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COMMERCIAL APPLICATIONS OF SOLAR TOTAL ENERGY SYSTEMS

Final Report, Volume 1, Summary

By
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July 1978

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Rockwell International
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Solar Energy

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ABSTRACT

A methodology has been developed by Atomics International under contract to the Department of Energy to define the applicability of solar total energy systems (STES) to the commercial sector (e.g., retail stores, shopping centers, offices, etc.) in the United States. Candidate STES concepts were selected to provide on-site power generation capability, as well as thermal energy for both heating and cooling applications. Each concept was evaluated on the basis of its cost effectiveness (i.e., as compared to other concepts) and its ability to ultimately penetrate and capture a significant segment of this market, thereby resulting in a saving of fossil fuel resources.

The photovoltaic STES appears favorable for applications under 800 kWe; whereas the organic Rankine STES would be more cost effective for larger energy demand applications. Initial penetration of these systems are expected to occur in the northeast for large shopping centers in the 1990-2000 time period. Such systems could provide about 0.8 to 1.8 quads (8×10^{14} to 1.8×10^{15} Btu) of energy per year for commercial applications by the year 2010.

FOREWORD

This is the final report for the Commercial Applications of Solar Total Energy Systems (STES) Program, developed under the Department of Energy (DOE) Contract EY-76-C-03-1210 [formerly, Energy Research and Development Administration (ERDA) Contract E(04-03)-1210]. The work was performed by Atomics International (AI) Division of Rockwell International Corporation, during the period from May 10, 1976 through June 1978. The technical effort was completed June 1, 1977; however, the final report was delayed due to requested changes to the preliminary report and the required authorization to revise the report during the period of ERDA transition to DOE.

The work is reported in four volumes as follows:

Volume 1 — Summary

Volume 2 — Technical

Volume 3 — Conceptual Designs and Market Analyses

Volume 4 — Appendices

The study was performed in the Advanced Programs Department of AI, under S. J. Nalbandian, Project Manager with support primarily from the following Rockwell personnel:

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In addition two subcontractors provided support relating to building configurations, energy demand, building codes and conventional total energy systems. They were the Envirodyne Energy Services and The Energy Group, a subsidiary of Welton-Becket Associates.

The DOE (Washington D.C.) Program Manager was Mr. J. E. Rannels. Technical direction for the study was provided by Dr. R. W. Harrigan, Technical Monitor, of Sandia Laboratories, Albuquerque, New Mexico.

1.0 INTRODUCTION AND SUMMARY

1.1 GENERAL

The application of solar energy to help meet the nation's future energy requirements is a potential alternative to presently used energy sources for the generation of electricity and thermal energy. The purpose of this program was to assess the feasibility of using solar energy to provide a significant fraction of the energy needs of buildings within the commercial sector that have energy demands >200 kilowatt electric (kWe). The specific type of application was the solar total energy system (STES) concept where electricity is generated on-site primarily from solar energy and the recovery of waste heat to help satisfy building heating and/or cooling requirements. Both solar thermal power conversion and solar photovoltaic system concepts were considered. Figure 1 presents a block diagram representation of the generalized form of these concepts.

As indicated in Figure 1 two types of STES were considered — a solar thermal and a photovoltaic. Both types of systems could provide on-site electrical and thermal energy with provisions for supplemental electric power from the utility as determined by cost effectiveness for the particular application considered.

1.2 PROGRAM OBJECTIVES

The specific objectives of the analytic study relative to the applicability of STES to commercial buildings requiring >200 kWe were:

- 1) Develop conceptual designs and establish requirements data
- 2) Identify key technology items and advanced technology requirements
- 3) Define a methodology for configuration and site selection criteria
- 4) Assess performance, cost, and market projections
- 5) Define requirements for a STES demonstration program plan.

1.3 APPROACH AND RESULTS

Specific system configurations were conceptualized based upon the STES definitions for solar thermal and solar photovoltaic applications shown in Figure 1. A methodology was developed for defining energy requirements for typical

78-JU14-86-2A

Figure 1. Solar Total Energy System (STES) Definition

commercial building applications, and selected system concepts were evaluated for six regions within the continental United States. Selection of specific system configurations were made on the basis of performance and cost effectiveness to define the desired amount of electricity to be provided from the utility, type(s) of energy storage and the economic split between vapor compression and absorption chiller cooling subsystems.

In general, the solar photovoltaic STES appeared favorable for applications under about 800 kWe; whereas the organic Rankine cycle STES appeared more cost effective for larger energy demand applications. Penetration of such systems appears most favorable in the northeast part of the United States especially for large shopping centers. The driving criteria for this conclusion are the higher electricity costs in the northeast region and normally the availability of more land area per energy consumption for the shopping centers compared to high rise office buildings. The following sections summarize the methodology and conclusions developed with a more detailed description of the study results provided in Volumes 2, 3, and 4.

Figure 2. STES Program Logic

78-JU14-86-3

2.0 PROGRAM APPROACH METHODOLOGY

To accomplish the objectives set forth in Section 1.2, the study effort was separated into five major technical task areas. The interrelation of these tasks are shown in Figure 2. The primary efforts for these tasks are discussed in the following paragraphs.

Task 1 — Requirements Development. Commercial building types, operating characteristics and configurations were evaluated and energy demand data were developed. Insolation and climatic data were evaluated for selection of candidate representative sites. An insolation evaluation methodology was developed and used to define the insolation at each representative site. The Task 1 effort was primarily performed by Rockwell Space Division personnel with support from the subcontractors and is discussed in detail in Volume 2.

Task 2 — Concept Definition and Component Evaluation. Various STES concepts were evaluated and organic Rankine cycle STES and a photovoltaic STES concept were defined as preferred configurations. Component and subsystem performance characteristics were evaluated and components state-of-the-art were assessed. Three modes of operation were assumed for the solar thermal STES (organic Rankine cycle). One was essentially an on-site stand alone concept utilizing auxiliary fossil fuel to supplement the solar energy with no electric utility interface. The second mode provided the total thermal energy requirements at the site from the cascaded energy from the organic Rankine cycle power conversion system with supplemental electrical energy purchased from the electric utility to meet any additional electrical energy demands of the site application. The third mode considered operation of the organic Rankine cycle power conversion system operation whenever adequate solar insolation was available regardless of the site application demand requirements and stored any excess electric energy in battery systems. This latter mode was the only operating mode assumed for the photovoltaic STES. Details are contained in Volume 2.

