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Solar Two Performance Evaluation Methodology

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ABSTRACT

Solar Two is a 10-MWe prototype central-receiver plant east of Barstow, California. Solar Two, which is sponsored by a consortium of utilities and industry in partnership with the U.S. Department of Energy, began regular electricity production in February 1997. The objective of Solar Two's performance evaluation activity is to understand the plant's performance and to use the evaluation information for the following purposes: optimize plant performance, extrapolate Solar Two's performance to general performance of molten-salt central-receiver technology, and recommend revisions to predictive models and engineering design methods for Solar Two and future-generation molten-salt central-receiver technology.

The primary aspect of the performance evaluation is the lost-electricity analysis. This analysis compares the actual generation with the generation predicted by the Solar Two model. (SOLERGY, a computer program designed by Sandia National Laboratories to simulate the operation and power output of a solar central-receiver power plant is the code used to model Solar Two.) The difference between the predicted and the actual generation (i.e., the lost electricity) is broken down into the different efficiency and availability categories responsible for the loss. Having the losses broken down by system and in terms of electricity is useful for understanding and improving the plant's performance; it provides a tool for determining the best operating procedures for plant performance and the allocation of operation and maintenance resources for the best performance payback.

NOMENCLATURE

E_{INC}	Daily incident thermal energy, kWhr. This is the daily integrated direct normal solar radiation multiplied by the total heliostat field reflective area.
$E_{UNAVAIL}$	Daily incident thermal energy during times that salt is not flowing through the receiver and SOLERGY indicates that the receiver should be in operation, kWhr.
E_{AVAIL}	Daily incident thermal energy during times that salt is flowing through the receiver, kWhr.
%AreaTracking	Daily fraction of field area that tracked the receiver. Averaged over the time that salt flowed through the receiver.
Clean	Cleanliness of the field, as measured throughout the month by the plant maintenance crew.
η_{field}	General field efficiency. Includes reflectivity, cosine loss, spillage, etc.
η_{REC}	Receiver efficiency.
E_{COLL}	Daily thermal energy collected by the receiver and transferred to the working fluid, kWhr.
η_{TS}	Loss factor for energy passed through thermal storage and the heat transport piping. Defined as the ratio of the thermal energy collected on the salt side of the steam generator system (SGS) to the thermal energy collected by the receiver throughout the month. Includes the effect of thermal energy consumed during short-term hold by the SGS.
E_{TOSGS}	Daily thermal energy sent to the steam generator for warmup and power production, kWhr.
$\eta_{SGS/EPGS}$	Combined thermal efficiencies of the steam generation system and the electric power generation system.
E_{GROSS}	Daily gross electric energy generated, kWhr.

E_{PARA}	Daily electric parasitic energy, kWhr.
E_{NET}	Daily net electrical energy generated, kWhr.

INTRODUCTION

In a molten-salt central-receiver plant, a field of sun-tracking mirrors called heliostats reflects the sun's energy onto a cylindrical receiver that is mounted on a tower. Molten salt runs through the receiver and is heated from 288°C to 566°C (550°F to 1050°F). From the receiver, the hot salt goes to thermal storage where it is then sent through a steam generation system to produce steam, which powers a turbine to produce electricity. The cooled salt then returns through the thermal storage system to the receiver. Figure 1 shows a diagram of a molten-salt central-receiver plant.

Solar Two is a 10-MWe central-receiver plant located outside of Barstow, California. Solar Two was built in 1996 and is currently demonstrating the viability of molten-salt technology at a reasonable size, which should allow a low-risk scaleup to commercial sizes in subsequent plants.

The objective of Solar Two's performance evaluation and prediction activity is to determine and understand the plant's performance (on an instantaneous, daily, and annual basis) and to use the evaluation information for the following purposes:

- Optimize plant performance
- Extrapolate Solar Two's performance to general performance of molten-salt central-receiver technology
- Recommend revisions to predictive models and engineering design methods for Solar Two and future-generation molten-salt central-receiver technology.

The overall approach of the performance evaluation as it applies to understanding and optimizing Solar Two performance is to compute the actual performance values (e.g., collection, production, consumption, availabilities), compare them with predicted values, and then attempt to understand the agreement or disagreement between them. The first step of this process is to reduce the actual Solar Two plant data to calculate the pertinent performance parameters listed above. The performance parameters are then compared to performance predictions from a Solar Two model. The model used is SOLERGY, a computer program developed at Sandia National Laboratories that simulates the operation and power output of a solar central-receiver power plant.[1] The SOLERGY predictions provide a design-point performance baseline for the plant that makes it possible to understand the details of why the plant is or is not performing as designed.

