The Effect of Piping Heat Losses on the Efficiency of Solar Thermal Water Heating in a Net-Zero Energy Home

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ABSTRACT

This study evaluates the thermal performance of a dual-tank domestic hot water (DHW) system designed for a net-zero home at the National Institute of Standards and Technology, Gaithersburg Maryland campus. Hot water demand for a virtual family of four in this facility is met with an active, indirect solar thermal water heater and a heat pump water heater that serves as the auxiliary heating method. Testing under a representative water-use schedule between February 2014 and June 2014 has shown that heat losses in interconnective plumbing between the two hot water storage tanks can significantly diminish solar fractions at times when solar thermal water heater output is high. For June, the monthly solar fraction of the DHW system was 86 %, while a 95 % solar fraction would have been achieved without heat losses. This highlights one known drawback of dual-tank hot water storage systems, where constant heating of interconnecting plumbing results in energy loss to the ambient environment and should be considered part of the total hot water storage volume.

INTRODUCTION

Residential buildings account for 22 % of all energy consumed in the U.S. (U.S. DOE 2011). The concept of achieving net-zero energy performance of buildings has received much attention in recent years as a means to reduce this energy expenditure. The United States' Department of Energy Building Technologies Program, for instance, has planned to support research and development activities in new residential construction that will lead to "marketable zero energy homes in 2020" (U.S. DOE 2008).

Net-zero cannot be achieved without the use of renewable energy and highly energy-efficient technologies, and without mitigating associated inefficiencies. A Net-Zero Energy Residential Test Facility (NZERTF) constructed on the Gaithersburg, Maryland campus of the National Institute of Standards and Technology (NIST) was built for the evaluation of such technologies. Details on the facility can be found in Fanney et al. (2014) and Pettit et al. (2014).

The focus of the current study is to describe one such inefficiency associated with the dual-tank domestic hot water (DHW) system of the facility, which was designed to reduce the electrical demand compared to that of conventional water heating equipment. According to Hiller (1996), dual-tank systems generally have lower efficiencies than single-tank storage water heaters of similar capacity. One reason is that interconnecting plumbing is hot for a majority of the time resulting in heat loss to the ambient environment if not heavily insulated. The results of this paper highlight this type of heat loss as it negatively impacted the solar energy utilization of the DHW system over the course of a 5-month period.

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BACKGROUND

During the first year of building operation, the NZERTF was used to demonstrate that a home similar in size and amenities to those in the surrounding community could generate as much energy through onsite renewable sources as used by a typical family of four. The family was in fact a virtual family whose water-use and electricity-use behaviors were automated according to a weekly schedule derived from the Building America Research Benchmark Definition (Hendron et al. 2008). Each week, an average of 2570 L (680 gal) of mixed hot and cold water was utilized at sinks, showers, and baths, and by the clothes washer and dishwasher. The hot water for these activities was supplied by a solar thermal water preheating system and a heat pump water heater downstream.

Description of Water Heating Systems

Solar Thermal Water Heater (SWH). The residential test facility is currently using an active, closed-loop solar thermal water heating system, Figure 1. The system utilizes two Solar Rating & Certification Corporation™ (SRCC) OG-100 certified single-glazed flat plate solar thermal collectors, with individual aperture dimensions of 1.1 m x 2.0 m (3.8 ft x 6.6 ft). The array is located on the porch roof and faces true south at an 18.4° tilt. The thermal energy absorbed by the collectors is transferred to a 303 L (80 gal) water storage tank, located in the house basement, with its 4500 W auxiliary heating element disabled. An insulated cross-flow heat exchanger external to the tank contains two pumps, one of which circulates a 50 % by volume propylene glycol in water solution (heat transfer fluid) used in the solar thermal collector fluid loops. The second pump circulates potable water from the storage tank through the heat exchanger. The controller turns the circulating pumps on when the temperature differential between the glycol solution leaving the collectors and the water in the lower portion of the storage tank exceeds 10 °C (18 °F) and turns them off when the differential is below 3 °C (5 °F) or when the storage tank temperature sensor exceeds a reading of 71 °C (160 °F).