Task 3 — Concept Application Evaluation. The building energy demand profile data and site environment and insolation data from Task 1 and the STES concepts component data and control mode data from Task 2 resulted in a large number of variables which required development of a computer simulation code for concept evaluation purposes. The computer code provided a means for parametric evaluation

of performance and economic parameters (from Task 4) for the various concept and building applications. As a result, preferred STES configurations including equipment sizing and costs could be defined inexpensively at the various sites. Volumes 2 and 3 contain data on twelve specific site applications considered in this study.

Task 4 — Cost and Market Projections. A costing methodology and algorithms for various components were developed for use with the Task 3 computer simulation code. In addition, cost of electricity at the various representative sites were obtained and the effects of the demand rates were assessed. Economic evaluation of the STES concepts at the various sites provided data on the amount of energy produced by the STES in comparison with that provided by the utility for each configuration at the different sites. These data, in conjunction with the Task 1 building census data, were then utilized to develop potential market applications and penetration rates estimates discussed in Volume 3.

Task 5 — Project Utilization Plan. The preceding tasks provided necessary data to enable identification of preferred STES utilization for commercial building applications, definition of key technology development issues and recommended demonstration objectives. These are also discussed in Volume 3.

3.0 STES CONCEPTS AND COMPONENT SELECTION METHODOLOGY

Various solar thermal and photovoltaic STES concept configurations were defined and compared on a qualitative basis for application to the commercial buildings sector. The concepts considered and their relative application advantages and disadvantages are summarized in Table 1. An organic Rankine cycle solar thermal STES and a photovoltaic STES configuration were selected on the basis of applicability and component technology evaluations. For this study, which was performed in the 1976-1977 time frame, the Brayton cycle collector was not sufficiently developed to include the system in comparisons of STES for commercial building application. However, solar collector technology suitable for the Rankine cycle STES was considered under development and some test data are available. Consequently, only the Rankine cycle was included in this study for the solar thermal STES concept. Figures 3 and 4 define the solar thermal and photovoltaic STES configurations and the components or other elements which comprise each system.*

3.1 STES CONTROL MODES

The performance of the STES is dependent on the control logic used to operate the system. In addition, the type of energy storage also depends on this control logic. Three generic methods of control of the STES were considered. These determine how the power conversion system (PCS) is operated and are as follows:

- 1) Thermal Control — When the power conversion system (PCS) is sized and operated to provide the building heating, ventilating, and air conditioning (HVAC) and process heating demand load (using reject heat), the system is controlled by the thermal load. In this mode, the PCS always operates to provide enough reject thermal energy for the heating and cooling (thermal) loads. Electricity purchased from the utility is used to meet any unsatisfied building electrical load.
- 2) Electrical Control — The PCS is operated to provide the entire electrical load for the building. Auxiliary fossil-fired boilers are

*See list of symbols, page 51

TABLE 1
COMPARISON OF STES CONCEPTS

Power Conversion System Concept	Advantages	Disadvantages
Organic Rankine	<ol style="list-style-type: none"> 1. Distributed Collector Can be Used 2. Can be Cascaded for Thermal Load 	<ol style="list-style-type: none"> 1. Requires Licensed Operator or Automatic Safety Controls 2. Fire Hazard 3. Low Performance
Steam Rankine	<ol style="list-style-type: none"> 1. High Performance Potential 	<ol style="list-style-type: none"> 1. Requires Licensed Operator or Automatic Safety Controls 2. Requires Point Focus Receiver (higher temperature) 3. Fire Hazard Because of Second Fluid for Storage 4. Large Performance Loss to Cascade
Brayton Cycle (High Pressure)	<ol style="list-style-type: none"> 1. High Performance Potential 2. Can be Cascaded for Thermal Load 	<ol style="list-style-type: none"> 1. Requires Licensed Operator 2. Requires Point Focus Receiver (higher temperature) 3. Current Concepts of Thermal Storage Not Feasible for STES 4. Fluid Leakage Problems
Brayton Cycle (Low Pressure)	<ol style="list-style-type: none"> 1. High Performance Potential 2. Can be Cascaded for Thermal Load 3. No Operator Required 4. Thermal Storage Feasible for STES 	<ol style="list-style-type: none"> 1. Requires Advanced Central Receiver Concept 2. Probably Requires Fossil Fuel Topping Cycle to Produce Needed Turbine Inlet Temperatures
Photovoltaic	<ol style="list-style-type: none"> 1. High Performance Potential 2. Simple Control Systems 3. No Operator Required 	<ol style="list-style-type: none"> 1. High Cost of Array 2. Cascading Inefficient

Figure 3. Diagram of Solar Thermal STES Concept
(Rankine Cycle Power Conversion System)

Figure 4. Diagram of Photovoltaic STES Concept

used in conjunction with the solar collector to provide sufficient energy to the PCS to make the system stand alone with no electricity purchased from the utility.

- 3) Solar Control — The PCS is sized and operated to utilize the solar energy collected by the system. Utility electricity is used to meet any unsatisfied building electrical or cooling load while fossil fuel is burned to meet any unsatisfied building heating requirements.

Solar thermal systems (Rankine cycle PCS) was considered operable in any one of the three control modes (i.e., electrical, thermal, solar) and used either hot thermal storage or battery storage for energy storage in conjunction with cold storage for refrigeration needs. The photovoltaic STES (nonconcentrator system) was operated in the solar control mode only since the flat plate collectors used for meeting the building thermal loads decouple the electrical and thermal requirements.

3.2 SOLAR COLLECTOR CHARACTERIZATION

The various solar thermal collectors considered for the solar thermal STES included the distributed concentrator configuration, distributed flat plate configuration and central receiver configurations. Figure 5 illustrates the solar noon efficiency characteristics selected to represent 1985 state of the art collectors for use in the analysis of the STES configurations for commercial buildings. The distributed collector characteristics were based upon a line focus collector assumed to be used with a two axis tracker system to maximize the solar energy collected.

A nontracking flat plate silicon photovoltaic cell array was selected for use in the photovoltaic STES configuration. This was based upon the intensive government sponsored activities devoted to low cost silicon arrays and the estimated cost reductions projected for the early 1980's (e.g., \$0.50 per peak watt). The performance characteristics of the array was based upon an input cell efficiency of 15% at 28°C with temperature characteristics shown in Figure 6.