The precise modeling of Solar Two performance is important to optimizing plant performance, but it is also an integral part of extrapolating the plant performance evaluation to the general performance of molten-salt central-receiver technology. One way Solar Two data will assist in developing future-generation molten-salt central-receiver technology is by helping to develop accurate modeling techniques for the technology. However, significant uncertainties still exist in the performance modeling of the plant. An important aspect of the performance analysis is that disagreement between predicted and actual plant performance may not be due to inadequacies on the part of Solar Two, but rather inaccuracies on the part of the SOLERGY model. The primary causes of these inaccuracies are due to uncertainties associated with the following:

- wind losses from the receiver (receiver efficiency tests have not yet been performed under high-wind conditions)
- calibration of instrumentation (primarily flow meters)
- degradation of the heliostat field
- modeling of the plant parasitics
- realistic operating patterns resulting from the

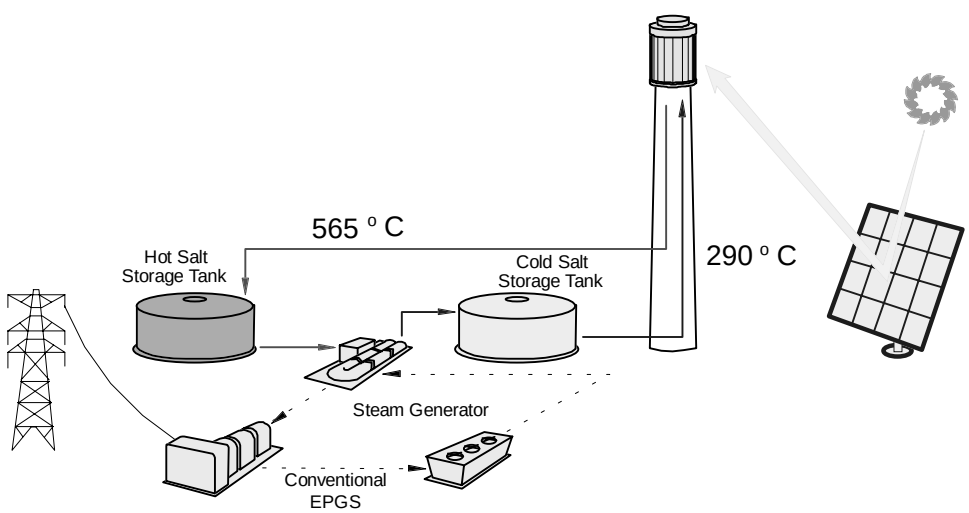

Figure 1: Schematic of a molten-salt central-receiver power plant.

plant's "human element."

As Solar Two operating experience accumulates and the performance evaluation progresses, Solar Two data also will become useful for future-generation central-receiver technology designs. A significant portion of the evaluation will be to examine which Solar Two operating procedures and equipment types best accommodate optimized performance. These procedures and equipment types will become part of future designs. Operating procedures and equipment not conducive to optimizing plant performance should be reviewed for exclusion from potential plant designs.

METHOD OF LOST-ELECTRICITY ANALYSIS

The primary aspect of the performance analysis is the lost-electricity analysis, which is summarized on a monthly basis. The analysis treats the gross electricity generation predicted by the model as the design performance level for the plant. Any difference between the design performance (modeled values) and the actual performance (measured values) is translated into lost electricity.

Losses = SOLERGY Prediction – Solar Two Performance

The results are useful in determining which operating procedures are best for plant performance and where to get the best return—in terms of power generation—on plant operation and maintenance resources.

Because the SOLERGY prediction is based on an ideal, design-level performance for the plant's current configuration and because the Solar Two design is still being debugged and operation is not yet fully optimized, Solar Two's actual performance is generally (but not always) lower than SOLERGY's performance. In this documentation, if Solar Two under-performs relative to the model, the calculated losses are positive. If Solar Two out-performs the model, all equations here are still valid but losses become negative.

The final product of the analysis is the calculated difference between the actual and predicted gross generation. The difference (i.e., the lost electricity) is broken down into the different efficiency and availability categories responsible for the loss. The steps that lead up to this final product, are as follows:

Step 1. Calculate and Process Actual Plant Performance

The plant data that are used in the lost-electricity analysis are:

- insolation
- wind speed
- heliostat field cleanliness
- heliostat field availability
- energy to the working fluid in the receiver
- energy to the steam generator system (SGS)
- gross electricity from the turbine.

