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An Analysis of Power Production Performance for Solar One, the 10 MWe Solar Thermal Central Receiver Pilot Plant

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AN ANALYSIS OF POWER PRODUCTION PERFORMANCE FOR SOLAR ONE, THE 10 MWe SOLAR THERMAL CENTRAL RECEIVER PILOT PLANT

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ABSTRACT

This report describes an analysis of power production performance for Solar One, the 10 MWe Solar Thermal Central Receiver Pilot Plant near Barstow, California. Solar One has been undergoing power production testing since August 1984. During this period plant performance indicators, such as capacity factor and system efficiency, have been studied to assess the capability of Solar One to supply electrical power.

Solar One has shown an improvement in performance since power production testing began. Considerable increases in capacity factor and system efficiency were achieved. The factors contributing to these increases and approaches for achieving further increases are discussed.

SOLAR THERMAL TECHNOLOGY
FOREWORD

The research and development described in this document was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100^{o}C in low-temperature troughs to over 1500^{o}C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal directed program to improve performance and provide technically proven options for eventual incorporation into the Nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Component and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

This report describes an analysis of Solar One's performance during the first two years of power production operation. Actual and predicted values of the plant's capacity factor and system efficiency are compared, and approaches for improving the plant performance are discussed.

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Introduction

In 1978 the Department of Energy (DOE) and the Associates* entered into a Cooperative Agreement to design, construct, and operate a solar thermal central receiver pilot plant near Barstow, California. The Pilot Plant, named Solar One, can supply ten megawatts of electrical power to the Southern California Edison grid, making it the world's largest solar central receiver electric generating plant (see Figure 1).

Solar One uses a large number of computer-guided tracking mirrors, called heliostats, that reflect the sun's energy to a receiver mounted on top of a tower. The receiver absorbs the solar energy in water that is boiled and converted to high-pressure steam. This steam powers a turbine-generator for the generation of electrical energy. Steam from the receiver, in excess of the energy required for the generation of 10 MWe net power to the utility grid, is diverted to thermal storage for use when output from the receiver is less than that needed for rated electrical power (see Figure 2).

Construction of Solar One was completed in 1981, and the plant is now undergoing a five-year Operational Test Period. The Operational Test Period consists of a two-year Experimental Test and Evaluation Phase followed by a three-year Power Production Phase.

The Experimental Test and Evaluation Phase, which began in mid-1982, was completed on July 31, 1984. During this phase, operating experience was achieved for all the plant's operating modes, and the plant's system and component performances were evaluated (Reference 1). The Power Production Phase, which began on August 1, 1984, will primarily demonstrate the operational capability of Solar One to reliably supply electrical power.

During the Power Production Phase two important measures of plant performance are being analyzed:

(1) capacity factor -- the plant's average electrical energy output relative to its rated output, based on a 24-hour time period; and

(2) system efficiency -- the overall plant efficiency for converting sunlight into electricity.

This report describes monthly and annual values for capacity factor and system efficiency during the first two years of power production operation. The actual annual values are compared to predicted values, and the impact of actual plant conditions on the values is analyzed. Finally, procedures are identified to improve plant performance and reach the predicted values.

* Southern California Edison, Los Angeles Department of Water and Power, and the California Energy Commission.