77-MA25-55-3A

Figure 5. Collector Efficiencies Used in Analysis

Figure 6. Solar Photovoltaic Devices Performance

3.3 ENERGY STORAGE SUBSYSTEMS

Energy storage is necessary for STES concepts to:

- 1) Prevent interruption of power due to intermittent cloud cover (smooth out the solar profile).
- 2) Extend the usable period of operation of the system to nonsunlight periods.

The amount of storage capability will depend upon the application and type of backup or auxiliary energy available. Both the thermal and battery storage systems were considered in evaluating the STES concepts.

The thermal energy can be stored in the collector fluid or in a secondary material (and/or fluid). For this study, it was assumed that the additional system complexity required to use a secondary fluid for the storage subsystem would not be cost effective, and only systems using the collector fluid as the transfer medium were considered. Performance characteristics for the energy storage subsystems is discussed in Section 3.2, Volume 2.

76-JY13-49-33

Figure 7. Heat Reject Temperature Effects on Rankine Cycle

3.4 RANKINE CYCLE POWER CONVERSION SYSTEMS

The Carnot efficiency of a thermal power conversion system (PCS) is defined by the upper and lower cycle temperature limits and represents the maximum efficiency attainable for those limits. Practical systems such as the Rankine cycle system will operate at a fraction of this efficiency so that the efficiency of a Rankine cycle power conversion system can be represented by*

$$\eta_{PCS} = R_c \left(\frac{T_t - T_{cnd}}{T_t} \right)$$

where R_c will be about 0.5 for an organic Rankine cycle. Without reheat, a steam Rankine cycle will give somewhat lower performance as indicated in Figure 7. Consequently, this study has assumed the use of an organic Rankine cycle PCS in the STES.

3.5 HEATING, VENTILATING AND AIR CONDITIONING (HVAC) SYSTEMS

Reject energy from the Rankine cycle PCS can be cascaded to an absorption chiller system to provide cooling for the building. A simplified model of the absorption system was assumed as a fixed fraction of the Carnot refrigeration cycle efficiency in the same manner as used for the PCS. A nominal 35 percent ratio was used in the analyzer giving the absorption cycle efficiencies shown in Figure 8 and represented by the equation:*

$$COP = 0.35 \frac{T_{cs}}{T_{ct}} \frac{T_{ct} - T_a - \Delta T_{cnd}}{T_a + \Delta T_{cnd} - T_{cs}}$$

Figure 8 also shows the range of coefficient of performance (COP) normally produced by commercial vapor compression chillers. A 4.5 COP was assumed in this study for vapor compression chillers.

*See list of symbols, page 51

76-JY12-49-30A

Figure 8. Air Conditioning (Cooling) Performance Comparisons

4.0 INSOLATION CHARACTERIZATION METHODOLOGY

Detailed evaluation with existing simulation programs [e.g., SOLSYS,⁽¹⁾ PVSOLSYS⁽²⁾ or modified TRNSYS⁽³⁾] using tabulated hourly weather data was beyond the funding level and scope for this study. Consequently, a deterministic model for solar insolation was developed to simulate flat plate, one-axis and two-axis tracking distributed collectors and central receiver STES configuration performance at selected sites in lieu of weather tape data. The United States was divided into six regions, based on the available solar insolation and degree day regimes. These regions are shown in Figure 9 and were based upon previous studies for solar heating and cooling (SHAC) applications.⁽⁴⁻⁷⁾ Characteristics of the twelve sites shown in Figure 9 within the six regions are summarized in Table 2. The deterministic model, based upon the data shown in Figure 10 and described in Section 4.2, Volume 2, was used to define a clearness number (CN) and cloud factor (CF) for each of the twelve sites to represent insolation characteristics of the sites. Climate and insolation data summary sheets are provided for each of the twelve sites in Section 4.2, Volume 2.

76-O18-49-19C

Figure 9. Candidate STES Study Regions/Sites
(Six Regions, Twelve Sites)

TABLE 2
CHARACTERISTICS OF STES SITES SELECTED

REGION	LOCATION	TOTAL INSOLATION (Btu/ft ² -DAY)			HEATING DEGREE DAY (HDD)*		COOLING DEGREE DAY (CDD)*		DESIGN WINTER TEMPER- ATURE (DRY BULB) (97-1/2 %) (°F)	DESIGN SUMMER TEMPER- ATURE (2-1/2 %) (°F)	WET BULB TEMPER- ATURE (°F)	HUMIDITY RATIO (W) lb H ₂ O lb DRY AIR	ANNUAL MEAN TEMPER- ATURE (°F)
		YEAR AVG.	DEC.	JUNE	DEC.	YEAR AVG.	JUNE	YEAR AVG.					
1	LAKE CHARLES, LA.	1542	923	2181	338	1498	471	2739	33	91	60	0.019	68.3
1	MIAMI, FLA.	1664	1166	1963	56	206	480	4038	47	90	65	0.019	70.3
2	NASHVILLE, TENN.	1310	553	2033	763	3696	348	1694	16	95	50	0.018	59.4
2	WASHINGTON, D.C.	1314	612	1822	856	4211	288	1415	19	92	55	0.017	57.3
3	ALBUQUERQUE, N. M.	1889	1018	2679	893	4292	291	1316	17	94	20	0.007	56.8
3	FT. WORTH, TEXAS	1642	904	2402	530	2382	468	2587	24	100	40	0.016	65.5
3	LOS ANGELES, CA.	1708	899	2199	218	1245	115	1145	44	90	36	0.011	64.8
3	PHOENIX, ARIZ.	1919	1037	2727	388	1552	588	3508	34	106	27	0.012	70.3
4	BLUE HILL MASS.	1210	498	1882	1094	6335	69	457	10	88	50	0.015	48.3
4	MADISON, WIS.	1196	424	1897	1336	7730	96	460	-5	88	53	0.015	44.9
5	OMAHA, NEB.	1399	627	2014	1147	6049	236	1173	-1	94	53	0.018	51.5
6	SEATTLE, WASH.	1003	218	1701	710	4695	23	200	32	79	47	0.011	52.6

