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# A COMPARATIVE ANALYSIS OF SIX GENERIC SOLAR DOMESTIC HOT WATER SYSTEMS

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## NOTICE

# A COMPARATIVE ANALYSIS OF SIX GENERIC SOLAR DOMESTIC HOT WATER SYSTEMS

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## ABSTRACT

Results were analyzed from experiments on six solar domestic hot water systems tested at National Bureau of Standards. Use of pumps, fans, controls, and solenoid valves in the pumped systems resulted in high parasitic energy consumption. Storage losses from double tank systems were greater than expected due to poor storage tank insulation. Direct systems performed better than indirect systems as expected. The thermosyphon delivered the most solar energy to the hot water load for the lowest initial cost. The air system performed poorly due to the parasitic energy consumption and poor heat transfer across the air-to-water heat exchanger. Reliable freeze protection needs to be developed for direct systems, especially thermosyphon systems, to take advantage of direct heat transfer.

## INTRODUCTION

The Solar Energy Research Institute (SERI) analyzed experimental data provided by the National Bureau of Standards (NBS) of six solar domestic hot water systems (SDHW).[1] The objective of this study is to aid users and designers in understanding existing systems and their relative benefits.[2,3,4,5] The systems tested in this study, selected as typical of those being installed at the time,** were exposed to the same climatic conditions and supported approximately the same thermal load. These systems, therefore, do not necessarily reflect the state of the art nor were they optimized to meet the thermal load. The six systems tested are shown in Fig. 1 and a description of each system is given in Table 1.

Table 1. SYSTEM DESCRIPTION

| System | Collector Area $m^2$ ($ft^2$) | Solar Storage Tank $\ell$ (gal) | Auxiliary Tank $\ell$ (gal) |
|---|---|---|---|
| Single[a] Direct[b] | 3.3 (36) | 310 (82) | - (--) |
| Double, Direct | 5.0 (54) | 310 (82) | 159 (42) |
| Single, Indirect | 5.0 (54) | 310 (82) | - (--) |
| Double, Indirect | 5.0 (54) | 310 (82) | 159 (42) |
| Air System | 7.3 (80) | 310 (82) | 159 (42) |
| Thermosyphon | 5.0 (54) | 250 (66) | - (--) |

[a] Single or double describes the type of system based on the number of tanks.
[b] Direct or indirect refers to the method of heat transfer.

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**Results discussed in this report are based on the performance evaluations of only those systems tested; therefore, the authors discourage generalizing these findings to apply them to systems with different thermal characteristics.

