REPORT NO. DOE/SF 10601-T1

MASTER

ECONOMIC ASSESSMENT OF ADVANCED CENTRAL-RECEIVER SOLAR-THERMAL POWER SYSTEMS

EXECUTIVE SUMMARY

PREPARED FOR
THE U.S. DEPARTMENT OF ENERGY
AS PART OF CONTRACT
DE-AC03-79SF10601

BY

ADVANCED SYSTEMS TECHNOLOGY DIVISION
WESTINGHOUSE ELECTRIC CORPORATION
EAST PITTSBURGH, PA 15112

OCTOBER 1980

Advanced
Systems
Technology

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ABSTRACT

This study was performed to estimate the value and potential electric utility impact of several advanced central-receiver solar-thermal plant concepts in the role of electric generating stations. The impacts of interest included economics, the cost of producing electricity, fuels displaced, and utility system reliability. The central receiver plants evaluated included solar/fossil hybrid concepts and solar stand-alone plants with thermal storage. Liquid metal/molten salt, closed Brayton cycle, improved water-steam, and combined Brayton/Rankine cycle concepts were among those investigated.

Detailed modeling of the operation of these plants, as they would operate on several electric utility systems, was the primary analytical method used in this study.

Because of the uncertainty of many assumptions, sensitivity analysis was used extensively. Analysis to optimize collector area and storage capacity was also performed.

The study indicates that if the DOE cost goals can be achieved and projected solar plant performance attained, then the advanced solar-thermal concepts can be competitive in regions with good insolation and some continued use of oil or other surrogate distillate or gaseous fuels. Some thermal storage (3-6 hours) was also found to be desirable for most applications.

Details of this study and results are reported in a separate, comprehensive final report, DOE/SF 10601-1.

ECONOMIC ASSESSMENT OF ADVANCED CENTRAL-RECEIVER SOLAR-THERMAL POWER SYSTEMS

INTRODUCTION/BACKGROUND

Over the past several years a number of concepts have been proposed and studied for the conversion of sunlight into electricity on a large commercial scale. The two methods receiving most of the attention for the direct use of sunlight into electricity are photovoltaic and solar thermal. The former directly converts the impinging sunlight directly into electricity (initially direct current) through the use of solid state photosensitive cells. The latter captures and concentrates the sun's heat, usually with a system of mirrors, which runs a heat engine driving an electric generator.

A solar-thermal electric configuration receiving much interest, and holding promise for relatively large electric generating modules, is the central receiver or power tower concept (see Figure 1). With this concept a field of steerable mirrors (heliostats) is used to focus the sun's energy on a heat receiver located atop a tower. Here the heat is transferred to a gaseous or fluid heat transfer medium, such as steam, which is used to run a heat engine (e.g., steam turbine).

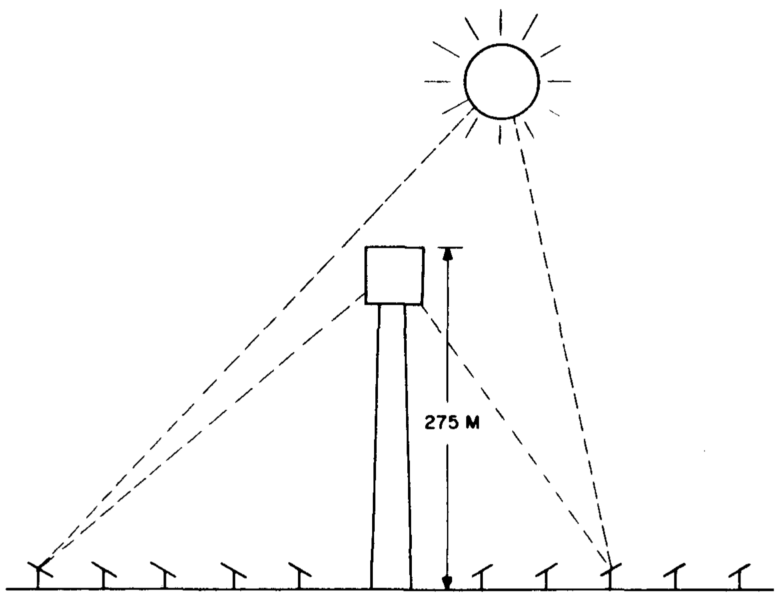

Figure 1. Central-Receiver Solar-Thermal Plant Concept

Early work by DOE on the central receiver concept concentrated on familiar thermal cycles and heat transfer media, such as the steam Rankine concept, operating at temperatures and pressures common to heat engines in use with nonsolar plants. It was recognized quite early that the major cost component of the central receiver concept was the heliostat field. On the order of 15,000 50 square meter heliostats are required to power a 100 megawatt electric power plant at a capacity factor near 0.4. In the hopes of reducing the required investment in heliostats a number of alternatives to improve the thermal-to-electric efficiency of the system have been proposed. Usually the efficiency improvement involves some combination of higher temperatures, different heat transfer fluids, and/or more complex thermal cycles. These higher efficiency central-receiver solar-thermal concepts are sometimes called advanced or improved solar-thermal concepts and are the subject of this study.

No attempt has been made to verify the validity of designs or rank them according to technical risk. Designs selected were assumed to work as specified by the conceptual designers and review by Sandia Laboratories.

