DESIGN AND TESTING OF DIRECT PHOTOVOLTAIC POWERED DRAINBACK SOLAR THERMAL HOT WATER SYSTEM

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ABSTRACT

A direct photovoltaic (PV)-pumped solar thermal drainback system was designed and constructed to provide residential domestic hot water. Design details and rationale are presented here along with testing and performance data that verify the performance of the PV-pumping scheme. This system is shown to incorporate benefits of direct PV-pumping (no parasitic energy requirement, simple controls) with the performance of a drainback system. In the system tested, 200-300 W/m² of insolation on the collector was sufficient to initiate flow to the collectors. Other advantages and limitations of this system are also discussed.

1. INTRODUCTION

Current state-of-the-art solar thermal systems for water heating in temperate and cold climates follow two primary strategies for freeze-protection: closed-loop glycol systems and closed-loop drainback [1], [2]. In either approach, a fluid is circulated through the solar thermal collectors, with the collected heat transferred via a heat exchanger to the end use, typically hot water or space heating.

Glycol systems protect against freezing by using antifreeze, usually a propylene glycol and water solution, in the closed loop. The use of the glycol imposes some costs: 1) the antifreeze solution has a lower heat capacity, thus reducing heat transfer effectiveness; 2) the antifreeze solution is more viscous, thus increasing pipe friction losses and pumping energy; and 3) the propylene glycol solution can degrade and become acidic over long time periods or if exposed to temperatures in excess of 100°C. The latter condition necessitates long term monitoring of fluid pH and ultimate replacement of the fluid to prevent degradation of the piping system.

In a drainback system, the fluid can be water, and freeze protection comes from the inclusion of a small drainback reservoir in the collector loop—when freeze protection is necessary the circulating pumps are shut off and the fluid drains back into the drainback tank which is located in the conditioned space. The closed loop piping network must be carefully designed to ensure that all the fluid will drain back into the drainback tank and the portion of the loop in the heated space to prevent any chance of freezing. Due to the need to fill the collector and the piping to and from the collector, the pump on the closed loop is usually larger than that used for a glycol system to meet the increased head requirements.

2. DESIGN RATIONALE

Drawbacks common to both glycol and drainback systems include heat exchanger losses, the need for additional controls, and parasitic pumping losses. The heat exchange process requires an additional pump in the case of a double-pumped counter flow heat exchanger, more expensive equipment in the case of heat exchangers incorporated into the storage, or a degradation in performance in the case of a thermosyphon heat exchanger. In the case of glycol systems, the heat exchangers are usually also required to be of double-wall construction to reduce the chance of potable water contamination by the glycol solution. Typically, control is accomplished via a differential temperature controller which turns the pumps on only when the temperature difference between the collector panels and storage indicates useful heat can be collected. Beside the cost, typically US$140, the differential controller requires reliable power, either from the grid or from the battery storage in an off-grid electric system. The pumps and differential controllers together impose a
Parasitic load which Lane [2], citing Tennessee Valley Authority test data, has reported to be 6-9% of the collected solar thermal energy for glycol systems. Based on pump and controller power requirements and typically running time, Lane projects 6% parasitic losses for drainback systems. Drainback systems are reported to outperform glycol systems in terms of energy collection due to the higher heat capacity of water compared to glycol solutions [2] and despite greater equipment costs (see 4.3 below), may be cheaper to install due to greater simplicity—they do not require the expansion tank and related hardware for managing the pressurized collector loop [5]. Drainback systems also do not require periodic replacement of the glycol.

Glycol systems that eliminate the parasitic losses and the need for a differential controller have been constructed, by coupling a small photovoltaic (PV) panel directly to the pumps and mounting that PV panel with the collector. In this configuration, a properly matched pump and PV panel will circulate the fluid when the insolation is sufficient to deliver useful energy. Pump speed varies in proportion with insolation and thus also varies in proportion to the thermal energy delivered by the collectors. Parasitic losses are thus eliminated while the cost of the PV panel is offset by eliminating the differential controller.

As Lane and Ramlow note [1],[2], the PV pumping option is not generally available for drainback systems due to the need for higher head pumps to initiate flow. This technical limitation is unfortunate, as PV-direct pumping not only eliminates parasitic loads, but also removes the need for line power to support system operation. Off-grid installations are thus more easily accomplished with PV-direct pumped glycol systems, as is sustaining system operation during power outages.

The foregoing considerations suggest the advantage of PV-direct pumping of drainback systems and lead to the effort presented here—the design and construction of a PV-direct pumped drainback solar hot water system.

