star® refrigerator consumes twice that amount.

leaving the solar storage tank is tempered before it is delivered to the tankless water heater. At its initial setting, the tempering valve reduced solar preheated water to 100°F or below. This caused the tankless water heater to reheat the tempered water, even when hot water in the solar storage tank could have met the entire load. The tempering valve setting was increased in mid-July to prevent the auxiliary water heater from being used more than was necessary. The second issue that was addressed in July was the overnight tank losses. It was discovered that the storage tank was losing 10-20 degrees Fahrenheit overnight, again leading to the unnecessary operation of the auxiliary water heater in the morning. The tank was wrapped with an insulation blanket. The combination of these two improvements led to higher solar fractions in late July (90%), August and September. The solar fraction in August was much higher than July or September; however this can be partially attributed to the decrease in hot water demand and higher average outdoor temperatures.

WMECO – Hadley, Massachusetts

Unlike the other two houses in this study, the circulation pump at the WMECO house is powered solely by photovoltaics. This avoids the electrical energy costs associated with running the solar thermal loop, and the savings offered by the solar thermal system are fully realized by the homeowner.

The solar fraction calculation for this house is similar to that of the Builder 2's prototype house. It differs, though in affect of the second storage tank on the energy balance. The useful solar energy supplied to the second storage tank and the total energy added to the domestic hot water are measured, but the second storage tank losses are not fully accounted for. These losses may be estimated by tank heat loss modeling or through energy balance on the solar storage tank, but have not been completed at this time. One would expect the solar fractions for the WMECO house to be slightly lower, were the standby losses of the second tank accounted for.

Discussion of SDHW in the Production Environment

In two of the cases covered by this study, installation issues negatively affected the performance of the solar water heating systems. Complications such as these are hardly uncommon. It's well known that commissioning of solar domestic hot water systems is very important. However, it does highlight some of the issues that act as a barrier to acceptance of such systems by large-scale and production builders.

For solar thermal systems to receive large scale acceptance, the difficulties with integration into the production building process must be addressed. The problems found during the commissioning of the above systems highlight the complexity of solar thermal systems, relative to typical plumbing arrangements. These complications occurred, despite installation of the systems by professional installers, detailed design schematics developed by the Building America teams, and considerable forethought by all parties involved. The wide variety of systems, designs, and equipment that offer flexibility of design and purpose can be very confusing to implement correctly. Frequently, the plumbing crews used in the production process are not familiar with solar thermal systems. Standard plumbing layouts and designs for SDHW systems one would see in a production environment would help this concern. However, integration of the SDHW systems into standard plumbing needs to be streamlined from design and equipment standpoints.

Currently, much of the country is serviced by small solar thermal system installers. The market for solar thermal installation is also typically piecemeal, in that retrofit and new construction contracts are acquired and installed in small numbers, if not one at a time. An adequate business model for a solar thermal company in the retrofit and custom installation market may not be compatible with a production environment. As an example of this, a larger-scale builder described his experiences with SDHW system installation (Builder 1 2006). He has had difficulty with installation teams being able to work on the predetermined timetable and to the bid price agreed upon. He knows that SDHW systems work and loves the system on his own home. He is very satisfied with its performance. However, from a business perspective, he is unable to rationalize incorporating SDHW systems on a large scale into his products, given these process integration challenges. The installer base is very region-dependent throughout the country, and these difficulties are not likely to be encountered everywhere. In some areas, the market may already be developed to the point that there are installation companies that are capable of working in the production environment. Alternatively, the builder could choose to internalize the process and have their own staff do the installations. Another option is that a large plumbing company may decide to add SDHW as a standard offering on a large scale, although low demand and high initial pricing are barriers for this to become prevalent in the marketplace at this point in time.

On the other hand, with the increasing awareness of the cost of energy in financial, environmental, and political terms, consumer demand may change rapidly. As natural gas and electricity prices rise, solar thermal technologies can, in theory, only look better from a simple economics perspective. “Green building” is becoming vogue in some mainstream circles and is receiving much favorable press. Government incentives for energy efficiency and renewable energy systems can create demand seemingly overnight, as was seen in the late 1970’s. The issues that make it difficult for large builders to incorporate SDHW systems need to be addressed and solved if solar domestic water heating is ever to become widespread.

Conclusions

Despite the challenges to large-scale application of single-family residential solar domestic hot water systems, the three houses in this study highlight the potential of this technology. Two of the systems had installation issues, yet all three systems exhibit significant energy savings. In Colorado, Builder 1’s low-energy house’s solar thermal space heating and domestic hot water system produced savings of approximately 105 therms of natural gas and $93 over the course of the first year of operation. The solar fraction ranged between 7% in the winter and 100% in the summer months. Builder 2’s prototype house saw SDHW savings of approximately 86 therms of natural gas and $58 for 10 months of operation, with solar fractions ranging between 16% in the winter to 93% in the summer. The WMECO house SDHW system offset approximately 72 gallons of heating oil/biodiesel fuel worth $133 by offering solar fractions between 26% and 87%. Discussion of installation issues in these applications has highlighted some of the barriers to SDHW system incorporation in the production environment.

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