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SERI/TR-35-078
Volume II

August 1979

Conversion System Overview Assessment

Volume II
Solar-Wind Hybrid Systems

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Operated for the
U.S. Department of Energy
under Contract No. EG-77-C-01-4042

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Available from:
National Technical Information Service
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5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $4.50

NOTICE

SERI/TR-35-078
VOLUME II OF III
UC CATEGORY: UC 59B,60,62

CONVERSION SYSTEM OVERVIEW ASSESSMENT
VOLUME II SOLAR-WIND HYBRID SYSTEMS

AUGUST 1979

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FOREWORD

This report documents work done on Task 3503, "Conversion System Overview Assessment," contained in SERI's FY78 Annual Operating Plan, on the following technologies:

- solar thermoelectrics,
- solar-wind hybrid systems,
- ocean thermal energy conversion, and
- synthetic fuels derived with solar energy.

SERI Task 3503 is divided into the following subtasks: Wind (3503.01); OTEC (3503.02); Solar-Wind Hybrid (3503.03); Solar Thermoelectrics (3503.04); and Synthetic Fuels (3503.05). This report documents work done on all of these subtasks except 3503.02 on Ocean Thermal Energy Conversion, which will be covered in a separate report.

This report is divided into three parts. Part I deals with solar thermoelectrics and Part II with solar-wind hybrid systems. Part III covers the production of synthetic fuels utilizing solar thermal heat. Two appendices document reports by General Atomics of LaJolla, California, and Syncal Corporation of Sunnyvale, California, on costing of thermoelectric generators. Each candidate technology was surveyed by reviewing the literature, by contacting individuals and companies active in the field, and by attending conferences.

Two of the technologies--solar thermoelectrics and solar-wind hybrid systems--are new. Presented here is a preliminary study to determine the viability of these new technologies and examples of typical applications.

Neil H. Woodley by D.R.Z.
Neil Woodley, Branch Chief
Systems Analysis

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

Kenell J. Touryan
for Dr. J. C. Grosskreutz
Director for Technology Development

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SUMMARY

The three volumes of this report cover three distinct areas of solar energy research: solar thermoelectrics, solar-wind hybrid systems, and synthetic fuels derived with solar thermal energy. Volume I represents the assessment, done at SERI, of thermoelectrics for solar energy conversion. It is concluded that there is significant potential for solar thermoelectrics in solar technologies where collector costs are low; e.g., Ocean Thermal Energy Conversion (OTEC) and solar ponds. It is expected that thermoelectrics also may have potential in other renewable energy source applications such as geothermal energy and waste heat utilization. Reports of two studies by manufacturers assessing the cost of thermoelectric generators in large scale production are included in the appendix, and several new concepts of solar thermoelectric systems are presented. Volume II discusses solar-wind hybrid systems. It is shown that there are large areas in the United States where solar and wind resources are comparable in magnitude and there are diurnal and seasonal complementarities which offer the potential for cost-effective hybrid systems. There are also distinct engineering features of the two conversion technologies. Electric power generation from wind is straightforward and cost-effective, whereas solar thermal conversion to generate heat is more cost-effective than to generate electricity. Examples of hybrid systems utilizing these features in total energy applications are presented. Volume III deals with the conversion of synthetic fuels with solar thermal heat. The method is a hybrid combination of solar energy with either coal or biomass. A preliminary assessment of this technology is made by calculating the cost of fuel produced as a function of the cost of coal and biomass. It is shown that within the projected ranges of coal, biomass, and solar thermal costs, there are conditions when solar synthetic fuels with solar thermal heat will become cost-competitive.

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SECTION 1.0

INTRODUCTION

Two rapidly developing solar technologies, solar thermal power systems (STPS) and wind energy conversion systems (WECS), have been under extensive research and development in recent years. Several types of solar thermal collectors have been developed which produce a wide range of temperatures. Applications range from domestic hot water heating to central station electric power generation. Similarly, different wind machines have been developed ranging from small machines for domestic applications to large machines producing hundreds of kilowatts for electric power generation in utility applications. Attention has been given to the selection of good sites for STPS in sunny regions and WECS in windy regions of the country. Both solar and wind resources are intermittent and depend on a reliable, expensive storage system. There are indications, however, that the two power systems can complement each other on both short- and long-term bases. In many areas of the country solar and wind resources are of comparable magnitudes but at different times, with wind peaking in the winter when the daily energy from the sun is minimal, and at night. Further, conversion from wind to electricity is quite straightforward and relatively cost-effective, whereas solar thermal systems are more economical for generating heat. In total energy applications where both electric and heat energy are required, solar-wind hybrid systems may be more attractive than wind or solar systems alone.

In the following discussion the complementarity of resources is established by studying solar and wind data at different sites. Example solar-wind hybrid systems and applications are discussed.

SECTION 2.0

COMPLEMENTARITY OF WIND AND SOLAR RESOURCES

2.1 METHODOLOGY

2.1.1 Selection of Data

In order to draw valid conclusions about a site, it is important that the resource data used are truly representative of the site. The sites examined for this study were selected from SOLMET cities for which a typical meteorological year has been computed. The statistical correlation of wind power and solar thermal power availability is examined for ten locations: Bismark, North Dakota; Dodge City, Kansas; Albuquerque, New Mexico; Santa Maria, California; Lake Charles, Louisiana; Madison, Wisconsin; El Paso, Texas; Fort Worth, Texas; Boston, Massachusetts; and Seattle, Washington. At the time of this writing, the typical meteorological years developed by Sandia Laboratories were not available. Instead the "Hedstrom year" (determined from multiyear simulations based on the fraction of load supplied by solar energy in a liquid flat plate residential heating system) developed by James Hedstrom of Los Alamos Scientific Laboratory was used. It was assumed that these years were also typical years for wind speed. Figures 2-1 through 2-10 compare data with long-term averages.

2.1.2 Power Availability

To compare the wind and solar resources, they must be converted to similar units of power. The hourly solar and wind inputs were converted to kW/m^2. The solar data used were direct normal solar radiation from the SOLMET data base. Hourly direct normals were estimated by Randall from standard year corrected data [1].

Since the wind speed was recorded at a different height at each location the wind data were extrapolated to a height of 150 feet by the 1/7 power rule [2] (see Table 2-1). The WECS power output was assumed to be a function of wind velocity, air density (Table 2-1), and swept area of the wind turbine. A swept area (1 m^2) was assumed to compare with a solar energy insolation density in kW/m^2. The wind power output per unit area is calculated hourly as follows:

$$P = 1/2 \rho A V^3 \tag{2.1}$$

where:

P = power output (kW)

ρ = air density (kg/m^3)

A = swept air of turbine (one m^2)

V = velocity of wind at 45 m hub height (m/s)

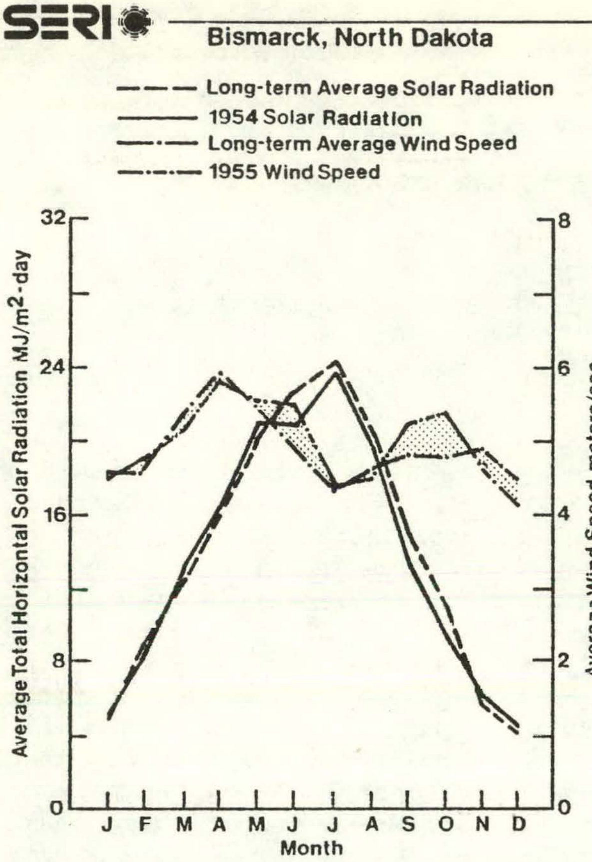
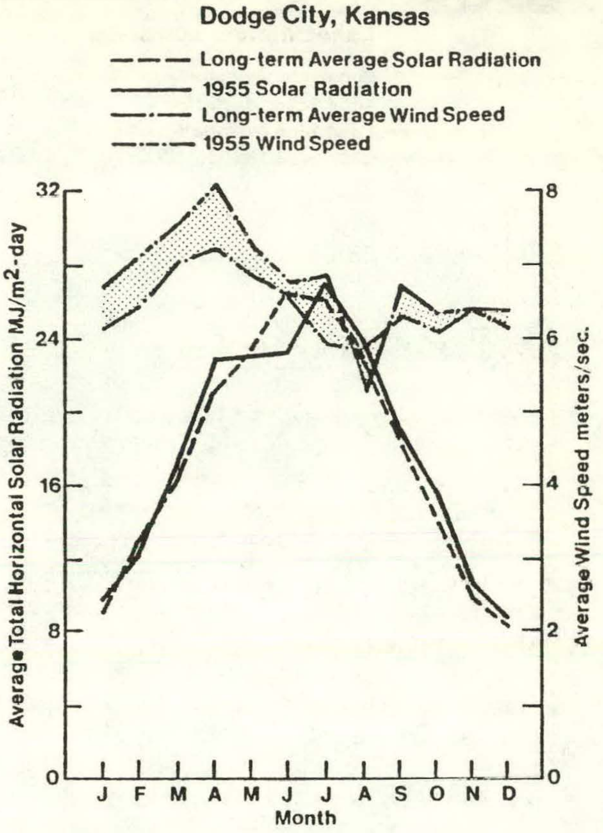