*BASE TEMPERATURE = 65°F

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- APPLIES ANALYTICAL EXPRESSIONS FOR PREDICTABLE EFFECTS
 - SUN POSITION (ZENITH ANGLE θ_Z) AS FUNCTION OF LATITUDE, TIME OF DAY, AND SEASON
 - TRANSMISSION THROUGH THE STANDARD ATMOSPHERE AS FUNCTION OF SEASON:

$$A \cdot \exp(-B/\cos \theta_Z)$$

- DERIVES AVERAGE LOCAL CORRECTIONS BASED ON MEASURED DIRECT AND HORIZONTAL RADIATION

- RADIATION IS OBSCURED BY CLOUDS FOR $(1 - CF)$ FRACTION OF THE TIME

- WHEN NOT CLOUDED, LOCAL ATMOSPHERIC EFFECTS ATTENUATE RADIATION BY THE CLEARNESS FACTOR, CN

$$I_{DN} = CN \cdot A \cdot \exp(-B/\cos \theta_Z)$$

- TOTAL HORIZONTAL RADIATION I_H (DIRECT AND DIFFUSE) ESTIMATED BY LINEAR FORMULA,

$$I_{DN} = \alpha'(I_H/I_H^0) + \beta'$$

76-018-49-46

Figure 10. Deterministic Insolation Model

5.0 COMMERCIAL BUILDING CHARACTERISTICS AND MODEL BUILDINGS SELECTION

Estimates of the number and distribution (i.e., by size and geographic region) of candidate STES applications within the commercial sector were required to be defined. For purposes of this investigation, these applications were defined as facilities which require at least 200 kWe. The candidate applications have been categorized as:

- 1) The retail sector, as represented by shopping centers or integrated shopping complexes having more than 1860 m^2 ($20,000 \text{ ft}^2$) of gross leasable area (GLA). It was assumed that the energy requirements for the lower size buildings is about 108 W/m^2 (10 W/ft^2) as discussed in Section 4.4, Volume 2.
- 2) Office buildings (including banks, federal, states, local, and privately owned) which are less than 10 stories high. It was assumed that high rise buildings would not have adequate available land area for the required solar collector field area.
- 3) Other, including hotels and motels below 3 stories, warehouses, nursing homes, dormitories, etc. (Schools, libraries, auditoriums, religious institutions, etc., were relegated to the institutional and recreational sectors).

5.1 COMMERCIAL BUILDING CENSUS

Shopping centers, including retail establishments, and office buildings were selected as representative commercial buildings based on census data and upon their adaptability to STES. Land area limitations (land lock considerations) and shadowing effects constrain building height to three stories for this study, while the 200 kWe minimum STES size groundrule indicated floor areas $>1860 \text{ m}^2$ ($20,000 \text{ ft}^2$) for conventional buildings were required. Within this framework, shopping centers including large retail stores represent most of the commercial building potential. Figure 11 shows the distribution by size for shopping centers in 1976.⁽⁸⁾ Table 3 shows the distribution of the shopping center and retail establishment GLA in each of the six climatic regions (refer to Figure 9).

Figure 11. Shopping Centers — Distribution by Size

TABLE 3
REGIONAL DISTRIBUTION OF SHOPPING CENTERS AND RETAIL
ESTABLISHMENTS (GLA)

Region	GLA	
	(10 ⁶ m ²)	(10 ⁶ ft ²)
1	27.5	296
2	72.9	785
3	41.3	444
4	65.7	707
5	30.0	323
6	5.9	63
Total Continental U.S.	243.3	2,618

Similar data for office buildings and for other commercial buildings considered are contained in Section 4.3, Volume 2.

5.2 ENERGY DEMAND CHARACTERISTICS

Evaluation of the energy demand requirements for these buildings was done by (1) survey and (2) by computer simulation. The survey results were disappointing since only incomplete load data could be obtained as discussed in Section 4.4.1, Volume 2. While the survey results were incomplete, the results that were obtained indicated that the demand loads for commercial buildings were primarily a function of how the building was operated (i.e., lighting level during off hours and total hours open) and the building internal heating, ventilating and air conditioning (HVAC) system. Environmental conditions had only a secondary influence on demand loads. Consequently, computer simulations of building loads with the AXCESS program,⁽⁸⁾ developed by Edison Electric Institute were made to evaluate the effect of the various HVAC systems in use for commercial buildings.

Figure 12 shows typical results from this simulation for a low-rise office building and illustrates the wide variation in building energy demand requirements that result with the different HVAC systems assuming other building load requirements are unchanged. The multi- and single-zone HVAC reheat systems

77-F23-9-64

Figure 12. Simulated Total Energy Demand
(Low Rise Office Building)

currently in common usage have total energy demands four to six times the lighting (electric) load, while the more expensive four-pipe fan coil system (or unitary heat pump in mild climates) potentially can reduce this demand to slightly over two times the lighting load. Although it may not be cost effective at the present time, as energy costs increase, the more initially expensive HVAC systems should become more common. Table 4 shows the ratio of thermal energy required compared to electrical energy usage depending upon the type of HVAC system utilized in the building.

From Table 4, it can be seen that the lower energy consumption HVAC designs will tend to reduce the thermal to electrical energy usage ratio for the building to about 1.1 or less from values as high as 5.7. The sensitivity of STES design to the energy usage and electrical to thermal ratio is discussed in Section 2.0, Volume 3.

Energy conservation considerations were also evaluated which indicate considerable savings are possible in commercial buildings depending upon the HVAC selection. Figure 13 presents data on the potential energy savings that may be expected in future designs implementing energy conservation trends such as recommended by ASHRAE 90-75,⁽¹⁰⁾ which will also result in the type of HVAC system most compatible with a STES concept.

5.3 SELECTED MODEL BUILDING CONFIGURATIONS FOR STES EVALUATION

Based upon the results of the census and energy demand evaluations for commercial buildings, six model building configurations were developed for STES application analysis. Table 5 summarizes the model building configurations and their energy requirement characteristics.