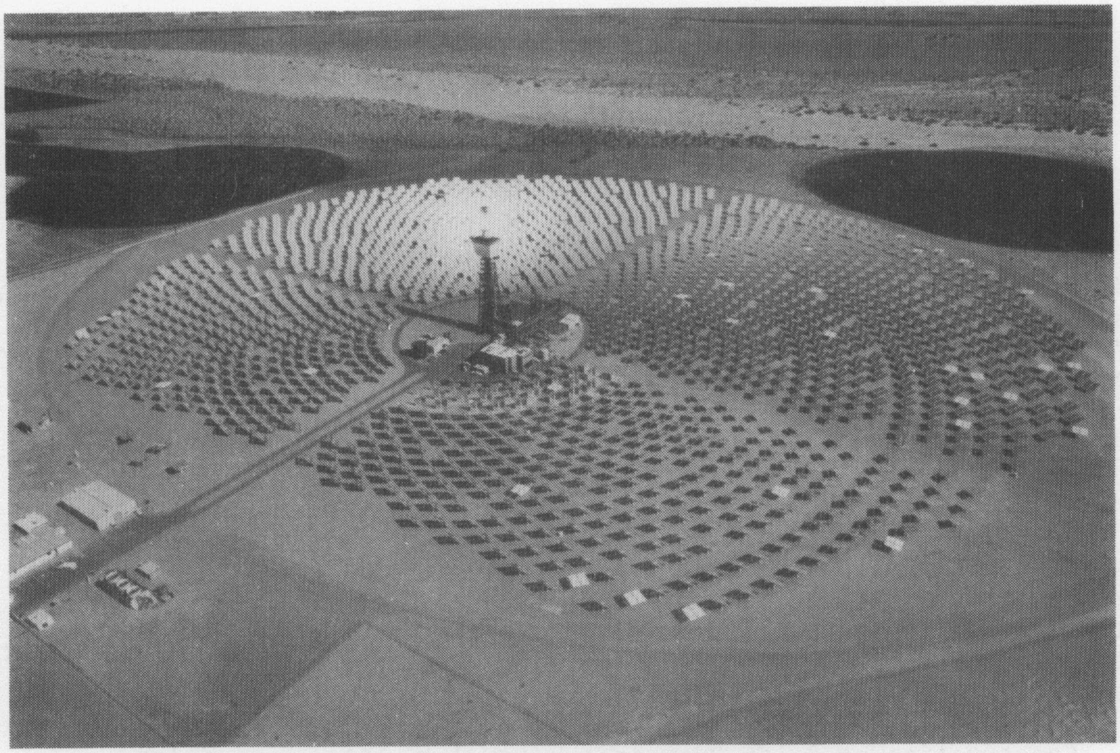
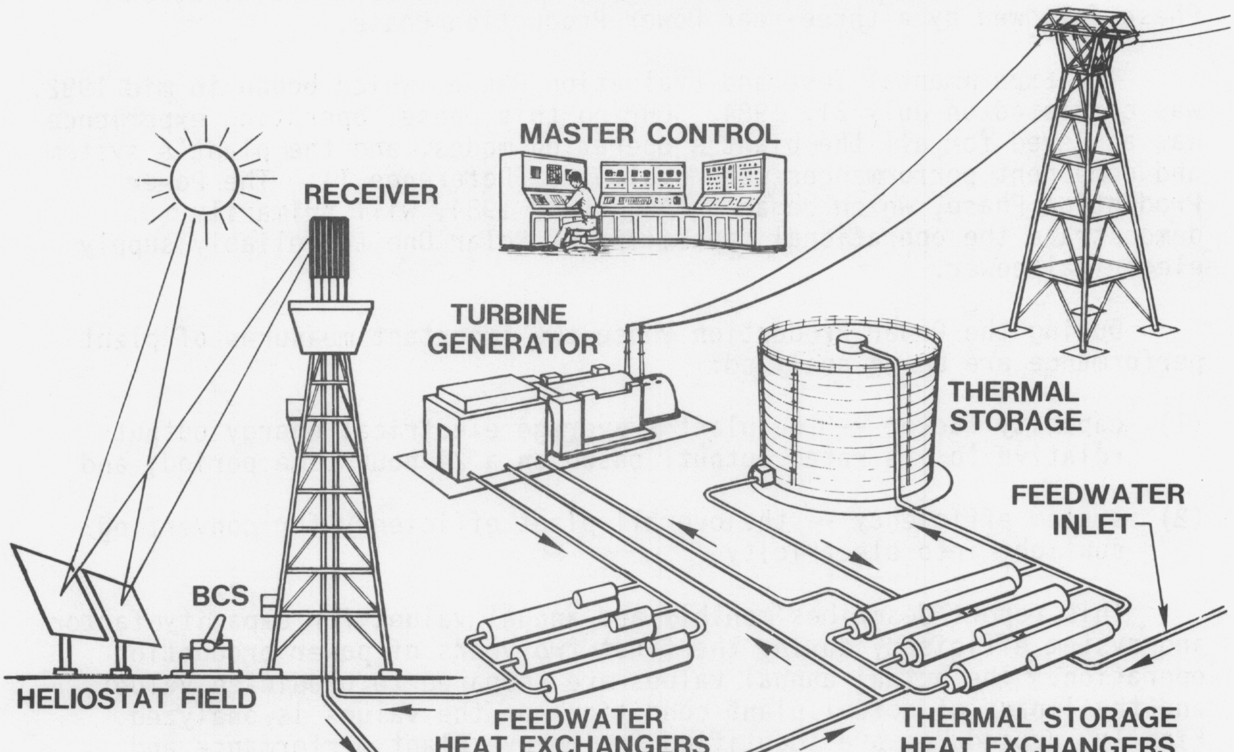


Figure 1. Solar One: 10 MWe Solar Thermal Central Receiver Pilot Plant near Barstow, California



SUPPORT SYSTEMS

- BACK-UP POWER
- SWITCHYARD
- ROADS
- WAREHOUSE
- ADMINISTRATION BLDG
- WATER SUPPLY
- FIRE PROTECTION

SL-20833A

Figure 2. Solar One System Schematic

Capacity Factor

Capacity factor is the plant's actual net electrical output* divided by its rated net output over a 24-hour period. Capacity factor is a commonly used electric utility term and is a measure of the energy generating potential of the plant. A plant which experiences a capacity factor significantly less than its design value will be unable to generate sufficient revenue to recover its capital and operating and maintenance expenses, as well as providing a profit for its investors.

The annual capacity factors for several solar central receiver electric plant designs have been estimated to be 20-70%. The low end of this range corresponds to plants with little or no storage while the high end corresponds to plants with significant storage (e.g., greater than 10 hours) and/or a fossil-fueled backup energy source.

The monthly capacity factors for the first and second years of Solar One's power production operation are shown in Figure 3. A negative value means that the plant consumed more power than it produced during the month, due to poor weather or scheduled and unscheduled plant outages. The best capacity factors generally occured during the months of April to September. Solar One achieved a maximum monthly capacity factor of about 24% during August 1985.

