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Cold-Climate Solar Domestic Water Heating Systems: Life-Cycle Analyses and Opportunities for Cost Reduction

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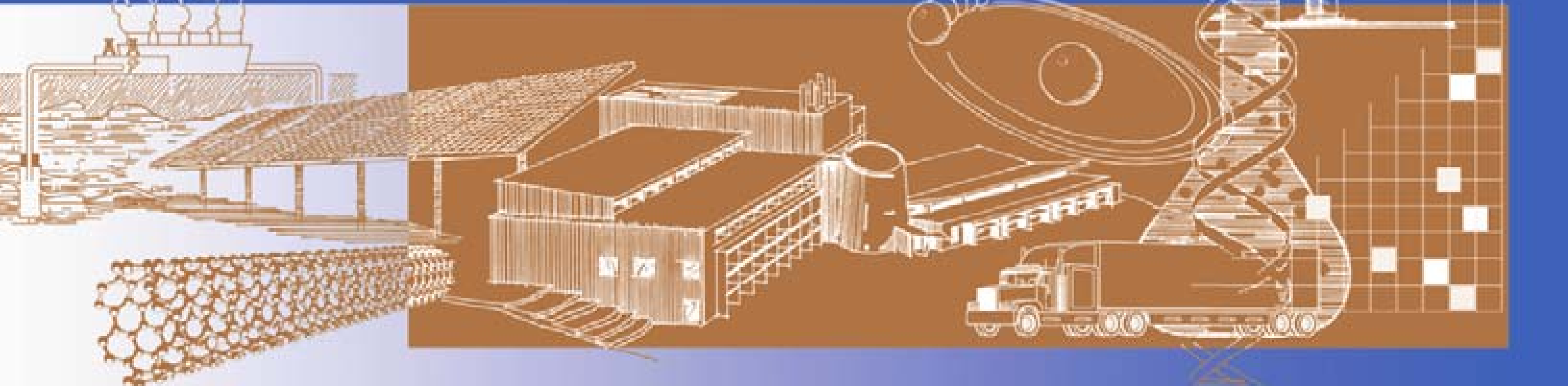

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COLD-CLIMATE SOLAR DOMESTIC WATER HEATING SYSTEMS: LIFE-CYCLE ANALYSES AND OPPORTUNITIES FOR COST REDUCTION

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ABSTRACT

To determine if the goal of 50% reduction in the cost of saved energy (C_{sav}) is attainable and prioritize research and development (R&D) for cold-climate solar domestic water heaters (SDWH), life-cycle analyses were done with hypothesized lower-cost components in glycol, drainback, and thermosiphon systems. Balance-of-system (BOS) measures include replacing conventional metal components with polymeric versions, and system simplification. With all BOS measures in place, C_{sav} could be reduced just over 50% with a low-cost, selectively-coated, glazed polymeric collector, and slightly under 50% with either a conventional selective metal-glass or a non-selective glazed polymer collector. The largest percent reduction in C_{sav} comes from replacing conventional pressurized solar storage tanks and metal heat exchangers with un-pressurized polymer tanks with immersed polymer heat exchangers, which could be developed with relatively low-risk R&D.

1. INTRODUCTION

Reducing costs of SDWH is necessary for a *substantial* SDWH market to exist in the U.S. (1), assuming no radical increases in the cost of fossil fuels. This position is supported by numerous market studies. Studies at (2) indicate that for *substantial* interest in SDWH, the installed cost should be less than \$1K-\$1.5K, depending on the responders (homeowners, builders, and architects) and definition of "substantial interest." However, the cost of systems installed today ranges from roughly \$2K to \$7K, depending on many factors such as market context (e.g., retrofit or new construction), local solar installation volume, and system type/size (3). Determining possible lower bounds for SDWH costs and identifying the best focus for cost-reduction R&D motivates the work reported here.

Because cost-reduction measures may also change performance and operation and maintenance (O&M) costs, it is necessary to frame cost-reduction analyses in terms of a normalized metric such as the cost of saved energy (C_{sav}):

$$C_{sav} = C_{total}/Q_{saved},$$

where C_{total} is the total cost (first cost + present value of O&M costs) and Q_{saved} is the direct auxiliary energy savings, discounted over the analysis period (1). This definition purposely excludes regulatory-related costs and reductions such as demand savings, rebates, tax credits, and/or renewable energy credits. These are policy issues, and the focus here is on "hard costs" that can be influenced by R&D.

