Three-Season Operation as a Method of Freeze Protection in Solar Domestic Hot Water Systems

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ABSTRACT

Since the yearly gains associated with solar thermal energy technologies are comparatively small in relation to the required capital investment, it is vital to maximize conversion efficiency. While providing the necessary function of freeze protection, the heat exchanger commonly included in SDHW systems represents a system inefficiency. There is both a significant energy loss due to a rise in collector operating temperature (resulting in a decreased collector efficiency) and a significant cost increase due to the cost of the heat exchanger and associated equipment. An alternative method of providing freeze protection by shutting the system down during the winter was analyzed. Both economic and thermal performance predictions were made for a large number of locations across the United States. These results show that the three-season system is an attractive alternative in some locations. In most locations, the three-season system provides a lower annual solar fraction than the four-season system. In a few locations however, three-season systems perform better than a four-season systems.

Because the solar fraction is decreased in most locations by shutting the SDHW system down during winter, it is beneficial to make the "winter" as short as possible. A method of extending the operating period by recirculating warm storage tank water through the collector at night to prevent freezing was analyzed and shown to be beneficial in many locations.

As a final step in the analysis, the impact of a three-season system ensemble on an electric utility was studied and compared to that of a four-season system ensemble. Because the three-season system is optimized for summer operation, it is better adapted to a summer peaking utility's needs. It is shown that the Milwaukee, WI utility analyzed can expect a significantly higher return on investment for a 1000 unit three-season system ensemble as compared to a 1000 unit four-season system ensemble under current economic conditions.

1. BACKGROUND

A common configuration for cold climate SDHW systems includes collectors, a liquid storage tank, two pumps and a heat exchanger. The heat exchanger allows propylene glycol to be circulated through the collector, heating potable water in the storage tank. However, previous work has shown that the effectiveness of the heat exchanger varies between 0.1 and 0.5 with a typical value of about 0.2 [1]. This low effectiveness introduces a significant inefficiency. However, the system still needs some sort of freeze protection.

One possibility for providing freeze protection is to simply turn the system off during the winter [2]. Choosing a three-season operating period means a number of things. First, the three-season system will have different optimums such as collector slope and area. Second, the wintertime solar energy incident on the collector will be unavailable for meeting a heating load. However, eliminating the heat exchanger will result in more energy arriving the storage tank during those periods in which the system is operating.

The primary factor involved in predicting the performance of a three-season system is the severity of winter in the system's location. If a location has a long, clear winter, then a large amount of energy is collected by the four-season system that can offset the heat exchanger losses that occur during non-freezing periods. Another important aspect of three-season system design is its sensitivity to design changes. The economic benefits of a three-season system due to its lower equipment costs are meaningless if only an ideally sized and located sys-tem has an acceptable annual performance.

2. SYSTEM SENSITIVITY

It is important that a system not be overly sensitive to design variable changes such as collector slope or azimuth because not all systems can be placed in ideal orientations. Figure 1 shows the change in life cycle savings associated with changes in collector azimuth angle for various three and four-season systems.

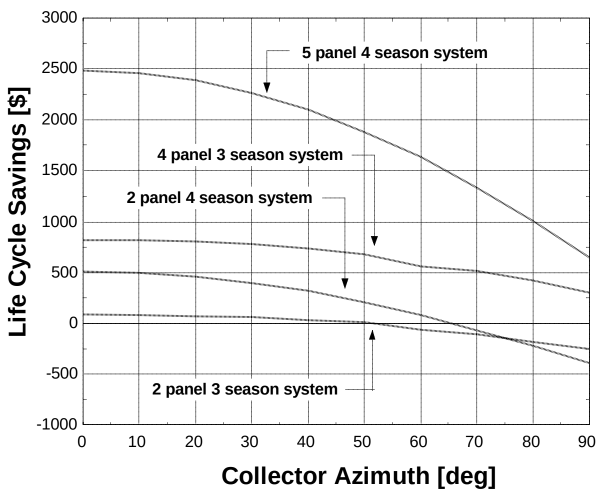

Fig. 1: Life Cycle Savings Sensitivity to Collector Azimuth for Three and Four-Season Systems

It can be seen from Fig. 1 that the four-season systems are actually more sensitive to azimuth changes than are three-season systems. The phenomenon can be attributed to the fact that the three-season system is optimized for summer operation when solar radiation is abundant. Four-season systems are optimized for year round operation, including winter when solar radiation is more scarce. Thus the four-season system annual performance is degraded for changes in azimuth angle because a non-zero azimuth significantly reduces the amount of energy collected during the winter months.

