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MASTER

SENSITIVITY ANALYSIS OF A COMMUNITY SOLAR SYSTEM USING ANNUAL CYCLE THERMAL ENERGY STORAGE

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SENSITIVITY ANALYSIS OF A COMMUNITY SOLAR SYSTEM USING ANNUAL CYCLE THERMAL ENERGY STORAGE

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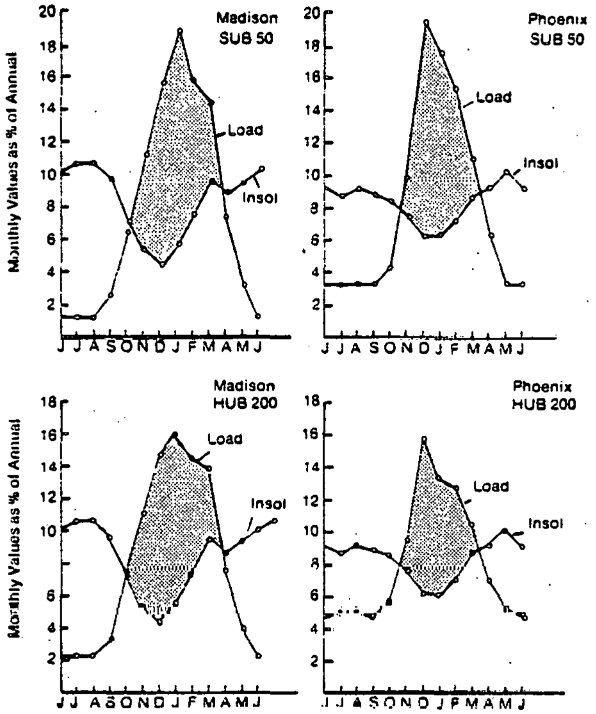
1. INTRODUCTION

Incorporating an annual cycle of thermal energy storage (ACTES) into a solar system may permit more effective utilization of solar energy than do conventional designs that are based on diurnal storages. Although a number of ACTES solar systems have been constructed in Canada [1,2] and Sweden [3] and designs for others are being developed in Canada, Sweden [4], and France [5], no systematic study has been performed to assess critical determinants of system component sizing and economic competitiveness. (Note that a good deal of research which examines ACTES is in progress [1-7].) The objective of this research is to assess the sensitivity of design parameters for a community solar heating system having annual thermal energy storage to factors including climate, building type, community size, and collector type and inclination. The system under consideration uses a large, water-filled, concrete-constructed tank for providing space heating and domestic hot water (DHW). This presentation outlines results and conclusions about system sizing; a system design study and economic analysis are underway.

The objective of ACTES is to store heat collected in the summer for winter use, when the load is greatest. The need for seasonal storage is demonstrated in Fig. 1, which shows month-to-month variation in load and insolation for both a northern city (Madison, Wisc.) and a southern city (Phoenix, Ariz.). The load shows a very sharp winter peak when insolation drops off. The load profile shows less of a peak for an apartment complex (HUB200) than for single family houses (SUB50) because the hot water load makes up a greater proportion of the total load for an apartment complex. Both load and insolation vary less throughout the year in Phoenix than in Madison, but even in Phoenix the discrepancy between load and insolation is large enough that ACTES systems may be feasible for large enough communities.