STUDY OBJECTIVE

The Advanced Systems Technology Division of Westinghouse Electric Corporation was funded by the DOE San Francisco office to perform an economic evaluation of several advanced central-receiver solar-thermal concepts in the role of central station generating plants. Direction was received from the DOE/SF office with solar plant cost and performance data being supplied by the Sandia National Laboratories, Livermore, California.

The study began at the end of June 1979 and was completed by the end of May 1980.

The objective of the study was to estimate the economic value of several advanced solar-thermal concepts through detailed modeling of their operation on utility systems. Parametric analysis was performed on major plant parameters such as collector area, storage capacity, penetration and location. Also, sensitivity to economic assumptions was investigated.

The value components consisted primarily of fossil fuels saved through the presence of solar plants and the displacement or deferral of new conventional generating plant installations. The impacts assessed included utility system fuel consumption, operating and reliability impacts, and the affects upon utility generation expansion plans.

GENERAL CONCLUSIONS

General observations resulting from this study are as follows.

- Assuming the cost goals and performance estimates used in this study can be achieved, then advanced central-receiver solar-thermal plants can be economical in some regions of the U.S. (cost/value ratios of less than one).

- Good sunshine (direct normal insolation) and the opportunity to displace oil or other high priced fuels are critical to the solar plant value exceeding cost.

- Because of good insolation and the opportunity to displace gas/oil, the Southcentral and Southwest regions of the United States offer the best potential for solar-thermal electric plants.

- Some advanced central receiver concepts, with their improved cycle efficiencies and performance when drawing heat from storage, offer advantages over prior central receiver concepts in their ability to reduce the number of required heliostats and their associated costs (annualized performance improvement of 20% or greater). Consequently the advanced central receiver concepts appear more cost effective than the first generation designs.

- For solar stand-alone plants and some hybrid plants thermal storage (3-6 hours) can be economically justified and is desirable for most regional applications.

- For the coal prices assumed in this study, large storage capacity (18 hour) and the supporting collector area needed to provide almost continuous operation from solar-derived energy did not appear economically justified.

- The optimum plant design (collector area and storage size) is not just a function of insolation when moving from one location to another. It also depends upon specific economic parameters and utility characteristics.

- Oil burning in solar/fossil hybrid plants must be minimized during periods when energy derived from conventional power plants is produced from coal.

- For the Texas/Oklahoma region the solar stand-alone plant and solar/fossil hybrid plants have approximately the same economic potential.

- Hybrid solar plants which have coal-burning capacity or which exhibit higher efficiency than conventional oil fired plants have attractive cost/value ratios quite independent of their solar features.

- Deferral of capacity credit is preferred for those utility systems with a high percentage of oil/gas-fired generation.

- In some utility systems the value of the incremental solar plant at 20% solar penetration may be 30% less than the first plant. This is primarily caused by the reduction in oil displacement potential for incremental solar plant additions with increasing solar penetration.

- With increasing solar penetration the optimum solar plant configuration tends toward larger collector area and storage capacity.

- For periods involving increasing solar penetration with time, the long-term savings may not catch up with the near-term costs until additional solar penetration ceases, even though the cost/value ratio for any individual solar plant may be less than one.

ASSUMPTIONS

The results of any study are dependent upon the assumptions and the analytical methods used. However, it is necessary to make assumptions for studies of this nature as a basis of learning, through analysis, the importance of various parameters and to obtain estimates of results. The best estimates available were used and valuable information has been gained from this study. The following is a summary of the principal assumptions.

Solar-Thermal Plant

Both plant cost and performance assumptions were required for each of the plants modeled. The solar plant cost and performance data was provided by the Sandia National Laboratories, Livermore, California. The plant concepts analyzed included three solar stand-alone concepts and four solar/fossil hybrid concepts. A single generic set of efficiencies was used to represent both the molten salt and liquid metal (sodium) plant designs. All plants modeled were central-receiver solar-thermal concepts with a common set of heliostat (cost and efficiency) parameters being used for all. The basic configurations modeled were as follows:

Solar Stand-Alone Concepts

(1) A generic representation of the liquid metal and molten salt (LM/MS) concepts with thermal storage

(2) A closed Brayton-cycle system (CB) with thermal storage

(3) An advanced water/steam (AWS) concept with thermal storage

Solar/Fossil Hybrid Concepts

(4) A generic representation of the liquid metal and molten salt concepts with thermal storage and coal-burning capability (LM/MS-HC)

(5) A generic representation of the liquid metal and molten salt concepts with thermal storage and oil-burning capability (LM/MS-HO)

(6) A closed Brayton-cycle system without thermal storage but with oil-burning capability (CB-HO)

(7) A Brayton/Rankine combined-cycle air/steam system without storage but with oil-burning capabilities (CC-HO)

The cost estimates were based on commercialized quantities and DOE cost goals. Heliostat cost assumptions were about 85 $/m^2 in 1979 dollars.

A summary of some of the basic configuration assumptions and the solar annualized efficiency are shown in Table 1.