The weather data and the gross electricity are metered directly at Solar Two. The actual weather data is used as input to the SOLERGY model. The energy to the working fluid and the energy to the SGS are calculated from actual plant data. The energy to the working fluid is used to determine whether or not the actual solar plant thermal delivery matches the design. The energy to the steam generator and the gross electricity are used together for power plant efficiency calculations. All plant performance data are processed over five-minute intervals with the exception of the weather data, which is processed in 15-minute intervals for SOLERGY.

Step 2. Calculate SOLERGY Predicted Performance

Using a given month's actual weather data, a SOLERGY model of Solar Two is run to calculate the design performance of the plant in terms of energy to the working fluid, energy to the steam generator, and the gross electricity from the turbine.

Important SOLERGY assumptions for the analysis are:

- 98% heliostat field availability
- 95% field cleanliness, corresponding to heliostat field washing on a two-week cycle
- heliostats are canted and tracking properly
- heliostat field efficiency includes what we know about existing mirror corrosion.

Using these assumptions in the model does not necessarily mean these values agree with actual plant conditions. Rather, their use results in a metric that describes what the collector system ought to be able to achieve. By design, 98% of the heliostats should be available for tracking the receiver. If the heliostat field availability is below 98%, the actual thermal collection will be lower than the predicted value. To bring the performance up to the design level, the heliostat field availability would need to be improved. All of the SOLERGY input values are based on values thought to be achievable after optimization is complete, given the plant's current design configuration.

SOLERGY data inputs and outputs are on a 15-minute time interval. When finer time intervals are required for comparing the SOLERGY output with the actual data, the analysis does a linear interpolation between the SOLERGY points. The SOLERGY run spans the entire month, but each day's performance is examined separately.

Step 3. Determine When Plant Was and Was Not Available for Operation

This is the first step in distinguishing between availability losses and efficiency losses. The analysis begins by examining the actual and modeled energy to the working fluid on a five-minute basis. It determines at which times the Solar Two

receiver was operating and the SOLERGY model determined it should have been and at which times the Solar Two receiver was not operating but the model determined it should have been. If both the actual and the modeled energy to the working fluid are nonzero for a five-minute time span, the plant is classified as available during that time span. If, on the other hand, the actual energy to the working fluid is zero and the modeled is nonzero, the plant is classified as unavailable during that time span.

For isolating times when the plant was unavailable, the assumption is that all Solar Two plant availability problems will either immediately or eventually force the receiver to become unavailable. For example, an SGS unavailability significant enough to cause a loss in gross generation (as opposed to just a slight shift in the generation profile) will result in a loss of receiver availability once the hot storage tank is full and there is no more cold salt to run through the receiver. This example illustrates why it is necessary to examine the energy to the working fluid as part of the lost-electricity analysis. Without looking at the energy to the working fluid, it could not be determined if a problem with the SGS caused a generation loss due to availability (i.e., shut down receiver operation) or just caused a slight delay in electricity generation.

The methodology for this portion of the analysis is illustrated in Figure 2. Figure 2 is a plot of the actual and predicted power to the working fluid for one day in March 1998. The total area under the curve represents the predicted energy collection for the day. The area labeled $E_{UNAVAIL}$ represents the predicted energy to the working fluid when the actual plant was not operating. The area labeled E_{AVAIL} represents the actual energy to the working fluid, which in this example is being collected during a time of predicted energy collection. Thus the plant was available during the time span indicated by the area labeled E_{AVAIL}.

It should be noted that times when the receiver was operating and SOLERGY predicted it should not have been are classified as times when the plant's performance beat the design-level performance. These times are tracked and reported in a category separate from the available and unavailable categories.

Step 4. Attribute Losses

The last step in the analysis breaks down the plant/system losses into different categories. The loss analysis begins with the energy incident on the heliostat field and tracks that energy through the plant to generated electricity. This analysis path is illustrated in the flow diagram in Figure 3.