Since 1998, the primary goal of the Solar Heating and Lighting (SH&L) subprogram has been to reduce C_{sav} by at least 50% (1). The technical strategy is to use polymer technology and concomitant system re-design to lower costs. Even though performance may be negatively impacted by lower-cost polymeric materials, cost reductions can be proportionally much larger. Focus was initially placed on reducing C_{sav} for SDWH systems appropriate for mild climates, where ambient temperatures rarely dip below 0 ^{o}C. Systems projecting reductions of 30% to 60% in C_{sav} are nearing market (1). Because of pipe freezing, mild climate systems are restricted mostly to parts of Florida, Arizona, and California (4). In this study, we consider the potential of technology R&D to achieve the goal of 50% reduction in C_{sav} specifically for systems appropriate for cold climates.

2. COST MODELING: GENERAL

C_{total} can be broken down into hardware, installation, marketing, and O&M. The first three costs compose the first cost to the homeowner. Costs are illustrated in Fig. 1 for two market scenarios: (i) retrofit at low volume (today's market, mostly) and (ii) new construction at high volume (hypothetical). Note from Fig. 1 that BOS costs exceed collector costs significantly. The BOS is relatively complex for cold-climate systems, and is clearly a candidate for cost-reduction efforts. Marketing and installation costs for the retrofit market are inherently higher than for the new construction market. By assuming a healthy, new construction market scenario, the analysis avoids the highly-variable, market-related cost inefficiencies of the present-day retrofit market that distort analyses for technology R&D. *To keep focus on the "hard" costs, we use a mature new-construction context and assume high volumes of production.* As a result, the "new construction" system costs here are significantly lower than costs actually seen in today's retrofit market.

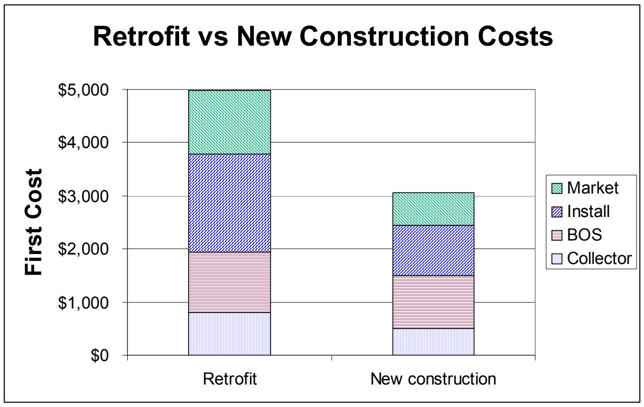

Fig. 1: First-cost comparison in retrofit and new construction markets, for a typical glycol system.

Marketing cost in new construction might include sales commission, market materials, and builder mark-up. Sales commission and market materials costs would presumably be zero when SDWH is a standard feature on all houses, and that is assumed here. Builder mark-ups vary (2) and are taken here as 25% of builder "hard cost" (hardware + installation). If hard costs are reduced by X%, any cost proportional to hard cost (such as marketing here) will also be reduced by X%. Thus, including this "soft" mark-up cost does not distort the conclusions about fractional reduction of costs, and it is a real, significant cost that should be accounted for.

Component costs are estimated by several different methods. For established components, costs were generally based on the lowest of large-volume quotes from supplier catalogues or conversations, or Internet listings (5). For hypothetical components, costs were estimated from a detailed accounting and/or by analogy to similar products. Nonetheless, for "hypothesized" components, the costs assumed here may also be considered as "reasonable technical targets." Installation costs were estimated from a task-time layout as in (6). This is an intermediate level of detail, with ~20 separate tasks defined so that each cost-reduction measure (such as eliminating the load-side pump) affects a unique time allocation. O&M costs are computed statistically. Each failure mode is postulated (e.g., storage tank leak), and parameters are then posited for a corresponding three-part failure distribution, as in (3). The expectation values of future O&M costs are calculated and transformed to present value costs.

3. SYSTEMS AND COST-REDUCTION MEASURES

Three system types are considered here: glycol, drainback, and indirect thermosiphon. System diagrams from (7) are shown in Figs. 2-4. For cold climates, glycol and drainback are common, whereas the indirect thermosiphon is relatively novel. Although thermosiphons are probably the most popular system worldwide, thermosiphons for cold climates are problematic because supply and return piping can freeze and catastrophically burst. The base-case parameters common to the systems are given in Table 1.