Table 1

STAND-ALONE PLANT CONCEPTS MODELED
(100 MWe Modules)

Plant Concept	LM/MS	CB	AWS
Turbine Cycle	Rankine	Brayton	Rankine
Collector Area (10^3 m^2)	663	709	695
Thermal Storage (Hrs)	3	3	3
Fossil Fuel	-	-	-
Net Solar Efficiency (%)	20.8	19.0	19.5
Cost ($/kWe 1985)	2307	3195	2578

SOLAR/FOSSIL HYBRID CONCEPTS MODELED
(100 MWe Modules)

Plant Concept	LM/MS	LM/MS	CB	CC
Turbine Cycle	Rankine	Rankine	Brayton	Brayton/Rankine
Collector Area (10^3 m^2)	663	1245	472	259
Thermal Storage (Hrs)	3	18	0	0
Fossil Fuel	Coal	Oil	Oil	Oil
Net Solar Efficiency	20.8	20.8	19.2	21.0
Cost ($/kWe 1985)	3188	4412	2140	1565

Insolation Data

For solar plant modeling, Typical Meteorological Year (TMY) weather and insolation data was used. This data was obtained from the National Climatic Center in the SOLMET format. A summary of the year's average direct normal insolation for each of the sites used is shown in Table 2. The EPRI synthetic utility designation is also indicated (see next paragraph).

Utility Parameters

Six synthetic utilities representative of various regions of the country were used. Specific load and generating mix parameters are detailed in Reference 1. A summary of the utility designations and regions are shown in Figure 2 and are as follows:

A - Heavily Coal Dependent - Southeast
B - Oil and Hydro Dependent - Far West
C - Coal Based - Central Plains
D - Coal Based - North Central
E - Oil/Gas Dependent - South Central (Texas/Oklahoma)
F - Oil Dependent - Northeast and Florida

Table 2

NATIONAL CLIMATIC CENTER SOLMET TAPES
TYPICAL METEOROLOGICAL YEAR DATA

Location	Synthetic Utility (Geographical Match)	Direct Normal Insolation ($kWh/m^2/Day$)
Boston, MA	F	3.26
El Paso, TX	E	7.26
Fresno, CA	B	6.13
Madison, WI	D	3.71
Medford, OR	B	4.32
Miami, FL	F	3.82
Nashville, TN	A	3.59
North Omaha, NE	C	4.47
*Midland, TX	E	6.86

*No typical meteorological year

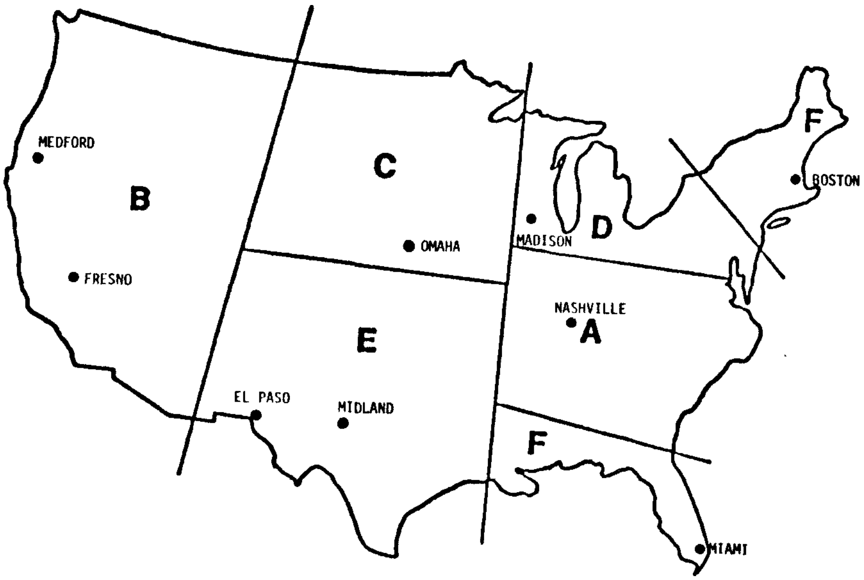

Figure 2. Regional Synthetic Utility Models

Economic Assumptions

Alternate economic scenarios were used for the analysis. However, the results shown in this summary report are based on the assumptions shown in Table 3. No natural gas is shown as it is assumed that the replacement fuel would take the cost profile as indicated for #2 Oil.

Table 3

"A" ECONOMIC SCENARIO

Present Worth Discount Rate	11%
Fixed Charge Rate	18%
Capital Cost, $/kWe (C-T, C-C, Coal, Nuc.)	300/600/1400/1500
Fuel Cost ($/MBtu) (#6 Oil, #2 Oil, Coal, Nuc.)	5.0/5.5/2.0/1.25
Fuel Escalation Rate (%) (Oil, Coal, Nuc.)	12/10/9,13*
Capital Escalation Rate	10%
O&M Escalation Rate	8%

*9% to year 2000, 13% thereafter

METHODOLOGY

The method of evaluating the various concepts involved the hourly modeling of the operation of the solar plants on the utility systems. By modeling the utility systems with and without solar plants, the value of the solar plants can be estimated, with both fuel and capacity displacement being determined. The use of thermal storage and the fossil side of hybrid plants was determined through hourly comparison with the incremental operating cost of the balance of the utility system.

Both detailed single-year analysis with lifetime impact projections and a utility optimal capacity expansion model were used. These techniques are documented in some detail in References 2 and 3 and the final report for this project.

For the detailed modeling of the impact of the various solar plants, a series of models were used as shown in Figure 3. This involved simulation of the hourly operation of the solar plant and the balance of the utility system.