Another important factor in system design is collector slope. There is a combination of collector slope and area that results in a peak life cycle savings as shown for Denver, CO in Figure 2.

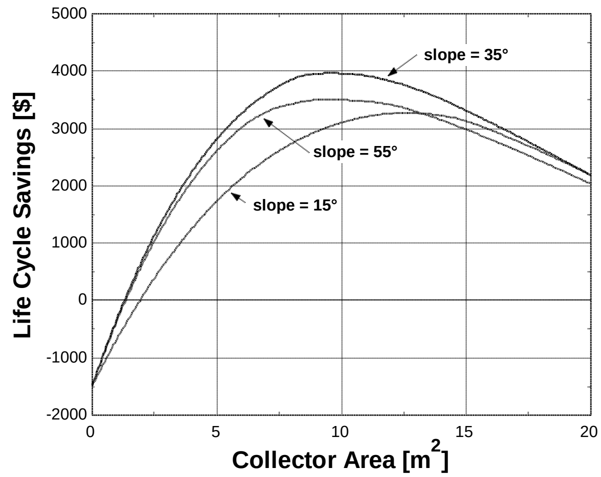

Fig. 2: Optimum Area for Maximum Life Cycle Savings

Any deviation from these optimums results in a decreased life cycle savings and a shift in optimum area. Table 1 shows the change in life cycle savings and change in optimum area due to a 40^o change in collector slope centered about the optimum for both three and four-season systems in various locations.

TABLE 1: Change in Optimum Life Cycle Savings and Optimum Area Due to a 40^o Change in Collector Slope

	Δ LCS [$]		Δ Ideal Area [m^2]	
	4seas	3seas	4seas	3seas
Madison, WI	374	270	3.1	2.9
Seattle, WA	443	449	2.9	2.6
Albuquerque, NM	228	210	3.7	1.8
Miami, FL	275	275	0.9	0.9

Table 1 shows that three-season systems tend to be less sensitive to changes in slope. The optimum slope for a four-season system is approximately equal to the latitude of the location (the yearly average solar altitude angle). For the three-season system, the optimum slope is the average solar altitude angle during the operating period. These slopes are less than the location latitude unless the location has no appreciable freezing period.

3. THERMAL PENALTY

Choosing to remove the heat exchanger from an SDHW system and to operate the system for three seasons out of the year results in a change (usually a reduction) in the annual solar fraction of the system. The *f*-Chart method, [3] was used to assess this penalty.

The design process proceeded as follows. First, a four-season system was designed with a collector area such that it met a chosen annual solar fraction. Next, a three-season system with the same collector area was designed with a collector slope optimized for the shorter operating period. The operating period was determined using "killing frost" maps for the United States [4]. The three-season solar fraction was then calculated and the thermal penalty of choosing a three-season system was assessed. Figure 3 shows the annual solar fraction for a three-season system based on a four-season system that meets 25% of the annual heating load. Locations are marked with a dot that corresponds to the annual solar fraction of the three-season system. Cities marked with a light gray dot (such as in the southeast) represent locations in which three-season systems have a solar fraction higher than 25%.