Component variations considered here are shown in Table 2. BOS variations include an un-pressurized polymer tank and heat exchanger, polymer piping, integrated valve package, and solar-side pump removal. Cost reductions assumed for the BOS variations are given in Table 4. Details of the BOS cost model changes are given in (5). Substituting a photo-voltaic-driven (PV) pump for the standard differential controller was considered in (5). However, reliability cost reductions were far outweighed by additional first cost, so the PV-pump option is not considered here. Five different collectors were considered, and the assumed collector cost and performance parameters are given in Table 3. Three polymer collectors were considered: glazed selective, glazed non-selective, and un-glazed. The glazed selective polymer collector is hypothetical, although it could be developed. The other two polymer collector types are on the market.

For simplicity, it was assumed that *for all BOS changes the performance impacts were negligible*. Only costs (hardware, installation, and O&M) change in the BOS substitutions. Performance changes from the base case only for collector substitutions with a change in the collector parameters. A good example of zero impact on performance impact is swapping out sweated copper piping for polymer piping with the same insulation value. For the tank-heat exchanger substitution, the heat exchangers are assumed large enough that performance is not significantly altered. Future work will relax this assumption.

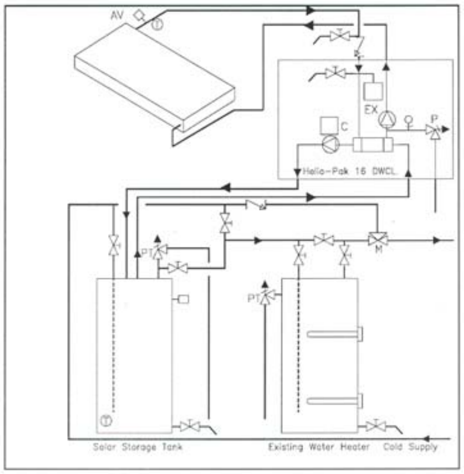

Fig. 2: The Heliodyne indirect glycol system, Heliopak model. Taken from (7), where symbols are defined also.

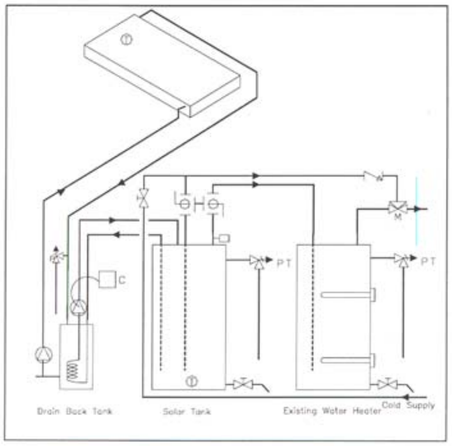

Fig. 3: The Radco drainback, model R-DBHX-8-65-D-40P. Taken from (7), where symbols are defined also.

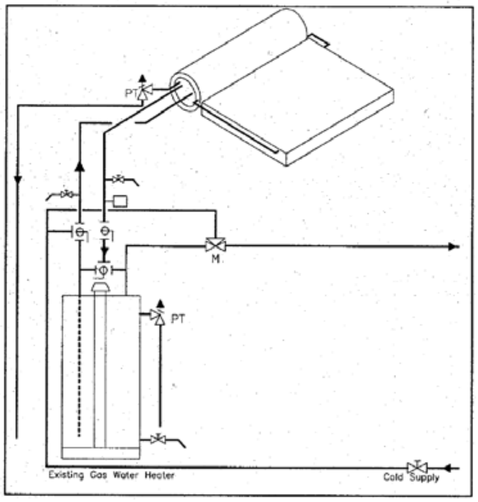

Fig. 4: The SunSiphon indirect thermosiphon from SunEarth. Taken from (7), where symbols are defined also.

TABLE 1: BASE-CASE SYSTEM PARAMETERS

Collector (metal-glass selective)	
Area	3.72 m^2 (40 ft^2)
Slope	33.7°
Solar Tank (pressurized)	
Volume	0.227 m3 (60 gal)
U-value	0.556 W/m^2-°C
Auxiliary Tank (pressurized)	
Volume	0.15 m^3 (40 gal)
U-value	0.981 W/m^2-°C
Setpoint Temp.	51.7 °C (125 °F)
Envir. Temp.	20 °C (68 °F)
Piping (hard copper)	
Length (sup. + ret.)	15.24m (50 ft)
U-value	2.27 W/m^2-°