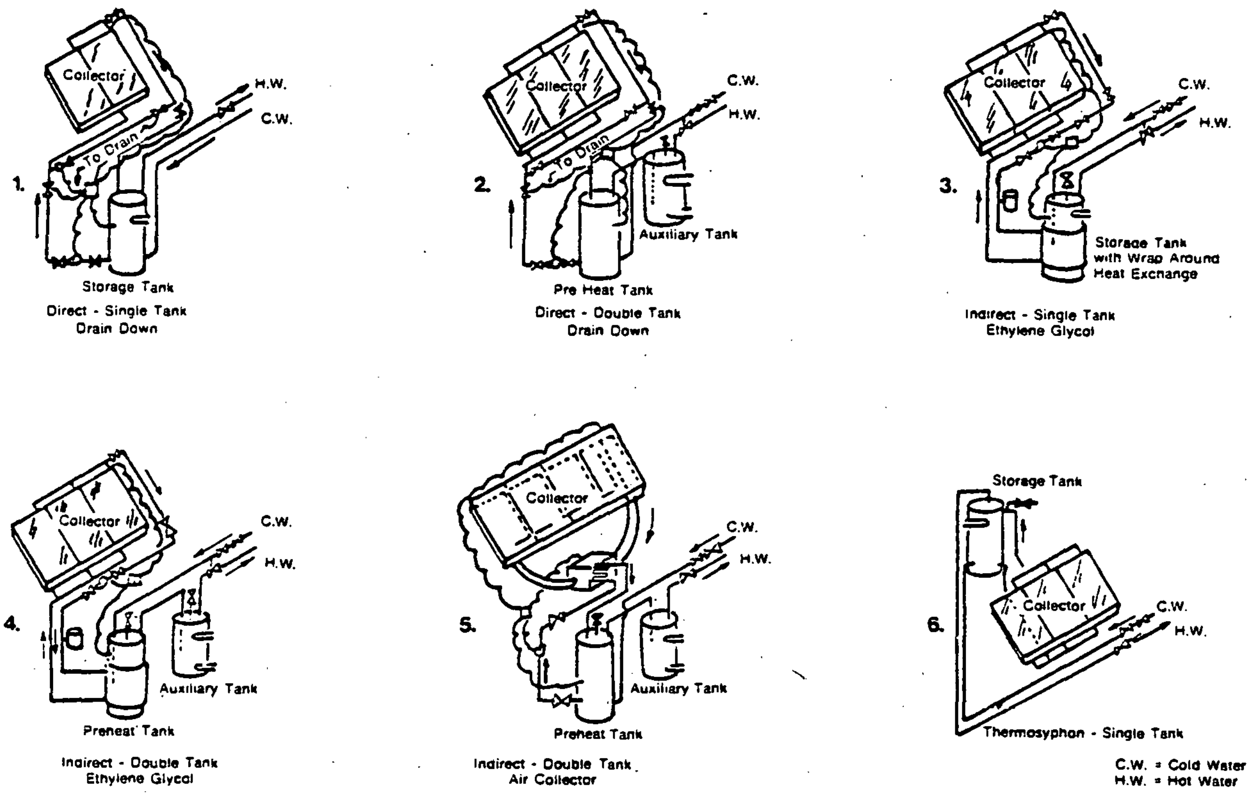

Figure 1. Six Common SDHW Systems Currently in Use

SYSTEM PERFORMANCE

This study included analysis of collector, piping, and storage tank losses as well as energy consumed by pumps, controls and solenoid valves (parasitic energy consumption), and auxiliary heating necessary to meet the load. The thermal efficiency was calculated as well as the system efficiency. The solar fraction was calculated for each system as well as a net solar fraction. When an electric backup was used, the system efficiency and net solar fraction were also calculated considering the energy used at the fossil-fueled generating plant (assumed at 33% efficiency).*

The results from the thermal and system analyses are shown in Table 2.

Table 2. SYSTEM PERFORMANCE[a]

| System | Thermal Efficiency (%) | System Efficiency (%) | Solar Fraction (%)[b] | Net Solar Fraction % |
|---|---|---|---|---|
| Single, Dir. | 28.2 | 21.4 (7.0) | 40.9 | 31.1 (11.4) |
| Double, Dir. | 17.9 | 12.5 (2.0) | 39.8 | 28.1 (4.6) |
| Single, Ind. | 22.1 | 19.6 (14.7) | 48.6 | 43.1 (32.3) |
| Double, Ind. | 17.1 | 14.6 (9.4) | 37.9 | 32.2 (20.9) |
| Air System | 6.6 | 3.1 (-4.0) | 21.7 | 10.1 (-13.2) |
| Thermosyphon | 23.3 | 22.6 (21.2) | 50.2 | 48.8 (45.7) |

[a] Figures in parenthesis represent values if parasitic energy consumption were considered as energy required at a fossil-fueled electric generating plant.
[b] Collector areas must be considered when comparing solar fractions.

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*For definitions of terms used, see nomenclature in back of report.

The double tank systems had lower efficiencies than the single tank systems because the additional tank provided a greater heat transfer area for heat loss. These tanks had $1.07 m^2 {}^\circ C/W$ (R6.1) insulation. Tank losses would be reduced and thermal performance enhanced for double tank systems having greater storage tank insulation.

Indirect systems had lower efficiencies than the corresponding direct systems due to the presence of a heat exchanger and use of an antifreeze. These led to high collector inlet temperatures and therefore lower collector efficiencies. The heat transfer fluid, a mixture of ethylene glycol and water, had 80% of the heat capacitance of water.

