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EVALUATION OF POWER PRODUCTION FROM THE SOLAR ELECTRIC GENERATING SYSTEMS AT KRAMER JUNCTION: 1988 TO 1993

Gregory J. Kolb
Sandia National Laboratories
Albuquerque, New Mexico

ABSTRACT

The five Solar Electric Generating Systems (SEGS) at Kramer Junction, California, now have nearly 30 years of cumulative operating experience. These 30 MW plants employ parabolic trough technology originally deployed by LUZ International in the late 1980's and are now managed, operated, and maintained by the Kramer Junction Company. In this paper, Sandia National Laboratories performed an analysis of the annual energy production from the five plants. Annual solar-to-electric conversion efficiencies are calculated and the major factors that influenced the results are presented. The generally good efficiencies are primarily attributed to the excellent equipment availabilities achieved at all plants.

INTRODUCTION

Over 90% of world's solar-electric energy is delivered from nine plants operating in the Mojave Desert of Southern California. Together these plants provide 354 MW_e to the Southern California Edison utility grid. The technology, known as the Solar Electric Generating Systems (SEGS) are Rankine-steam-cycle plants that are powered by large fields of parabolic trough solar collectors (Figure 1). The trough concentrates solar heat onto a receiver tube, called a heat collection element, containing oil at the focal line of the collector. The hot oil gives up its heat in a steam generator and is recirculated back to the solar field. The plants are owned by private investors. The basic characteristics of these plants are listed below in Table 1.

It can be seen that as the technology progressed, larger plants were built with progressively higher solar field temperatures. Larger plants enjoy better economies of scale and the higher solar field temperatures lead to greater conversion efficiencies. Fossil-fired boilers are used to provide a portion of the power production. Using the methodology mandated by the Federal Energy Regulatory Commission (FERC), 25% of the thermal energy to the steam is allowed to be derived from natural gas. Due to different conversion efficiencies between solar and gas, the actual split on a gross electricity basis is about 70% solar and 30% gas.

In this paper, an analysis of the energy production from SEGS III through VII from 1988 to 1993 will be presented. A previous paper [1] summarized performance during 1989. These plants are located at the Kramer Junction site near Boron, California (Figure 2). KJC Operating Company (KJCOC), a subsidiary of the Kramer Junction Company and the operator of these plants, provided the basic data to Sandia National Laboratories as part of a project aimed at lowering operations and maintenance costs [2, 3, 4, 5, 6].

TABLE 1 BASIC CHARACTERISTICS OF SEGS PLANTS

Plant	Startup Yr	Capacity MW net	Solar Field Temp °C	Solar Collector Technology	Solar Field Size m^2	Solar Mode Rankine Efficiency
I	1985	14	307	LS1/LS2	82960	31.5*
II	1986	30	315	LS1/LS2	165376	29.4
III	1987	30	349	LS2	230300	30.6
IV	1987	30	349	LS2	230300	30.6
V	1988	30	349	LS2/LS3	250560**	30.6
VI	1988	30	390	LS2	188000	37.5
VII	1989	30	390	LS2/LS3	194280	37.5
VIII	1990	80	390	LS3	464340	37.6
IX	1991	80	390	LS3	483960	37.6

* SEGS I efficiency includes fossil superheating
** Field size was 233120 in 1988