Solar One's capacity factor averaged 8 and 12% during the first and second years of power production operation, respectively. A significant improvement in capacity factor was observed during the second year of power production operation as a result of better weather conditions and improved operating and maintenance procedures. Better insolation permitted more hours of operation at or near full load. Improved operating and maintenance procedures resulted in increased plant availability, heliostat availability, heliostat cleanliness, receiver absorptance, and reduced start-up times. These factors all contributed to an increased steam flow to the turbine and more hours of full-load operation.

System Efficiency

System efficiency is the plant's actual net electrical output (based on a 24-hour plant load) divided by the direct insolation incident on the collector field reflective surface. System efficiency is a measure of a plant's capability to convert sunlight into electrical energy.

*Net energy production is obtained by subtracting the 24-hour plant load from the gross energy production. The 24-hour plant load is the energy needed to supply the plant's parasitic load for twenty-four hours per day.

Plant designs with high system efficiencies are desirable in order to maximize the use of the solar energy resource. The annual system efficiencies for several solar central receiver electric plant designs have been estimated to be 11-15% (Reference 2). The low end of this range is typical for a small plant like Solar One which, because of its size: (1) uses a relatively large portion of its output for parasitic energy needs; and (2) cannot use a more efficient turbine technology. The more efficient reheat steam turbines are only available in large plant sizes.

The high end of the range is an estimate for a large solar central receiver plant, typically 100 MWe in size. Such a plant would use advanced technologies, such as molten salt or liquid sodium working fluids, as well as the high-efficiency, reheat, steam Rankine cycles.

The monthly system efficiencies for the first and second years of power production operation are shown in Figure 4. A negative value again indicates that the plant consumed more power than it produced during the month. Solar One achieved a maximum monthly system efficiency of about 8.7% during August 1985.

The annual system efficiencies for the first and second years of power production operation were 4.1 and 5.8%, respectively. System efficiency, like capacity factor, increased considerably during the second year of power production operation and for the same reasons.

Capacity Factor and System Efficiency Predictions

At the beginning of Solar One's preliminary design, Aerospace Corp. developed predictions for the plant's annual capacity factor and system efficiency (Reference 3). These predictions, although they were not performance requirements, were derived to provide an indication of the plant's expected annual performance.

The annual capacity factor and system efficiency that were initially predicted for Solar One were optimistic values because they were based on the design value for the receiver absorptance and assumed a 100% annual availability of plant equipment. With these and other ideal assumptions an unrealistically high annual capacity factor of 30% (corresponding to an energy production of 26,000 MWe-hr net)* and a system efficiency of 13% were predicted for the plant, based on an available incident insolation of 202 x 10^3 MWt-hr (1976 insolation data).

*Capacity factor and annual energy production are not independent variables. For a given plant rating in megawatts electric, specifying one of these automatically defines the other.