Parasitic energy consumption is a major factor in determining the system efficiency of a solar domestic hot water system. Parasitic energy affected the direct systems more than the indirect systems because of the addition of solenoid valves for freeze protection and the double tank systems more than the single tank systems because of the longer operating time. The direct systems had two 15W solenoid valves, which used more energy than the pumps, for draindown freeze protection. (see Table 3).

Table 3. PARASITIC ENERGY CONSUMPTION

| System | Hours of Operation (6 mo. total) | Estimated Energy Consumed by Pumps (kWh) | Estimated Energy Consumed by Solenoid Valves (kWh) |
|---|---|---|---|
| Single, Dir. | 681.66 | 68.2 | 91.4 |
| Double, Dir. | 882.87 | 88.3 | 91.4 |
| Single, Ind. | 690.24 | 69.0 | 91.4 |
| Double, Ind. | 870.49 | 87.1 | NA |
| Air System | 644.94 | 64.5(+48.Fan) | NA |
| Thermosyphon | - | NA | 32.4 |

Because a greater temperature difference existed across the collectors of the double tank systems, they operated longer than the single tank systems. The greater temperature difference resulted from water (or antifreeze) which had never been heated by the auxiliary heating coils entering the collectors at a lower temperature.

The efficiencies of the single and double tank direct systems decreased 24% and 30%, respectively, due to the parasitic energy consumption. The efficiencies of the single and double tank indirect systems decreased 11% and 15%, respectively, due to the parasitic energy consumption.

The air system, the only double-glazed system tested, did not perform well as a stand alone* solar domestic hot water system. This was due to the poor heat transfer across the air-to-water heat exchanger, resulting in high collector inlet air temperatures and large collector losses. Only 22% of the incident energy on the collectors was absorbed by the air. The efficiency of the air system decreased by 53% due to parasitic energy consumption.

Of the systems tested, the thermosyphon systems had the best overall system performance due to low parasitic energy consumption.** Thermal performance was enhanced by the direct method of heat transfer rendering it more efficient than the indirect systems.

## SYSTEM ECONOMICS

The economics of solar domestic hot water systems depends on both system cost and system performance.

The initial system cost was broken down into five areas: collector costs; storage costs; pumps, controls, and solenoid valves; miscellaneous component costs (relief valves, gate valves, expansion tanks, thermometers, air vents, heat exchangers, piping, and various fittings); and installation costs. Collector costs were assumed to vary from $81/m$^2$ ($7.50/ft$^2$) to $162/m$^2$ ($15/ft$^2$). Collector costs tended to be the largest and the most variable of these and most influenced the total system cost. The other four areas of the cost breakdown were essentially fixed costs. The total installed cost for a system varied substantially depending on the collector cost used.

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*As opposed to a combined water and space heating system.

**Solenoid values were added to this system midway through the testing. The degradation of the system efficiency due to the parasitic energy consumption should not, therefore, be compared directly to the other systems.

The cost per joule (Btu) delivered was calculated for the testing period. Table 4 shows the cost of delivered energy for the lowest cost for the collector ($81/m$^2$). The effect of parasitic energy consumption is included in column 6 and not included in column 5.

Table 5 shows the cost of delivered energy for the highest cost for the collector ($162/m$^2$). As in Table 4, parasitic energy is accounted for in column 6 and not considered in column 5.

Because of the cost per joule (¢/kJ) reflects only the period of testing of the above systems, a more helpful number for comparison is the cost per GJ ($/Btu) as determined using the initial cost, a system lifetime of 20 years (without system degradation), and the assumption that these systems would deliver approximately three times as much energy to the thermal load during one year of operation as they did during the testing period. Although this is a simplified method that does not include maintenance costs, uncertainties existing in the escalating costs of fuel make it useful for relative comparison of the systems and estimating the cost of energy delivered to the thermal load.

In order to facilitate comparison of those systems, we calculated a relative ranking with the best system equal to one unit of cost per GJ delivered to the thermal load. The result, shown in Table 6, includes the negative effect of parasitic energy by subtracting it from the energy delivered to the thermal load.