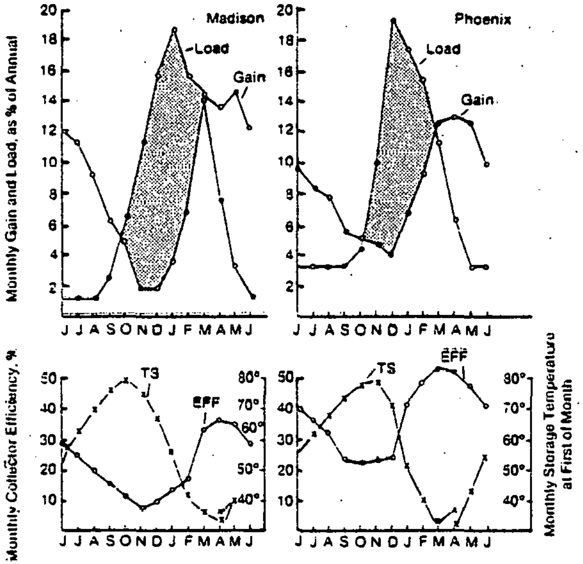
Figures 2a and 2b outline the simulated operation of a seasonal storage system for the two cities (Madison and Phoenix) and building types (single family and apartment). The top graphs show monthly load and collector gain. The difference between the two (shaded area) indicates the amount of heat to be provided by storage during the winter. The bottom graphs show the storage temperature and the collector efficiency. Storage temperature follows a similar pattern for both cities, rising to the mid-70s° C by early autumn and then dropping through the winter as heat is drawn to satisfy the winter load. The collector efficiency drops sharply in the winter months. This effect is much more severe for Madison, where efficiency drops below 10%, than for Phoenix when efficiency remains above 20%. The low winter collector efficiency is another important reason for investigating seasonal storage, especially in northern cities.

In addition to collecting summer heat for use in winter, ACTES systems provide other advantages. Collector stagnation during the summer months is all but eliminated. Collector field size is substantially reduced. ACTES systems can provide close to 100% solar heat, reducing or even eliminating the costs of a backup system and avoiding the burden of an increased winter peak load for electric utilities.



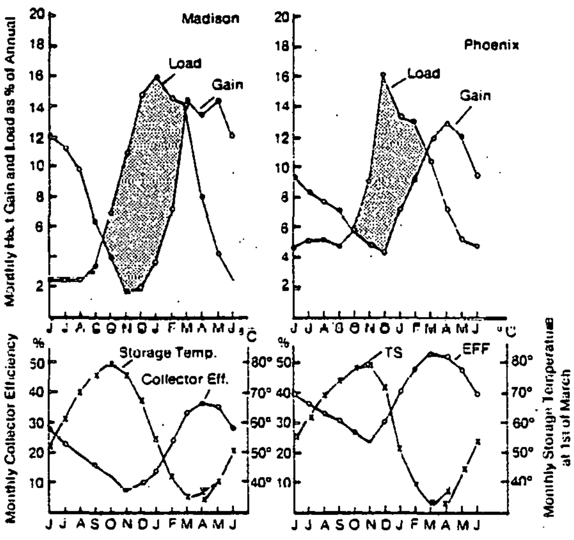
Note: Tilt = Latitude

Figure 1. Month-by-Month Insolation and Heat Loads (Including Hot Water)



Note: Flat Plate, Tilt = Latitude, SUB 50

Figure 2a. Month-by-Month Collector Gain, Heat Load, Collector Efficiency (EFF), and Storage Temperature (TS)



Note: Flat Plate Collector, Tilt = Latitude, HUB 200

Figure 2b. Month-by-Month Collector Gain, Heat Loads, Collector Efficiency (EFF), and Storage Temperature (TS)

Use of a community-wide system rather than individual systems provides other advantages. As storage size increases, the unit cost decreases. As well, the unit heat losses decrease and storage efficiency increases because the surface-area-to-volume ratio of the container decreases proportionately to increase in the radius. Statistical averaging of demand in a community increases system reliability and may decrease overall power requirements. Operation and maintenance is a shared expense. Finally, a community system may have financing and tax advantages of a public utility.

Disadvantages include the extra cost and energy losses in the storage and distribution system, increased problems of water freezing in the distribution system in winter, possible overheating of buildings in summer, and the need for ongoing system management by trained personnel.

The trade-off between collector and storage size is being investigated further. The 440 systems in this study were designed to supply 100% of the annual space heating load requirement and about 85% of the domestic hot water. Storage volume was minimized with the constraint that heat would not be dumped in the summer. A larger storage size with the chosen collector field would result in a lower maximum storage temperature.

2. METHODS

An analysis based on an hourly simulation of an ACTES system is used to (1) size systems in 10 locations, (2) identify critical design parameters, and (3) provide a basic conceptual approach for future studies and designs. The computer code was developed by Hooper and his associates at the University of Toronto [8]. This code was used because it is the only hourly simulation available in North America, because it has been validated and updated in one demonstration project, Provident House [2], and because it has been used to design a second, larger facility, the Alymer community.