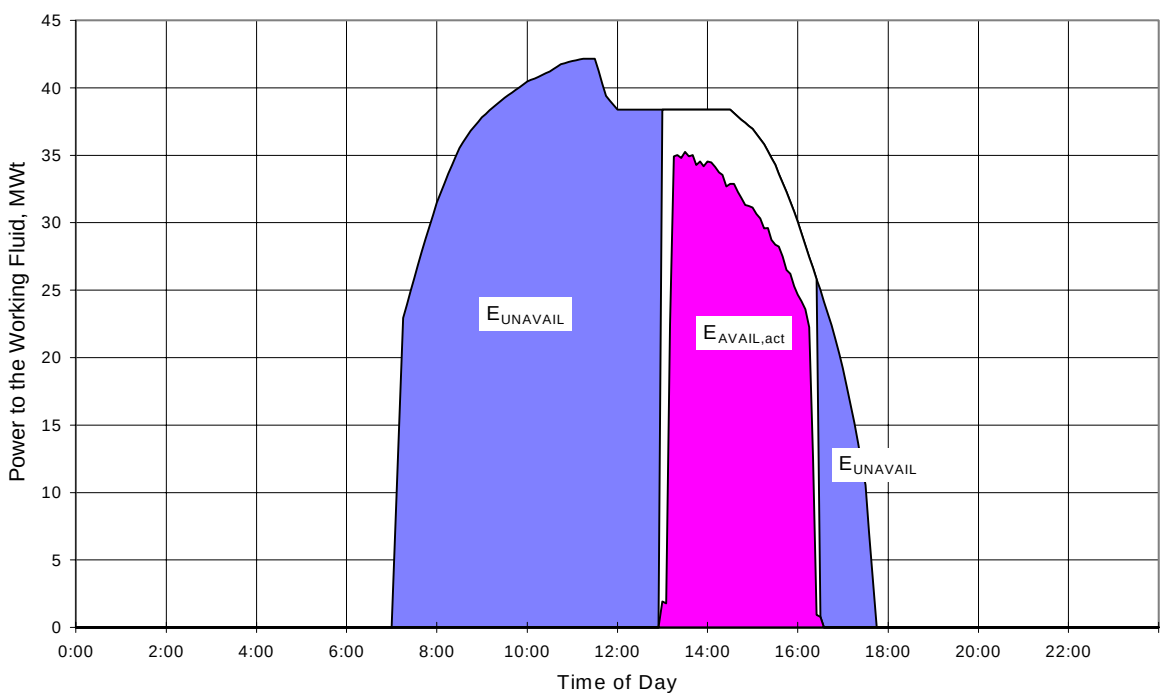

Figure 2: Energy to the Working Fluid — Available and Unavailable Time Spans for SolarTwo and SOLERGY

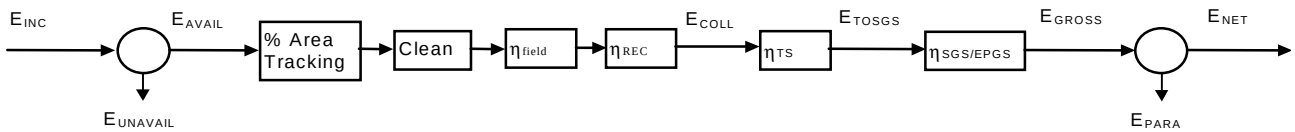

Figure 3. Energy Flow Diagram for Solar Two Lost-Electricity Analysis

The mathematical relationship for the energy flow shown in Figure 3 is as follows in Equation 1:

$$E_{GROSS} = (E_{AVAIL})(\%AreaTracking)(Clean)(\eta_{field}) \bullet (\eta_{REC})(\eta_{TS})(\eta_{SGS/EPGS}) \quad [1]$$

All of the terms in Figure 3 can be calculated from plant data except for $E_{UNAVAIL}$ and E_{AVAIL}, which require SOLERGY results. The receiver efficiency, η_{REC}, has been measured by testing (for low-wind conditions) and documented.[2]

The sensitivity to a change in each term on the right-hand side of Equation 1 on the gross electrical production, E_{GROSS}, can be estimated by taking the partial differential of E_{GROSS} with respect to that term. That is:

Sensitivity to Change in Available Energy =

$$\frac{\partial E_{GROSS}}{\partial E_{AVAIL}} = -(\%AreaTracking)(Clean)(\eta_{field})(\eta_{REC})(\eta_{TS})(\eta_{SGS/EPGS}) \quad [2]$$

And the energy lost due to a difference in the factor relative to the SOLERGY model can be estimated by multiplying the sensitivity by the magnitude of the change in the factor:

Energy Lost due to fewer heliostats tracking than predicted =

$$E_{LOSS,\%TRACK} = (E_{AVAIL})(Clean)(\eta_{field})(\eta_{REC})(\eta_{TS}) \bullet (\eta_{SGS/EPGS})\Delta\%AreaTracking \quad [3]$$

Energy Lost due to soiled heliostats =

$$E_{LOSS,CLEAN} = (E_{AVAIL})(\%AreaTracking)(\eta_{field})(\eta_{REC}) \bullet (\eta_{TS})(\eta_{SGS/EPGS})\Delta Clean \quad [4]$$