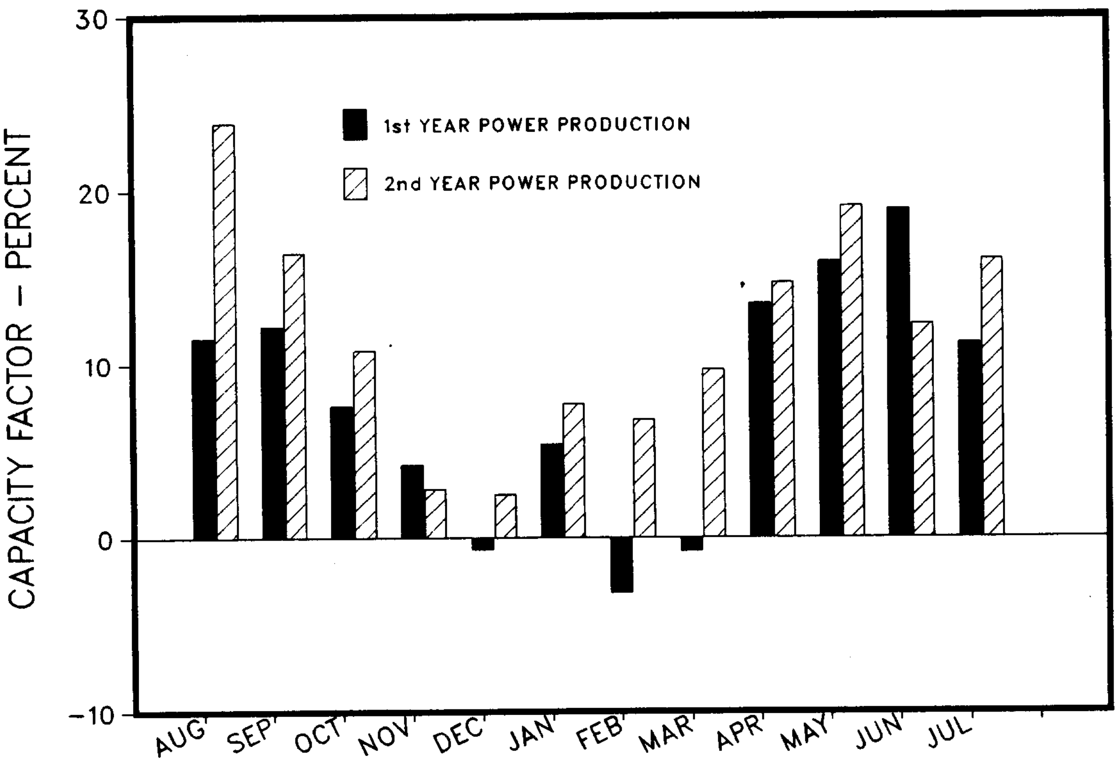


Figure 3. Solar One Capacity Factor - August 1984 to July 1986

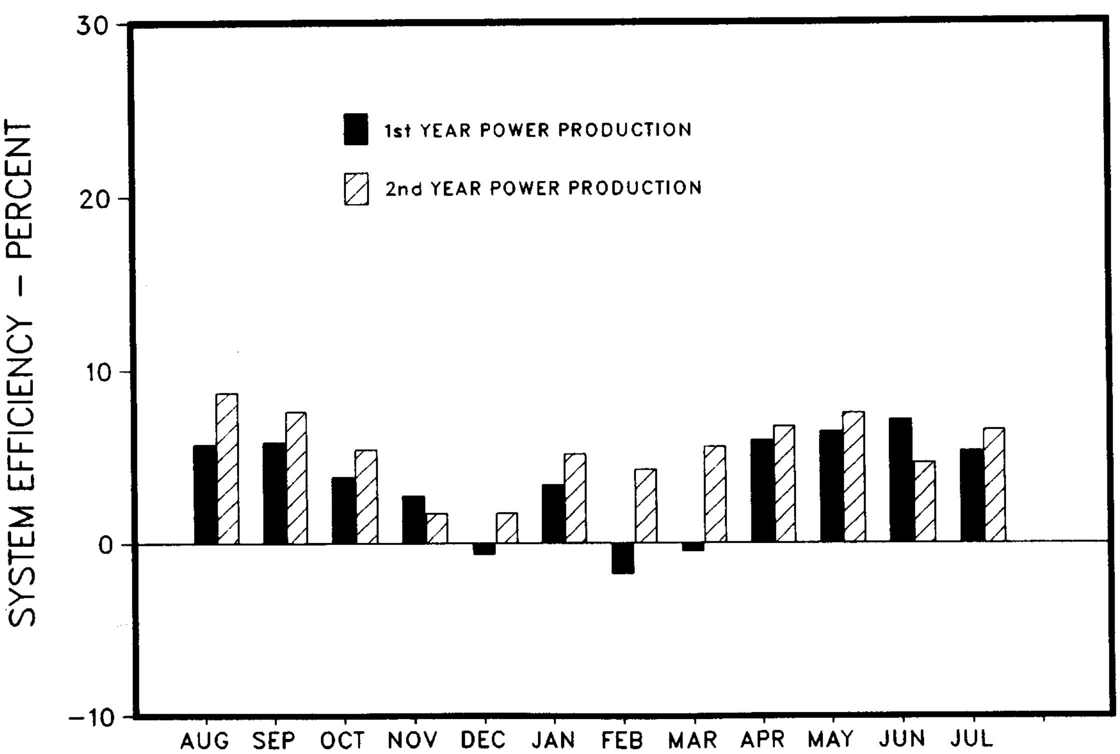


Figure 4. Solar One System Efficiency - August 1984 - July 1986

Substitution of actual plant conditions for design values lowers the capacity factor and system efficiency considerably. The current predictions for Solar One are a capacity factor of 17% (corresponding to an energy production of 15,000 MWe-hr net) and a system efficiency of 8.2%.

The initial and current annual efficiency and annual energy predictions are summarized for Solar One in Figure 5 and Table I. The initial predictions for efficiency and energy production are taken from Reference 3. The current predictions are based on measured plant data or projected improvements to several key plant factors, such as plant availability, mirror reflectivity and receiver absorptance, which affect efficiency and energy output. A discussion of the initial and current values for each factor is presented below.

Incident Normal Insolation--The initial annual energy value of 202 x 10^3 MWt-hr is based on insolation data collected in Barstow during 1976. The current value of 183 x 10^3 MWt-hr is based on a 25-year average value. The 25-year value, which is 9.4% less than the 1976 insolation value, was selected to derive the current prediction because it is more representative of a typical operating year.