Community size and housing type, geographic location, and collector type and tilt angle were varied. Discussion of these design parameters follows.

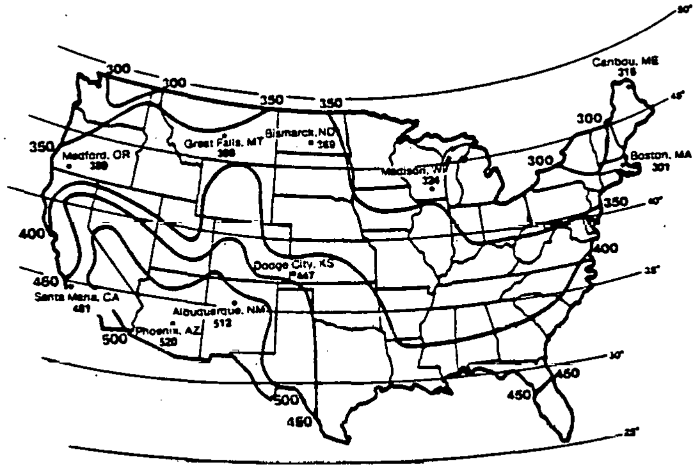
2.1 Community Size and Housing Type

Several community sizes and housing types were examined. Single family detached homes, 10-unit condominiums, and 200-unit apartment complexes provide a range of building types and are judged to be representative of present U.S. housing trends. Community sizes were varied from 50 through 200, 400, and 1,000 units. Thus, a total of 11 configurations (3 x 4 minus the excluded 50-unit apartment complex) were considered.

The choice of building configuration was based on those from the recent OTA report on solar energy [9]. Single family 2,000 ft^2 residences and 10-unit 3-bedroom 1,300 ft^2 condominiums were modelled. The 200-unit apartment complex had 10 stories; each consisted of 160 one-bedroom 850-ft^2 units and 40 two-bedroom 950-ft^2 units.

2.2 Geographic Location

Typical meteorological year weather data from 10 U.S. cities were used. An isoinsolation map, Fig. 3, shows the location of those cities chosen for investigation. A number of variables—including total yearly insolation per square meter, yearly degree days, or yearly community heating load—are used in the analysis as proxies for location.



Note: Numbers indicate mean daily solar radiation in langleys (gram-calorie-cm-2)
Source: Adapted from *Solar Energy Handbook 1979* Popular Science Copyright 1979, page 108

Figure 3. Geographic Locations of Cities

2.3 Collector Type and Tilt Angle

Two collector types are examined in this study: evacuated tube collectors (ETC) and a medium performance flat plate collector (FPC).

The collector parameters are:

	$F_r(\tau\alpha)$	F_rU_L [w/m^2 °C]
FPC	0.711	6.1041
ETC	0.447	1.1697

Two collector tilt angles were chosen: tilt equal to latitude and tilt equal to latitude plus 10°. No procedure, has been devised, as yet, to determine the optimal tilt angle for annual storage. Such a procedure would be based upon the relative magnitudes of energy gains and losses and building loads over an entire season. In total, four configurations of collectors were used for this study.

A variety of parameters were chosen to have either a fixed value or a value which changed somewhat across the unconstrained variables. These were transmission losses; heat load factor; domestic hot water (DHW) delivery temperature; maximum design tank top temperatures; inlet temperature to the DHW System; DHW demand rate; thermostat setting; design ambient temperature; insulation thickness; and soil density, thermal capacity, and conductivity.

Soil Conductivity. The following values were used to describe the soil conditions:

- soil thermal conductivity—1.7307 w/m°C,
- soil density—1762.0 Kg/M^3, and
- soil thermal capacity—1.0 KJ/Kg°C.

The values are considered to be representative of soil conditions in North America.

Transmission Losses. The University of Toronto simulation was designed to model an ACTES system which would provide heating and DHW for only one building. Losses resulting from transmission of thermal energy among the storage facility, the load, and the collectors was, therefore, considered negligible. In order to estimate conservatively the effect of transmission losses in the piping, we assumed that single unit, multifamily, and apartment complexes had losses of 10%, 5%, and 0% added to the community heat load factor (see below). The ACTES was assumed to be either integral to or adjacent to the apartment complex. The single-family community has substantially more piping than does the multifamily group.