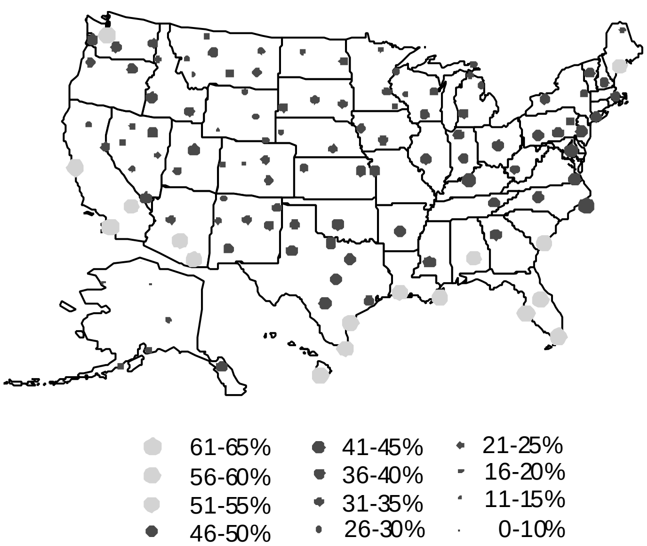

Fig. 3: Annual Solar Fraction of a Three-Season System Based on a Four-Season System Meeting 25% of an Annual Heating Load

Figure 4 shows the thermal penalty for a three-season system with the same area as a four-season system that meets 50% of the load. Comparing Figs. 3 and 4, it can be seen that the relative penalty for three-season systems increases with increasing annual solar fraction. The area in which the three-season systems give a greater annual solar fraction has shrunk considerably. Among others, three-season systems in Oklahoma City, OK and Little Rock, AR perform better than four-season systems if the system size is small. However, they perform worse than four-season systems as the system size increases.

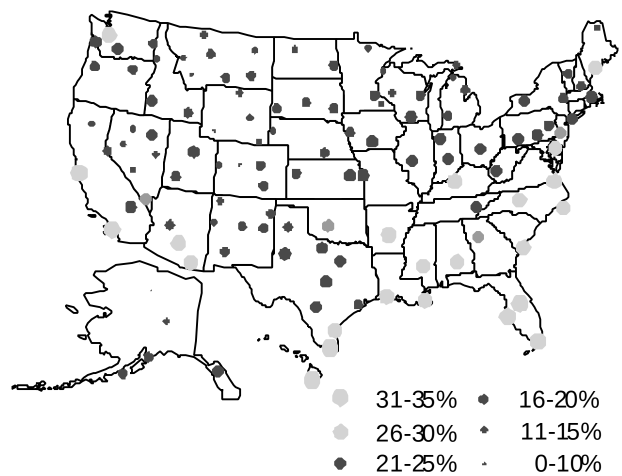

Fig. 4: Annual Solar Fraction of a Three-Season System Based on a Four-Season System Meeting 50% of an Annual Heating Load

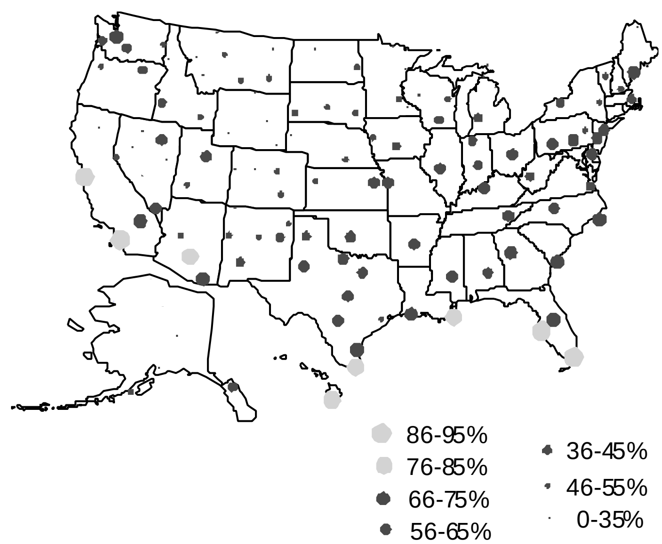

Fig. 5: Annual Solar Fraction of a Three-Season System Based on a Four-Season System Meeting 75% of an Annual Heating Load

Figure 5 shows the thermal penalty associated with a three-season system based on a four-season system meeting 75% of the load. There are almost no locations in which a three-season system performs better than the corresponding four-season system. Furthermore, local weather effects have become more important. It is not uncommon to see a relatively small penalty very near to a location with a very large penalty as in Salt Lake City, UT. Often, this is because urban areas create heat islands that affect the three-season penalty outcome on a very location specific level.