Figure 2-1



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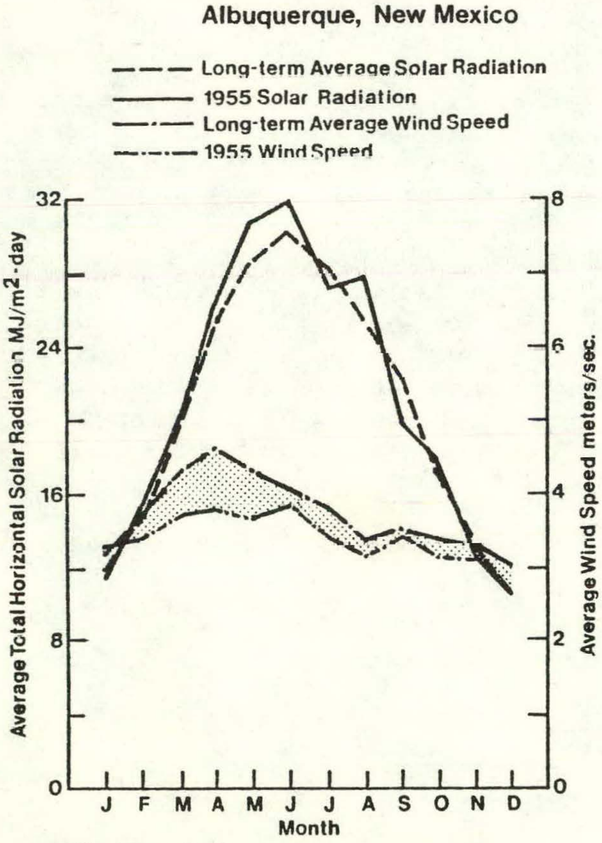

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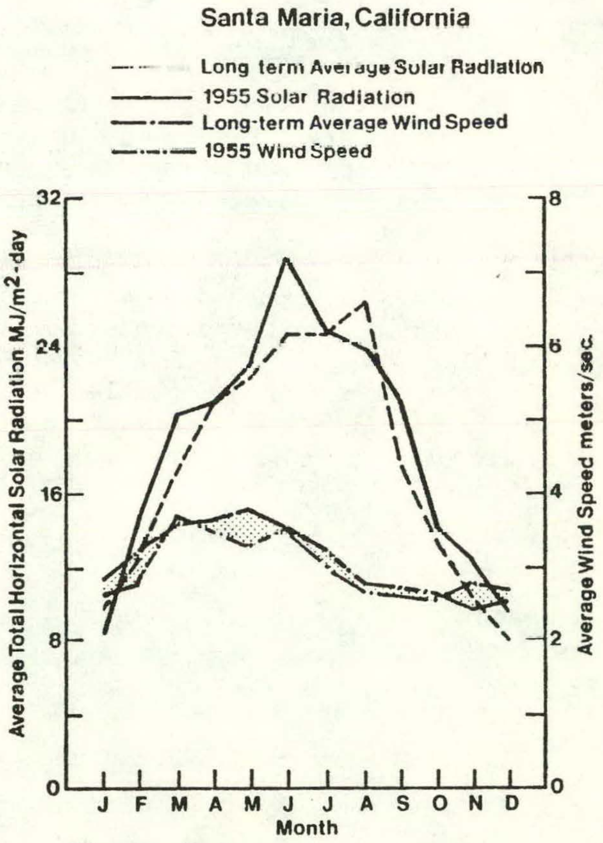
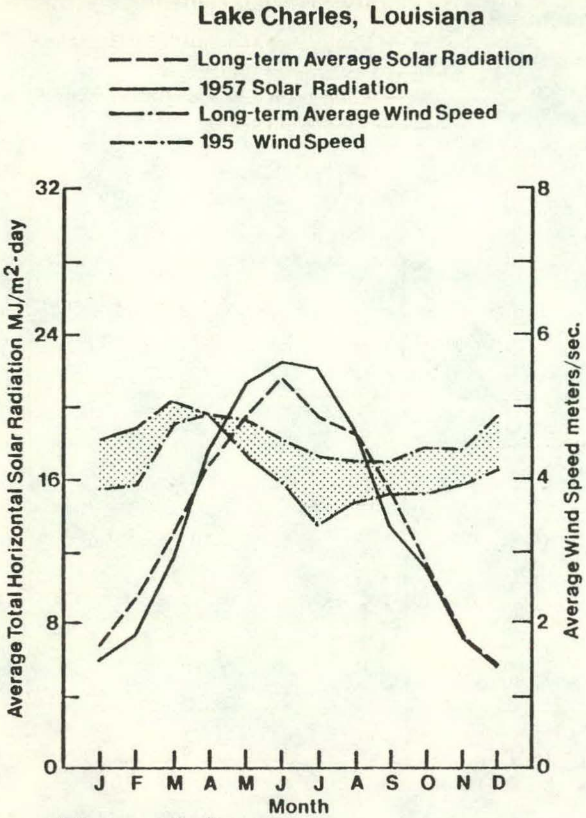


Figure 2-4

LONG-TERM AVERAGE SOLAR RADIATION AND WIND SPEED FOR SELECTED SOLMET CITIES



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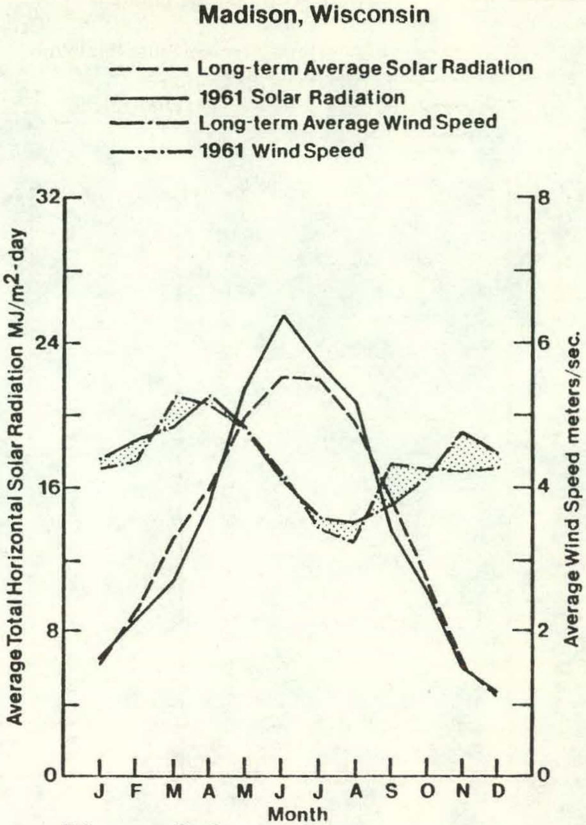

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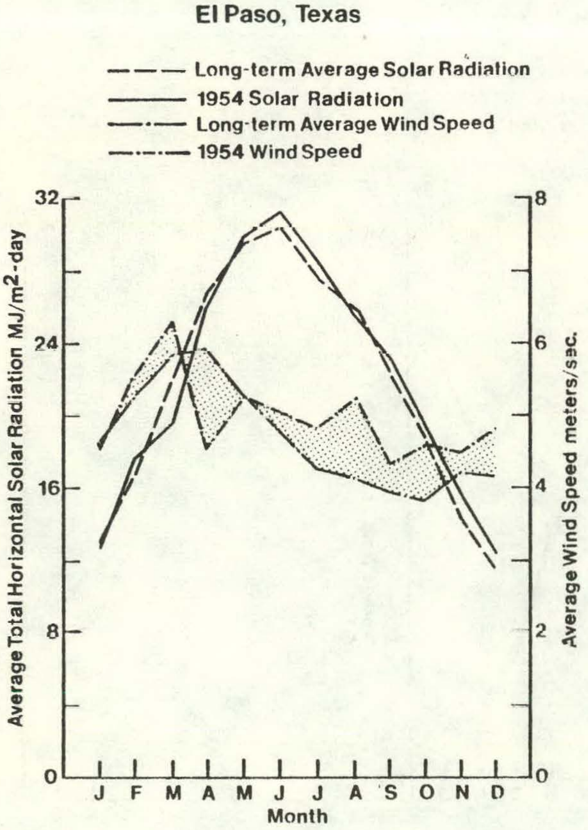

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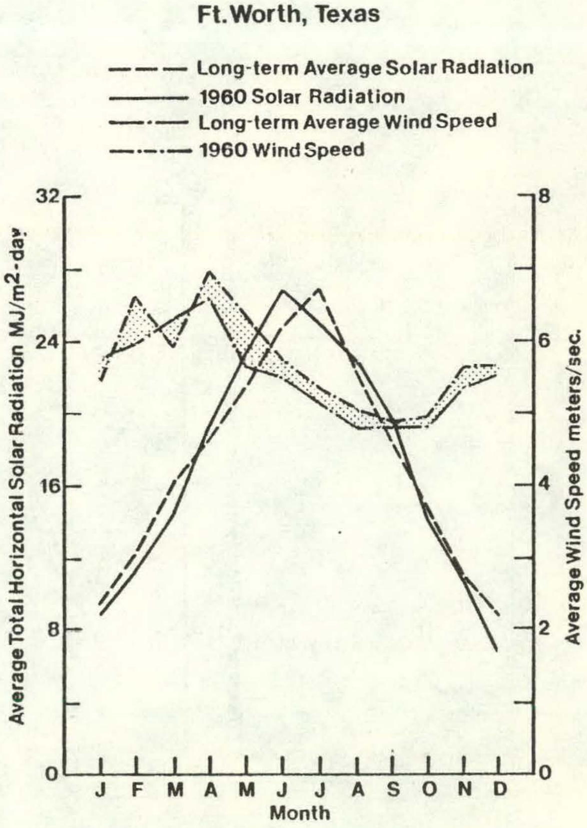