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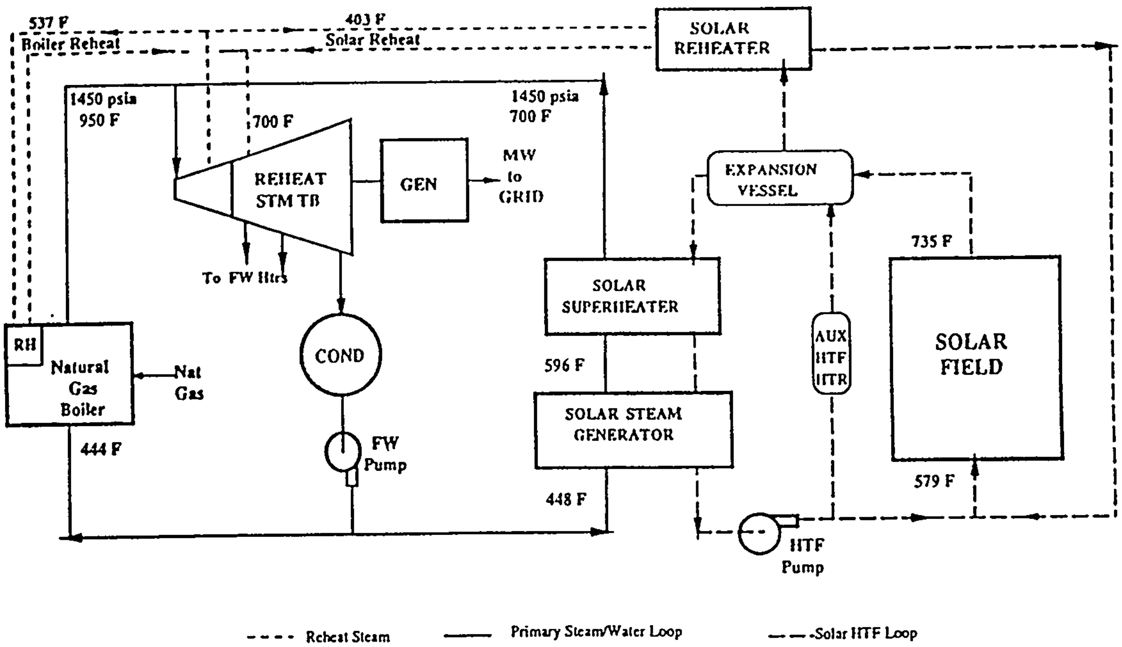

FIGURE 1 PROCESS FLOW DIAGRAM FOR SEGS VI
AND VII

FIGURE 2 AERIAL VIEW OF SEGS III THROUGH VII
PLANTS, KRAMER JUNCTION, CALIFORNIA

In the analysis presented here, Sandia will focus on the solar-only energy production from the plants. The aim is to calculate solar-to-electric conversion efficiencies, on an annual basis, and to identify the major factors that influenced the results. The assumptions that were necessary to remove fossil-hybrid influences are annotated. The analysis techniques are consistent with how Sandia judges the solar-only performance of other solar thermal technologies such as "power towers" and "solar dishes."

In 1991, LUZ declared bankruptcy, but since the plants are owned by financially sound private investors (large U.S. utilities, insurance companies, etc.) all 9 plants are currently operating. The LUZ bankruptcy has, however, caused a lack of spare parts for the solar field. As will be seen in the next section, this has caused a small degradation in performance. Other sources of spare parts are currently being secured by the Kramer Junction Company and it is expected that performance of the plants will be restored to full design levels within a few years.

DEFINITION OF SOLAR-ONLY ANNUAL EFFICIENCY

The net annual solar-conversion efficiency (η) is the ratio of plant output energy (MWh_e) divided by input energy (MWh_t):

$$\eta = \frac{\text{Gross solar} - \text{Parasitics}}{\text{Insolation} * \text{Collection Area}} \qquad (1)$$

The gross solar term is taken directly from KJCOC control room meters. This then is the actual energy produced and includes all factors that influence solar production, i.e., thermal losses, equipment malfunctions, etc. Insolation only includes the direct beam component as measured by several normal-incidence pyroheliometers at Kramer Junction. The collection area is based on the aperture areas installed at the plants and listed in Table 1. These areas are not corrected for cosine foreshortening or reduced because of broken mirrors.

Parasitics consist of electrical parasitics and gas parasitics. Electrical parasitics are derived from the operation of auxiliary equipment such as pumps, lighting, etc. Natural gas is also used periodically to keep the heat transfer fluid above the freezing point and to provide auxiliary steam during offline periods. The viewpoint Sandia has taken in this analysis is that all parasitic consumption should be attributed to the solar operation except those additional electric parasitics generated when the fossil boiler is on-line. This means that all parasitics when both the solar system and the boiler are offline are attributed to the solar plant. The rationale is that even if the boiler was never used, the offline parasitics would not change significantly. A review of offline loads at the plants indicates that this is a reasonable assumption.

The total solar-electrical parasitics (SEP) must be estimated since they are not measured directly:

$$SEP = TEP - 0.08 * GBE \qquad (2)$$

Total station electric parasitic energy (TEP) and gross boiler electric energy (GBE) are both measured at each plant. It has also been observed that while the fossil boiler is on-line that parasitic energy is approximately 8% of the gross boiler electric output.