With further research and development parasitic

Table 4. SYSTEM ECONOMICS I[a]
[Collectors at $81/m$^2$ ($7.50/ft $^2$)]

| System | Initial Cost ($) | ¢/kJ | (¢/Btu) (w/o parasitics) | ¢/kJ | (¢/Btu) (w/ parasitics) | Days of Testing |
|---|---|---|---|---|---|---|
| Single, Dir. | 1718 | .092 | (.097) | .121 | (.128) | 127 |
| Double, Dir. | 2325 | .131 | (.139) | .186 | (.197) | 127 |
| Single, Ind. | 2397 | .109 | (.115) | .123 | (.129) | 127 |
| Double, Ind. | 2802 | .164 | (.174) | .193 | (.204) | 127 |
| Air System | 3329 | .343 | (.362) | .757 | (.799) | 127 |
| Thermosyphon | 1267 | .054 | (.058) | .057 | (.060) | 121 |

Table 5. SYSTEM ECONOMICS II
[Collectors at $162/m$^2$ ($15.00/ft $^2$)]

| System | Initial Cost ($) | ¢/kJ | (¢/Btu) (w/o parasitics) | ¢/kJ | (¢/Btu) (w/ parasitics) | Days of Testing |
|---|---|---|---|---|---|---|
| Single, Dir. | 2123 | .114 | (.120) | .150 | (.158) | 127 |
| Double, Dir. | 2933 | .166 | (.175) | .235 | (.248) | 127 |
| Single, Ind. | 3005 | .137 | (.144) | .154 | (.162) | 127 |
| Double, Ind. | 3410 | .200 | (.211) | .235 | (.248) | 127 |
| Air System | 4229 | .436 | (.460) | .962 | (1.015) | 127 |
| Thermosyphon | 1875 | .081 | (.086) | .084 | (.088) | 121 |

Table 6. COST OF DELIVERED ENERGY AND RELATIVE RANKING I
(Including parasitic energy consumption)

| System | $/GJ | ($/MBtu) (Collectors at $81/m$^2$) | Relative Ranking | $/GJ | ($/MBtu) (Collectors at $162/m$^2$) | Relative Ranking |
|---|---|---|---|---|---|---|
| Single, Dir. | 20.21 | (21.32) | 2.12 | 24.98 | (26.34) | 1.79 |
| Double, Dir. | 31.07 | (32.77) | 3.26 | 39.20 | (41.34) | 2.80 |
| Single, Ind. | 20.45 | (21.57) | 2.16 | 25.64 | (27.05) | 1.83 |
| Double, Ind. | 32.24 | (34.00) | 3.39 | 39.23 | (41.38) | 2.80 |
| Air System | 126.24 | (133.16) | 13.28 | 160.37 | (169.16) | 11.45 |
| Thermosyphon | 9.42 | (9.93) | 1.00 | 13.94 | (14.70) | 1.00 |

energy consumption can be reduced. Therefore, the cost per GJ neglecting parasitic energy consumption calculated for each system can serve as an incentive to reduce parasitic energy consumption.

The relative rating without considering parasitic energy is shown in Table 7.

The relative rankings from Table 6 and 7 are combined in Table 8. Notice in Table 8 the same order results regardless of whether parasitic energy consumption or collector cost is considered. However, considerable differences do exist among the relative rankings depending on the collector cost and the inclusion or exclusion of parasitic energy consumption. Systems should be compared only for a given collector cost and parasitic energy consideration because of the assumptions used in normalizing the cost of energy for the best system, i.e., the thermosyphon system. In other words, comparisons should only be made within a given column, not across rows.