Figure 2-8

LONG-TERM AVERAGE SOLAR RADIATION AND WIND SPEED FOR SELECTED SOLMET CITIES

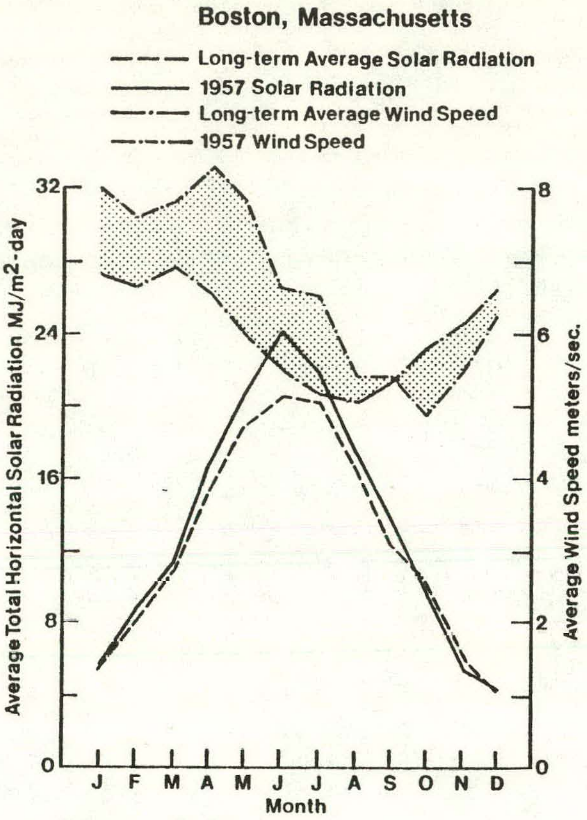


Figure 2-9

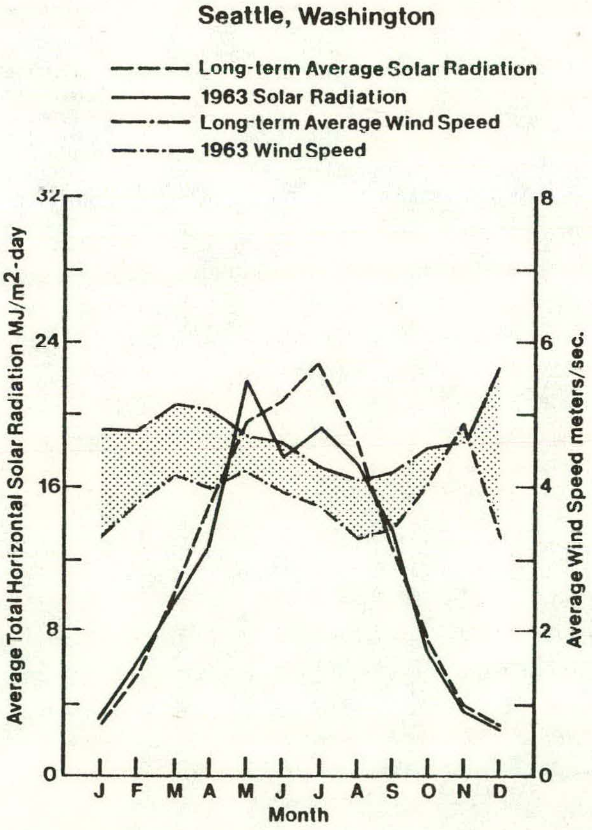


Figure 2-10

LONG-TERM AVERAGE SOLAR RADIATION AND WIND SPEED FOR SELECTED SOLMET CITIES

Table 2-1. **WIND POWER HEIGHT EXTRAPOLATION**

Location	Height Recorded (ft)	Height Recorded (m)	Wind Speed Extrapolation Factor[a]	Air Density (kg/m^3)
Bismarck, N. Dak.	43	13	1.195	1.16
Dodge City, Kans.	58	18	1.145	1.13
Albuquerque, N. Mex.	33	10	1.241	1.04
Santa Maria, Calif.	54	16	1.157	1.21
Lake Charles, La.	15	5	1.39	1.22
Madison, Wis.	21	6	1.32	1.19
El Paso, Tex.	20	6	1.33	1.09
Ft. Worth, Tex.	62	7	1.32	1.21
Boston, Mass.	62	19	1.13	1.22
Seattle, Wash.	20	6	1.33	1.21

[a] 1/7 rule

2.1.3 Complementarity of Power Outputs

The complementarity of power available was calculated in reference to hourly, daily, and monthly average outputs. This complementarity factor is similar to the statistical correlation between two random variables [3]. The general equation was:

$$F_c = \frac{\sum_{i=1}^{n} (s_i - \bar{s})(w_i - \bar{w})}{\left[\sum_{i=1}^{n} (s_i - \bar{s})^2 \sum_{i=1}^{n} (w_i - \bar{w})^2\right]^{1/2}} \qquad (2.2)$$

where:

F_c = complementarity factor, representing quantitatively the complementarity of the two sources

s_i = solar power for time interval i

s = mean solar power

w_i = wind power for time interval i

w = mean wind power

n = number of intervals (e.g., hours or days per month).

This complementarity factor was studied over three time periods. First, hourly wind and solar outputs, converted to kW/m^2, were compared for each month. In both cases, the monthly mean was determined by summing hourly outputs over a full month, then dividing by hours per month to produce a monthly average hourly output in kW/m^2. Daily totals were compared with monthly averages to assess the daily complementarity factor. Finally, the complementarity factor for the monthly averages was calculated.

The use of these three different time periods enables a more complete evaluation of the complementarity of the two outputs. For optimum hybrid utilization, a factor of -1 is desired. As the factor approaches 1, available solar and wind power are approaching being in phase and the two outputs are not complementary.

2.1.4 Estimation of Power Output

To relate these results to actual power systems, simplified system models were developed to determine wind, solar, and hybrid power outputs per square metre for a chosen site. Solar-to-electric conversion efficiency of 19% from the available direct normal insolation is assumed for the solar power plant [4].

A hypothetical wind turbine is assumed to produce a rated output of 87 W/m^2 at a wind speed of 18 miles per hour (mph). The turbine cuts in at 8 mph, and power output increases with wind speed to 18 mph. Above 18 mph, the output of the turbine is a constant 87 W/m^2 until wind speed exceeds 40 mph, in which case the machine cuts off.

Schematic diagrams of the wind and solar systems are shown in Figure 2-11. The output of the wind turbine is determined as follows. A mechanical output, P_m, is calculated assuming a constant C_p of 0.38 and a mechanical transmission efficiency η_m of 0.95. The result is divided by the rated output and an electrical efficiency, η_e, is determined as a function of this ratio [5]. The electrical power output is $(\eta_e \times \eta_m) \times P_m$. No power production results if the wind speed is not within the turbine's range of operation (8 mph-40 mph).

A hybrid system having equal capacities of solar and wind was studied and its output calculated as follows:

$$HYB = S/2 + W/2 \qquad (2.3)$$

where:

HYB = hourly output of hybrid system, kW/m^2

S = hourly output of solar system, kW/m^2

W = hourly output of wind system, kW/m^2

No attempt was made to optimize the hybrid design to each site with respect to the ratio of solar/wind installed capacity. Detailed site-specific studies obviously would be required to optimize the hybrid design.

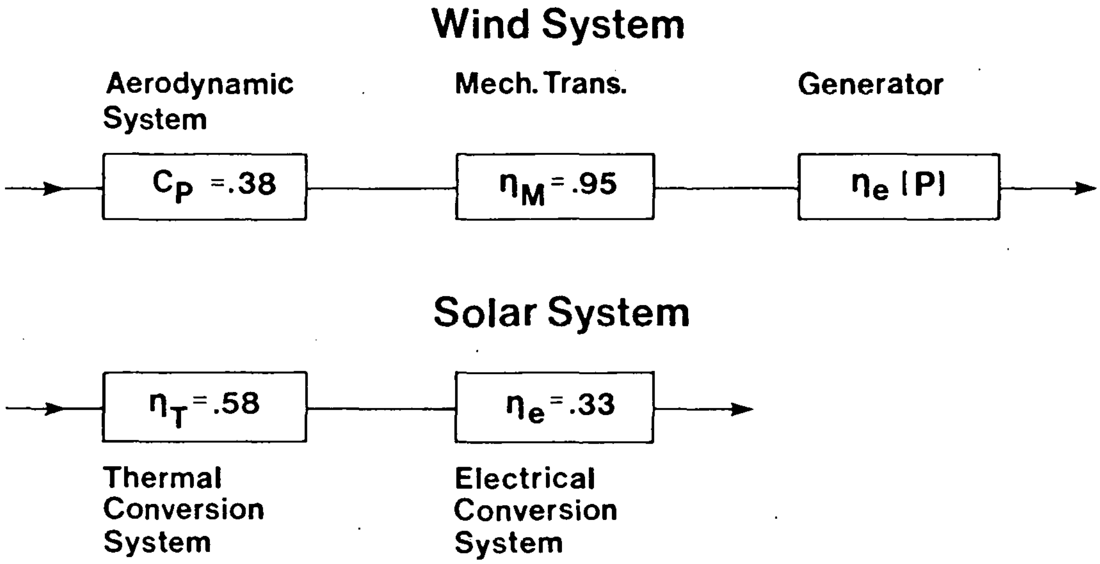


Figure 2-11. SCHEMATIC DIAGRAMS OF WIND AND SOLAR SYSTEMS

2.2 RESULTS

2.2.1 Complementarity

The solar and wind power available for the ten locations are displayed in Figures 2-12 through 2-21. The results of the complementarity factor analysis are given in Figures 2-22 through 2-31. In general, the daily outputs are more complementary than the hourly outputs. There is also a trend toward a better negative complementarity factor in the winter months. Of the ten locations, only Santa Maria, Calif.; Boston, Mass.; and Lake Charles, La., indicate poor complementarity.

A good daily complementarity is evidenced in the Bismark, N.D., data. Bismark was subjected to a more detailed analysis of resultant hybrid system power output variations. It is assumed that demonstrating that the power output from a hybrid system is greater (with a higher system capacity factor*) than that for either a wind or solar thermal system alone, is sufficient to demonstrate that the hybrid system is a more desirable source of power.

2.2.2 Power Output of Hybrid System

To determine how system output varied on an hourly and daily basis, a histogram of hourly and daily system outputs was completed. The results of this analysis are given in Tables 2-2 and 2-3. These tables show how much power can be supplied 100%, 90%, 80%, etc., of the entire year, both on a daily basis (Table 2-2) and on an hourly basis (Table 2-3).

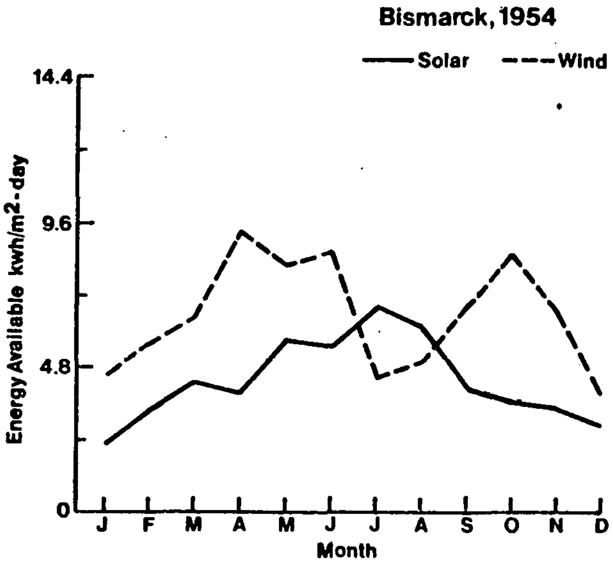
The most significant result is that the minimum daily output of the hybrid system during the whole year is 63 Wh/m^2-day. Thus, 1 m^2 of a hybrid system (50% solar, 50% wind by aperture) could meet this load. In comparison, the minimum daily output of the WECS was 0 Wh/m^2-day. The minimum daily output for the STPS was 0.2 Wh/m^2-day.

2.3 CONCLUSIONS

From the comparisons of wind and solar energy resources, significant complementarity is shown for all sites except Santa Maria, Boston, and Lake Charles. Generally the daily complementarities are quite good, although the complementarity factors do vary from site to site. Of the ten sites, Bismark and El Paso showed the greatest complementarity.