TABLE 4
RATIO OF THERMAL TO ELECTRICAL ENERGY USAGE

HVAC System	Consumption Rating	Low-Rise Office	High-Rise Office	Small Retail Store	Large Retail Store	Small Shopping Center	Large Shopping Center
Unitary Cooling With Separate Reheat	1	NC*	NC	0.4	NC	0.4	0.3
4-Pipe Fan Coil	2	0.9	1.1	NC	NC	NC	NC
Unitary Heat Pumps	3	1.2	NC	0.4	NC	0.5	0.3
Variable Volume With Reheat	4	2.9	2.0	NC	NC	NC	NC
Multizone	5	4.0	NC	NC	0.7	1.8	1.8
Dual Duct	6	5.4	4.0	NC	NC	NC	NC
Single Zone Reheat	7	5.7	3.8	0.6	1.1	1.6	2.1
4-Pipe Induction	8	NC	3.9	NC	NC	NC	NC

* NC = System not considered in this building.

TABLE 5
SELECTED MODEL BUILDING CONFIGURATIONS

Building		Floor Area [m ² (ft ²)]	HVAC System	Energy Demand (Mwh/yr)		
Type	Computer File Name			Electrical	Thermal	
					Cooling	Heating
Large Shopping Center	SHOPCL	69,700 (750,000)	Conventional Multizone	25,565	27,604	17,195
Large Shopping Center	SCLECR	69,700 (750,000)	Energy Con- serving Retro- fit-Multizone	12,694	13,716	8,508
Large Shopping Center	SCLNS	69,700 (750,000)	Energy Con- serving New Standards- Multizone	4,381	4,732	2,943
Medium Shopping Center	SHOPCM	41,820 (450,000)	Conventional Multizone	16,815	16,306	14,432
Large Retail Store	STOREL	18,590 (200,000)	Conventional Multizone	7,762	3,677	1,701
Low Rise Office	OBLCH	18,590 (200,000)	Conventional Dual Duct	2,432	5,663	4,476

Figure 13. Energy Conservation Potential

6.0 STES APPLICATION EVALUATION

In order to evaluate the various STES configuration options depicted by Figures 3 and 4 for each of the six model building configurations for each of the twelve site locations considered, a second computer program was developed. This program designated STESEP (for solar total energy system evaluation program) was used in conjunction with the data generated from the deterministic model computer program. This program, discussed in Section 5.0, Volume 2, used approximate algorithms for component performance and cost in conjunction with the deterministic weather simulation to evaluate the size and cost tradeoffs of various STES configuration options (i.e., turbine temperatures, cascaded absorption chillers, type of energy storage) in terms of the ERDA-JPL cost methodology.⁽¹¹⁾ The ERDA-JPL cost methodology was modified to evaluate the total life cost of a system under assumed inflation-escalation rates for either utility or private investors. Nominal costs of \$100/m² were used for concentrating distributed collectors and photovoltaic arrays (Si cells), \$82/m² for central receivers (heliostats and tower), and \$50/kWh for batteries with a fixed general inflation rate of 5% and with fuel and operation and maintenance escalation rates between 6 and 10% per year.

Tables 6 and 7 depict the computer printout data for a solar thermal and photovoltaic STES application for a large shopping center located in Albuquerque, New Mexico. Component sizing data as well as the auxiliary electricity required for the most cost effective configuration for the given assumptions are provided by this computer program. The STES configurations depicted by Figures 3 and 4 can then be modified using the data from Tables 6 and 7 as represented by Figures 14 and 15.

An application sensitivity analysis was performed to define component sizing and performance effects at the various sites.

As might be expected, a large effect of site location on concentrating collector efficiency was found. This is illustrated in Figure 16 which shows a 3 to 1 difference in efficiency between Phoenix, Arizona, and Seattle, Washington. This difference was not nearly as large for the tilted flat plate used for low temperature thermal energy applications in the photovoltaic systems. Also, a 10% change in efficiency was predicted for the photovoltaic solar cell arrays

TABLE 6

SOLAR THERMAL STES

STES EQUIPMENT SIZES FOR A LARGE SHOPPING CENTER LOCATED IN ALBUQUERQUE, N.M.
 FLOOR AREA IS 70755, SQ.M AND ELECTRICAL DEMAND IS 141099, KWH/DAY AT 0, KWH/KW
 BASED ON INCIDENT INSOLATION OF 698, LANG./DAY, HDD/YR OF 4418, CDD/YR OF 1437,

ASSUMPTIONS:

FOR A 2006 START OF OPERATION, COST PARAMETERS ARE

FCR=0,159 K=0,080 G=0,050 GF=0,100 N= 20 FUEL= 2,37 \$/GJ, ELECT= 8,40 \$/GJ (1976 \$)

RANKINE CYCLE STES CONCEPT WITH PCS CONTROL BY SOLAR LOAD

WITH A DISTRIBUTED COLLECTOR

EQUIP	SIZE	EFF	TIN DEG C	TOUT DEG C	ENERGY KWH/DAY	INST'LD CST, \$/UNIT SIZE	CAP, INV, K\$	REC'G CST, K\$	CMPT, LIFE YEARS
COLLECT.	14161, SM	0,379	233,	321,	42386,	100,	1416,	76,	20,
BATTSTU,	1152, KWH	0,723	0,	0,	218,	78,	90,	20,	20,
HEAT EX,	16015, SM	0,941	321,	233,	449639,	14,	220,	0,	20,
AUX, HTG,	67325, KW	0,750	228,	371,	543008,	3,	190,	1566,	20,
PCS	10229, KW	0,203	371,	110,	91091,	330,	3380,	492,	20,
V, C, RFG,	7041, TON	4,500	0,	0,	110618,	268,	1886,	0,	20,
AB, RFG,	5667, TON	0,698	108,	8,	183392,	329,	1866,	0,	20,
PRO, HTG,	8256, KW	1,000	110,	19,	0,	12,	97,	0,	20,
CDDL TWR	8168, SM	0,700	110,	108,	95655,	5,	37,	0,	20,
COLD STU	719, CM	0,700	8,	17,	0,	91,	66,	0,	20,
AUX, ELEC	2463, KW	0,0	0,	0,	9010,	0,	0,	142,	20,

COST ANALYSIS RESULTS:

SOLAR ENERGY FURNISHES =0,8% OF LOAD, UTILITY 8,4%, AND FOSSIL FUEL 92,4%

TOTAL CAP, INV, IS \$,92461E+07 WITH YEARLY REC'G, COSTS, ,22970E+07

ANNUALIZED COST OF \$,24542E+08 WITH A YEARLY SAVING OF -,70786E+07 DRUI= -40,5%

TABLE 7

PHOTOVOLTAIC STES

STES EQUIPMENT SIZES FOR A LARGE SHOPPING CENTER LOCATED IN ALBUQUERQUE, N.M.
FLOOR AREA IS 70755.50.4 AND ELECTRICAL DEMAND IS 141099. KWH/DAY AT 306. KWH/KW
BASED ON INCIDENT INSULATION OF 616. LANG./DAY, HDD/YR OF 4418. CDD/YR OF 1437.