Downstream of the solar storage tank and before the piping enters the heat pump water heater, a thermostatic mixing valve is installed and set at 49 °C (120 °F). The cold water inlet into the thermostatic mixing valve was manually shut and not opened until June 2014 when mixing valve operation was required.

Heat Pump Water Heater (HPWH). The heat pump water heater provides hot water in the event that the solar thermal water heating system cannot meet the demand. The unit consists of a 189 L (50 gal) storage tank with an integrated air source heat pump. The system is operated in the "Hybrid" mode with a temperature set-point of 49 °C (120 °F). The "Hybrid" mode ensures that the heat pump provides a majority of the hot water load while its 3800 W electric element only energizes when the heat pump cannot meet the hot water demand. In the "Hybrid" mode, under test conditions of 57 °C (135 °F) set-point temperature and 20 °C (67.5 °F) ambient temperature, the manufacturer-reported Energy Factor (EF), Coefficient of Performance (COP), and standby loss of the unit are 2.5, 2.6, and 0.20 °C/h (0.36 °F/h), respectively.

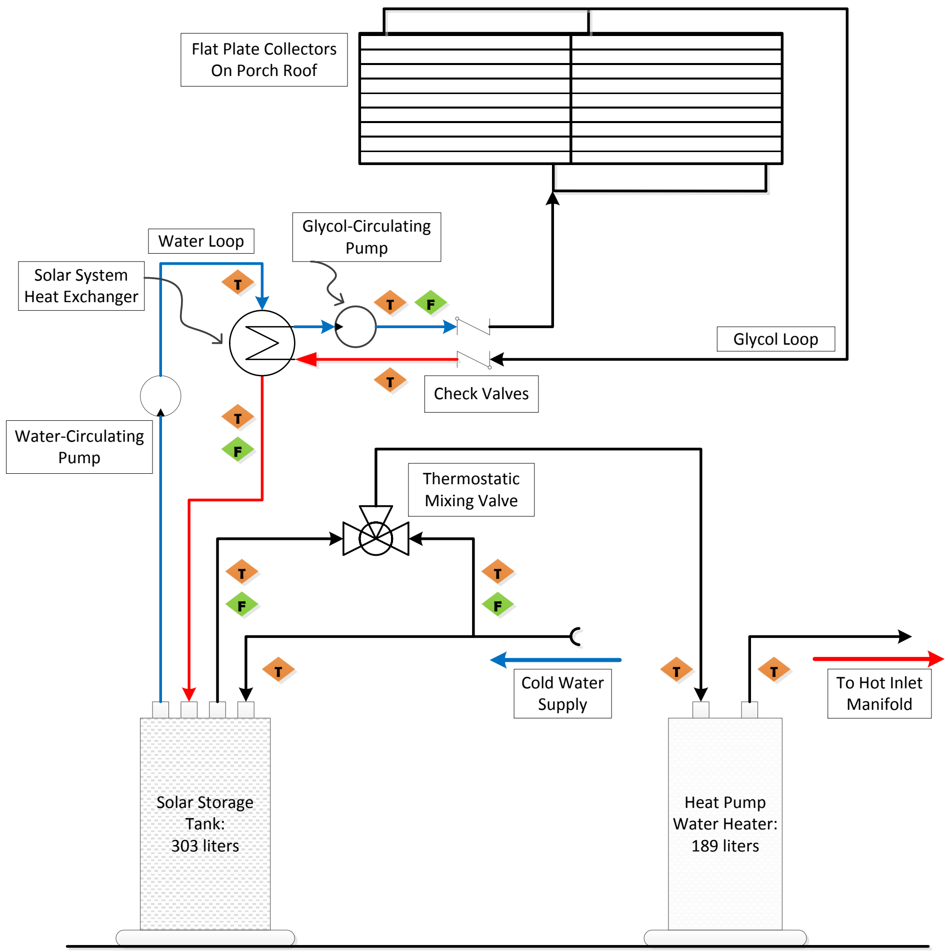


Figure 1 Schematic of solar thermal and heat pump water heaters. Diamond symbols with "T" indicate temperature measurement locations in the stream of fluid flow and diamond symbols with "F" show flow measurement locations.