Energy Lost due to lower field efficiency than predicted =

$$E_{LOSS,FIELD} = (E_{AVAIL})(\%AreaTracking)(Clean)(\eta_{REC}) \bullet (\eta_{TS})(\eta_{SGS/EPGS})\Delta\eta_{field} \quad [5]$$

Energy Lost due to lower receiver efficiency than predicted =

$$E_{LOSS,REC} = (E_{AVAIL})(\%AreaTracking)(Clean)(\eta_{field}) \bullet (\eta_{TS})(\eta_{SGS/EPGS})\Delta\eta_{REC} \quad [6]$$

Energy Lost due to greater heat losses from the storage tanks and thermal transport system than predicted =

$$E_{LOSS,TS} = (E_{AVAIL})(\%AreaTracking)(Clean)(\eta_{field}) \bullet (\eta_{REC})(\eta_{SGS/EPGS})\Delta\eta_{TS} \quad [7]$$

Energy Lost due to lower SGS and EPGS thermal efficiency than predicted =

$$E_{LOSS,SGS/EPGS} = (E_{AVAIL})(\%AreaTracking)(Clean) \bullet (\eta_{field})(\eta_{REC})\Delta\eta_{SGS/EPGS} \quad [8]$$

The change in the efficiency factor is determined by the predicted values being chosen as the reference case. For example, Equation 8 would be computed as:

$$\left[(E_{AVAIL})(\%AreaTracking)(Clean)(\eta_{field})(\eta_{REC})\right]_{PRED} \bullet \left(\eta_{SGS/EPGS_{PRED}} - \eta_{SGS/EPGS_{ACT}}\right) \quad [9]$$

where the subscripts PRED and ACT indicate predicted and actual (i.e., SOLERGY and Solar Two) terms, respectively.

The sum of the loss estimates in Equations 3-8 is not equal to the total lost electricity. This is because the loss expressions assume discrete difference. Because the same reference (predicted) is used in Equations 3-8, they do give the relative contribution of each loss factor, so the actual losses can be quantified. To apportion that part of the lost electricity not accounted in the partial differential equations, all loss factors are multiplied by the correction factor in Equation 10.

$$F_{CORR} = \frac{E_{GROSS,PRED} - E_{GROSS,ACT}}{E_{LOSS,UNAVAIL} + E_{LOSS,\%TRACK} + E_{LOSS,CLEAN} + E_{LOSS,FIELD} + E_{LOSS,REC} + E_{LOSS,TS} + E_{LOSS,SGS/EPGS}} \quad [10]$$

The equations and energy flow diagram in this section were originally documented in a July 15, 1998, memo by S. Faas.[3]

It is important to note that $E_{UNAVAIL}$ in Figure 3 goes through the same loss analysis that E_{AVAIL} does. This method of loss attribution was used rather than attributing all generation losses during these times to plant availability losses because it more accurately categorizes losses. The lost-electricity analysis serves as a tool for plant optimization, and this method of dealing with $E_{UNAVAIL}$ provides a more accurate picture of the electricity that would be gained if a specific problem were corrected. Using this method, the electricity loss attributed to plant availability is the actual amount that would be gained if the plant availability were at the design level. Correcting the availability problems would not, however, influence the plant's performance in areas such as the percent area of the field area tracking, receiver efficiency, etc.

The results of the lost-electricity analysis are summarized in monthly plots. Examples of two of these plots for September 1998 are shown in Figures 4 and 5. Figure 4 shows a pie chart that quantifies the gross electricity lost due to various causes. One advantage of this plot is that it quantifies each loss fraction in terms of electrical energy. The whole pie represents the difference between the total SOLERGY predicted gross generation and the actual Solar Two generation. The individual pie wedges quantify the fraction of loss attributed to each loss factor. Another advantage of this plot is that it also explicitly calls out the availability losses; all of the wedges from Miscellaneous Availabilities through Operator Discretion are availability losses.