It can clearly be seen that the larger the system, the larger the relative penalty associated with choosing the three-season option. The area of the country in which a three-season system provides a higher solar fraction shrinks as the system size gets larger. Also, the penalty paid in mountainous regions becomes detrimental and the three-season system cannot hope to compete. This makes intrinsic sense; a system that operates for only 6 months out of the year due to freezing temperatures is going to have a very hard time meeting 75% of the annual heating load. It can only meet 50% of the annual load if it meets 100% of the load during its operating period.

4. RECIRCULATION

Because the potential for freezing in some locations lasts so long (6 months in Madison, WI), the three-season system has a hard time attaining the same solar fraction as a four-season system. It is therefore beneficial to make the winter shut down period as short as possible. The benefit of recirculating warm storage tank water through the collector in order to gain an extra month at either end of the operating period was examined. The idea is that a place such as Madison, WI has a six month down time in which freezing may occur. During the first and last month of the down time however, the days are warm and sunny enough to collect a sizeable amount of energy while some nights may experience freezing temperatures. If substantially more energy can be collected during daylight than is needed to keep the collector free of ice at night, then the performance would benefit from the more complex control strategy.

A TRNSYS [5] simulation was developed in order to quantify the benefits of recirculation. TRNSYS is a modular program in which computer models of individual system components are written and then connected to form an overall system model. The component inputs and outputs are linked together to form a large set of algebraic and differential equations. At each time step of the simulation, TRNSYS solves this set of equations using a multi-dimensional equation-solving algorithm to determine the system's performance.

The TRNSYS simulation had two benefits. First, for a few test locations it confirmed the results obtained using the *f*-Chart method and second, it showed that recirculation can benefit three-season SDHW systems in most locations. Table 2 shows results for four locations.

TABLE 2: Effect of Recirculation on Annual Solar Fraction in Various Locations

Location	Four-Season System	Three-Season System	Three-Season Recirculation System
Madison, WI	0.43	0.32	0.4
Caribou, ME	0.48	0.24	0.36
Saint St. Marie, MI	0.49	0.27	0.24
Denver, CO	0.51	0.32	0.52

Three different situations can arise. Most commonly, adding two months to the operating period increases the annual solar fraction of a three-season system. In some cases, the increase can be so great that the three-season system solar fraction is greater than that of the four-season system, meaning that the yearly heat exchanger energy loss is greater than the energy that can be collected during the winter. In a few cases, (e.g., Sault Saint Marie) the annual solar fraction is further decreased by extending the operating period.

5. UTILITY IMPACT

With the increase in popularity of residential air conditioning, electric utilities often see their highest demand during the third or fourth consecutive hot day during the summer. Many utilities maintain extra generating capacity in order to meet this demand; a costly undertaking as the capacity remains idle throughout much of the year.

If, however, a large number of customers in the utility's service district have SDHW systems then there is in essence a diversified power generator capable of reducing the peak demand seen by the utility [6]. It is therefore to the utility's advantage to promote large-scale SDHW initiatives for demand reduction. Utilities could purchase SDHW systems at wholesale prices and lease them to customers. Ideally, the customer could install an SDHW system inexpensively and would be able to call upon the utility for maintenance issues and would see a decrease in their electric bill. There are also obvious benefits to the environment from reductions in CO_2 and SO_2 emissions garnered by shifting power generation away from coal fired plants.

A fair amount of research has been carried out to date concerning the impact of a large scale SDHW initiative on a utility. EUSESIA [7], a TRNSYS based program evaluates the impact of any design alternative on a utility by first determining the hourly energy demand of an electric hot water heater. Next, it determines the hourly energy demand of the SDHW alternative. By comparing the two demand profiles, the relative benefits of the SDHW alternative become apparent. Both an energy and an economic analysis are performed. Table 3 shows the

EUSESIA results for both three and four-season system ensembles located in Milwaukee, WI. The lease rate for each system was assumed to be the same. Each ensemble is comprised of 1000 systems.