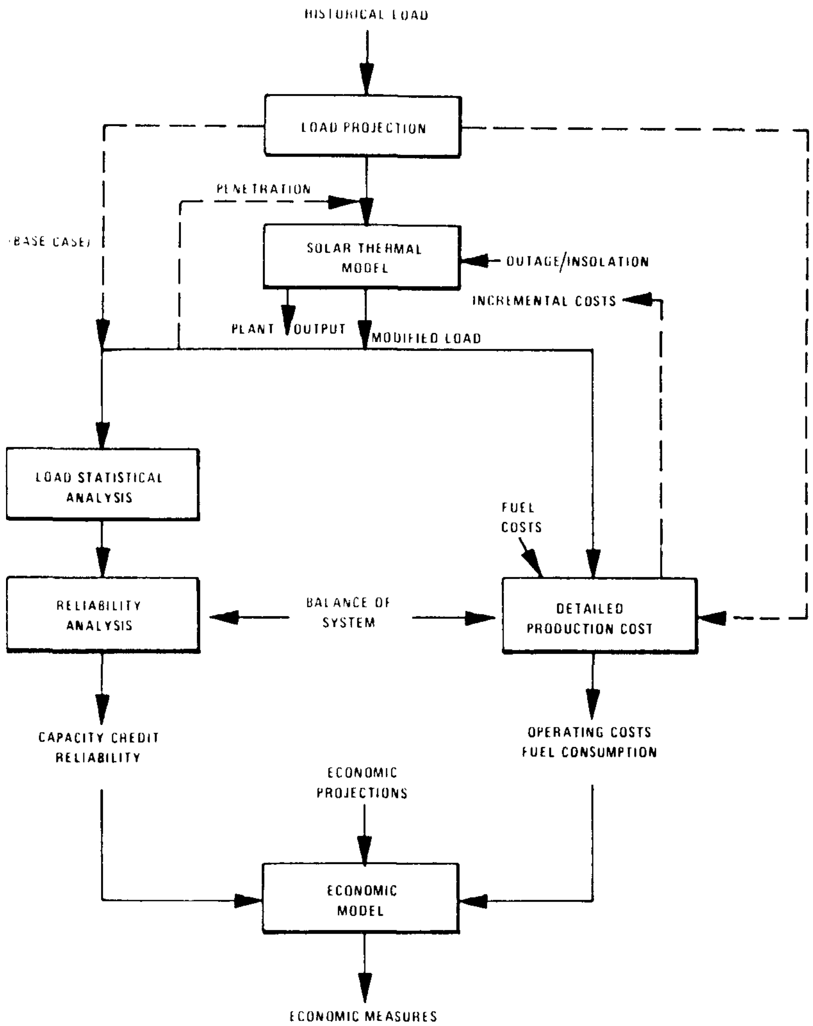

Figure 3. Solar-Thermal Plant Static Analysis Sequence

RESULTS

Included below are summary results for experiments involving variations in:

- Plant Concept
- Collector Area
- Storage
- Location (Insolation/Utility)
- Fuel Cost Assumptions

Considerable detail, not presentable in a summary report, lies behind the results shown. Also, plant cost and economic scenario variations produce sensitivities which are documented in the final report but are not shown here.

Plant Concept

It should be remembered that the following results are dependent upon the many assumptions used. Table 4 shows a preliminary comparison of the stand-alone plants, and Table 5 the hybrid concepts. These results are based upon Midland, Texas insolation, E utility system, and the 1985 installation of a 100 MWe module.

Table 4

SOLAR-THERMAL STAND-ALONE CONCEPTS
(Costs and Value in Lifetime PWRR 1985 M$)

Type	LM/MS	CB	AWS
Collector Area (10^3 m^2)	762	815	695
Thermal Storage (Hrs)	3	3	3
Solar Plant Cost	523	713	528
Operating Value	585	580	515
Capacity Value	49	49	45
Total Value	634	629	560
Cost/Value Ratio	.82	1.13	.94
Capacity Factor	.375	.372	.332

Table 5

SOLAR/FOSSIL HYBRID CONCEPTS
(Costs and Value in Lifetime PWRR 1985 M$)

Type	LM/MS	LM/MS	CB	CC
Collector Area (10^3 m^2)	663	762	472	259
Thermal Storage (Hrs)	3	3	0	0
Fuel Type	Coal	Oil	Oil	Oil
Solar Plant Cost	653	572	438	321
Operating Value	1036	630	594	737
Capacity Value	50	50	50	50
Solar Plant Fuel	-209	-48	-199	-440
Total Value	877	632	445	347
Cost/Value Ratio	.74	.90	.98	.92
Capacity Factor	.769	.403	.363	.466

The results shown for the "E" utility system are based upon an incremental 100 MWe solar plant being added to the system in 1985 and the capacity credit being deferred until 1995. This is the most appropriate direction since the utility system desires substantial coal, with the economic scenario imposed. Displacing coal capacity in the 1985-1995 time frame would be disadvantageous to the economic effectiveness of the solar plant (see Reference 4). This is peculiar to the high oil usage systems and also explains the preference for a coal hybrid. An incremental coal plant, if allowed in this time frame, would have a cost/value ratio close to .6; however, the conventional capacity has been restrained to a fixed percent reserve of the load peak.