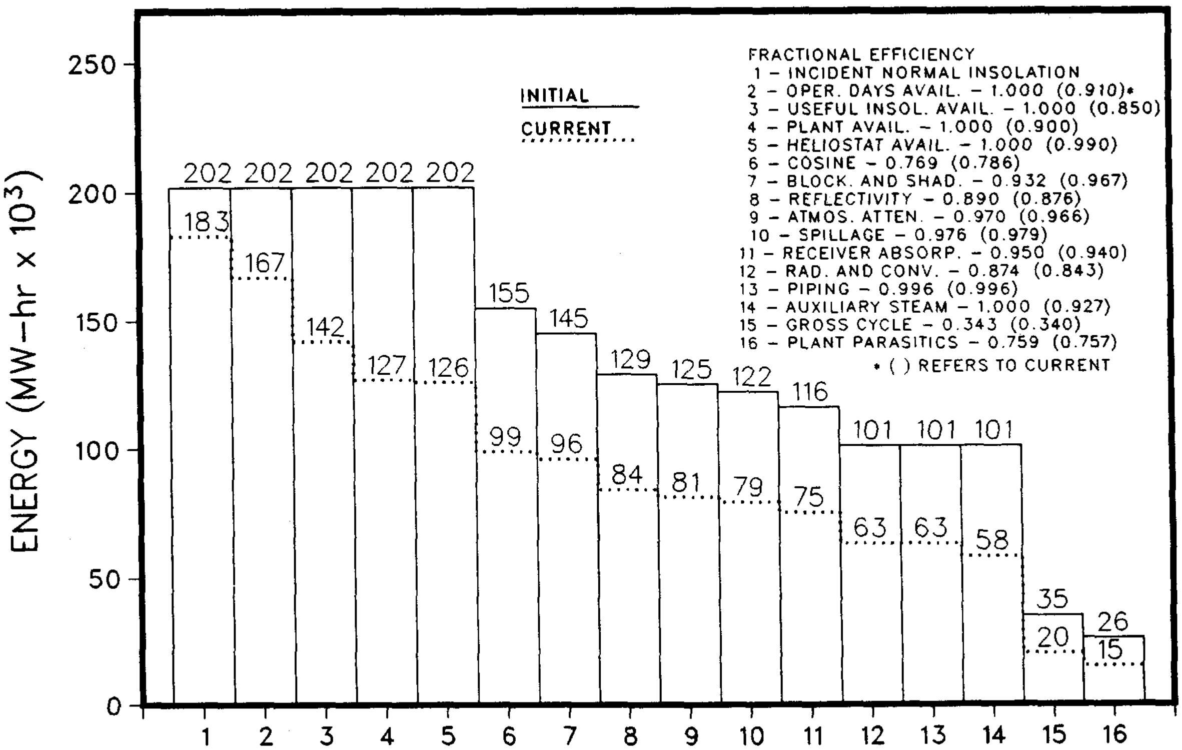


Figure 5. Comparison of Initial and Current Solar One System Efficiency and Annual Energy Predictions

Operating Days Insolation Availability--Operating days insolation availability refers to the fraction of the annual horizon-to-horizon insolation that is available on the days when the plant was operating or could have operated. The difference between the total (365 day) horizon-to-horizon insolation and the operating days insolation is the insolation occurring on the plant's non-operating days -- that is, days when insolation levels were too low or wind speeds were too high. For 1984, the operating days insolation was estimated to be 2080 kW-hr/m^2 (Reference 4). This value corresponds to an operating days insolation availability of 0.887. A slightly higher availability of 0.91, which was assumed to be representative of a better weather year and improved operating procedures, was used for the current prediction, while an availability of 1.0 was assumed for the initial prediction.

Useful Insolation Availability--Useful insolation is the insolation above 500 W/m^2 that is available on the plant's operating days. An insolation level of at least 500 W/m^2 is desirable for Solar One operation although the plant has operated at levels less than this level. For 1984, the useful insolation was estimated to be 1733 kW-hr/m^2 (Reference 4). This corresponds to a useful insolation availability of 0.833. A slightly higher availability of 0.85, which was assumed to be representative of a better weather year and improved operating procedures, was used for the current prediction, while an availability of 1.0 was assumed for the initial prediction.

Plant Availability--In this analysis, plant availability refers to the fraction of daylight hours that the plant is available to operate, assuming good weather conditions. Thus, plant availability reflects scheduled and unscheduled plant maintenance outages but does not reflect weather outages. (Any overlap between maintenance and weather outages is considered to be a weather outage.) A plant availability of 1.0 was used for the initial annual energy prediction reported in Reference 3. The current value is based on a Solar One design requirement of 0.90 (Reference 5). Actual plant availability for power production operation has been slightly less than this value.

Heliostat Availability--Heliostat availability refers to the fraction of the heliostat field that is operational. For the initial prediction, a heliostat availability of 1.0 was used since all 1,818 heliostats were assumed to be operational for the entire year. The current value of 0.990 is based on an average daily outage of 18 heliostats which should be achievable with a vigilant maintenance program.

TABLE I. COMPARISON OF INITIAL AND CURRENT SOLAR ONE SYSTEM EFFICIENCY AND ANNUAL ENERGY PREDICTIONS

ITEM	INITIAL		CURRENT	
	EFFICIENCY (FRACTION)	ENERGY (MW-hr x 10^3)	EFFICIENCY (FRACTION)	ENERGY (MW-hr x 10^3)
Incident Normal Insolation		202		183
Operating Days Availability	1.000	202	0.910	167
Useful Insolation Availability	1.000	202	0.850	142
Plant Availability	1.000	202	0.900	127
Heliostat Availability	1.000	202	0.990	126
Cosine	0.769	155	0.786	99
Blocking and Shadowing	0.932	145	0.967	96
Reflectivity	0.890	129	0.876	84
Atmospheric Attenuation	0.970	125	0.966	81
Spillage	0.976	122	0.979	79
Receiver Absorptance	0.950	116	0.940	75
Radiation and Convection	0.874	101	0.843	63
Piping	0.996	101	0.996	63
Auxiliary Steam	1.000	101	0.927	58
Gross Cycle	0.343	35	0.340	20
Plant Parasitics	0.759	26	0.757	15
Overall	0.130	26	0.082	15

Cosine, Blocking and Shadowing--The current values for these factors were derived from MIRVAL computer calculations because no experimental confirmation of the values exists at this time. See Reference 6 for a description of MIRVAL.