Heat Load Factor. The heat load factor was used to determine building energy load. When coupled with the hourly weather data, hourly building load could be calculated. The heat load factor for a single-family residence of 2,000 ft^2 was chosen to be 500 Btu/degree hour, based on a recent SAI study [10] and advice from SERI researchers. The value for the multifamily condominium based on the OTA study [9] was 202 Btu/degree hour per unit. (This is an average since the units on the end of the building with more exposed surface area will have higher heat losses than the intermediate units.) The heat loss factor for the apartment complex was 25,748 Btu/degree hour or 130 Btu/degree hour per unit (also drawn from the OTA study).

Domestic Hot Water (DHW) Delivery Temperature. The DHW delivery temperature was chosen to be 120°F (48.0°C), lower than the normal 140°F (60°C) but still in a perfectly functional range. This was selected for two reasons. First, this allows attainment of more nearly 100% solar systems. Other designs—for example, having one ACTES tank plus multiple DHW tanks that would be charged first—would easily permit attainment of 100% solar systems. Second, the lower temperature is in keeping with the philosophy of this study—use of renewable energy sources and conservation of energy.

Maximum Design Tank Top Temperature. The maximum design tank top temperature was chosen to be 175°F (79.4°C). This temperature is well within present limits on plastic liners for storage tanks. It places less stress on tank insulation than would higher temperatures. It is also the maximum design temperature of the Lyngby's home in Denmark, an ACTES design that is currently in operation [11]. It could be argued that higher tank temperature would allow better utilization of the ETC, but this change in design would result in greater heat losses from storage and the transmission system.

Inlet Temperature to DHW System. The water main temperature was taken to be the average temperature of shallow groundwater and is, therefore, location dependent.

Thermostat Setting. The effective thermostat setting is the temperature requirement that is actually experienced by the space heating system. It is always a few degrees lower than the actual thermostat setting. In this study, 68°F (20°C) was chosen as the actual thermostat setting and 65°F (18.3°C) was used as the design thermostat readings.

3. FINDINGS

Results are organized as follows. First, critical factors in sizing the collector field area and storage tank volume are analyzed. Second, the sensitivity of design parameters to community size are investigated. Third, a preliminary comparison is made of annual- versus daily-cycle storage/solar energy systems. (Single, 10-, and 200-unit building sizes are abbreviated by SUB, TUB, and HUB, respectively, in the following discussion.) It should be noted that even if further analysis would result in the resizing of some components, the consistency from design to design in this analysis allows us to have confidence in searching for system to system variations. Similarly, although the sizes of the collector fields and the storage tanks can be proportionately different within limits, the choice of relative sizes was reasonable and consistent across all systems.

3.1 Sizing Components

It was found that as total annual insolation and average ambient temperatures increased, then collector efficiency increased. However, each of these factors could vary somewhat independently and the above relations were only approximately linear. A parameter that combines both the effects of average ambient temperature and total annual insolation on collector efficiency can be derived from the familiar relationship:

= Heat gain less heat loss

$$= F_r\ (\tau\ \alpha) - F_r\ U_L \frac{T_i - T}{I}$$

where T = outdoor ambient temperature
T_i = collector inlet temperature
and I = insolation.