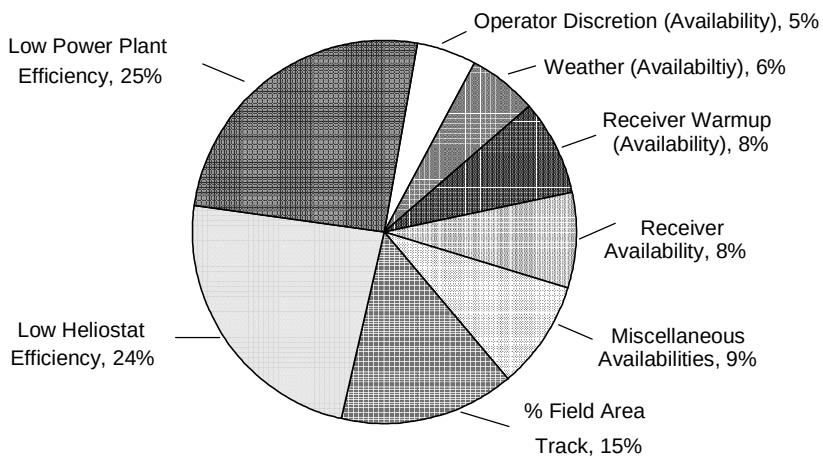

Figure 4: September 1998 Solar Two Gross Electricity Loss Contributions

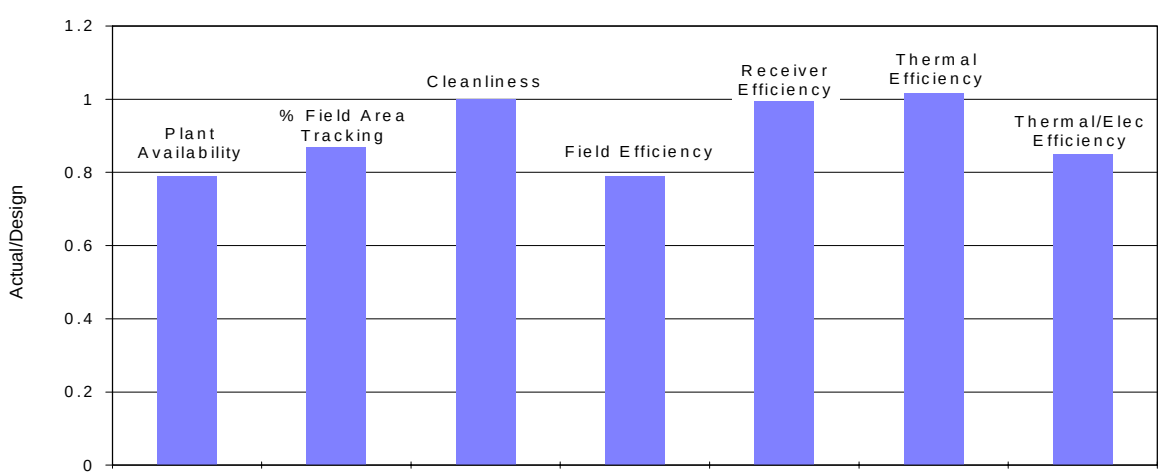

Figure 5. September 1998 Solar Two Plant System Effectiveness (Actual System Efficiency/SOLERGY System Efficiency)

Figure 5 shows an "effectiveness" chart that corresponds to the energy flow diagram shown in Figure 3. Each bar in Figure 5 is a ratio of the Solar Two system efficiency to the SOLERGY system efficiency. A bar with a value of one represents a Solar Two system that met predicted performance; any value less than one represents performance below the predicted level. Figure 5 illustrates that the September 1998 plant availability was approximately 80% of design availability, which was 90%. It also shows that the field cleanliness, the receiver efficiency, and thermal efficiency were at design level, whereas the percentage of the field tracking, field efficiency, and the thermal-to-electric conversion efficiency were below design level. It should be noted that the thermal-to-electric conversion efficiency losses were more significant than usual in September because of a test that was run to characterize the SGS. The losses illustrated in this plot are consistent with those in Figure 4.

As pointed out earlier, there is still uncertainty in several areas of the data and modeling. The two potentially most significant uncertainties are the SGS flow meter readings and the true receiver efficiency during windy conditions. We suspect that the SGS flow meter readings are higher than the actual flow rate and that the actual receiver efficiency is at times lower than that calculated under non-windy test conditions. The plot in Figure 6 illustrates the effect on the loss distribution if each of these factors were reduced 10%. The difference in the modified bar heights from the baseline bar height can be treated as a preliminary uncertainty band.

MODEL VALIDATION

In validating the SOLERGY model for Solar Two, to the extent possible, we incorporate actual plant conditions into the model as opposed to design plant conditions. At a minimum this includes actual heliostat availability (daily average) and cleanliness.

The areas we have chosen for model validation are:

- energy to the working fluid
- thermal losses between the receiver and the SGS
- operating efficiency of the SGS/EPGS
- electric parasitic consumption.

The SOLERGY validation for Solar Two is still in its early stages; we are currently working on validation of energy to the working fluid.