DATA COLLECTION AND MONITORING

Figure 1 shows the location of various temperature and flow measurements used to characterize the performance of the DHW system. The temperature of the inlet and outlet of each storage tank, the mixing valve cold inlet temperature, and the ambient temperature were measured with Type-T thermocouples with a calibrated accuracy of ± 0.1 °C (± 0.2 °F). The water flows through the solar thermal storage tank, the heat pump water heater, and the cold side of the thermostatic mixing valve were measured by pulse-output paddle-type flow meters with a resolution of 0.013 gal/pulse (0.049 L/pulse) and a calibrated accuracy within ± 1.7 % of reading. At end-use fixtures, the water delivered is also measured using scales, providing a redundant measure by which the accuracy and drift of the flow meters could be assessed.

Over the course of a day, 44 draws were intiated at the fixtures by the real-time event controller according to a water draw schedule described by Omar and Bushby (2013). Individual sink draws were terminated after 2.4 L (0.63 gal) were drawn, showers at 33 L (8.75 gal) or 53 L (14 gal), and bath draws at 114 L (30 gal). The clothes washer and dishwasher cycles were initiated and ran until completion. The hot water provided by the DHW system flowed at various rates: approximately 3.8 L/min (1.0 gpm) for sink and shower draws, 6.4 L/min (1.7 gpm) for clothes washer use, 7.2 L/min (1.9

gpm) for dishwasher use, and 10 L/min (2.7 gpm) for bath water draws. All fixtures installed in the residential test facility are of the low-flow variety.

Volumetric flow and temperature data were logged for the duration of each water event and the following values were subsequently calculated at 3-second intervals: the thermal energy ouput of the domestic water heater systems before hot water delivery through the distribution system, $Q_{load} = m \cdot c_p \cdot (T_{HPWH,out} - T_{SWH,in})$; the thermal energy in hot water delivered by the solar thermal storage tank, $Q_{del,SWH} = m \cdot c_p \cdot (T_{SWH,out} - T_{SWH,in})$; and the thermal energy contribution from the heat pump storage tank, $Q_{del,HPWH} = m \cdot c_p \cdot (T_{HPWH,out} - T_{HPWH,in})$. In these equations, m is the mass delivered, c_p is the specific heat of water, $T_{HPWH,out}$ is the outlet temperature from the heat pump water heater, $T_{SWH,in}$ is the inlet potable water temperature to the solar water heater, $T_{SWH,out}$ is the outlet water temperature from the solar water heater, and $T_{HPWH,in}$ is the inlet water temperature to heat pump water heater. These equations are slightly modified in the event that mixing valve operation occurs. In an ideal system without energy losses, $T_{SWH,out} = T_{HPWH,in}$, and the sum of $Q_{del,SWH}$ and $Q_{del,HPWH}$ would be equivalent to Q_{load}.

RESULTS AND DISCUSSION

Piping Heat Loss

Months of data collection and analysis of the performance of the SWH and HPWH led to the observation of significant piping heat losses that diminished the contribution the solar hot water system made to the total hot water load provided. For example, Figure 2 shows daily data from a week in May that compares the energy delivered by each component of the water heating system to Q_{load}. Error bars represent the combined standard uncertainty in thermal energy values propogated from temperature and flow measurement uncertainties. It can be seen that the discrepancy between the computed Q_{load} and the sum of the contributions of each water heater is greater on days when the solar water heater provides a large load (i.e. Tue 5/6), but that the sum better matches Q_{load} on days when the majority of water heating is provided by the heat pump water heater (i.e. Thu 5/1).