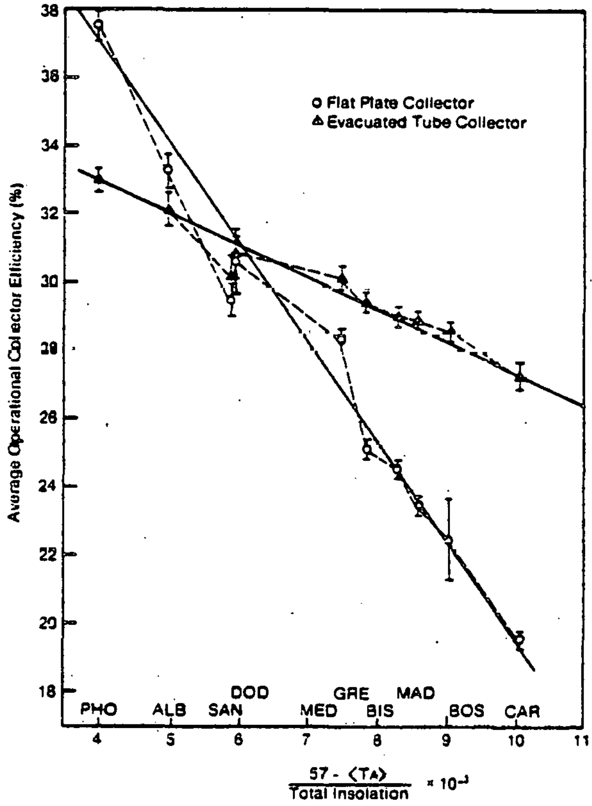
Collector efficiency was plotted versus a yearly average quantity $57 - \langle T_A \rangle$ (where $\langle T_A \rangle$ is the average ambient temperature) divided by total yearly insolation per square meter. (57°C is chosen here because it is approximately the average temperature of the storage fluid and is, therefore, the yearly average inlet fluid temperature to collectors.) As seen in Fig. 4, this relationship is approximately linear.

Using this relationship and knowing the space and DHW load requirements and the storage and distribution loss estimates, the collector area can be calculated from:

$$\text{Collector area} = \frac{\text{Total yearly space plus DHW load + storage and distribution losses}}{\text{Yearly insolation per m}^2 \text{ x efficiency}}$$

An algorithm for estimating storage volume is presented below.

Figure 4 also shows the relationship between flat plate (FPC) and evacuated tube collectors (ETC). For selected performance parameters, FPCs perform better when the difference between operating temperature and ambient temperature is small; ETCs perform better when this difference is large. As a consequence, ETCs are more advantageous in relatively cold and cloudy locations while FPCs are more efficient in the warmer climates.



Note: Tilt = Latitude

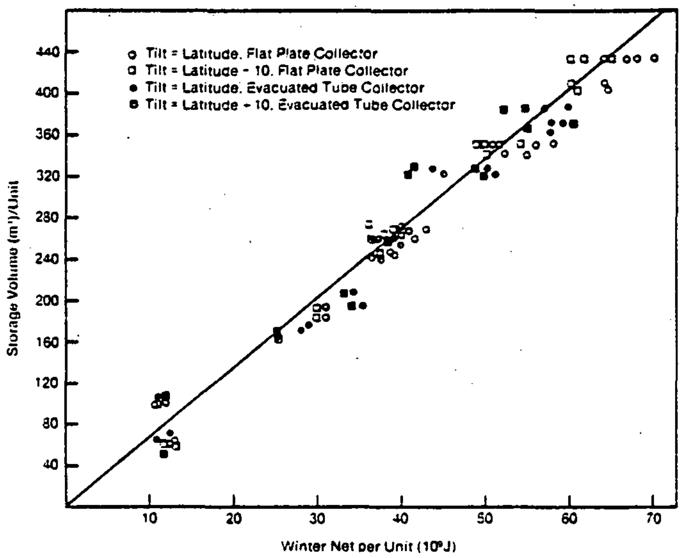
Figure 4. Average Operational Collector Efficiency vs. $\frac{57-\langle T_A \rangle}{\text{Total Insolation}}$

3.2 Storage Size

The difference between heat load and collected solar heat in winter (the shaded area in Fig. 2a and 2b) must be provided by storage. Storage size per unit versus this difference, the "winter net load" for November through February, is plotted in Fig. 5, 6, and 7. A linear relationship is obtained for all locations, community sizes, and collector types. This linearity makes the relationship useful for general system design.