ASSUMPTIONS:

FOR A 2006 START OF OPERATION. COST PARAMETERS ARE

FCR=0.159 K=0.080 G=0.050 GF=0.100 N= 20 FUEL= 2.37 \$/GJ, ELECT= 8.40 \$/GJ (1976 \$)

PHOTOVOLTAIC STES CONCEPT WITH PLS CONTROL BY SOLAR LOAD

WITH A FLATPLATE ARRAY

EQUIP	SIZE	FFF	TIN DEG C	TOUT DEG C	ENERGY KWH/DAY	INST'LD CST. \$/UNIT SZE.	CAP. INV. K\$	REC'G CST. K\$	EMPT. LIFE YEARS
PV ARRAY	42484. SM	0.120	0.	0.	35444.	100.	4248.	0.	20.
BATTERY	656. KWH	0.723	0.	0.	231.	50.	33.	7.	20.
AUX. ELEC	12999. KW	1.000	0.	0.	107489.	0.	0.	1223.	20.
BLDG. HT.	430. KW	1.000	19.	19.	63348.	25.	11.	29.	20.
INVERT.	4744. KW	0.950	0.	0.	0.	65.	308.	112.	20.
V.C. RFG.	9300. TON	4.500	0.	0.	294010.	240.	2234.	0.	20.
AB. RFG.	0. TON	0.650	0.	0.	0.	0.	0.	0.	20.
PRO. HTG.	7826. KW	1.000	0.	0.	2534.	5.	36.	0.	20.
FP COLL.	28302. SM	0.537	60.	69.	105935.	54.	1523.	0.	20.
HEAT STD	40023. CM	0.700	60.	60.	0.	6.	236.	0.	20.

COST ANALYSIS RESULTS:

SOLAR ENERGY FURNISHES 26.1% OF LOAD, UTILITY 72.2%, AND FOSSIL FUEL 1.7%

TOTAL CAP. INV. IS \$.86298E+07 WITH YEARLY REC'G. COSTS, .13704E+07

ANNUALIZED COST OF \$.15150E+08 WITH A YEARLY SAVING OF .23025E+07 DROI= 13.2%

Figure 14. Solar Thermal STES Concept (Rankine Cycle)
for a Large Shopping Center in Albuquerque, NM

76-019-49-56B

Figure 15. Photovoltaic STES Concept for a Large Shopping Center in Albuquerque, NM

1 = SEATTLE	5 = WASHINGTON, DC	9 = LAKE CHARLES, LA
2 = MADISON, WI	6 = OMAHA, NE	10 = FORT WORTH, TX
3 = BLUE HILL, MA	7 = ALBUQUERQUE, NM	11 = PHOENIX, AZ
4 = LOS ANGELES, CA	8 = NASHVILLE, TN	12 = MIAMI, FL

77-MA25-55-26

Figure 16. Effect of Location on Collector Efficiency

77-MA25 55-24

Figure 17. Breakeven Electricity Cost vs Local Electricity Cost

at the different locations. In spite of the efficiency variation, the breakeven cost of electricity was found not to vary significantly between sites. The breakeven cost is defined as the cost of making energy from the STES being equal to the cost of purchasing electricity from the grid. This is shown in Figure 17 where the local cost of electricity (1976)⁽¹²⁾ is compared with the predicted breakeven costs for the Rankine and photovoltaic systems based on escalation rate assumptions of 6% and 10%. The low cost of electricity existing over most of the country indicates that under the low escalation rate conditions, only a small portion of the northeast coast could economically install an organic Rankine cycle STES in large shopping centers. As the system size decreases, the results indicate the labor costs become dominant and must be reduced to enable economical use of commercial STES. Figure 18 shows the effect of system size on breakeven cost of electricity and also illustrates the much larger effect of uncertainties in escalation rates on photovoltaic systems costs over Rankine cycle system costs.

77-MA25-55-17A

Figure 18. Effect of STES Size on Breakeven Costs in Blue Hill, MA

7.0 MARKET ANALYSIS

Limited initial market scope and projection analyses indicated that there will be a commercial market for systems ≥ 200 kWe of about 35,000 MWe in 1990. Although they represent only 2% of the total number of potential commercial units, shopping centers will account for about 75 to 80% of the potential market. Initially, this market might be penetrated in the northeastern region of the U.S. (e.g., New York, Boston, and Washington, D.C.) which now has the highest electricity costs, if recurring costs (e.g., operations, maintenance, fuel, etc.) continue to increase at a "nominal" rate of about 8% annually. In large systems (e.g., ≥ 1 MWe) the organic Rankine STES exhibits a lower breakeven cost of electricity than photovoltaic systems. Below 1 MWe peak capacity, the lower operating and maintenance cost associated with photovoltaic systems make them more cost effective.

An analytical method has been developed to estimate the market penetration rates. Assuming an annual new construction rate equal to 2.5 to 5% of the existing inventory and a progressively compounded new construction penetration rate of 5% per year coupled with a retrofit penetration rate of 1% per year, it will take about 20 years to penetrate 50% the potential market and 25 to 35 years for STES to achieve 70% adoption in the classic Fisher — Pry⁽¹³⁾ diffusion manner.

Figure 19 shows the penetration potential, expressed in quads (i.e., 10^{15} Btu), as a function of time. The solar contribution from the STES will probably account for about 50%, or less, of the energy requirements for the site because of the limited land availability for solar collectors near commercial buildings.

	RETROFIT PENETRATION RATE (%/yr COMPOUNDED)	NEW CONSTRUCTION PENETRATION RATE (%/yr COMPOUNDED)
SCENARIO I	1	2.5
SCENARIO II	1	5.0

ANNUAL NEW CONSTRUCTION IS 5% OF INVENTORY

Figure 19. Commercial Sector Market Penetration Potential by STES

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The following is an overall summary of important conclusions from the study effort.