It should be recognized that the same plant concept cost/value relationships do not necessarily hold for other utility systems. In particular, the combined-cycle plant becomes much less competitive on other utility systems. Also, as each concept design matures, plant cost estimates may be revised either up or down.

An investigation to find the optimum collector area, in terms of minimum cost/value ratio, is shown in Figure 4. This figure is for the generic liquid metal/molten salt stand-alone concept with three hours storage, and shows all six utilities. The heliostat cost assumptions are approximately 85 $/m^2 (1979 $). The minima are shown as circled values. A relative insensitivity of cost/value ratio to collector area is revealed.

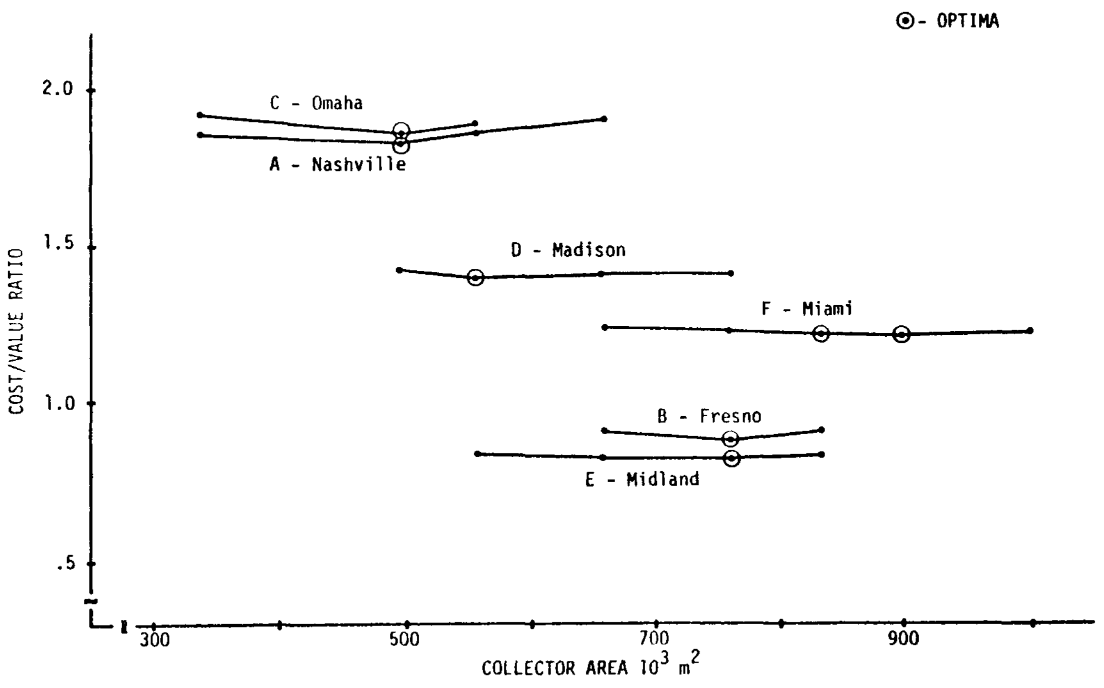

Figure 4. Collector Area Experiment (100 MWe, LM/MS-SA, 3-Hour Storage)

Similar collector area insensitivity was exhibited for other storage amounts and most other concepts (see Figure 5). The solar/coal hybrid concept has an optimum collector area of zero. This is because, with the coal cost assumptions used, the cost of a square meter of heliostat cannot be justified for purely coal displacement. With this plant, which operates continually, increasing collector area displaces coal burned within the same plant.