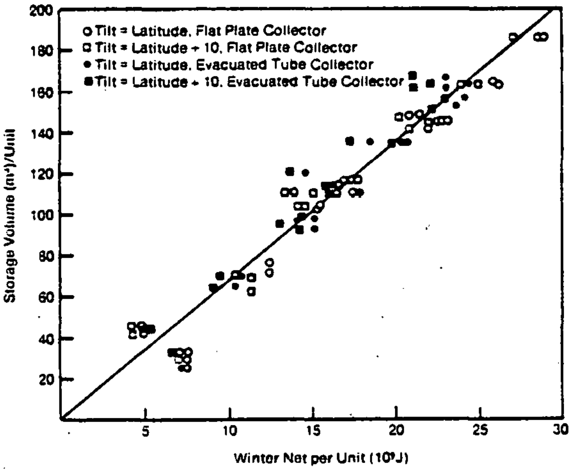
Winter net load may be calculated by adding space heat and hot water loads, estimating storage loss, and subtracting collected solar heat for November through February. (The percentage of the DHW load must be estimated; it typically is 75% for the four winter months. Storage loss may be taken as one-third the annual loss.) Calculating collected solar heat presents some problems because collector efficiency for the winter months must be estimated. Table 1 gives representative average winter collector efficiencies for the 10 cities that are suitable for use in sizing storages.

Storage sizes were also plotted versus the total winter load without considering collector gain. The plot (see Fig. 8) is close to linear and also could be used for system sizing. However, this relationship is not as linear as the preceding plots. Some irregular patterns, such as the reduced storage size needed for evacuated tube collector and for warmer locations, are not accounted for and corrected in the storage size versus total winter load graphs.



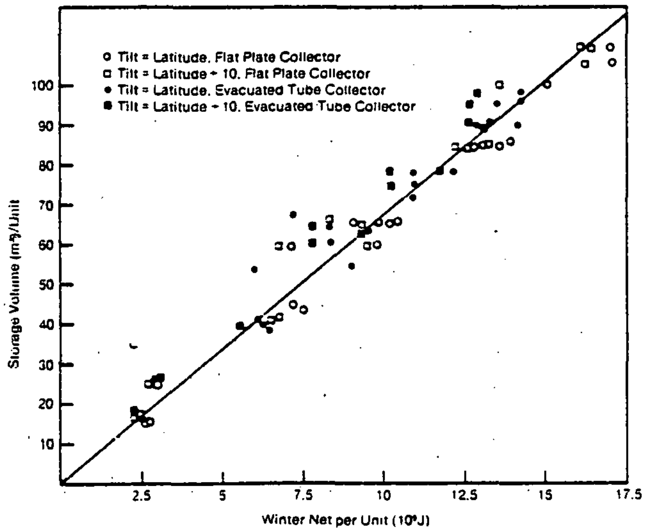
Note: The diagonal line is the same as the diagonal lines in the 10- and 200-unit graphs.
Winter net load is equal to load plus storage and transmission losses minus collector gain for the months of November through February.

Figure 5. Storage Volume per Unit vs. Winter Net Load per Unit: Single-Unit Building



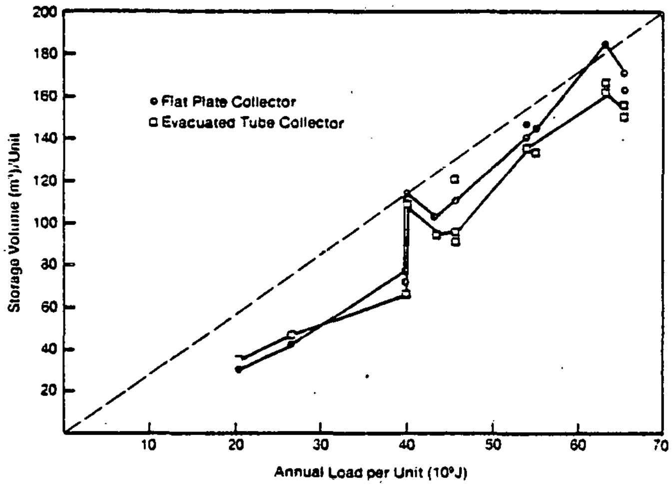
Note: The diagonal line is the same as the diagonal lines in the immediately preceding and following graphs, for single and 200-unit buildings.
Winter net load equals building load plus storage and transmission losses minus collector gain for the months of November through February.

Figure 6. Storage Volume per Unit vs. Winter Net Load per Unit: 10-Unit Building



Note: The diagonal line is the same as the diagonal lines in the single and 10-unit graphs immediately preceding.
Winter net load is equal to load plus storage and transmission losses minus collector gain for the months of November through February.