- 1) Shopping centers and large retail stores are primary applications areas for STES >200 kWe
- 2) Building loads are highly sensitive to the type of internal system and operating mode selected
- 3) STES applications are sensitive to building energy demand and available land
- 4) Energy displacement by solar below 50% for existing building loads – may be increased significantly by energy conservation
- 5) Operating and maintenance costs affect STES configuration selection by favoring photovoltaic systems at small sizes and solar thermal for large systems.
- 6) Utility interface can be improved by use of on-site backup systems
- 7) Applications can be cost effective for selected sites for demonstration projects
- 8) Initial market penetration is expected to occur in 1990's

Market Characteristics

Initial market penetration can be expected in the 1990-2000 time period on the northeast coast of the U.S. for large shopping centers. Low fuel escalation rates will favor solar thermal systems as will large energy consumption applications (above 800 kWe); while high fuel escalation rates and lower energy consumption applications will favor photovoltaic systems under the conditions assumed for this study. Also, a significant market for STES below 200 kWe will exist in the 1990-2000 time period if the operations and maintenance costs for these systems can be reduced and energy conservation measures are implemented for new construction. Safety problems exist for solar thermal STES that must be solved before commercialization is possible.

Components Technology

Components suitable for use in experimental solar total energy systems exist, but only in a limited size range and small quantities. Neither collectors nor arrays suitable for commercial application exist at this time (1976), but

could be available for utilization in the 1985 to 1990 time frame without requiring any technology breakthrough. Performance of the experimental designs being tested at Sandia Laboratories, Albuquerque, New Mexico, and elsewhere is probably adequate if costs for the components and subsystems can be reduced to the projected levels, and system lifetimes will meet the assumed durations of 20 to 30 years.

Present concepts of storage systems have unsatisfactory efficiencies and costs, and hence will probably be one of the prime factors in limiting the size of solar total energy systems relative to the building demand loads in the commercial sector since much of the excess solar energy (above the building demand) is lost while in storage for systems in the 200-kWe to 10-MWe power size range.

Power conversion systems for STES are currently limited to organic Rankine cycle systems when line focus distributed collectors are used while steam Rankine cycles are available when point focus or central receiver STES are used.

HVAC systems of conventional designs and heat exchangers are components available in wide range of capacities and quantities although the efficiency of the components needs improvement for STES application.

Costs of solar system components require further definition since the cost estimates for collectors, arrays, etc., are based on analytical estimates rather than actual production cost data which can only be obtained after production lines have been established.

Application Considerations

There is a considerable variability in weather conditions in the United States which can be categorized into six climatic regions. The Gulf and South Atlantic regions are considered to be highest in apparent growth potential for commercial buildings.

The commercial market sector was evaluated for STES application through census data which indicated that shopping centers and large retail stores were the most likely markets for STES in the commercial sector. The census data also indicated that the size of urban shopping centers is relatively independent of the city population with an average size of $16,000 \text{ m}^2$ ($150,000 \text{ ft}^2$). Rural shopping centers tend to be smaller with an average size of $9,000 \text{ m}^2$ ($100,000 \text{ ft}^2$).

The energy usage in commercial buildings varies widely depending on store hours and internal HVAC systems utilized more than on the external weather conditions. Most of the buildings considered in this study were "thermally heavy" and external thermal losses were not a major part of the building heating and cooling requirements. Computer simulation study results using the AXCESS substantiated this conclusion for six model building configurations that were assumed as representative of the commercial sector buildings.

Because of the sensitivity to internal HVAC and lighting systems, building energy demand will be strongly affected by conservation methods and standards so that prediction of building energy usage in the 1985-1990 time frame is difficult. New standards such as ASHRAE 90-75 could cause a reduction in average building energy usage by a factor of 3 to 4, if implemented. Consequently, any study of the 1980-2000 period must consider a wide range of energy usage rates in projecting market demand.

Effects of changes in the energy usage to demand rate will have an important impact on the acceptability of STES in commercial buildings and must not be allowed to put the burden for backup spinning reserves on the utility. Instead, the STES needs onsite backup capability to maintain existing load profiles for the buildings.

Land utilization will always be a problem with solar systems and will favor use of non-tracking photovoltaic systems if their cost goals (\$0.50 per peak watt) are met. In addition, the small amount of usable land around commercial buildings will limit the STES capability to provide the buildings' energy needs to below 50% and will make efficient usage of energy storage systems difficult.

The concept evaluation studies have indicated that a single STES configuration suitable for all applications does not exist and that the local costs of electrical and fossil fuel energy play a dominant role in determining the most cost effective STES configuration for commercial buildings.

The land locked nature of commercial buildings limits the power capability of the STES and produces systems with poor utilization of energy storage systems. This, in turn, makes the systems using "on site" backup with fossil fuel or off-peak purchased power the most cost effective systems.

For locations with a high cost ratio of electrical-to-fossil energy, Rankine cycle systems should drive absorption cycle chillers with the PCS reject heat while locations with a low cost ratio favor use of the reject energy for heating only.

The operation and maintenance costs for these systems are two of the primary variables affecting the cost effectiveness of STES as are the future economic trends of fuel costs.

On-site backup systems for commercial building STES can solve the most probable utility interface problems satisfactorily.

8.2 RECOMMENDATIONS

Before wide spread application of STES for commercial buildings is realized, successful demonstration programs will be required. These demonstration programs should emphasize technology developments that will result in a cost effective system for the building configuration and site location. Simultaneously, it should be representative of typical applications which commercial building owners and operators can relate to their particular needs. The key technology items required are:

- 1) Operation and maintenance cost reduction
- 2) Brayton cycle collector STES development which could eliminate some of the current drawbacks with the organic Rankine cycle STES.
- 3) Component performance improvements
- 4) Component cost reduction

Further application analyses should be performed for applications below 200 kWe STES; however, the primary emphasis at present must be in experimental programs for demonstrating STES capabilities.