The total gas parasitics are estimated from a knowledge of gas usage, the heating value of the gas, and the annual heat rate of the fossil boiler. The viewpoint taken here is that gas used for auxiliaries could have been converted to electrical energy if the boiler was on-line. Natural gas at Kramer Junction has a heating value of 922 Btu/ft^3. With heat rate for each fossil boiler expressed in units of Btu/kWhr$_e$, gas parasitics can be converted to equivalent electrical parasitics with the following equation:

$$\text{Solar gas parasitics} = \frac{\text{Aux Gas used (ft}^3) * 922 \text{ (Btu/ft}^3)}{\text{Heat rate (Btu/kWhr)}} \qquad (3)$$

CALCULATION OF SOLAR-ONLY ANNUAL EFFICIENCY

In this section, the equations presented above will be used to calculate the solar-to-electric annual efficiency as well as other performance parameters. The raw data collected from Kramer Junction that is necessary to calculate annual efficiency is given below in Tables 2 through 8.

TABLE 2 DIRECT NORMAL INSOLATION (kWhr/m^2/day)

	SEGS III - VII
1988	7.80
1989	8.08
1990	7.93
1991	7.53
1992	6.32
1993	7.41

TABLE 3 GROSS SOLAR-ELECTRIC PRODUCTION ($MWhr_E$)

	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII
1988	61594	64887	63711	X	X
1989	63031	70470	65216	47950	38818
1990	70443	75712	72368	62608	57661
1991	60134	64308	59009	64156	58260
1992	48702	50970	55383	47095	46940
1993	58248	58935	67685	55725	54110

TABLE 4 GROSS FOSSIL-BOILER PRODUCTION ($MWhr_e$)

	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII
1988	25604	26299	25211	X	X
1989	33392	34688	34305	26431	18926
1990	32564	33501	31908	25050	23980
1991	29011	29051	26524	26976	26310
1992	30671	29962	25617	28077	28026
1993	42400	43019	51850	40910	40750

TABLE 5 SOLAR FRACTION (% OF TOTAL GROSS)

	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII
1988	70.6	71.1	71.6	X	X
1989	65.3	67.0	65.5	64.4	67.2
1990	68.4	69.3	69.4	71.4	70.6
1991	67.5	68.9	69.0	70.4	68.9
1992	61.4	63.0	68.4	62.7	62.6
1993	57.9	57.8	56.6	57.7	57.0

TABLE 6 TOTAL ELECTRIC PARASITIC ENERGY FOR SOLAR AND FOSSIL PLANTS ($MWhr_e$)

	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII
1988	9734	10617	11706	X	X
1989	8630	10265	12143	10149	8590
1990	9846	11128	12830	13017	11812
1991	6458	8798	10841	11445	11572
1992	5986	8297	10503	11275	10443
1993	8255	9269	13243	13071	11990

TABLE 7 FOSSIL BOILER GAS USAGE (KSCF)

	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII
1988	315426	329456	314340	X	X
1989	410068	434537	415165	259445	216004
1990	415247	428433	411370	311533	284451
1991	365499	371279	349022	323808	304741
1992	387774	383623	332759	314732	312770
1993	537128	544997	683707	455988	451323

TABLE 8 AUXILIARY (PARASITIC) GAS USAGE (KSCF)

	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII
1988	39159	37396	51447	X	X
1989	20653	30132	37631	564	932
1990	12580	20317	22510	336	487
1991	9289	22487	12882	1329	1252
1992	8722	20847	16474	3572	3686
1993	10473	10415	13454	3241	3136

Before performing an analysis of the data presented in Tables 2 through 8, a few observations should be made.

Review of Table 2 indicates that insolation dropped significantly in the last 3 years relative to the first 3 years and was especially poor during 1992. This was caused by aerosols from the eruption of the Mt. Pinatubo volcano in June of 1991 and a concurrent year of El Nino weather patterns. The effect that this drop in insolation had on gross solar production can be clearly seen in Table 3. In general, all plants experienced their lowest solar production during 1992; the exception is the expected low production at SEGS VI and VII during their 1989 startup year. Because of the reduced insolation, KJCOC received a waiver from FERC to increase fossil-boiler usage at the end of 1992 and early 1993 to make up for lost solar production. The FERC waiver caused the lower solar fraction (Table 5) for the years 1992 and 1993.