When the data for Bismark are converted to power outputs, a hybrid system is demonstrated to be able to meet a signficant daily load. Although only a thorough analysis using detailed system models can verify these power output results, hybrid systems do appear to deserve more study.

$$^*\text{capacity factor} = \frac{\text{plant output over period, kWh}}{\text{rated capacity x period, kWh}}$$



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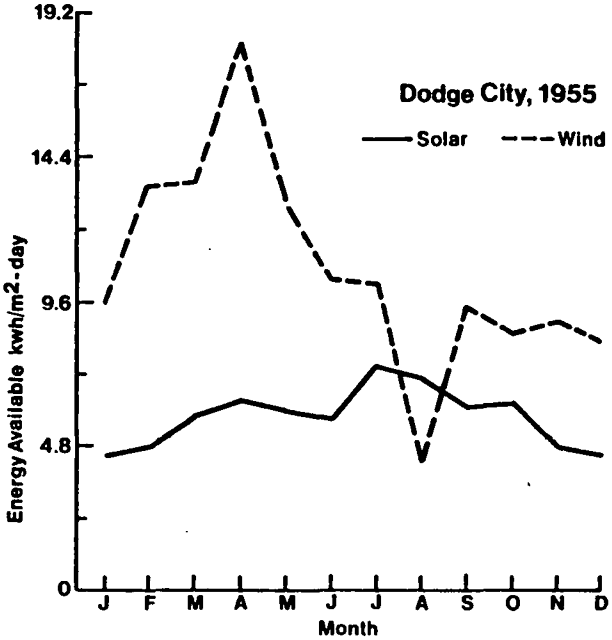

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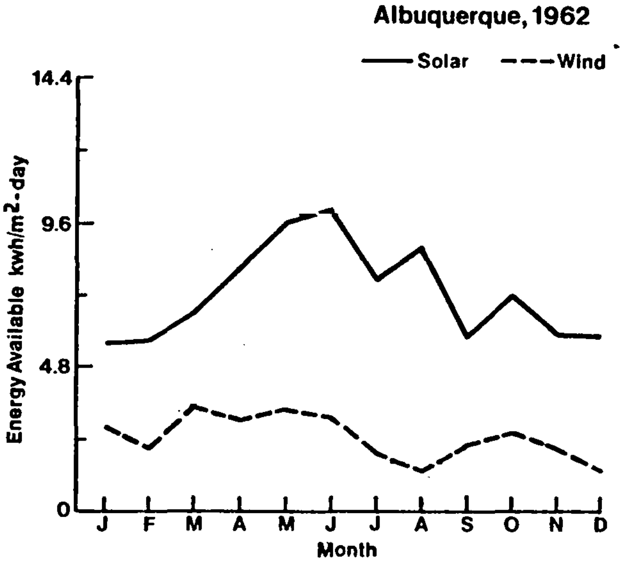

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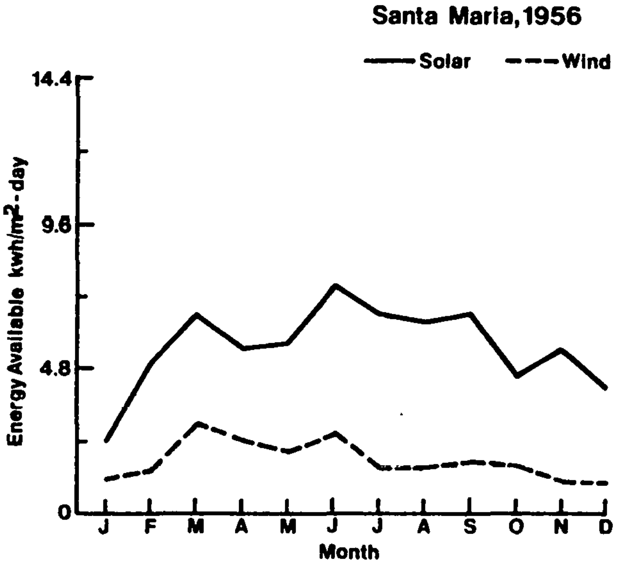
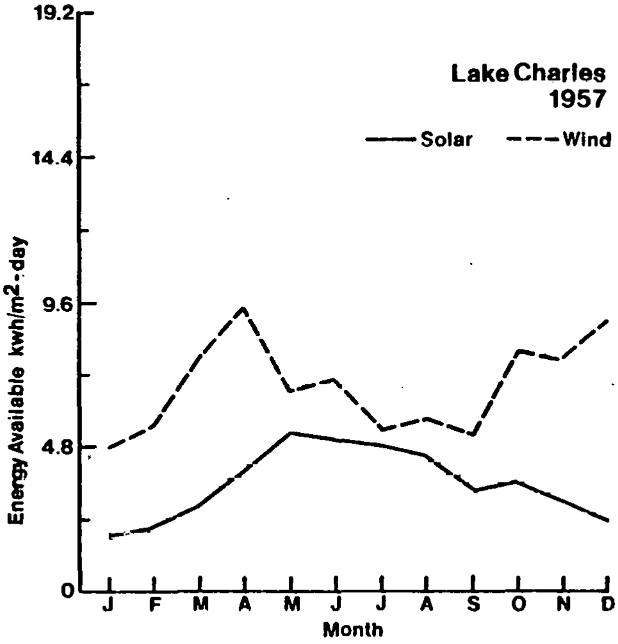


Figure 2-15

SOLAR AND WIND ENERGY AVAILABLE FOR SELECTED SOLMET CITIES



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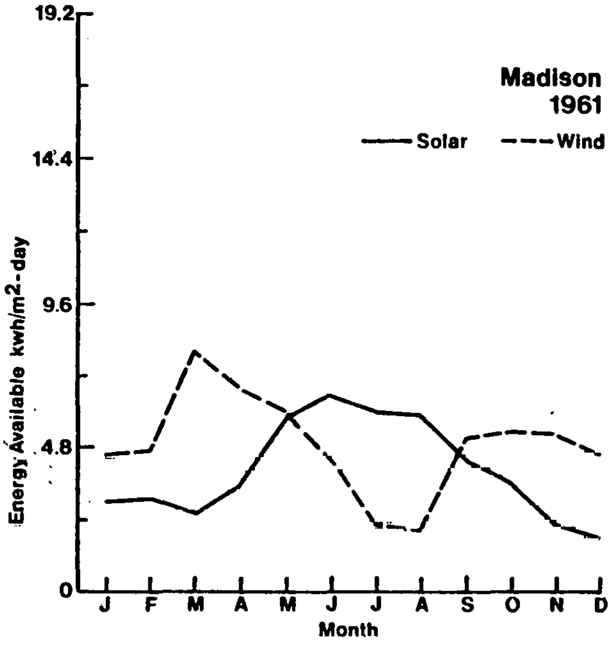

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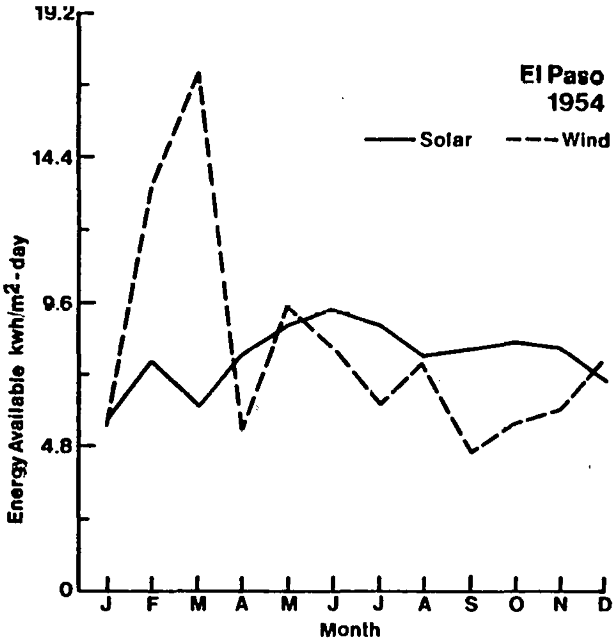

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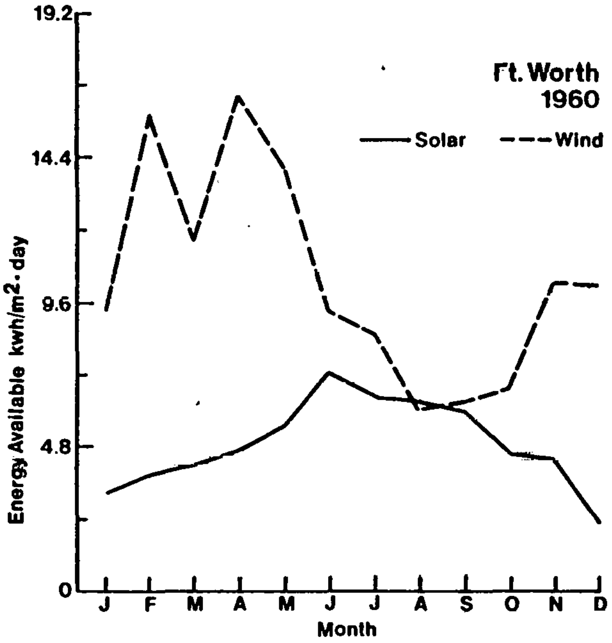

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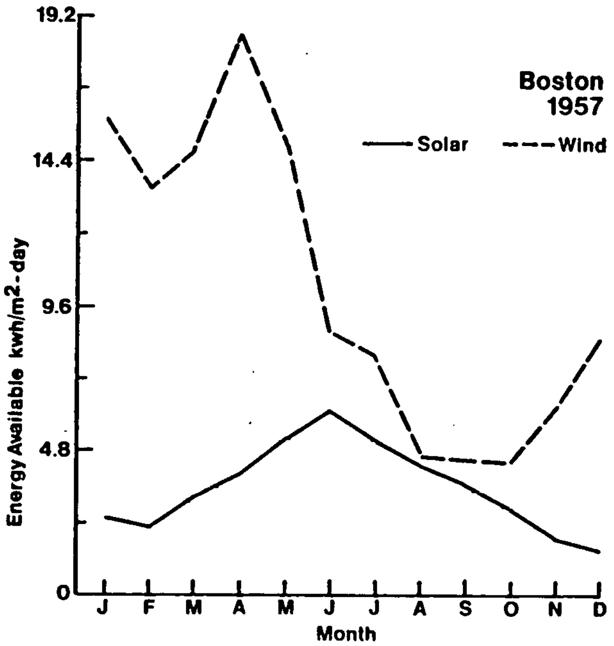
SOLAR AND WIND ENERGY AVAILABLE FOR SELECTED SOLMET CITIES