Reflectivity--Heliostat reflectivities of 0.890 and 0.876 were used for the initial and current predictions, respectively. The actual average reflectivity of the Solar One heliostat field is 0.903 if the heliostats are perfectly clean. A reflectivity of 0.876 corresponds to an average cleanliness of 97% (expressed as a percent of the clean field reflectivity) and should be achievable with a bi-weekly wash program.

Atmospheric Attenuation and Spillage--The current values for these factors were derived from MIRVAL computer calculations because no experimental confirmation of the values exists at this time.

Receiver Absorptance--The design receiver absorptance is 0.95. The receiver absorptance was measured to be: November 1982 -- 0.92; November 1983 -- 0.90; September 1984 -- 0.88; and February 1986 -- 0.97 (after repainting). In this analysis a current value of 0.94 was assumed to be representative of the average absorptance which could be achieved by periodic repainting of the receiver surface.

Radiation and Convection--The radiation and convection efficiency in the initial prediction is based on a constant radiation and convection loss of 4.7 MWt during receiver operation. The loss corresponds to an annual energy loss of about 15 x 10^3 MWt-hr. An annual loss of 11.8 x 10^3 MWt-hr was used for the current prediction. This loss was based on an annual receiver operation of 2350 hours and a 5 MWt loss during operation. A comparable estimate of the receiver radiative and convective losses was reported in Reference 7.

Piping--The current value for this factor was assumed to be equal to the initial value because no experimental confirmation of the value exists at this time.

Auxiliary Steam--In plant operation a portion of the receiver steam flow is used periodically to charge thermal storage. The stored energy is used to provide auxiliary steam during the plant's shutdown periods but has not been used to generate electrical power. An annual input to storage of 4.6 x 10^3 MWt-hr was estimated based on data analyzed for the first two years of power production operation.

Gross Cycle--A gross cycle efficiency of 0.343 resulted from the initial annual energy calculation reported in Reference 3. The current efficiency of 0.340 was based on the design turbine cycle performance characteristics (Reference 8) for an average gross output of about 8.5 MWe while on line. An average gross output of 8.24 MWe was achieved during the second year of power production operation.

Plant Parasitics--The plant parasitic values are based on the 24-hour plant load. The current value of 4.8×10^3 MWe-hr is less than the initial value of 9×10^3 MWe-hr. The current value is an average annual load for the first two years of power production operation and reflects a successful effort to reduce the parasitic power requirements for Solar One.

Overall--Weather data for 1976 and design plant conditions resulted in a predicted annual system efficiency of 13% and a plant output of 26,000 MWe-hr net (corresponding to a capacity factor of 30%). In contrast, the use of 25-year average weather data and the substitution of more realistic plant conditions for some design conditions resulted in a predicted annual system efficiency of 8.2% and a plant output of 15,000 MWe-hr net (corresponding to a capacity factor of 17%).

Analysis of Plant Data

The actual plant capacity factors, system efficiencies, and energy outputs for power production operation were less than either their initially or currently predicted values. The effects of actual plant conditions on these values were analyzed to determine where further operating and maintenance improvements are needed to achieve the currently predicted values. The analysis results are shown in Table II and described below.

Incident Normal Insolation--The current predictions for plant performance are based on an annual insolation of 183×10^3 MWt-hr, the 25-year average value. The measured values for the first two years of power production operation, which are shown in the Table, are both lower than this value.

Operating Days Insolation Availability--For 1984, the operating days insolation was estimated to be 2080 kW-hr/m^2 (Reference 4). This value corresponds to an operating days insolation availability of 0.887. An operating days availability of 0.90 was assumed for the first two years of power production operation since the weather was slightly more favorable over these periods and plant operators had more operating experience compared to 1984. However, the availability value is slightly less than the predicted availability of 0.91, which is based on better weather than was observed during the two years of power production operation.

Useful Insolation Availability--For 1984, the useful insolation was estimated to be 1733 kW-hr/m^2 (Reference 4). This value corresponds to an useful insolation availability of 0.833. An useful insolation availability of 0.84 was assumed for the first two years of power production operation since the weather was slightly more favorable over these periods and plant operators had more operating experience compared to 1984. Again, the availability value is slightly less than the predicted availability of 0.85, which is based on better weather than was observed during the two years of power production operation.