VOLUME 1 REFERENCES

1. M. W. Edenburn, N. R. Grandjean, "Energy System Simulation Computer Program — SOLSYS," SAND 75-0048, Sandia Laboratories, Albuquerque, NM (June 1975)
2. M. W. Edenburn, A. R. Case, L. H. Goldstein, "Computer Simulation of Photovoltaic Systems," 12th IEEE Photovoltaic Conference, 1976, Baton Rouge, LA, p 667
3. "TRNSYS, a Transient Simulation Program," Engineering Experiment Station Report 38, University of Wisconsin, Madison, Wisconsin (March 31, 1975)
4. "Solar Heating and Cooling of Buildings — Phase 0," NSF-RA-N-74-021E, General Electric Company, Contract Performed for the National Science Foundation, RANN (May 1974)
5. "Solar Heating and Cooling of Buildings — Phase 0," NSF-RA-N-74-023C, Westinghouse Electric Corporation, Baltimore, Maryland, Contract Performed for the National Science Foundation, RANN (May 1974)
6. "Solar Heating and Cooling of Buildings — Phase 0," NSF-RA-N-74-022C, TRW, Systems Group, Redondo Beach, California, Contract Performed for the National Science Foundation, RANN (May 1974)
7. "System Level Plan for Solar Heating and Cooling Commercial Buildings - National Solar Demonstration Program," InterTechnology Corporation, ERDA. Report C00-2688-76-7 (Contract E(11-1)2688) (May 1976)
8. "Directory of Shopping Centers in the United States and Canada," 17th Edition Volume XVII, The National Research Bureau, Inc. (1976)
9. "The Computer Users Subcommittee," ASHRAE Task Group on Energy Requirements for Heating and Cooling of Buildings Subcommittee Report, ASHRAE Transactions (1976) p 5
10. "ASHRAE Standard 90-75," ASHRAE (August 1975)
11. J. W. Doane et al, "The Cost of Energy From Utility-Owned Solar Electric System," Jet Propulsion Laboratory, Pasadena, California, Report JPL 5040-29, ERDA/JPL01012-76/3 (June 1976)
12. FPC R 88 Electric Bills for 1976 Federal Power Commission (FPC) Bureau of Power (1976)
13. J. C. Fisher and R. H. Pry, "A Simple Substitution Model of Technology Change," published in "Industrial Applications of Technology Forecasting," M. H. Citron and C. H. Ralph (ed.), John Wiley, New York (1971)

LIST OF SYMBOLS

$A_{a,0}$	Equation constants	T_{cnd}	Condenser temperature
$A_{a,1}$	Absorber area that is 1 unit water	T_{ci}	Collector inlet temperature
A_c	Collector area	T_{co}	Collector outlet temperature
A_v	Absorber area that addresses	T_e	Heat exchanger inlet temperature
η_e	Heat exchanger area	T_{er}	Heat exchanger outlet temperature
C_p	Specific heat	T_{cs}	Cold storage temperature
C_{TL}	Coefficient of heat generation from electrical lighting	T_c	Cooling tower temperature
CF	Cloud factor	T_{mn}	Monthly minimum air temperature
η_{PG}	Coefficient of process heat	T_{mx}	Monthly maximum air temperature
η_{HL}	Coefficient of heat loss	T_{SF}	Building internal temperature setpoint
CN	Cloud number	T_t	Turbine inlet temperature
CPL	Coefficient for humidity effects	U	Overall heat transfer coefficient
C_{VH}	Coefficient of heating ventilation	V_{sm}	Single media fluid volume
CVR	Coefficient of cooling ventilation	w	Fluid mass flow rate
COP	Coefficient of performance	W_c	Collector (heliostat) width
D	Diameter	W	Weight
dr	Decomposition rate of oil	X	E-W collector (heliostat) spacing
E-W	East-West	x	Quality
EL(t)	Fraction of maximum electrical as a function of time	Y	N-S collector (heliostat) spacing
F_o	Eigenfunction of matrix temperature	y	Distance coordinate
g_c	Gravitational constant	y_d	Submersion depth of diffuser
h	Solar hour angle	<u>GREEK</u>	
HL(t)	Fraction of maximum process heat as a function of time	α, α^2	Insolation constants
H_{DN}	Daily total direct normal insolation	α	Absorptivity
H_h	Daily total horizontal insolation		Solar cell temperature loss coefficient
I_c	Solar constant		Specific heat ratio
I_1, I_2, I_3	Insolation integrals	δ	Solar declination angle
I	Direct insolation		Void fraction of matrix material
I_{DN}	Direct normal insolation	ϵ	Emissivity
I_h	Total horizontal insolation	η	Efficiency
J	Mechanical equivalent of heat	η_{PCS}	Power conversion efficiency
k	Thermal conductivity	η_{ST}	Storage tank thermal efficiency
L	Length	η_{OC}	Optical efficiency
L_c	Collector (heliostat) length	ν	Viscosity
MTD	Mean temperature difference	ρ	Density
N-S	North-South	σ	Stefan-Boltzman constant
N_{Nu}	Nusselt number	τ	Transmissivity
n^*	Day of year	Δ	Incremental change
N_{Pr}	Prandtl number	<u>CAPITAL</u>	
N_{Re}	Reynolds number	O_a	Solar azimuth
OL(t)	Fraction of maximum occupancy load	O_E	Solar elevation angle
p	Wetted perimeter	γ_z	Zenith angle
PP	Percent possible sunshine	ϕ	Site latitude
P	Pressure	<u>ECONOMIC PARAMETERS</u>	
Q	Energy	AC	Annualized cost
q	Heat transfer rate	BECE	Breakeven cost of electricity
Q_{BS}	Battery electrical storage energy	CI	Capital investment
Q_{CS}	Cold thermal storage energy	CRF	Capital recovery factor
Q_{ED}	Electrical load demand	FCR	Annualized fixed charge rate
Q_{HD}	Heat load demand	g	General inflation
Q_{HS}	Hot thermal storage energy	g_f	Fuel escalation rate
$(q/A)_{ins}$	Insulation heat transfer loss rate	k	After tax cost of money
Q_{RD}	Cooling load demand	n	Power law exponent
Q_T	Maximum load constant for building	N	Number of years of system life
Q_{use}	Usable heat transfer rate	NO	Number of units
R	Solar distance ratio	OPM	Recurring cost - electricity cost
R_c	Cycle efficiency ratio	p	Years to start of operation
r	Reflectivity	RCC	Recurring cost
T	Collector tilt angle	R O I	Return on investment
$\bar{T}$	Average temperature	Y_{co}	First year of operation
t	Time	<u>Subscript</u>	
t_L	Building heating lag time	pv	Present value
T_{cell}	Temperature of solar cell	o	Original building
T_{ref}	Reference temperature of solar cell (nominally 28°C)	STES	Solar total energy system
T_a	Ambient temperature	max	Maximum