Another observation from the raw data is that gas parasitics are significantly lower at SEGS VI and VII than at SEGS III through V. Since SEGS III through V maintain condenser vacuum throughout the nighttime shutdown period and SEGS VI and VII do not, the former requires more auxiliary steam to maintain seals. The source of auxiliary steam is initially derived from residual heat from a shutdown steam generator. After this heat is exhausted, natural gas is used as a heat source. It can be noted, however, that gas parasitics at SEGS III through V were significantly reduced after the first 2 years of operation as more was learned regarding conserving gas.

The computation of annual solar-only efficiency was performed by applying equations 1 through 3. This produced the results presented in Tables 9 through 11 below.

TABLE 9 GROSS ANNUAL SOLAR-TO-ELECTRIC CONVERSION EFFICIENCY (%)

	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII
1988	9.39	9.90	9.60	X	X
1989	9.28	10.4	8.83	8.65	6.77
1990	10.6	11.4	9.97	11.5	10.2
1991	9.50	10.2	8.57	12.4	10.9
1992	9.17	9.59	9.58	10.9	10.5
1993	9.35	9.46	9.99	11.0	10.3

TABLE 10 NET ANNUAL SOLAR-TO-ELECTRIC CONVERSION EFFICIENCY (%)

	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII
1988	7.74	8.14	7.52	X	X
1989	8.16	8.92	7.13	7.19	5.53
1990	9.33	9.85	8.32	9.47	8.48
1991	8.73	8.86	7.16	10.6	9.12
1992	8.37	8.18	7.90	8.70	8.57
1993	8.44	8.39	8.50	8.98	8.58

TABLE 11 PARASITIC LOSSES (%)

	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII
1988	17.6	17.7	21.7	X	X
1989	12.1	14.0	19.2	16.9	18.4
1990	11.7	13.3	16.6	17.7	17.2
1991	8.1	12.8	16.4	14.6	16.4
1992	8.7	14.8	17.6	19.8	18.2
1993	9.8	11.3	15.0	18.1	16.7

Several trends can be observed from Tables 9 through 11.

Since SEGS VI and VII use a reheat turbine cycle that is not present at SEGS III through V, they have a higher power conversion efficiency in both the solar and fossil modes. This causes a lower annual fossil-boiler heat rate and a higher gross solar-to-electric conversion efficiency (Table 9) for SEGS VI and VII. The lower boiler heat rate can be verified by combining Tables 4 and 7; the heat rate is about 1000 $Btu/kWhr_e$ lower at SEGS VI and VII.

Another reason for the larger solar efficiencies at SEGS VI and VII is because the solar field temperature is higher. Table 1 indicates that the solar field outlet temperature is 41°C higher at SEGS VI and VII.

Except for SEGS V, the plants attained their best annual efficiency during the years 1990 or 1991. Turbine-generator problems at SEGS V caused a lower than normal power block availability during 1991 and a consequent drop in annual efficiency. There were 3 main factors why 1990 and 1991 were generally the best years:

1. The plants had been on-line for at least 2 years and most startup problems were solved. After this 2-yr startup period, Sandia has observed that all plants have routinely achieved a solar field availability >98% and an overall plant availability >93%; the latter includes the annual outage to perform scheduled maintenance.

2. The insolation during 1990 and 1991 was better than 1992 and 1993. Since thermal losses from the solar field are approximately constant when the plant is operating, the efficiency of power collection will decrease when insolation is lower. This can be seen from the following equation:

$$\eta_{col} = \frac{P_{out}}{P_{in}} = \frac{P_{sun\,in} - P_{loss}}{P_{sun\,in}} \qquad (4)$$

   With P_{loss} constant, efficiency will decrease when solar input power decreases. Thus, solar collection efficiency was poorer during 1992 and 1993.

3. LUZ International declared bankruptcy in late 1991. This led to a shortage of spare parts for the solar field. Prior to the bankruptcy it was common practice to replace broken mirrors and degraded heat collection elements, thus maintaining a higher solar collection efficiency. Sources for new spare parts are currently being sought and there is a plan to return the solar collection efficiency to its design level by 1996.