TABLE II. EFFECTS OF ACTUAL PLANT CONDITIONS ON SOLAR ONE SYSTEM EFFICIENCY AND ANNUAL ENERGY OUTPUT

ITEM	FIRST YEAR EFFICIENCY (FRACTION)	FIRST YEAR ENERGY (MW-hr x 10^3)	SECOND YEAR EFFICIENCY (FRACTION)	SECOND YEAR ENERGY (MW-hr x 10^3)
Incident Normal Insolation		170		181
Operating Days Availability	0.900	153	0.900	163
Useful Insolation Availability	0.840	129	0.840	137
Plant Availability	0.800	103	0.830	114
Heliostat Availability	0.967	99	0.982	112
Cosine	0.786	78	0.786	88
Blocking and Shadowing	0.967	76	0.967	85
Reflectivity	0.808	61	0.840	71
Atmospheric Attenuation	0.966	59	0.966	69
Spillage	0.979	58	0.979	67
Receiver Absorptance	0.870	50	0.920	62
Radiation and Convection	0.801	40	0.814	50
Piping	0.996	40	0.996	50
Auxiliary Steam	0.884	35	0.910	46
Gross Cycle	0.328	12	0.335	15
Plant Parasitics	0.593	7	0.681	10.4
Overall	0.041	7	0.058	10.4

Plant Availability--The current predictions for plant performance are based on a plant availability of 0.90, the Solar One design requirement (Reference 5). Actual plant availabilities for the first and second years of power production operation were 0.80 and 0.83, respectively.

Heliostat Availability--The current predictions for plant performance are based on a heliostat availability of 0.990. Actual availabilities for the first and second years of power production operation were 0.967 and 0.982, respectively. The heliostat availability for the second year of power production operation excludes a collector field outage in November 1985 that shut down the entire plant. This outage, however, is accounted for in the plant availability of 0.83 for the second year of power production operation. The heliostat availability including the November 1985 outage would be 0.960.

Cosine, Blocking and Shadowing--The values for these factors were derived from MIRVAL computer calculations because no experimental confirmation of the values exists at this time.

Reflectivity--The current predictions for plant performance are based on a heliostat reflectivity of 0.876. The measured reflectivities of the heliostat field averaged 0.808 and 0.840, for the first and second years of power production operation, respectively. The measured reflectivities correspond to heliostat cleanliness values of 89.5 and 93.0%.

Atmospheric Attenuation and Spillage--The values for these factors were derived from MIRVAL computer calculations because no experimental confirmation of the values exists at this time.

Receiver Absorptance--The current predictions for plant performance are based on a receiver absorptance of 0.94. The receiver absorptance was measured to be: November 1982 -- 0.92; November 1983 -- 0.90; September 1984 -- 0.88; and February 1986 -- 0.97 (after repainting in December 1985). As a result, absorptance values of 0.87 and 0.92 were used for analyzing the first and second years of power production operation, respectively.

Radiation and Convection--The current predictions for plant performance are based on an annual radiation and convection energy loss of 11.8×10^3 MWt-hr. This loss assumed an annual receiver operation of 2350 hours and a 5 MWt loss during operation. Losses for the first two years of power production operations were based on: (1) actual hours of plant operation, which includes on-line hours, thermal storage charging hours, and an estimate of effective start-up and shutdown hours; and (2) a 5 MWt loss during operation.

Piping--The actual values for this factor were assumed to be equal to the predicted value because no experimental confirmation of the values exist at this time.

Auxiliary Steam--The current predictions for plant performance are based on an annual input to storage of 4,600 MWt-hr. Storage input for the first and second years of power production operation was estimated to be 4,650 and 4,525 MWt-hr, respectively. These amounts were determined from the actual hours of thermal storage charging and estimates of the average receiver output power.

Gross Cycle--The current predictions for plant performance are based on an annual gross cycle efficiency of 0.340. This efficiency was estimated from the design turbine cycle performance characteristics (Reference 8) for an average gross output of about 8.5 MWe while on line. Similarly, efficiencies were estimated for power production operation from the design turbine cycle performance characteristics and actual average gross power outputs for each year. The average gross outputs while on line were 7.34 and 8.24 MWe during the first and second years of power production operation, respectively.

Plant Parasitics--The current predictions for plant performance are based on an annual plant load of 4.8×10^3 MWe-hr, the average annual load for the first two years of power production operation. Actual measured loads were substituted for analyzing the first and second years of power production operation.

Overall--The current predictions for plant performance are an annual system efficiency of 8.2% and a plant output of 15,000 MWe-hr net (corresponding to a capacity factor of 17%). The actual performance values achieved during power production operation were less than these values. The best performance occurred during the second year of power production operation when the plant achieved an annual system efficiency of 5.8% and a plant output of 10,465 MWe-hr net (corresponding to a capacity factor of 12%). Further operating and maintenance improvements are needed to achieve the predicted values and are discussed below.

Potential Performance Improvements

An examination of Tables I and II shows several areas where plant performance can still be improved. The major areas for further improvement are plant availability and heliostat reflectivity. Other areas where improvements are possible include the operating days availability, useful insolation availability, heliostat availability, and receiver absorptance.

Plant availability, although improving during power production operation, remained below the plant design value of 0.90. Leaks resulting from the thermal cycling of plant equipment, in particular, the receiver tubes, pumps, and valves, were the primary contributors to a reduced availability. An improvement in availability from 0.83 to the design value of 0.90 would increase the plant net electrical output by about 2,000 MWe-hr.

Heliostat cleanliness, which affects the heliostat reflectivity, also improved during power production operation. Cleanliness averaged 89.5 and 93.0% during the first and second years of power production operation, respectively, but remained well below the 97% value used to develop the predicted plant performance. An increase in cleanliness from 93 to 97% would increase the plant net electrical output by about 900 MWe-hr.