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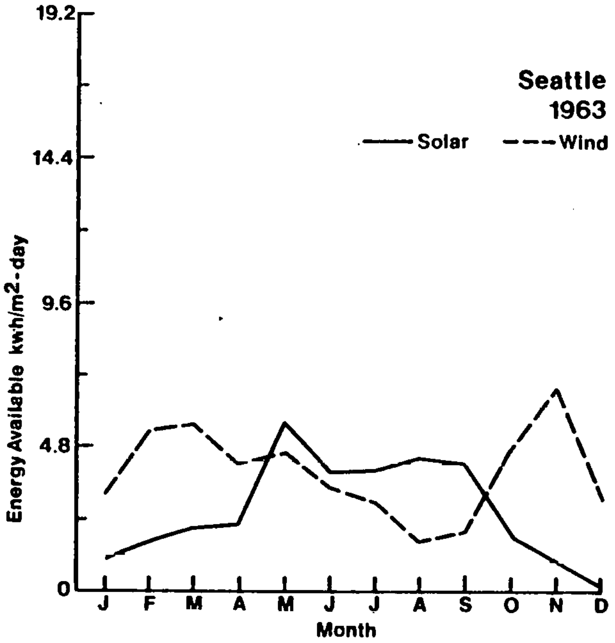

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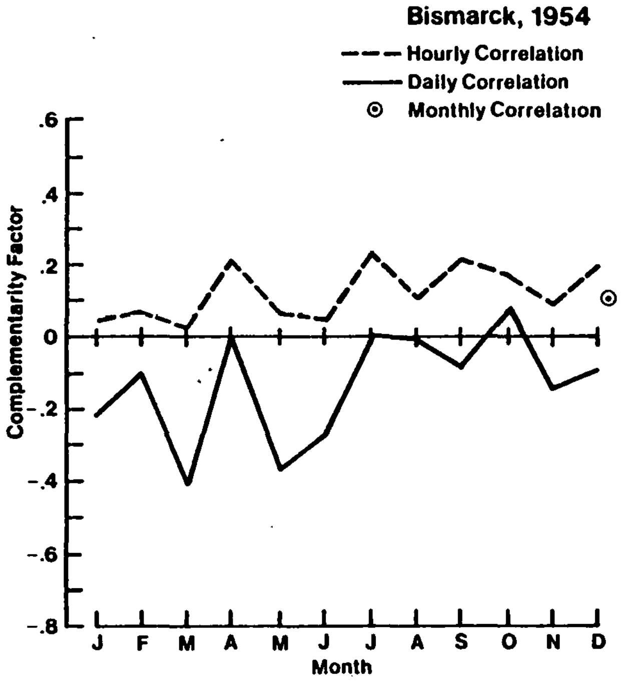
SOLAR AND WIND ENERGY AVAILABLE FOR SELECTED SOLMET CITIES



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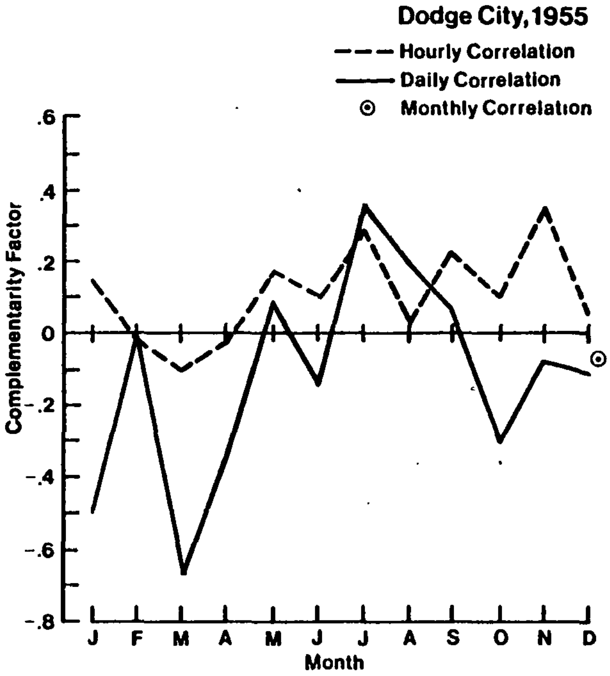

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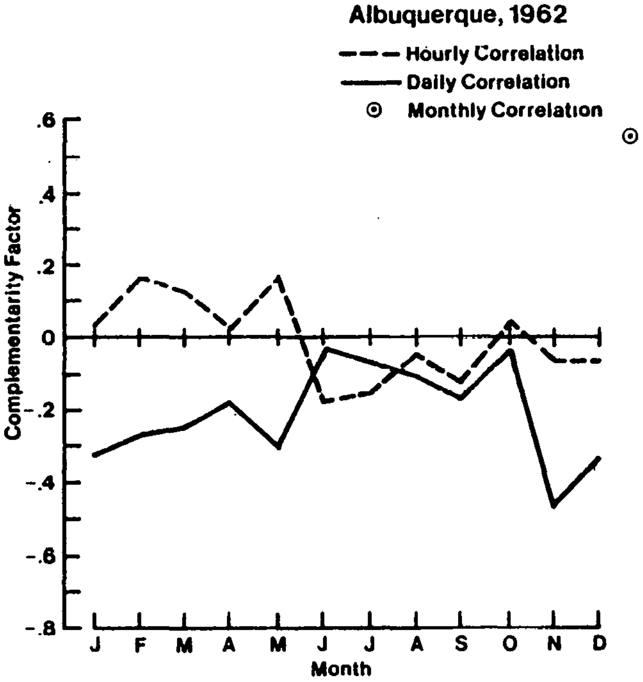

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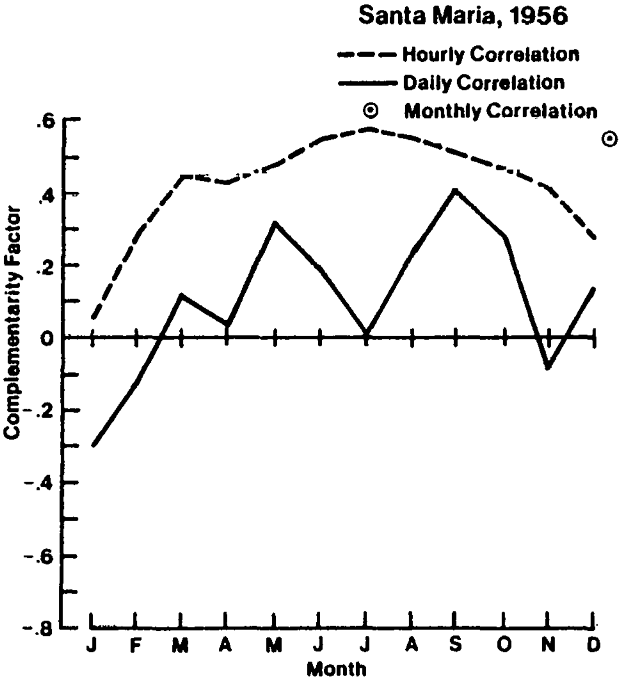
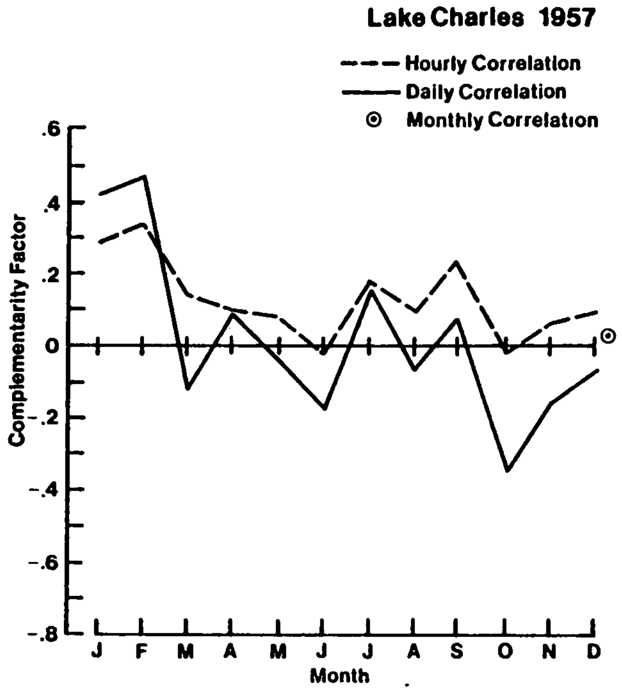


Figure 2-25

MONTHLY, DAILY, AND HOURLY COMPLEMENTARITY CORRELATION FOR SELECTED SOLMET CITIES



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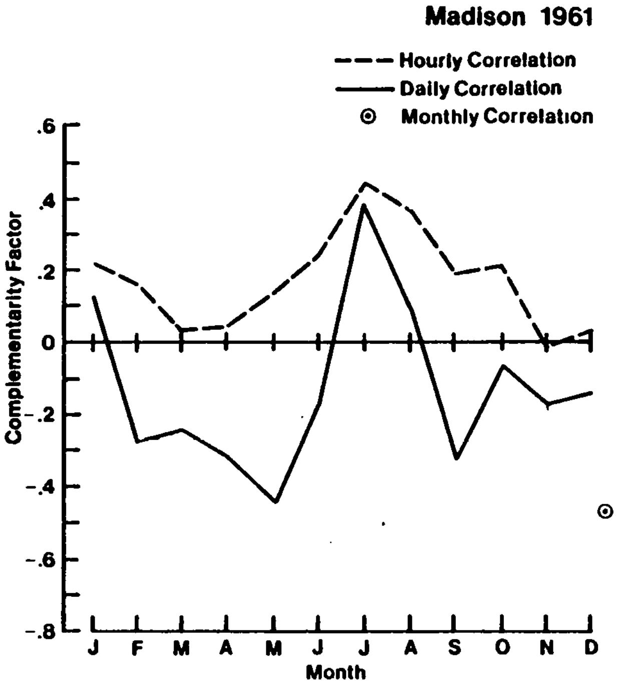