Fig. 1: System schematic including physical location in residence. NTS.
3. SYSTEM DESIGN AND CONSTRUCTION

The PV-direct pumped drainback solar hot water heating system was designed for and installed in a 1.5 story house (5 occupants) located at an approximate latitude of 37°34’ N and approximate longitude of 84°14’ W. Azimuthal orientation of the collectors was set at 43° west of true south due to the orientation of the house. The tilt angle of 52° (latitude plus 15°) was chosen to maximize winter collection (the house is often unoccupied during June and July). A solar window of 10 AM to 2 PM solar time is clear year round. A 9 AM to 3 PM window solar time is also clear most of the year, with some shading from a tree occurring from 2:30 to 3:00 PM solar time onwards during October to March.

As constructed, the complete system includes two 3-m² solar thermal collectors. A double-pumped external heat exchanger delivers the heat from the drainback loop to 340 L (90 gal) of thermal storage that then feeds into the backup electric water heater (180 L or 48 gal) before hot water delivery to the end use (Fig. 1).

To enable standard DC circulating pumps to meet the head requirements, the drainback tank was installed separately from the storage tank in the upper story of the house. The top inlet of the solar thermal collectors is approximately 3 m above the drainback tank. In addition, a linear current booster (LCB), usually used in solar water pumping applications, couples 150 Wp of PV panels to the pump (Fig. 2). The LCB better matches PV output to the pump.

Preliminary pipe flow calculations indicated adequate head with a March 809 BR-HS 12 V pump to lift water from the drainback tank to a height of 3 m.

Tests with the PV panels (oriented to simulate the eventual installation) demonstrated that pumping through the drainback loop (with 3 m of static head) would begin with 200-300 W/m² of beam radiation on the panels. Radiation levels were measured with a silicon pyranometer and beam radiation levels normal to the tilted panels were calculated following Duffie and Beckman [3].

This performance is similar to that desirable for direct PV pumped glycol systems where the expectation is that pumping will begin at 200 W/m² [2]. Under the test conditions, when the voltage output from the panels could be sustained at 9.7 V across the parallel combination of both pumps, there was sufficient pumping head to overcome the 3 m static head and initiate flow. This testing also suggested that while a single 75 Wp PV panel might be marginally sufficient, two 75 Wp panels would guarantee proper operation.

A thermal snap switch is mounted on the collector output and coupled with the control circuit of the LCB (normally intended for use with a float switch in pumping applications). The snap switch allows the circulation pumps to turn on when the collector output temperature reaches 31°C and turns the pumps off when the temperature drops to 23°C. When the pumps are operating, flow varies with available insolation—below the minimum threshold of 200-300 W/m² the drainback pump does not deliver water to the collectors as the pump RPM are insufficient to maintain the pumping head.
To prevent overheating the solar storage, the pumps are also coupled with a thermostat on the solar thermal storage.

4. TESTING

System construction was completed and the system began operating in mid-October 2006. The following summarizes testing data from that time until April 15 2007. Automated data collection was done with two Onset Hobo™ data loggers with thermocouples and AC current probe as well as an Onset Hobo™ weather station.

4.1 Verification of System Operation and Control

Observation of the system under various conditions confirmed the PV-direct pumping system and associated control scheme functioned as designed. A six day example series of storage and heat exchanger temperatures (Fig. 3) shows the snap switch opening and the pumps turning on in the late morning, consistent with the westerly orientation of the panels. Note that the heat exchanger is connected to the top and bottom of the storage—as a result the tank stratification is destroyed by mixing when the pumps turn on. The storage thermocouple is located near the top of the storage and the temperature remains high there (if the storage has not been fully utilized overnight) until the tank is mixed by the heat exchanger pump when it turns on causing a sharp drop in measured storage temperature before collected energy begins to raise the temperature.

Fig. 3: Six day sample of system temperatures showing two days with little solar radiation followed by four clear days

Fig. 4 shows data from a day (March 14 2007) of mixed clouds and sunshine. Based on the heat exchanger and storage temperature variations, the pumps are turning on at about the 9.7 V threshold measured in the preconstruction testing. The pump voltage drops below this threshold (and temperature rise in the storage stops) when the insolation normal to the collectors drops below 200-300 W/m². Note that the pumps stop operation late in the day even when the insolation remains high due to late afternoon shading from trees reaching the PV and solar thermal panels before reaching the pyranometer.

Observation of the system operation on colder days when the storage tank energy had been depleted by morning revealed an oscillatory behavior at start up. While empty, the collectors would be heated above the thermostat set point, but after a few minutes of transferring heat to the colder storage, the panels would cool below the shut off threshold and the pumps would be shut down until the panels could warm up again. If the ambient temperature was in the -10°C range, many such cycles can occur before the pumps remain on for extended periods. A lower shut-off threshold on the snap
4.2 Thermal Performance

In the three years prior to the installation of the system, the electrical energy consumption of the household hot water heater (with the same occupants) had been measured several times (measurements during March and November). From this sample of 12 days, average hot water heater consumption was measured with a AC electric current probe connected to a Hobo™ data logger. The average hot water heater power consumption was 9.9 KWH/day with less than ± 1 KWH/day variation between samples.