The operating days and useful insolation availabilities, although dependent on the weather to a major extent, can also be affected by the plant procedures for start-up, shutdown, and intermittent cloud operation. Improved operating procedures could increase the fraction of the useable direct normal insolation for the plant and contribute to increased power production. Increases in both the operating days availability from 0.90 to 0.91 and the useful insolation availability from 0.84 to 0.85 would increase the plant net electrical output by about 500 MWe-hr.

Significant improvements in heliostat availability and receiver absorptance were achieved during power production operation. Increased maintenance activities brought the heliostat availability to 0.982, close to the desired value of 0.99. Repainting the receiver restored the receiver surface absorptance to 0.97. As a result, the receiver absorptance averaged 0.92 during the second year of power production operation. Increasing the average heliostat availability from 0.982 to 0.99 and the receiver absorptance from 0.92 to 0.94 by means of additional maintenance activities would increase the plant net electrical output by about 200 and 500 MWe-hr, respectively.

Improvements in the heliostat reflectivity, heliostat availability, and receiver absorptance also have a synergistic effect. The improvements result in the turbine-generator operating more at full load than part load, thereby increasing the average turbine cycle efficiency.

Analyses for Solar One have indicated that it would be cost effective to strive for these three improvements. The benefit, in the form of increased plant revenues, exceeds the cost of making the improvements.

An improvement in plant availability is also most desirable but is probably the most difficult to implement. Plant availability is governed, to a large degree, by unscheduled outages. Preventative maintenance, equipment redesign, or the addition of equipment redundancy could improve plant availability, but the costs of these activities are unknown.

Analyses are under way to quantify the benefits of improved operating and maintenance procedures for future commercial-scale power plants. The Solar One plant data are being used to validate the SOLERGY computer code, a code for calculating the annual energy output from a solar central receiver power plant (Reference 9). Initial results indicate that a good correlation between theoretical and actual Solar

One results can be obtained. After validation, SOLERGY will be used to identify factors important to annual energy production and assess the costs and benefits of altering the factors.

Conclusions

Solar One's capacity factor averaged 8 and 12% during the first and second years of power production operation, respectively (corresponding to annual energy productions of 7,024 and 10,465 MWe-hr net). The system efficiency averaged 4.1 and 5.8% over the same periods. Capacity factor and system efficiency have increased considerably during power production testing.

The current predictions for Solar One are an annual capacity factor of 17% (corresponding to an annual energy production of 15,000 MWe-hr net) and an annual system efficiency of 8.2%. Additional operating and maintenance improvements in the areas of plant availability, heliostat availability, and heliostat cleanliness, as well as improved insolation and operating procedures, are required to reach the predicted values.

Early predictions of Solar One performance that were developed at the start of preliminary design are based on overly optimistic plant conditions. For example, the early predictions of a 30% capacity factor (corresponding to an annual energy production of 26,000 MWe-hr net) and a 13% system efficiency are based on 1976 direct insolation data and assume a 100% annual availability of plant equipment. Actual insolation for 1984 to 1986 was lower than 1976, and actual plant and heliostat availabilities were less than 100%. The substitution of more realistic values for these factors and others reduces the plant's expected annual capacity factor from 30% to 17%, annual system efficiency from 13% to 8.2%, and annual energy output from 26,000 MWe-hr net to 15,000 MWe-hr net. A capacity factor of 30%, system efficiency of 13%, and annual energy output of 26,000 MWe-hr net are not possible at Solar One with the current plant configuration.

References

1. L. G. Radosevich, "Final Report on the Experimental Test and Evaluation Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant," Sandia National Laboratories, SAND85-8015, 1985.

2. P. K. Falcone, "A Handbook for Solar Central Receiver Design," Sandia National Laboratories, SAND86-8009, 1987.

3. "Solar Ten Megawatt Pilot Plant Performance Analysis," Solar 10 MW Project Office, Government Support Operations, The Aerospace Corporation, El Segundo, CA, Aerospace Report No. ATR-81(7747)-1, 1981.

4. "Solar One Solar Thermal Central Receiver Pilot Plant: 1984 Meteorological Data Report," McDonnell Douglas Astronautics Company, contractor report SAND86-8181, 1986.

5. "Pilot Plant Station Manual (RADL Item 2-1), Volume 1, System Description," prepared by McDonnell Douglas Astronautics Company under Department of Energy Contract DE-AC03-79SF10499, revised September 1982.

6. P. L. Leary and J. D. Hankins, "A User's Guide for MIRVAL -- A Computer Code for Comparing Designs of Heliostat-Receiver Optics for Central Receiver Solar Power Plants," Sandia National Laboratories, SAND77-8280, 1979.

7. M. C. Stoddard, "Convective Loss Measurements at the 10 MWe Solar Thermal Central Receiver Pilot Plant," Sandia National Laboratories, SAND85-8250, 1986.

8. "10 MWe Solar Thermal Central Receiver Pilot Plant Mode 1 (Test 1110) Test Report," McDonnell Douglas Astronautics Company, contractor report SAND84-8181, 1984.

9. M. C. Stoddard, S. E. Faas, C. J. Chiang, and J. A. Dirks, "SOLERGY--A Code for Calculating Annual Energy from Solar Central Receiver Power Plants," Sandia National Laboratories (to be published).

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