Figure 7. Storage Volume per Unit vs. Winter Net Load per Unit: 200-Unit Building



Note: The dotted line provides a common reference frame among the three storage vs. annual load graphs.

Figure 8. Storage Volume per Unit vs. Annual Load per Unit: 10-Unit Buildings (Space and Water Heat)

3.3 Sensitivity of Design Parameters to Community Size

Design variables were plotted against community size with building type and solar collector type as parameters. Results were as expected: collector area, solar energy collected, storage volume, and solar energy stored all increase linearly with community size and with building load. Collector efficiency remained constant for all community sizes within a given location. Storage losses became proportionately smaller with increasing community size, enabling the collector area per unit to drop slightly.

Storage size per unit was proportionately smaller for HUB and TUB than for SUB. This is because the DHW load is a greater proportion of the total load in larger buildings. As a result, winter load is a smaller percentage of the yearly load for the larger buildings and, therefore, storage size is reduced.

3.4 Annual Versus Daily Storage

A fundamental question in these considerations is how ACTES solar systems compare to conventional solar systems based on diurnal storages. Although a more thorough answer to this question, which examines the economics of collector-storage trade-offs, is presently under study; we can draw some preliminary conclusions here. To this end we compare those ACTES solar systems designed in this study with conventional solar systems for similar building types (SUB) in all 10 locations. Conventional systems are sized here by using the F-chart method, assuming 75 liters of storage per square meter of solar collection.

The percentage of solar heat that could be delivered by conventional systems with the same size collector are designed for the seasonal storage systems was calculated. Three observations were apparent.

- Without annual storage, about 65% of the heat load is provided by solar energy. Therefore, the annual storage can be viewed as adding 30% additional energy, correspondingly reducing the need for backup equipment.
- Annual storage provides the greatest advantage in cities with poor winter insolation, but this trend is not as pronounced as was expected. Medford, Oreg., which receives a very small percentage of its annual insolation in winter, is the city where annual storage is by far the most advantageous. Annual storage tended to be less useful in warmer climates (Phoenix, Albuquerque), but the difference between these cities and places like Boston and Madison was not very striking from this analysis.

- ETCs improve performance of an ACTES solar system as compared with FPCs because ETCs operate well over the relatively large temperature differences in seasonal storages. An annual cycle storage system can collect and store heat at 60-70°C, but conventional systems operate, on the average, at lower temperatures. Consequently, ETCs are more advantageous for ACTES solar systems. A counterbalancing trend occurs in cities with severe or cloudy winters. In such places, effective collection of winter insolation requires use of ETCs. Consequently, in Medford, which has a cold, cloudy winter, use of a diurnal storage system is less effective with FPCs than with ETCs.

The F-chart also was used to size daily storage systems that match the performance—96% solar—of the ACTES solar systems designed here. It was found that double to triple the collector area is required compared to the corresponding ACTES solar system.

4. CONCLUSIONS

Collector field area and storage volume have been sized for 440 community designs in 10 geographic locations. Analysis of the data has allowed identification of those parameters that have first order effects on component sizing. Storage size is determined by the difference between "winter net" and collected energy. Collector area then is sized to fully change storage.

Two linear relationships were derived which allow system sizing. The average ambient temperature is used to determine average yearly collector efficiency. This parameter combined with estimates of space/DHW loads, storage/distribution losses, and total yearly insolation per square meter allows estimation of collector area. Storage size can be estimated from the winter net load which is based on space and DHW loads, storage/distribution losses, and collector solar heat for the winter months.

The algorithms, which would be applicable to other types of annual storages such as aquifers, can be further refined as results from the operation of ACTES solar systems become available. Calculations also can be refined with more detailed knowledge of a particular community design.

In order to more accurately judge the relative merits of ACTES solar systems in different climates, a more detailed systems study and economic analysis is underway. Preliminary results indicate that as the DHW-to-space-heating-load ratio increases and as community size decreases, system economics become less favorable. Modifications to the design presented here such as incorporating a two-tank (annual storage for space heating; daily storage for DHW) storage systems or using multiple tanks for annual storage of both heat and cold, may be economically promising technologies.

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