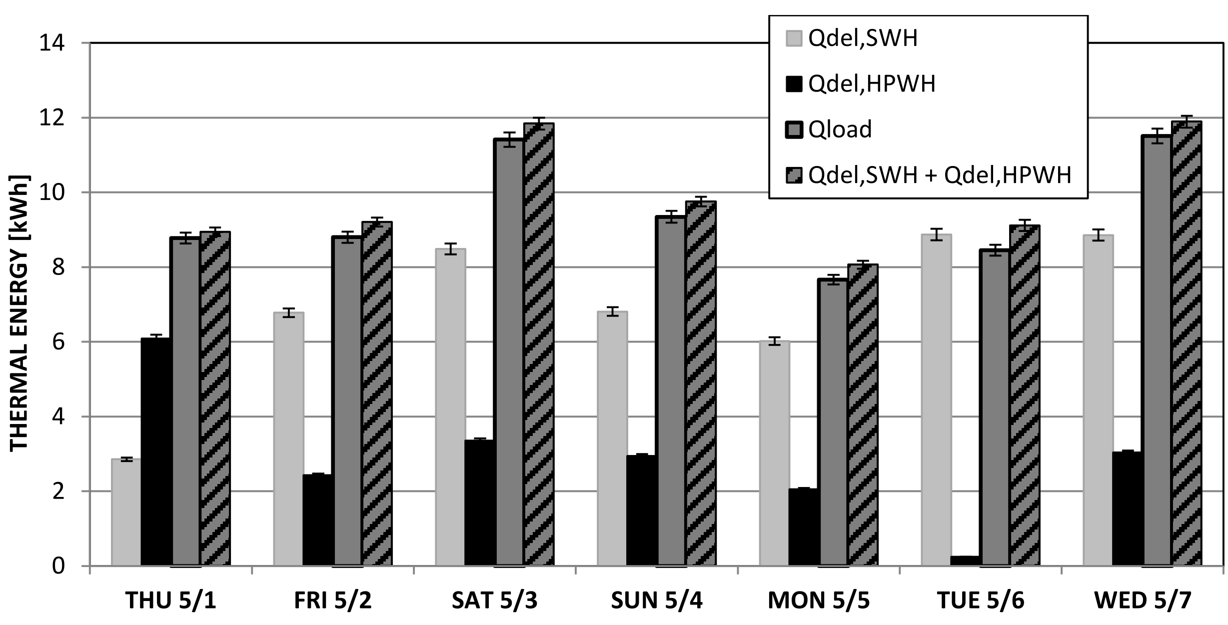


Figure 2. Daily thermal load provided by SWH and HPWH compared to the load delivered by overall system for the first week of May.