The base-case solar storage tank is a conventional, pressurized, electric-auxiliary storage tank, with glass-coated steel pressure vessel. A side-arm heat exchanger with storage-side pump is the glycol base case. For drainback, an external heat exchanger in the drainback tank is used. For thermosiphon, a pressurized tank with solar fluid in an outside annulus (i.e., mantle tanks) is most common and was assumed here. A potentially low-cost variation of these pressurized tanks is an un-pressurized tank with load-side heat exchanger. An additional solar-side heat exchanger is required for glycol and thermosiphon (unless all storage water is freeze-tolerant, such as with lower-cost brine fluids contacting only all-polymer materials). The water storage vessel is assumed to be made from thin-wall polymers (thin film, membrane or blow-molded). A schematic drawing of a thin-film membrane tank is shown in Fig. 5, from (9). A similar 100-gal (380-l) commercial tank sold for ~$200 and was used in 1990s utility load-shifting programs (10). For the drainback system, the un-pressurized tank replaces the drainback tank and heat exchanger, storage side pump and piping, and the solar storage tank. The heat exchangers in the unpressurized tank are presumed to be made of polymer materials, as in Fig. 6. These low-cost heat exchangers are under development with a DOE partner, as in (1).

TABLE 2: COMPONENT VARIATIONS

Component	Baseline	Variation(s)
All types:		
Collector	Selective	Non-selectve; unglzd
Storage	Pressurized	Un-pressurized
Heat exch.	Metal/copper	Polymer tube bundle
Piping	Hard copper	Polymer tubing
Valves	Piece-by-piece	Integrated package
Glycol/dback:		
Storage-side pump	9-10W pump	Remove pump (use tsiphon or imm. coil)

TABLE 3. COLLECTOR PARAMETERS AND COST

Collector[1]	$F_r(\tau\alpha)_n$	F_rU_l[2]	Cost
Selective metal-glass[3]	.779	4.77	$500
Nonselectve metal-glass[3]	.768	7.25	$450
Polymer- selective[4]	.779	4.77	$250
Polymer- non-selective[3]	.739	8.16	$200
Polymer- unglazed[5]	0.88-.029*v_w	10.24 + 4.69*v_w	$100

1. Collectors are all 40 ft^2.
2. Units of F_rU_l are [W/m^2].
3. From SRCC directory (7).
4. Same parameters as base case metal-glass collector.
5. From (8), test results for a pool collector; v_w = wind speed at collector.

TABLE 4: BOS COST REDUCTION MEASURES

BOS Measure	Δ$[1] Hardware	Δ$ Install[2]	Δ$ O&M	Δ$ Total[3]
Glycol only:				
Remove pump	$82	$22	$73	$220
Poly. tank/HX	$280	$74	$256	$761
Drainback only:				
Remove pump, poly tank/HX	$562	$192	$358	$1390
Thermosiphon only:				
Poly. tank-HX & piping	$400	$30	$542	$1215
Glycol/DrainBack:				
Poly. piping	$70	$284	$148	$553
All Systems:				
Valve package	-$25	$130	$0	$131

[1] Savings (+) of the measure over the base case.

[2] Includes direct labor and consumables, and overhead/profit on installation of 100%/50%.

[3] Sum of savings from previous three categories, +25% markup.

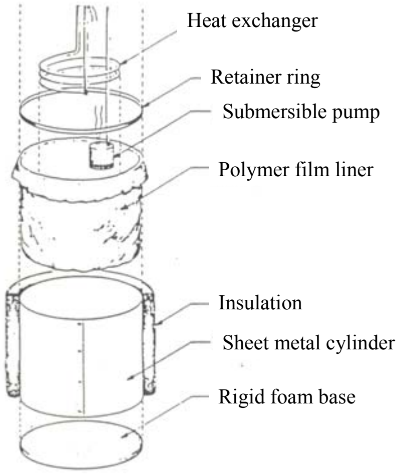

Fig. 5: Low-cost thin-film membrane tank with immersed load-side heat exchanger and solar-loop pump, for a drainback system [taken from (9)].

Fig. 6:. Prototype low-cost polymer heat exchanger (10). Tubes are 1/8-inch (3 mm) diameter. Tube weaving and tube-to-header welding are automated processes, contributing to a low cost projection.

4. RESULTS: PERFORMANCE, COST AND C_{sav}

The well-known simulation tool TRNSYS (11) was used for performance prediction at all U.S. TMY2 sites (12). Detailed assumptions and results are given in (5). The unglazed results are based on unglazed collector test procedures that incorporate wind and sky-infrared affects, as in (13).