Preliminary results show that during ideal weather conditions (i.e., no wind or high, thin clouds) SOLERGY does a fairly good job of predicting energy collected by the working fluid. The plot of power to the working fluid for September 30, 1998, in Figure 7 shows an example of this. This was a day that had morning clouds that cleared abruptly and ideal weather once the clouds cleared. During the time SOLERGY determined the receiver should be collecting energy for this day, the results show 6.5% error between Solar Two and SOLERGY. (Notice that Solar Two actually "beat" SOLERGY at the end of the day. This is because the operators tracked the sun into the ground.) This margin of error is indicative of days with no equipment or weather problems.

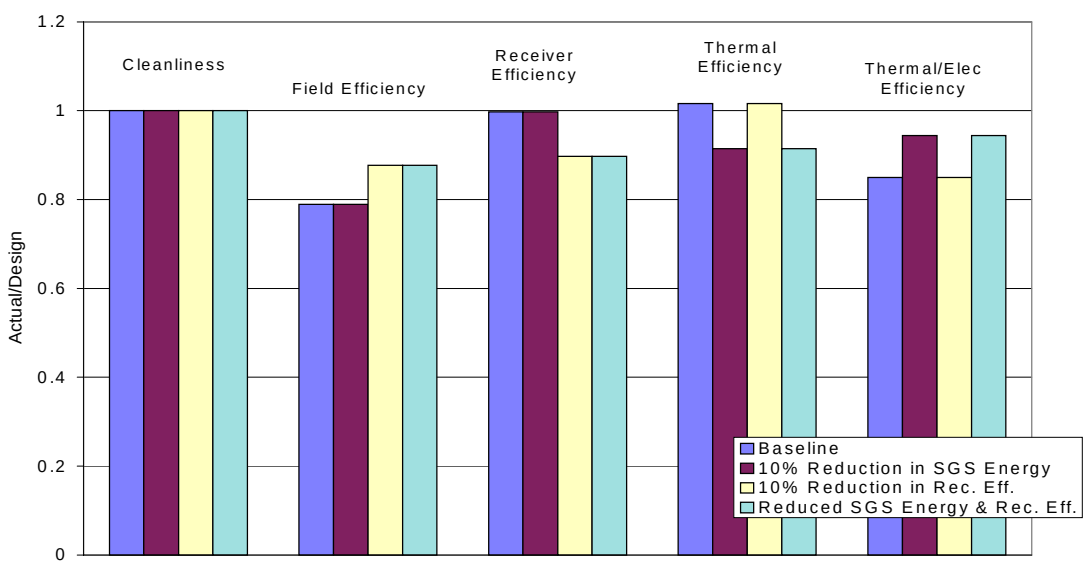

Figure 6. September 1998 Sensitivity of System Effectiveness (Actual System Efficiency/SOLERGY System Efficiency).