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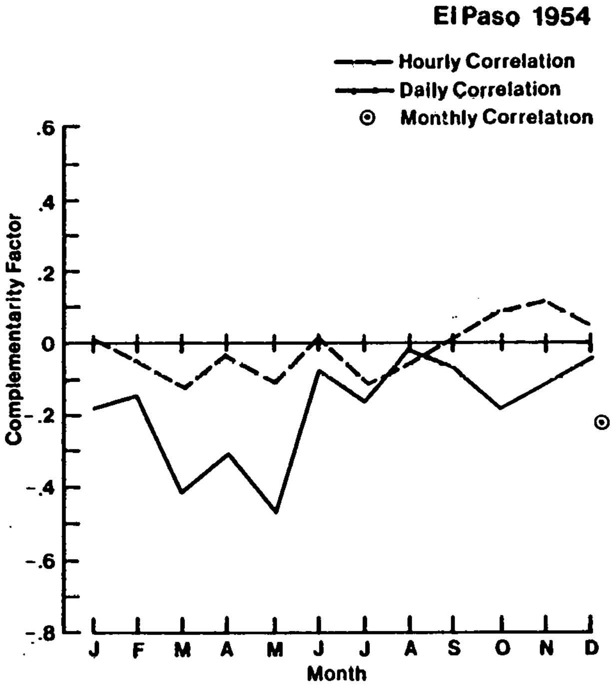

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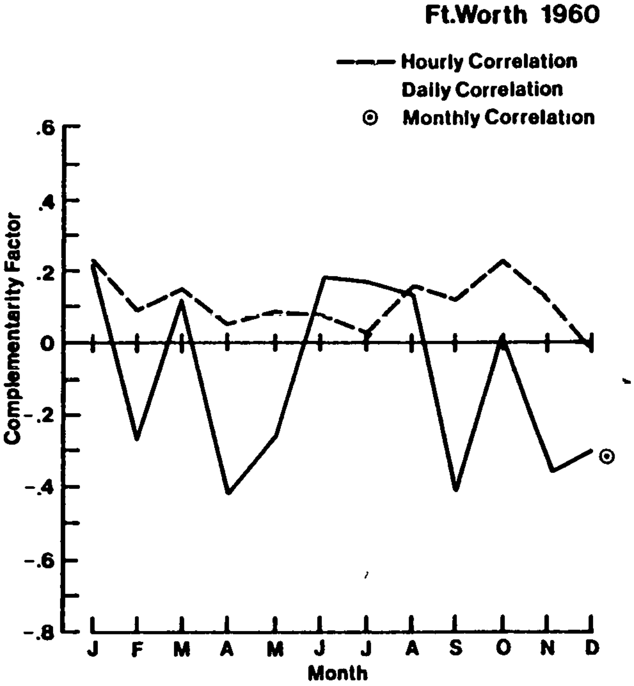
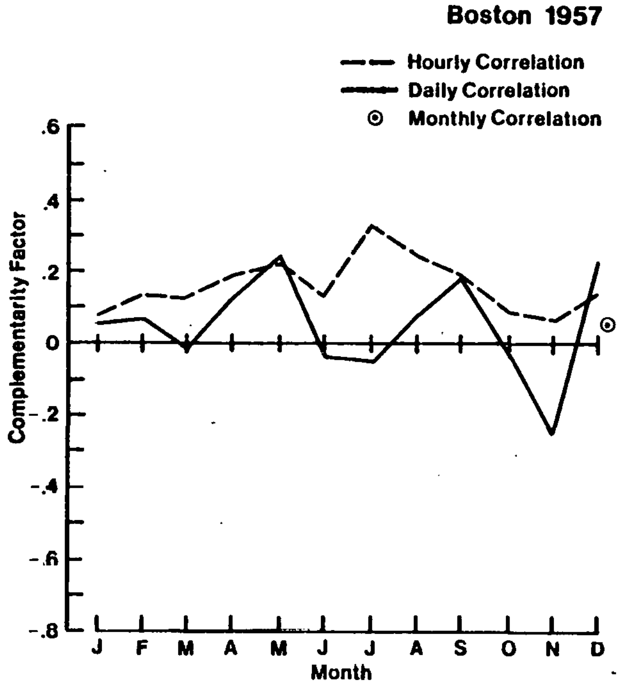


Figure 2-29

MONTHLY, DAILY, AND HOURLY COMPLEMENTARITY CORRELATION FOR SELECTED SOLMET CITIES



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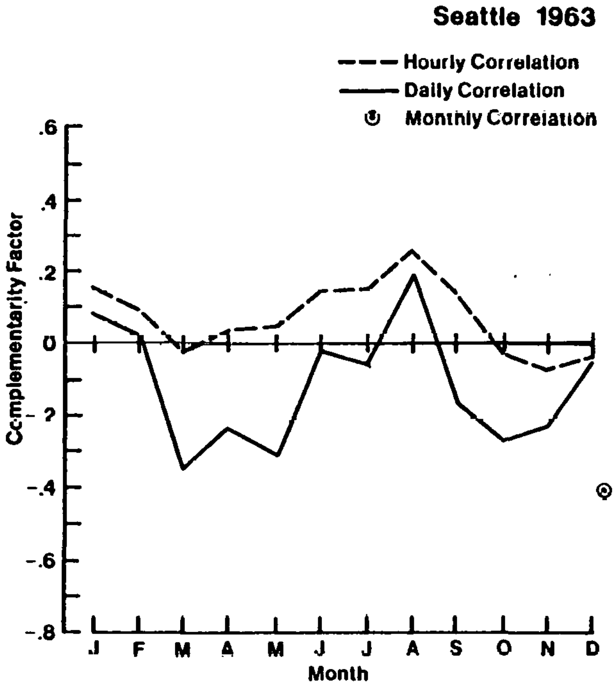

Figure 2-31

MONTHLY, DAILY, AND HOURLY COMPLEMENTARITY CORRELATION FOR SELECTED SOLMET CITIES

Table 2-2. DAILY SYSTEM OUTPUT VARIATION FOR BISMARK, N.D.: LOAD WHICH CAN BE SUPPLIED

% of Time Load is Supplied	Load Supplied (W/m^2) Wind	Solar	Hybrid
100%	0	0	63
90%	240	50	400
80%	430	250	600

Table 2-3. HOURLY SYSTEM OUTPUT VARIATION FOR BISMARK, N.D.: LOAD WHICH CAN BE SUPPLIED

% of Time Load is Supplied	Load Supplied (W/m^2) Wind	Solar	Hybrid
80%	0	0	0.0
70%	0	0	7.5
60%	14	0	14.0
50%	23	0	32.0

SECTION 3.0

SOLAR-WIND HYBRID SYSTEM IN INDUSTRIAL APPLICATIONS

3.1 SYSTEM DESCRIPTION

A computer simulation was undertaken to demonstrate the potential of solar-wind hybrid systems for industrial applications. The energy scheme incorporated a nonconvecting, salt-gradient pond for solar collection and low temperature thermal storage with a wind turbine to provide electrical energy. Any auxiliary energy was assumed to be provided by the electric utility grid.

The study examined two industrial applications, a meat packing plant and a concrete-block manufacturing plant. The load requirements and hybrid system sizes of these facilities are listed in Table 3-1. This information was taken from the McDonnell Douglas final report on industrial solar total energy systems [6]. The energy requirements of each plant are dominated by the low-temperature process heat loads, with the electrical demands occurring only during production hours.

The hybrid system was designed to supply both process heat and electricity. Flow-graphs of the two energy distribution systems are given in Figures 3-1 and 3-2. The concrete block manufacturing process uses electricity for 8 hours during the day and saturated steam for 12 hours at night. The meat packing operations require electricity 16 hours a day and a large amount of hot water during production hours.

The solar pond and wind turbine ratings were estimated to provide the process heating requirements and peak electrical demand respectively. The solar pond operates as a heater/preheater and as an elevated-temperature heat source for an electrical industrial process heat pump.

The electricity from the wind turbine could be used to meet any of the three loads: the plant electrical demand, operation of the heat pump, and resistive heating in the solar pond. The distribution of this electricity is determined by the availability of wind energy, the plant loads, the amount of process heat storage, and the temperature of the solar pond thermal storage. Ideally, the wind turbine would supply the electrical demand during production hours and operate the heat pump to provide the process heat requirements. Surplus electric energy from the WECS was assumed to be dumped into the solar pond thermal storage by electric resistance heating.

3.2 SYSTEM PERFORMANCE

Operation of each plant was simulated for one year. The hourly standard weather data for Fort Worth, Tex., provided the wind, temperature, and insolation data. The solar pond was described by the lumped parameter finite difference model discussed in Part I.

The average monthly plant performance results are plotted in Figures 3-3 and 3-4. The graphs show that the solar pond can provide the process load on a

Table 3-1. LOAD REQUIREMENTS AND HYBRID SYSTEM SIZE FOR TWO INDUSTRIAL APPLICATIONS

CONCRETE BLOCK
Energy Demand:
Electrical: 490 kW
8 hr/day, 5 days/week
Process heat: Steam 0.923 kg/s (1.72×10^5 Pa)
12 hr/day at night, 5 days/week

HYBRID SYSTEM:
Wind Turbine: 528 kW at 8.9 m/s
Solar Pond:
Area: 23,000 m^2
Depth: 2.3 m
Depth of convection storage layer: 1 m

MEAT PACKING PLANT
Energy Demand:
Electrical:
Production Hours: 302 kW
16 hr/day, 5 days/week
Nonproduction Hours: 97.6 kW
Process Heat: Hot water: 5.07 kg/s, 82°C
16 hr/day, 5 days/week

HYBRID SYSTEM:
Wind Turbine: 301 kW at 8.9 m/s
Solar Pond:
Area: 18,000 m^2
Depth: 2.3 m
Depth of convection layer: 1 m