TABLE 3: EUSESIA RESULTS

	Four-Season Sys. Ensemble	Three-Season Sys. Ensemble
Energy Reduction [kW-h/system-yr]	4000	2500
SO_2 Emissions [kg/system-yr]	35	21
CO_2 Emissions [kg/system-yr]	2100	1300
Demand Reduction [kW/system-yr]	0.62	0.71
Return on Investment [%]	19.5	28.7
Capacity Contribution [-]	0.363	0.412

Because it is operational throughout the entire year, the four-season system ensemble provides a greater overall emissions and energy reduction. However, the three-season system ensemble is optimized for summer use and so performs better during peak demand periods. Furthermore, it provides a higher return on investment because of its lower installation cost. The capacity contribution index compares the relative contributions to overall utility reliability. An important feature of the index is that it takes into account the effect of a demand side project on an interconnected utility system, not just an isolated system [8]. The three-season CCI is greater than that of the four-season system, meaning that a three-season system ensemble contributes more to the utility's ability to meet their load.

6. CONCLUSIONS

A three-season operating period provides a simple solution to the inefficiency problems associated with heat exchangers in SDHW systems while still providing freeze protection. Three-season systems are less sensitive to changes in collector orientation and slope because they are optimized for summer use when radiation is abundant.

The thermal performance predictions indicate that three-season systems are highly preferable to four-season systems in the southeastern United States. Three-season systems are less desirable as large installations in mountainous regions with long, clear winters. The performance of smaller installations is harmed less by choosing a three-season alternative. As a general rule, small installations should be seriously considered for three-season operation, as they will provide only slightly less energy to the customer at a significantly lower first cost. Mid size installations not located in the southeast will require a more careful examination of local economic factors in order to determine whether a three or four-season system is preferable. Large systems (relative to the annual load) will almost always want to include a heat exchanger and operate year round. The large collector area means that enough energy is collected that some may be wasted in order to provide freeze protection to the system. An example TRNSYS simulation of three and four-season systems can be downloaded from the web site <http://sel.me.wisc.edu/trnsys/>.

It was also shown that recirculation of warm tank water during the swing months can be of great benefit to three-season system performance by preventing collector freeze up at night while allowing energy collection during the day.

Perhaps the most potentially useful result of this work was that involving utility impact. Deregulation is forcing many utilities to find innovative moneymaking programs in order to remain competitive. Lease programs involving SDHW would appeal to environmentally minded customers while providing significant income to the utility and reducing emissions levels mandated by legislation. Since three-season systems are operate during peak demand periods and are shut down during times when the utility has sufficient generating capacity, they are far better tailored to the utility's needs than are four-season systems.

7. REFERENCES

[1] Buckles, W.E., MS Thesis, Mechanical Engineering, University of Wisconsin-Madison. *Short Term Monitoring and Performance Evaluation of SDHW Systems*, 1983

[2] Bradley, D.E., MS Thesis, Mechanical Engineering, University of Wisconsin-Madison. *Promising Freeze Protection Alternatives in SDHW Systems.* 1997

[3] Duffie, J.A. and W.A. Beckman, *Solar Engineering of Thermal Processes*. 2nd edition, New York: John Wiley and Sons, Inc., 1991

[4] Smith, C.R. Secretary, *Weather Atlas of the United States*. Detroit; Gale Research Company, 1975

[5] Klein, S.A. et al., TRNSYS 14.2 Reference Manual. Solar Energy Laboratory, University of Wisconsin-Madison, 1996

[6] Enstar, *USH2O Utility User Group Meeting Report for March 11-14*, Palm Springs, FL: 1996

[7] Trzesniewski, J.A., MS Thesis, Mechanical Engineering, University of Wisconsin-Madison. *Electric Utility Interest in Solar Energy Systems*, 1995

[8] Arny, M.D. and R.J. Harsevoort, *"A Method for Comparing the Contribution of Supply Side and Demand Side Resources to Customer Reliability."* Draft, 1994