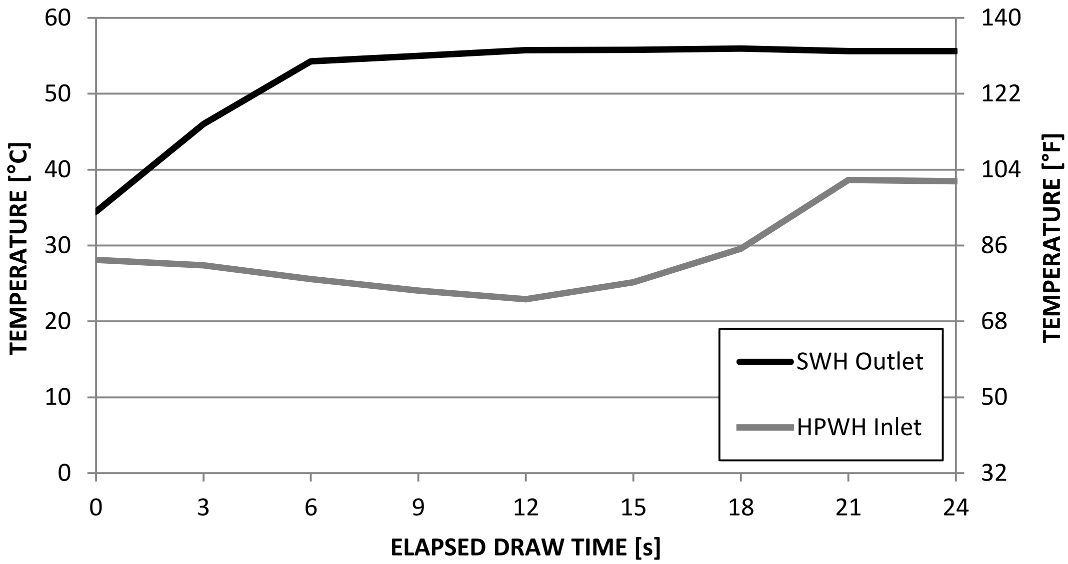
Extending these findings to monthly performance, Table 1 shows DHW thermal energy totals for February through June, putting the data into context with the solar irradiation incident on the flat plate solar collectors for each month. As winter transitioned to summer in Gaithersburg, MD, the output of the solar thermal system went from $Q_{del,SWH}$ = 124 kWh in February to $Q_{del,SWH}$ = 239 kWh in June due to increased solar resource and daylight hours. However, as the thermal energy stored in the solar storage tank increased so did the discrepancy between ($Q_{del,SWH} + Q_{del,HPWH}$) and Q_{load}. The energy loss percentage, with a propogated uncertainty of 2.1 percentage points for each month, is shown in the last column of Table 1. In February, the heat loss in the two-tank water heating system was well within the uncertainty band; however, in June the heat loss grew to 8.7 %.

Table 1. Energy Loss Comparison by Month

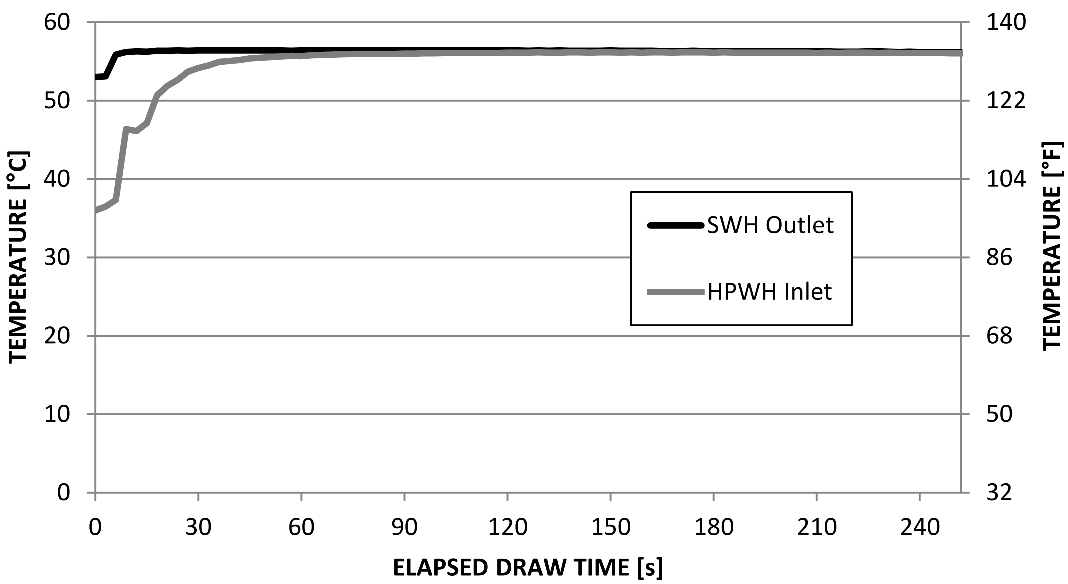
Month	Total Solar Irradiation [kWh/m²]	Avg. Solar Storage Outlet Temp. [°C] ([°F])	Avg. Basement Temp. [°C] ([°F])	*Total* $Q_{del,SWH}$ [kWh]	*Total* $Q_{del,HPWH}$ [kWh]	*Total* Q_{load} [kWh]	Energy Loss [%]
February	98	25.9 (78.6)	19.5 (67.0)	124	208	330	0.5
March	117	29.5 (85.2)	19.5 (67.0)	158	187	341	1.3
April	153	40.8 (105.5)	19.7 (67.4)	227	84	300	3.7
May	161	46.4 (115.5)	20.9 (69.6)	237	55	277	5.1
June	164	52.1 (125.8)	21.3 (70.3)	239	35	251	8.7