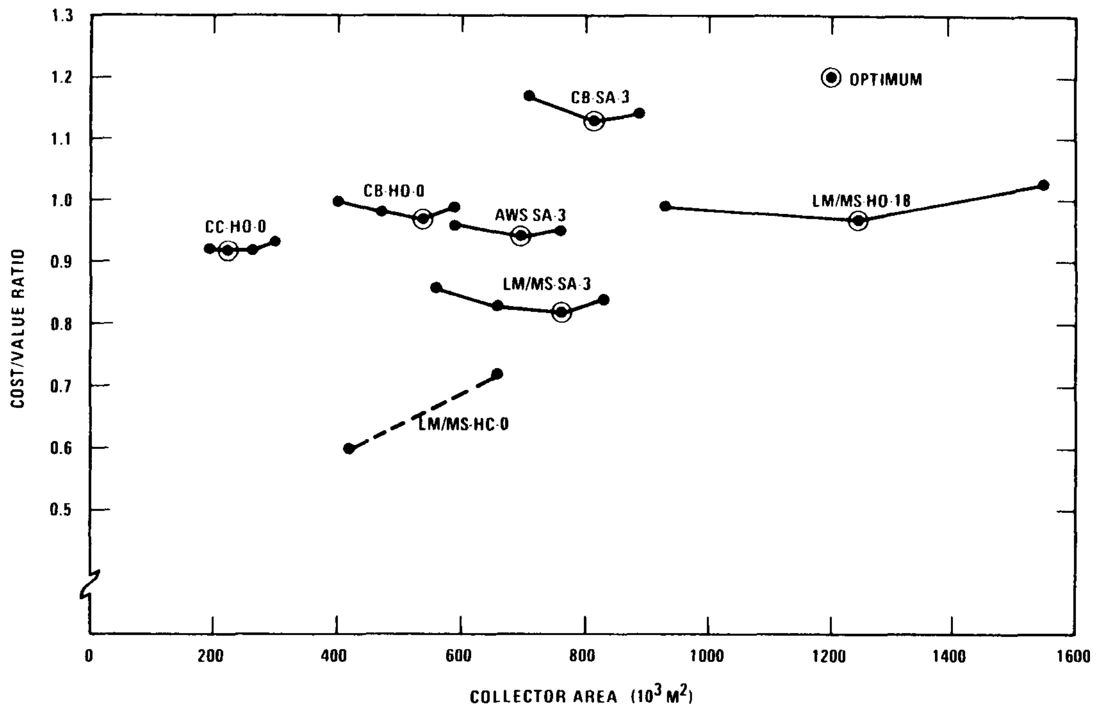

Figure 5. Collector Area Experiment (Various 100 MWe Plants, Utility E, Midland Site)

Thermal Storage

A storage capacity experiment was run for each utility system. Inherent buffering of cloudy day insolation transients was assumed for all concepts. The results for the generic liquid metal/molten salt stand-alone plant are shown in Figure 6. This figure shows a definite preference for some storage on all utilities with an optimum of close to three hours of rated output. The B utility shows a slight favoritism for six hours storage.

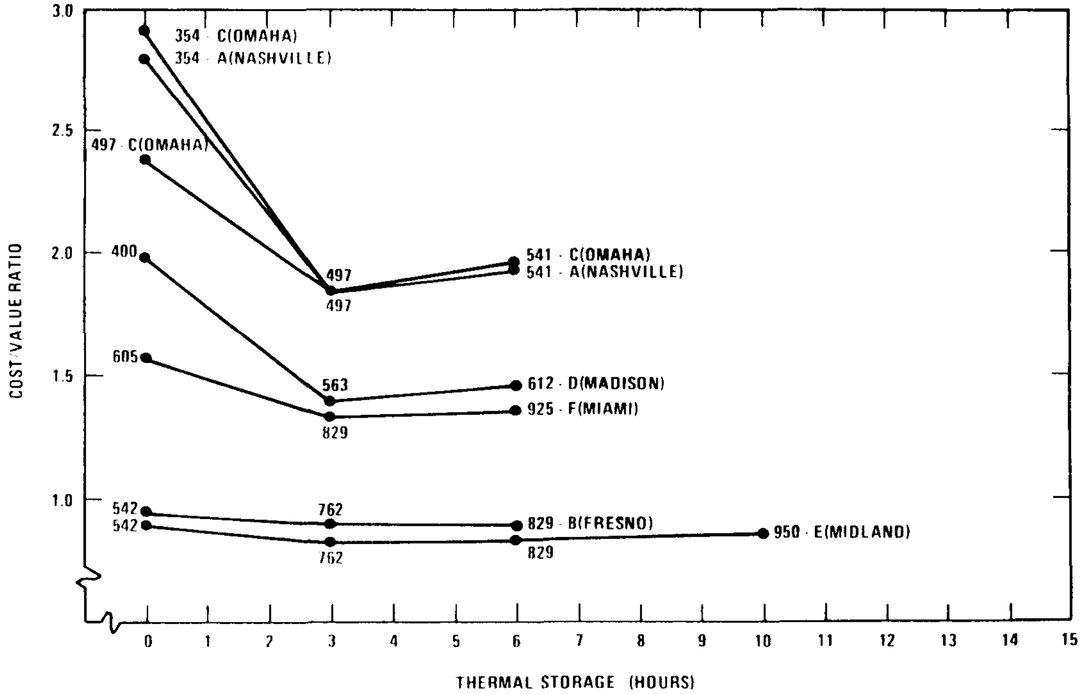

Figure 6. Thermal Storage Evaluation (LM/MS-SA Plant, Six Synthetic Utilities)

This analysis reflects first-plant penetration parameters. It was shown that the optimum storage requirements have a tendency to increase with increasing penetration. Figure 7 shows storage experiment results for other concepts, on the E utility system. Again, three to six hours of storage are preferred.

Location

Figures 4 and 6 have already shown the relative cost/value ratios for the generic liquid metal/molten salt concept as a function of location (utility and insolation). The relatively good numbers for utilities E and B are due to a good opportunity to displace oil along with relatively good insolation. Table 6 shows the annual fuel mix displacement, in gigawatt-hours electric, for a 100 MWe liquid metal/molten salt stand-alone plant with 663,000 m^2 collector area and three hours storage. The relationship between the cost/value ratio and the oil displacement is evident.