Another trend can be noted upon examination of Table 11. The data indicates that the overall parasitic losses are generally lower at SEGS III and IV than at SEGS V through VII. The losses are lower for primarily 2 reasons. Firstly, the pressure drop across a solar-field-flow loop is less at III and IV which results in reduced pump parasitics. The pressure drop is less because there are 14 serially-connected solar collector assemblies (SCA) per loop at III and IV, whereas there are 16 SCAs at SEGS V through VII. Secondly, the maintenance shops for all five plants are assigned to the parasitic load of SEGS V and VI. Finally, it can be noted from Table 11 that parasitic losses have significantly dropped at SEGS III through V over the years. The primary reason for this is the reduction in gas parasitics at these plants as discussed previously.

INFLUENCE OF HYBRID OPERATION ON SOLAR EFFICIENCY

In order to compare the SEGS efficiencies presented in this paper with other solar technologies, it is important to understand the influence that the operation of the fossil-boiler has on SEGS solar efficiencies. The effect on plant parasitics was discussed and the results were modified as discussed in the previous section. However, there is one influence that has not been included. When a SEGS plant is operating at full turbine load with a portion of the energy coming from solar and the remainder from fossil energy (i.e., in hybrid mode), the solar energy is converted to electricity at a higher efficiency than if the turbine was running at part load on the energy from solar alone. This is because a turbine is more efficient when operating at full load than at part load. This effect occurs most often in the winter; because of the low sun angles the solar field is only capable of providing 10 to 15 MW_e. When operating the 30 MW turbine in solar-only mode at this derated power, the conversion efficiency is about 33%. If fossil energy is added to bring the turbine to full load the solar-conversion efficiency is raised to 37.5%. The hybrid operation therefore causes the efficiencies presented in the previous section to be slightly higher than if the plants always operated in a solar-only mode.

To obtain an estimate of how much the hybrid operation could influence the annual efficiencies, a bounding analysis was performed with a SOLERGY [9] model of the SEGS VI power plant. With this model the solar production that occurred at SEGS VI during 1991 can be closely approximated. The model was run twice, once assuming solar-only operation and another time assuming hybrid operation during the weekdays. (SEGS plants always run solar-only on weekends and holidays.) Assuming hybrid operation during all weekdays is a bounding assumption because there are many weeks during the year in which the plants run solar-only or fuel-only. In both cases, energy required to start the turbine was derived from solar energy, which is also the case for the real SEGS plants. This analysis indicated that annual efficiency would not be improved by more than 2%. Thus the 10.6% annual efficiency that SEGS

VI achieved during 1991 could be no lower than 10.4% if the plant ran in a solar-only mode.

CONCLUSIONS

The SEGS plants at Kramer Junction have achieved admirable annual solar efficiencies. The efficiencies are generally higher than what was achieved during a calendar year at the 10 MW Solar One central receiver power plant on both a gross and net basis [7]. Based on our current knowledge, Sandia believes that the net annual efficiency of 10.6% achieved by SEGS VI during 1991 is better than what has been achieved by all photovoltaic and solar thermal systems except for the ~12% achieved by the 25 kW MDAC Stirling dish during its third and last year of operation by Southern California Edison [8]. A primary reason for the good efficiencies at Kramer Junction is the very high availability of the plant equipment; the availabilities of the solar field and entire plant are typically greater than 98% and 93%, respectively. This high availability has also resulted in all plants meeting or exceeding all on-peak energy production targets established for the plants (Table 12).

TABLE 12 KRAMER SEGS HISTORICAL PERFORMANCE SUMMARY - % OF PEAK PERIOD CAPACITY

[Data in table taken directly from Reference 4]

	SEGS III	SEGS IV	SEGS V	SEGS VI	SEGS VII
1988	103.7	103.1	104.1	X	X
1989	106.9	108.8	107.6	101.9	102.7
1990	104.7	105.7	104.6	102.5	102.9
1991	103.8	104.4	102.6	103.8	101.5
1992	107.7	106.8	103.1	105.6	106.3
1993	107.0	108.8	106.1	106.9	107.4

Since the majority of the electricity revenues are earned during the on-peak period, this is a crucial achievement to ensure the future economic viability of the SEGS technology. The definition of annual efficiency used in this paper includes all effects that influence plant performance and is a much better indicator, than a peak or daily efficiency, to judge the potential economic viability of a solar technology. The annual efficiencies presented in this paper could be used as a benchmark to judge the performance of future solar-thermal electric systems.

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