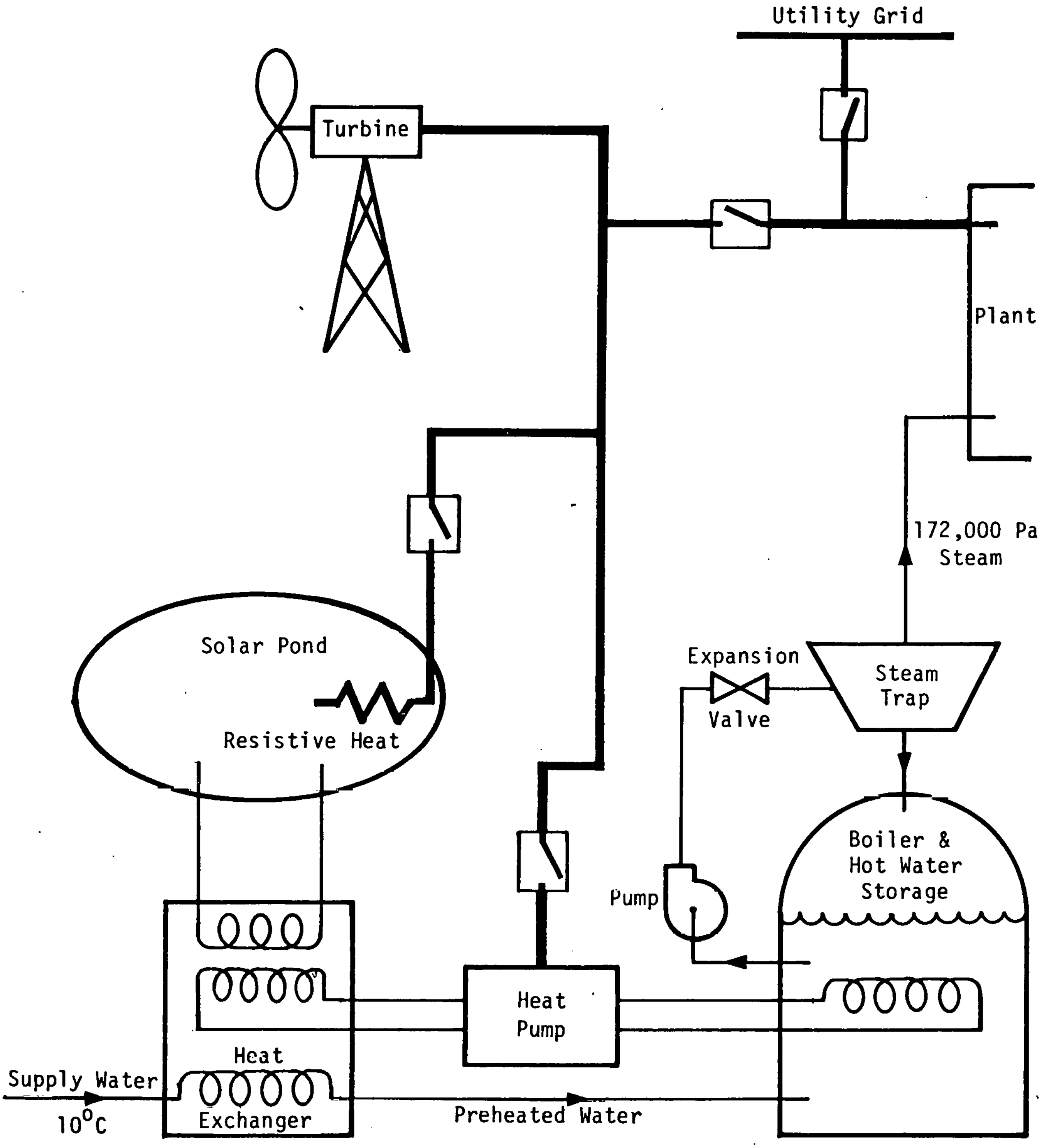

Figure 3-1. CONCRETE BLOCK MANUFACTURING PLANT IN FORT WORTH, TX

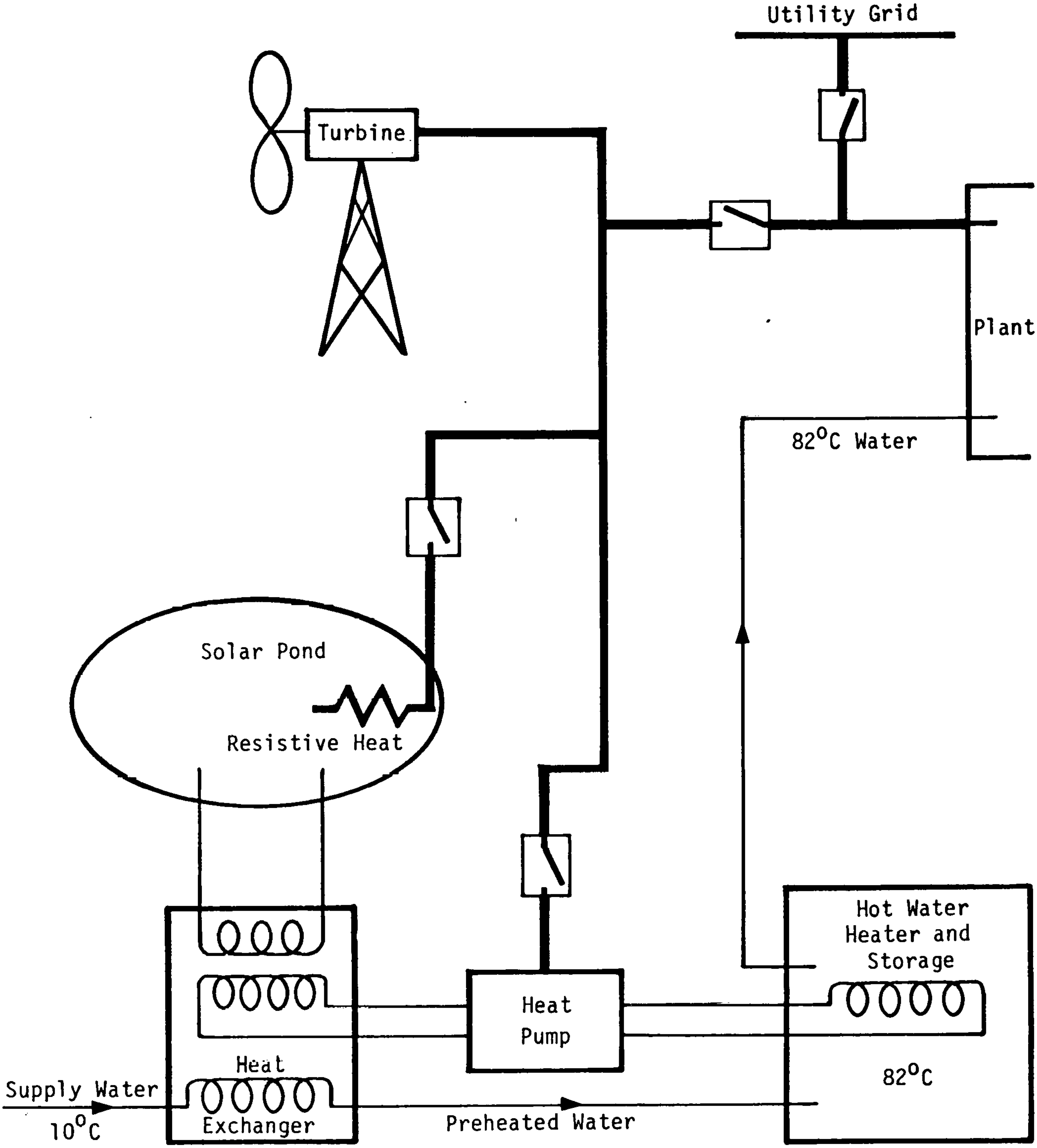

Figure 3-2. MEAT PACKING PLANT IN FORT WORTH, TX

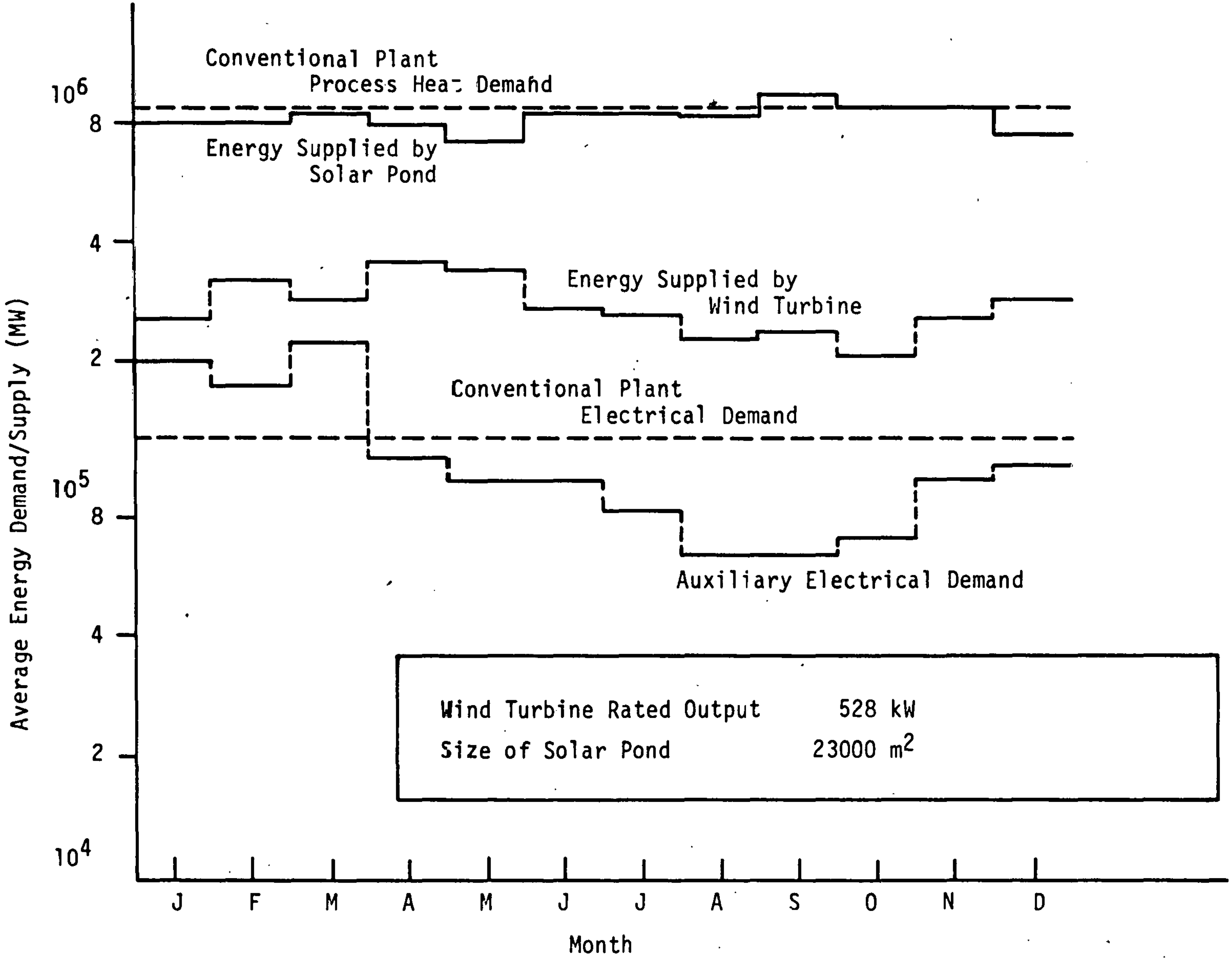

Figure 3-3. MONTHLY AVERAGE PERFORMANCE OF THE HYBRID CONCRETE BLOCK PLANT

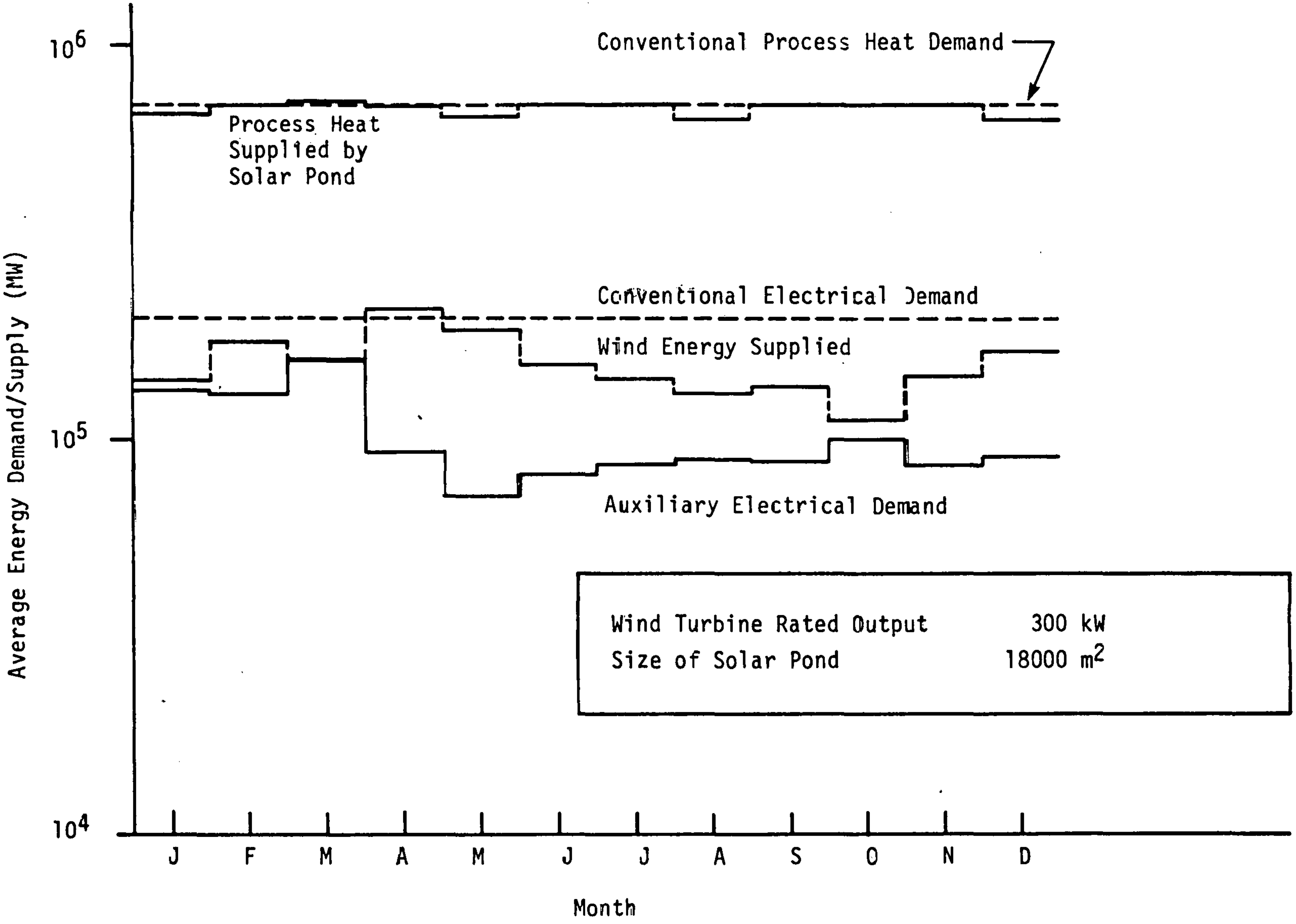

Figure 3-4. MONTHLY AVERAGE PERFORMANCE OF THE MEAT PACKING PLANT

Table 3-2. PRELIMINARY HYBRID SYSTEM COST ASSESSMENT

	Cost (dollars)	
Cost Factors	Case 1	Case 2
CONCRETE BLOCK PLANT		
Conventional Design		
Annual electricity cost		
at 6¢/kWh	61,500	
at 4¢/kWh		41,000
Annual fuel cost		
at 2¢/kWh	152,600	
at 1¢/kWh		76,300
Total Annual Cost	214,100	117,300
Hybrid Design		
Wind turbine ($500/kW)	264,000	264,000
Solar pond		
at $\$10/m^2$	230,000	
at $\$20/m^2$		460,000
Capital cost	494,000	724,000
Fixed charge rate (at 18%)	88,920	130,000
Annual O&M costs	10,000	10,000
Annual electricity costs	54,750	43,800
Total Annual Cost	153,670	184,100
MEAT PACKING PLANT		
Conventional Design		
Annual electricity cost	105,650	70,430
Annual fuel cost	127,200	63,600
Total Annual Cost	232,850	134,030
Hybrid Design		
Wind turbine	150,500	150,500
Solar pond	180,000	360,000
Total capital costs	330,500	510,500
Annual fixed charge rate (at 18%)	59,490	91,890
Annual O&M Costs	8,800	8,800
Annual electricity costs	64,650	43,100
ANNUAL HYBRID SYSTEM COST	133,940	143,790

continuous basis, but the available wind energy is much less consistent. The auxiliary electrical power usage is only moderately reduced from the electrical power usage of the conventionally powered plants. This results in part from the variability of the wind and from the additional electrical demands of the heat pump. One interesting characteristic of the auxiliary electrical demand is that it peaks in the winter, a fact that would be looked upon favorably by local utilities that are highly summer peaking and concerned about load management.

A detailed economic comparison of the hybrid scheme with a conventional power supply system was not possible within the time allotted to this task. However, preliminary annual cost calculations were performed (Table 3-2). Case 1 assumes lower boundary cost estimates for the hybrid system and upper boundary cost estimates for electricity and fuel. Case 2 considers the opposite end of the economic cost-band -- higher hybrid system costs and lower projected fuel costs. The preliminary analysis suggests that the hybrid scheme might be attractive in locations where solar and wind resources are available. The annual cost comparisons are shown in Table 3-3. It should be emphasized that the solar pond or WECS alone cannot meet the requirements of this load, but the hybrid system can be economically competitive with conventional sources.

Table 3-3. PRELIMINARY COST COMPARISONS

Design	Cost (Dollars)	
	Case 1[a]	Case 2[b]
Conventional Design -- Concrete Block Plant	214,000	117,300
Hybrid Design--Concrete Block Plant	153,670	184,100
Conventional Design--Meat Packing Plant	232,850	134,030
Hybrid Design--Meat Packing Plant	133,940	143,790

[a]Case 1:	Electricity	6¢/kWh	Solar Pond	$10/m^2$
	Heat	2¢/kWh	Wind System	$500/kW
[b]Case 2:	Electricity	4¢/kWh	Solar Pond	$20/m^2$
	Heat	1¢/kWh	Wind System	$500/kW

SECTION 4.0

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APPENDIX II-A: WIND SYSTEM MODEL

The wind-generated electricity was calculated each hour from the weather data. First the wind speed at 45.7 m (150 ft) was extrapolated from the measured speed at a height of 6.7 m (22 ft) using the one-seventh rule.