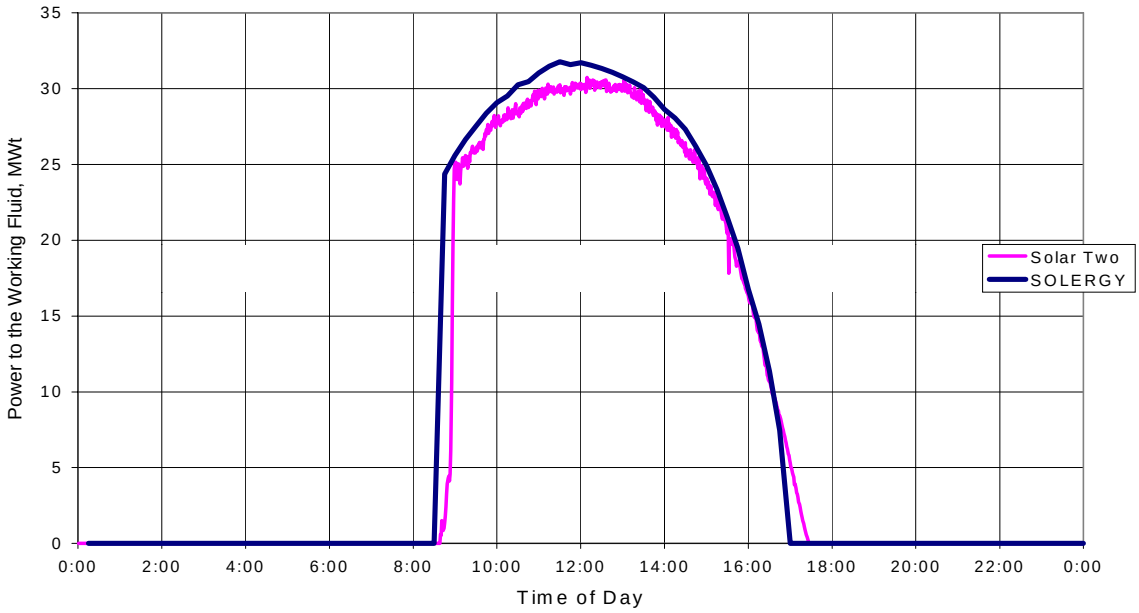

Figure 7: Actual and Predicted Power to the Working Fluid, September 30, 1998

On windy days, however, this analysis pointed out discrepancies that need further investigation. An example of this is shown in the September 29, 1998 power to the working fluid plot shown in Figure 8. (It should be noted that the Solar Two plant was shut down early on September 29th for reasons unrelated to the weather.) The difference between the modeled collections and the actual is greater than 20%. The SOLERGY wind loss model (based on a study conducted by Siebers and Kraabel[4]) is based solely on receiver surface area, but it is suspected that during even slightly windy conditions there may be significant thermal losses from the connecting tubes on the receiver. These losses need to be investigated and incorporated into SOLERGY. While not absolutely necessary, it would be beneficial to have the results of receiver efficiency tests in high winds in developing a wind-loss model for this receiver. These tests are planned for the near future.

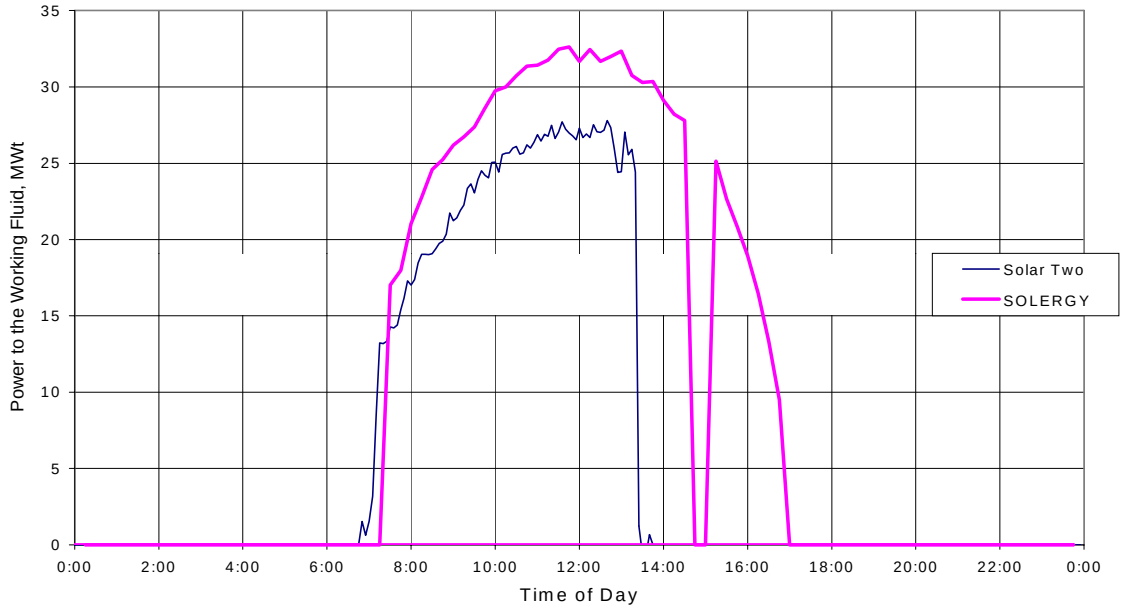

Figure 8: Actual and Predicted Power to the Working Fluid, Windy Conditions, September 29, 1998

CONCLUSIONS AND RECOMMENDATIONS

The Solar Two performance evaluation activity has reached the point where it is able to help with the plant optimization objectives. Using the relatively general results of the lost-electricity analysis, we have tracked down abnormally large system losses and we are now in the process of examining the details of these losses. However, this process needs to continue and expand. To refine the loss isolation and performance optimization process, we must complete the model validation. The biggest challenge in model validation is better characterizing the heliostat field conditions and the receiver losses. We also need to extend the analysis to include the electric parasitic consumption. This process is currently under way.

ACKNOWLEDGEMENTS

I would like to thank the Scott Faas, Greg Kolb, and Hank Price for their assistance in developing and reviewing the performance evaluation methodology.

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