Table 7. COST OF DELIVERED ENERGY AND RELATIVE RANKING II
(Excluding parasitic energy consumption)

| System | $\$/GJ$ ($\$/MBtu$) (Collectors at $\$81/m^2$) | | Relative Ranking | $\$/GJ$ ($\$/MBtu$) (Collectors at $\$162/m^2$) | | Relative Ranking |
|---|---|---|---|---|---|---|
| Single Dir. | 15.34 | 16.19 | 1.70 | 18.96 | (20.00) | 1.41 |
| Double, Dir. | 21.91 | 23.11 | 2.43 | 27.64 | (29.16) | 2.05 |
| Single, Ind. | 18.17 | 19.17 | 2.02 | 22.78 | (24.03) | 1.69 |
| Double, Ind. | 27.41 | 28.92 | 3.04 | 33.36 | (35.19) | 2.47 |
| Air System | 57.20 | 60.33 | 6.35 | 72.66 | (76.64) | 5.38 |
| Thermosyphon | 9.13 | 09.63 | 1.00 | 13.52 | (14.26) | 1.00 |

Table 8. RELATIVE SYSTEM RANKINGS

| | Collectors at $\$81/m^2$ | | Collectors at $\$162/m^2$ | |
|---|---|---|---|---|
| System | w/o parasitics | w/ parasitics | w/o parasitics | w/ parasitics |
| Thermosyphon | 1.00 | 1.00 | 1.00 | 1.00 |
| Single, Dir. | 1.70 | 2.12 | 1.41 | 1.79 |
| Single, Ind. | 2.02 | 2.16 | 1.69 | 1.83 |
| Double, Dir. | 2.43 | 3.26 | 2.05 | 2.80 |
| Double, Ind. | 3.04 | 3.39 | 2.47 | 2.80 |
| Air System | 6.35 | 13.28 | 5.38 | 11.45 |

## CONCLUSIONS AND RECOMMENDATIONS

Results clearly demonstrate that the thermosyphon is the best choice from an economic perspective. This relative ranking is valid only for the systems tested. If freeze protection requiring sizeable parasitic energy were added to the thermosyphon system the order might change. It should be noted that pumps and solenoid valves that use less energy than the ones used in this experiment are available and are beginning to be used. Parasitic energy consumption is not negligible for systems similar to these tested. Designs should minimize parasitic energy consumption by using properly sized pumps and other parasitic equipment.

It can be concluded that single tank systems perform better than double tank systems if the tank insulating value is similar to ones in this experiment. Double tank systems may be preferred for other reasons, such as greater capacity and use of existing equipment. With different insulation schemes the double tank systems may perform better than the single tank systems.

The air system that was tested performed considerably below all the other systems. However an air SDHW may be desirable if it is coupled with an air space heating system. Care must be taken to minimize the parasitic energy consumption.

The direct systems performed more efficiently than their respective indirect systems even with large parasitic losses associated with the direct systems. With lower powered solenoid values or other means of freeze protection the margin between the direct and indirect system can be expected to increase. Other aspects of direct systems require further study. Reliability of the freeze protection equipment needs to be considered. Corrosion due to the constant filling and draining of direct systems needs to be examined. Direct systems inherently transfer energy more effectively than indirect systems and work needs to be done to design reliable and efficient direct systems.

Although thermosyphon systems have definite advantages—low parasitic consumption (if at all), low initial cost, and operational simplicity—they also have the disadvantages of being difficult to protect from freeze damage without degrading the thermal performance. Manual or seasonal draindown freeze protection should be considered. Seasonal draindown of thermosyphons can compete economically with active direct and indirct systems.

It is our recommendation, finally, that to increase SDHW system performance on the whole, designers, manufacturers, and researchers need to concentrate on reducing parasitic energy consumption, increasing reliability of components, and maximizing the system efficiency.

## NOMENCLATURE

Net solar fraction: Solar energy used at the thermal load minus the parasitic energy consumption divided by the thermal load.

Parasitic energy consumption: Energy consumed by pumps, fans, and controls and solenoid valves in a solar energy system.

Solar fraction: Percentage of the thermal load met by solar energy.

System efficiency: Solar energy delivered to the thermal load minus the parasitic energy consumption, divided by the solar energy incident on the collector surface.

Thermal efficiency: Percentage of the incident radiation used at the thermal load.

Thermal load: Thermal energy required to meet the hot water load, excluding storage tank losses.

Thermosyphon system: System which depends on density gradients for fluid circulation instead of mechanical pumps.

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