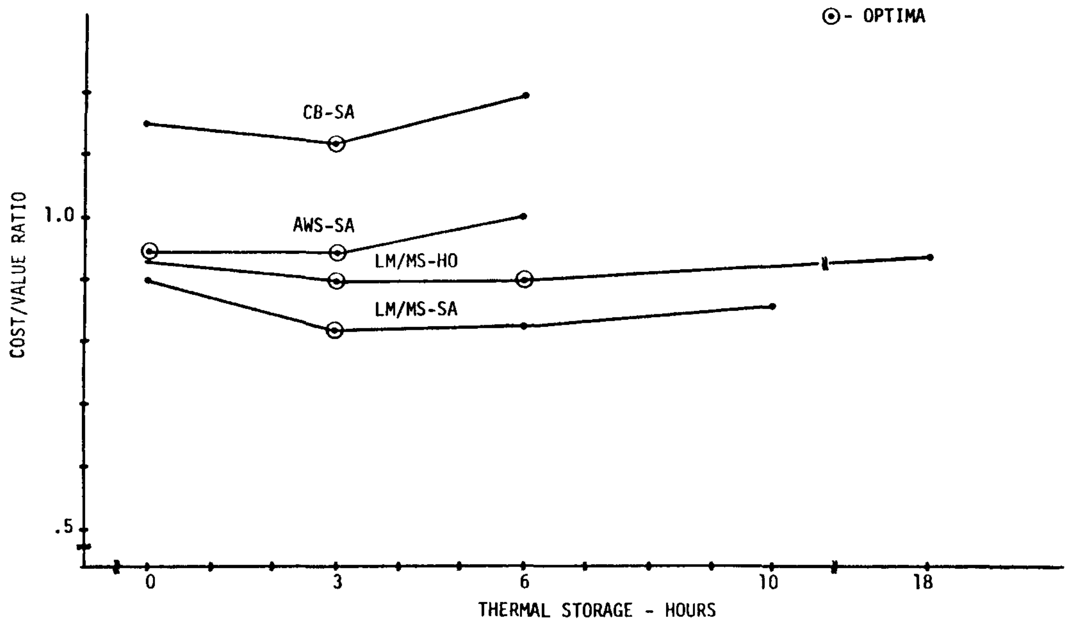

Figure 7. Storage Capacity Experiment (100 MWe Plants, Midland)

Table 6

SOLAR PLANT FUEL DISPLACEMENT
(GWhe/yr for 100 MWe LM/MS Stand-Alone Plant, 3-Hr Storage, 663,000 m^2 Collectors)

Utility Site	A Nashville	B Fresno	C Omaha	D Madison	E Midland	F Miami
#2 Oil	39	183	1	73	141	29
#6 Oil	21	40	47	51	147	135
Coal	94	0	147	31	4	0
Total GWh/yr	154	223	195	155	292	164
Cost/Value	1.91	.91	1.88	1.41	.83	1.39

Fuel Cost Sensitivity

The assumptions used for the costs of each unit of fuel saved are major factors in determining value. In the A economic scenario the assumptions were 5 \$/MBtu for oil and 2 \$/MBtu for coal in 1985, escalating 12% and 10% respectively in each remaining year of the 30-year plant life.

Figure 8 shows combinations of 1985 oil cost and post-1985 oil escalation rates that produce the same present worth of lifetime fuel value (discount rate at 11%). The fuel value in the referenced Midland LM/MS-SA case was 578 M\$, based on all solar plant output displacing oil. The scenario A assumptions are shown by the intersection of the dashed lines labeled "A". There is an infinite number of combinations of 1985 oil cost and oil escalation rate assumptions that would produce the same fuel value, as described by the line labeled "Fuel Value = 578 M\$." Other lines show combinations of fuel cost assumptions producing alternate values. Although developed for oil, these curves would apply to any combination of fuels having the assumed average costs and net escalation rates. The curves are specific for 3.744 million MBtu's of fuel displaced per year.

Arguments can easily be made that the Scenario A values of 5 \$/MBtu (30 \$/bbl) for oil is too low, and that the 12% per year escalation rate continuing for 30 years is too high. The vertical dashed lines on Figure 8 show the actual July 1980 OPEC fuel prices and the 1985 price assuming 8% escalation. From the curve it can be seen that if U.S. oil prices approach

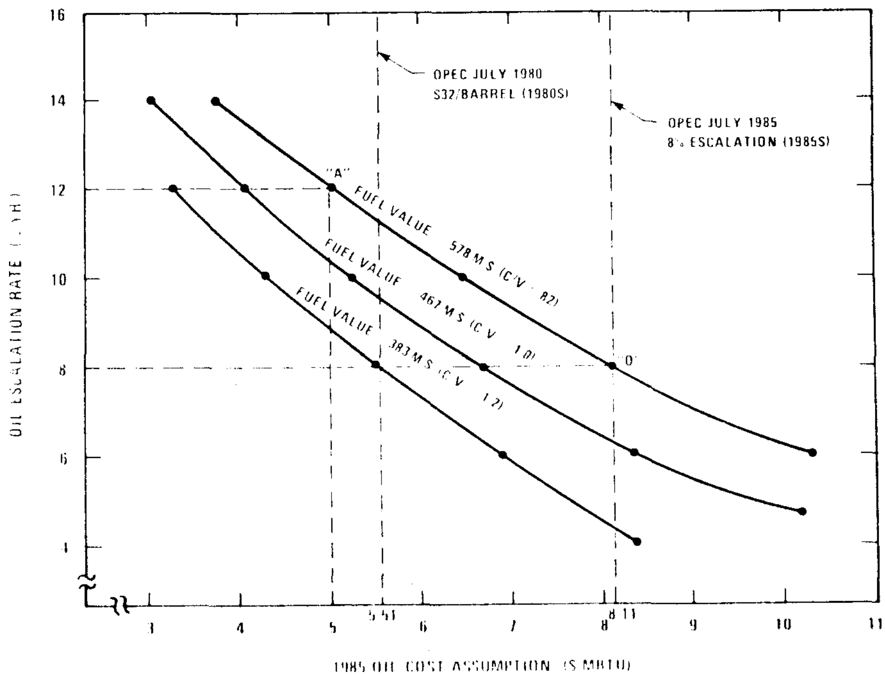

Figure 8. Combinations of 1985 Fuel Cost and Post 1985 Escalation Rates Producing the Same Fuel Value
(11% Discount Rate, 3.744 Million MBtu/yr Fuel Displacement)
(LM/MS-SA Plant; 762,000 m^2 Collector. 3 hr Storage)