Linking the two hot water storage tanks is 2.54 cm (1 in) nominal diameter Type L copper tubing, 3.2 m (10.5 ft) in length with a storage volume of 1.7 L (0.45 gal) . The entire surface area of the piping, including that of the mixing valve, was carefully covered with 1.3 cm (½ in) thick foam insulation (0.51 m²-K/W or R 2.9 h-ft²-°F/Btu) to minimize heat loss. The heat loss from the domestic hot water systems, however, can still be attributed to hot water in this piping cooling down between active draw periods (Hiller 2005).

Take for instance, the first draw of the day of 2.4 L (0.63 gal) at a sink, Figure 3a. The 1.7 L (0.45 gal) volume of water in the piping has cooled down close to the ambient temperature of the basement since the last draw the evening prior. Assuming plug flow, it is not until the last quarter of the first draw of the day that the cooled-down water has traversed the piping in between the two tanks. Realistically, there is some mixing with the cold water as the hot water flows into the piping, so it takes longer for the cooled water to leave the connective piping. In the case of a shower beginning 1 min after the first sink draw of the day, as featured in Figure 3b, the temperature of the water in the pipe does not reach that of the solar outlet temperature until 60 s into the draw. Ultimately, the heat pump storage tank receives the cooled water and the heat pump must operature longer to compensate for the piping energy loss.



(a)



(b)

Figure 3 SWH outlet and HPWH inlet temperatures during draw events. (a) First water use of day, master bathroom sink, mixed hot and cold water volume drawn = 2.4 L (0.63 gal). (b) Second water event, master bathroom shower, mixed hot and cold water volume drawn = 33 L (8.75 gal).

On a daily basis, 91 % of the scheduled fixture water used in the facility are short sink draws, an arrangement that is consistent with field data showing the preponderance of short draws in residences (Lutz et al. 2012). Additionally, on the days that the dishwasher runs its cycle, its hot water use is intermittent. Therefore, a significant portion of the hot water drawn from the solar storage tank has the potential to remain in the piping and cool, losing useful energy provided by the solar thermal water heating system. The extent to which this cooling occurs depends on the timing of subsequent draws as well as the temperature of the water leaving the solar storage tank. In February, when the heat loss was found to be minimal, the DHW load was met largely by the operation of the heat pump water heater and the water leaving the solar storage tank was at an average temperature only 6.4 °C (12 °F) above the basement ambient temperature. In comparison, the average solar storage outlet temperature was 31 °C (55 °F) above the basement ambient temperature in June.

Implications

A standard metric in evaluating the performance of a solar thermal system is the solar fraction (SF), which is the fraction of the heating load met by solar energy. This metric will further aid in understanding the implication of piping heat loss to the performance of the DHW system. The monthly SF used in this context is calculated according to Equation (1):

$$SF = 1 - \frac{Q_{del,HPWH}|_{month}}{Q_{load}|_{month}} \quad (1)$$

This definition of solar fraction is most appropriate because it is the fraction of the utilized portion of solar water heating thermal energy to the total water heating load, taking into account any heat losses that might have occurred. Figure 4 shows the solar fraction for February through June together with the solar fraction that could have been achieved under ideal conditions, according to an alternative definition of solar fraction provided by Equation (2). Error bars in the figure represent the combined standard uncertainty in SF and SF* propogated from temperature and flow measurement uncertainties.