After the solar hot water system was installed, hot water heater electrical energy was again measured for 25 days between 28 October and 25 November 2006 (not all days in this period were measured due to memory limitations on the data logger). Average backup hot water heater energy consumption with the solar hot water heater was 4.8 KWH representing an estimated 51% reduction (assuming household water consumption remained constant). The criteria used to design the system were set for a desired solar fraction of 50% during the winter months and near 100% solar fraction in the summer months. The observed solar fraction is consistent with the design specification of the system. Another measurement of hot water heater usage with the solar hot water system in operation was done from 28 to 30 March 2007 (two of the three days were partly cloudy while the third day was mostly sunny). In this case, average daily backup hot water heater energy use was 3.1 KWH.

4.3 Economic and Other Design Issues

At the time of this report, the system has been operating for 6 months inclusive of the winter season. All aspects of the control and operation have been tested and shown to operate as designed. One lingering concern drawn from observation is whether or not early morning or late evening periods of low sun might run the heat exchanger pump loop for an extended period and waste some stored heat energy. With less than 200 W/m² of insolation on the panels, the drainback loop pump cannot circulate water to the panels, but both pumps still turn in low light conditions. The heat exchanger pump can thus circulate storage water through the heat exchanger. While the lack of flow through drainback tank prevents large losses of heat, there may be minor losses due to this circulation.

In terms of the overall PV-direct pumping scheme, the cost of the PV panels at current market rates poses a question about the cost-effectiveness of this design. Based on the design and testing effort presented here, the system under consideration probably would have been effectively served by one 125 Wp PV panel versus 30 Wp [2] for a glycol system. Table 1 was constructed to compare the differential costs of PV-direct pumped glycol and drainback systems, as well as a conventional drainback system. The analysis shows that the PV-pumped drainback system costs US$178 more than the conventional drainback system over the 20-year life, while the difference is US$460 compared to the PV-pumped glycol system. This comparison excludes labor which may be less due to the simpler configuration of the drainback system [5].

The cost penalty relative to the glycol system must be weighed against the claimed higher energy production of drainback systems [2]. Fig. 5 is based on the energy production values measured in this study and the extrapolation of that production to higher solar fractions on a yearly basis (due to higher summer time production). Cash payback can be achieved if the solar fraction is 75% and the drainback system produces about 13% more net energy per year. If the solar fraction is only 50%, then the performance differential needs to be 19% to break even.

The cost difference between the PV-pumped and conventional drainback systems must be weighed against the intangible benefit drawn from independence of grid power. Likewise, the cost gap will close if electricity costs rise above the assumed level of US$0.08/KWH.

It is also possible to make other economic uses of the PV capacity. During the time it takes the solar thermal panels to warm up, and when PV production is insufficient to initiate flow in the drainback loop, there are several hours each day when even marginal PV output could be used to charge batteries for household and lawn equipment (i.e. rechargeable lawn trimmers and UPS backup power supplies).

<table>
<thead>
<tr>
<th>System type</th>
<th>Standard drainback</th>
<th>PV-pumped glycol</th>
<th>PV-pumped drainback</th>
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<tr>
<td>Cost variations</td>
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<tr>
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<td><strong>Total</strong></td>
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<td><strong>515</strong></td>
</tr>
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</table>
5. CONCLUSION

The PV-direct pumped drainback solar hot water system was designed, constructed and tested. The following conclusions are based on the design and testing effort:

(1) The effort presented here demonstrated the successful application of direct PV-pumping to a drainback solar hot water system by proper placement of the drainback tank and pump sizing.

(2) By using the control circuitry of the linear current booster, system operation can be controlled with minimal additional hardware, eliminating the need for a differential controller. The system initiates pumping when panel insolation reaches levels of 200-300 W/m².

(3) The PV-direct pumping system does not impose an energy cost on system operation as AC-powered pumps do nor does it require propylene glycol antifreeze. It is also independent of the grid and thus will continue to function during power outages.

(4) The inclusion of sufficient PV capacity for PV-direct pumping imposes an additional cost. Under the conditions of this design effort, cash payback of that cost requires a minimum 13% performance benefit from the drainback system if the solar fraction is 75%.

(5) Since the additional PV power is usually only needed to initiate flow, it may be possible to share the extra capacity for battery charging (e.g. charging battery-powered appliances and equipment, UPS backup power charging, etc.)

6. REFERENCES


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Lane is inconsistent in reporting this data and also claims such losses are 4-6%.

Items where cost varies significantly between the two systems. Costs drawn from published vendor prices. Systems are assumed to have equal costs for panels, piping, mounting, HW storage and backup, heat exchangers, and installation. Glycol loop hardware includes pressure relief valve/air vent, check valve and pressure gauge. The drainback pumps are assumed to operate 4 hours per day [2] using 200 W of power and electricity cost is assumed to be constant at US$0.08/KWH. A 20-year operating life is assumed.