OPEC prices in 1985, then a cost/value ratio of less than 1.0 can be attained with 8% escalation over the life of the plant (point labeled "0"). Escalation rates greater than 8% would yield lower C/V ratios, enhancing the value of a solar plant to a utility system.

Because of the importance of the value of the fuel displaced to the economic value of the solar plant, an analysis was performed considering various mixes of fuel displacement. The analysis may be helpful to utilities which have generation capacity somewhat balanced between oil and coal. Figure 9 shows combinations of fuel cost assumptions producing a constant fuel value for different mixes of fuel displacement. The value used was 467 M$ lifetime fuel savings which produced a cost/value ratio of 1.0 in the case just referenced (LM/MS-SA, Midland, etc.). Thus, each curve in this figure represents break-even fuel cost assumptions. For these

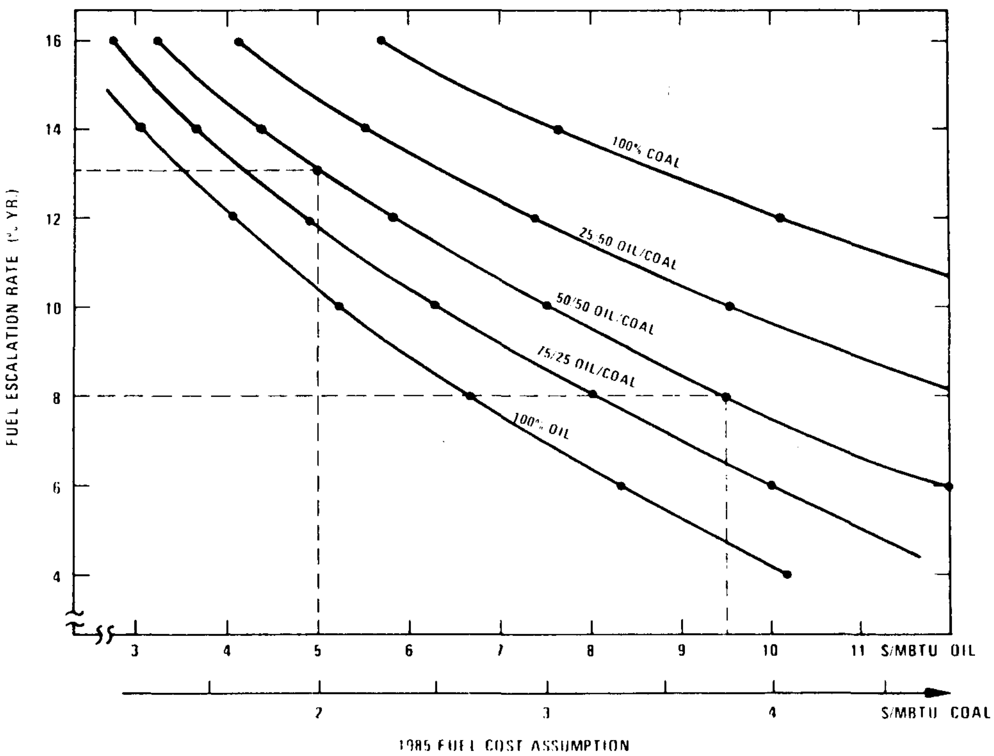

Figure 9. Fuel Cost and Displacement Mix Assumptions Producing a Value of 467 M$, C/V = 1.0
(11% Discount Rate, 3.744 Million MBtu/yr Displacement)
(LM/MS-SA Plant, 762,000 m^2 Collector, 3 hr Storage)

curves to be valid the coal must be paired with an oil cost 2.5 times as great. That is, a 5$ oil cost must be paired with the 2$ coal for the oil/coal curves. The same annual escalation rate, as read from the vertical axis, is applied to both fuel types. As an example, for a utility in which a 50/50 mixture of 5$ oil and 2$ coal would be displaced by the solar plant, the breakeven fuel escalation rate would be approximately 13%. Conversely, at an annual fuel escalation rate of 8%, the breakeven 1985 fuel cost would be approximately $9.50/MBtu for oil and $3.80/MBtu for coal. The figure assumes a total fuel displacement of 3.744 million MBtu/yr and a LM/MS plant with 762,000 m^2 collector with 3 hr. thermal storage.

For fuel cost/escalation rate pairings producing points below the line of interest, the solar plant lifetime fuel displacement value would be less than 467 M$ and the cost/value greater than one.

As can be seen in Figure 9, the larger the proportion of the solar plant energy output that goes to displacing coal, the higher the oil/coal price combination must be to justify the solar plant.

COMMENTS

Only some of the highlights of the study have been extracted for this executive summary. For details regarding the assumptions and further results please see the final report, the table of contents of which is appended.

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APPENDIX

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