$$SF^{*} = \frac{Q_{del,SWH}|_{month}}{Q_{load}|_{month}} \quad (2)$$

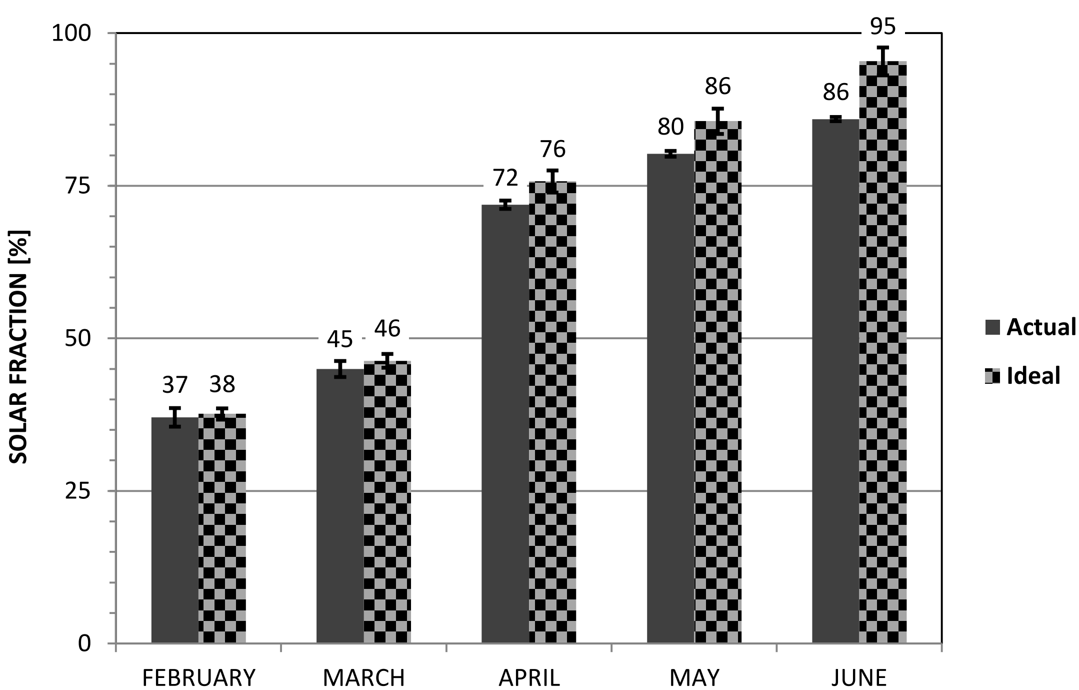


Figure 4 Actual monthly SF versus ideal SF assuming no piping heat loss.

The piping heat loss between the two tanks does not have a considerable effect on what the solar thermal water heating sytem can provide in the winter months, considering a solar fraction drop of 1 % in February and March, which is within the uncertainty band. However, the solar fraction drop increases to 9 perentage points in June where 95 % of the month's hot water needs could have been met with the solar thermal preheat system.

CONCLUSION

In a dual-tank water heating system installed in a net-zero energy residential test facility at NIST Gaithersburg, it has been observed that heat losses in the piping between two storage tanks diminishes the contribution of the solar thermal water heating unit when a realistic hot water draw pattern consisting of numerous short draws is implemented. A monthly solar fraction loss of 9 percentage points was estimated for June 2014. Findings from this study highlight an important consideration when choosing to implement a dual-tank DHW system in which a solar thermal water heater serves to preheat hot water and has high thermal output in the summer.

Five months of energy performance measurements has yielded insight into the ways in which solar energy absorbed and stored by the solar thermal water heating system can be wasted. Further research is planned to quantify the energy lost from the hot water distribution piping between the water heaters and the end-use fixtures.

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