The annual efficiency is defined as annual saved energy divided by annual solar incidence on the collector. Fig. 7 shows the efficiency versus TMY2 site annual average temperature for a glycol system using the four *different* collectors (the two selective collectors have the same performance parameters). It can be seen that for each collector the annual efficiency is approximately constant, falling slightly with increasing site temperature, as in (14). Efficiency for the unglazed collector is about 1/2 of the glazed/selective efficiency, with the other two collectors between these two extremes.

The system first cost and C_{sav} are shown in Figs. 8-10, one figure for each system type. The highest cost and C_{sav} are for the baseline system, at far left of each graph. Going left to right, the BOS variations are shown first, followed by the collector variations. *The BOS changes are cumulative, and the collector variations are done with all the BOS changes in place.* Collector substitutions proceed from more expensive to less expensive. The non-selective metal-glass collector was not done for the drainback and thermosiphon systems, because results with the glycol data show that it leads to increased C_{sav} relative to other collectors. The unglazed collector was not done with the thermosiphon due to convergence problems that were not yet resolved.
The base-case first costs of the glycol, drainback, and thermosiphon systems were $3059, $3336, and $2377,

respectively. With all BOS variations in place, first cost was reduced by $1203, $1509, and $671 for the glycol, drainback, and thermosiphon systems, respectively. The C_{sav} reductions mirror these BOS cost reductions. With the collector variations, the first cost continues to decrease as collector costs decrease. However, C_{sav} is reduced from the base case only with the selective polymer collector (which by definition is equal performance-wise to the selective metal-glass collector at half the cost). This is because the other three collectors lead to a significantly lower system efficiency (see Fig. 7), which is proportionally larger than the lowered cost.

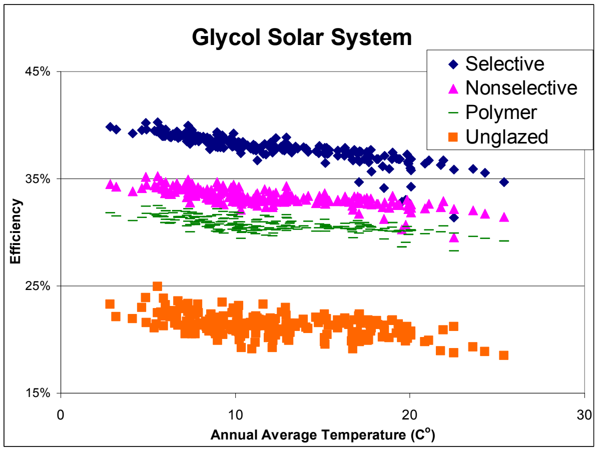

Fig. 7: Annual efficiency (savings/incidence) vs. site annual average temperature for the glycol system with four different collectors. The base case is the selective collector.

With all cost-reducing BOS variations in place, the lowest C_{sav} is obtained using the hypothetical selective polymer collector, with > 50% reduction. The 2nd-lowest C_{sav} occurs with the base-case metal-glass selective collector, somewhat under 50%. The result for the non-selective polymer collector is about equal to the selective base-case. Table 5 summarizes the base case and the best two cases for the three system types. First cost is under $1500 only with polymer collectors. The cold-climate thermosiphon is the lowest-cost system at all stages, with lowest C_{sav} and best chance to meet the 50% reduction goal; however, it has the highest barriers to overcome (freezing and piping/tank/heat exchangers in attic). The non-selective metal-glass collector and the unglazed polymer collector are not effective measures because performance is lowered proportionally more than first costs, compared to the base collector.

Table 6 gives the % reduction in C_{sav} due to key measures, averaged over the system types to which the measure is applicable. The polymer tank substitution made the largest impact, ~17%, with polymer heat exchangers accounting for an additional 9%. The R&D cost and risk are also given in Table 6. It would appear that cost reduction efforts focused on the tank-heat exchanger combination are a good focus for technology R&D, since the reduction is the largest and R&D costs would be moderate.