$$V = V_{measured} \times \left(\frac{45.7}{6.7}\right)^{1/7}$$

The total available wind power is:

$$P = 1/2\rho \ AV^3$$

with

$$\rho = 1.205 \text{ kg/m}^3$$

The swept areas for the meat packing and concrete block plants were 2280 m^2 and 4000 m^2, respectively.

The available power is attenuated by the coefficient of performance of the wind turbine, COP, the mechanical efficiency, EM, and the electrical generator efficiency, EE. The values used were:

$$COP = 0.38$$
$$EM = 0.95$$

$$EE = 0.85 \quad 1-e^{\frac{-5.83*COP*EM*P}{P_{Rated}}}$$

The rated power was the power output at a rated windspeed of 8.95 m/s (20 mph). A cut-in speed of 3.57 m/s (8 mph) and cut-out speed of 17.9 m/s (40 mph) were included in the model.

SERI

Document Control Page	1. SERI Report No. TR-35-078	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle
Conversion System Overview Assessment
Volume I: Solar Thermoelectrics
Volume II: Solar-Wind Hybrid Systems
Volume III: Solar Thermal/Coal or Biomass Derived Fuels

5. Publication Date
August 1979

6.

7. Author(s) T. S. Jayadev, J. Henderson, J. Finegold, C. Bingham, R.S. Copeland, D. Benson

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Solar Energy Research Institute
1536 Cole Boulevard
Golden, Colorado 80401

10. Project/Task/Work Unit No.
Task # 3503

11. Contract (C) or Grant (G) No.
(C)
(G)

12. Sponsoring Organization Name and Address

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report, in three Volumes, covers three distinct areas of solar energy research: solar thermoelectrics, solar-wind hybrid systems, and synthetic fuels derived with solar thermal energy. Volume I presents the assessment of thermoelectrics for solar energy conversion. There is significant potential for solar thermoelectrics in solar technologies where collector costs are low; e.g., Ocean Thermal Energy Conversion (OTEC) and solar ponds. Thermoelectrics also may have potential in other renewable energy source applications such as geothermal energy and waste heat utilization. Reports of two studies by manufacturers assessing the cost of thermoelectric generators in large scale production are included in the appendix and several new concepts of solar thermoelectric systems are presented. Volume II discusses solar-wind hybrid systems. There are large areas in the United States where solar and wind resources are comparable in magnitude, and there are diurnal and seasonal complementarities which offer the potential for cost-effective hybrid systems. Volume III deals with the conversion of synthetic fuels with solar thermal heat by a combination of solar energy with coal or biomass. A preliminary assessment calculating the cost of fuel produced as a function of the cost of coal and biomass shows that within the projected ranges of coal, biomass, and solar thermal costs, there are conditions when solar synthetic fuels will become cost-competitive.

17. Document Analysis

a. Descriptors Solar Energy ; Hybrid systems ; Wind Power ; Thermoelectric Conversion ; Ocean Thermal Energy Conversion ; Wind Energy Conversion Systems ; Thermoelectric Generators ; Solar Ponds ; Synthetic Fuels ; Refuse Derived Fuels ; Load Management ; Gasification

b. Identifiers/Open-Ended Terms

c. UC Categories
Volume I: 59b, 62, 62e, 64 Volume III: 62e
Volume II: 59b, 60, 62

18. Availability Statement

NTIS, US Dept. of Commerce
5285 Port Royal Rd.
Springfield, VA 22161

19. No. of Pages Vol. I-214
Vol. II-41 Vol. III-35

20. Price Vol. I-$9.25
Vol. II-$4.50 Vol. III-$4.50

Form No. 8200-13 (6-79)

☆U.S. GOVERNMENT PRINTING OFFICE: 1979—681-437/79