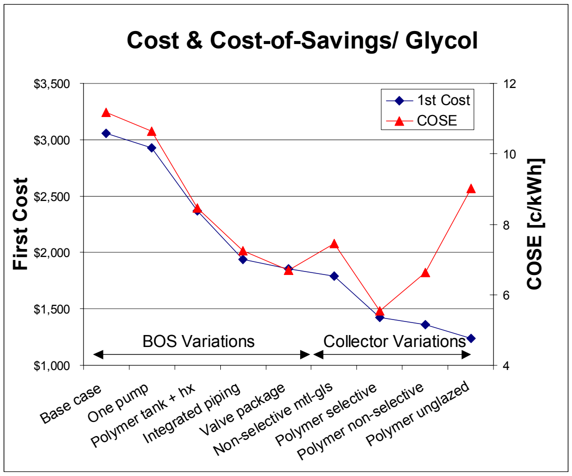

Fig. 8: First cost and C_{sav} for the glycol systems.

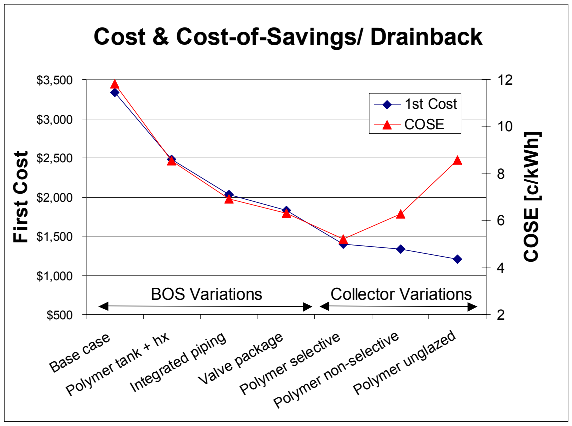

Fig. 9: First cost and C_{sav} for the drainback systems.

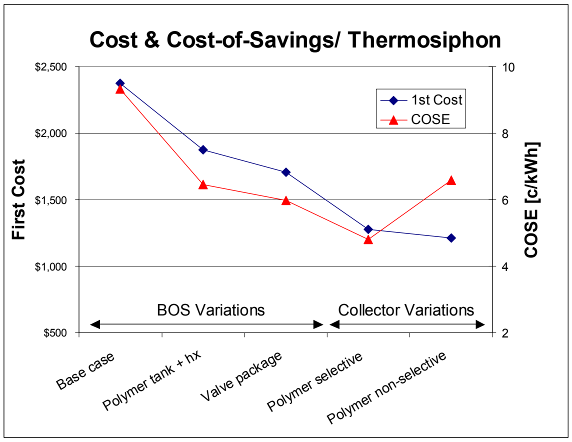

Fig. 10: First cost and C_{sav} for the thermosiphon systems.

TABLE 5: 1^{ST} COST & C_{sav} FOR BASE & BEST CASES

System:	**Glycol**		**Drainback**		**Thermosiphon**	
	Base	Best	Base	Best	Base	Best
First cost	\$3,059	\$1,363	\$3,336	\$1,396	\$2,377	\$1,213
C_{sav} [1,2]	11.2	5.5/6.3	11.8	5.2/6.3	9.3	4.8/6.6
% reduction[2]	50%//41%		53%//44%		57%//46%	

[1] C_{sav} units are (¢/kWh).

[2] For "C_{sav}/Best" and "% reduction" cells, two results are given: (polymer selective result)//(metal-glass selective result).

TABLE 6: MEASURE EFFECT, R&D RISK AND COST

Variation	**Reduction in C_{sav}**	**R&D Risk**	**R&D Cost**
Remove pump	4.8%	None	None[1]
Polymer storage	17%	Low	Med
Polymer heat exch.	9%	High	Med
Polymer piping	9%	Low[2]/ Med[3]	Low[2]/ Med[3]
Valve package	7%	Low	Low
Non-sel. poly. coll.	0%	Med	Med
Selec. poly. coll.	10%	High	High

1. A comprehensive study is available (15).
2. For glycol/drainback, where freeze protection is not needed.
3. For thermosiphon, where freeze protection is needed.

5. CONCLUSIONS

Cost and performance were estimated for glycol, drainback, and thermosiphon system types over a set of lower-cost BOS components and collectors. All BOS measures here reduced C_{sav} and were assumed in place when analyzing the collector variations. Reductions in C_{sav} of somewhat over 50% are attained when using a hypothetical polymer collector with selective absorber. The 2nd-largest reductions in C_{sav}, somewhat under 50%, are attained when using the conventional metal-glass selective collector. C_{sav} for this latter case was about equal to C_{sav} for the glazed selective collector, for all three system types. About 26% reduction in C_{sav} came from replacing the pressurized solar storage tank with un-pressurized tanks with polymeric heat exchangers, which may be a good focus for R&D efforts.

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