Validation of the FLAGSOL Parabolic Trough Solar Power Plant Performance Model

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NOTICE

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ABSTRACT

This paper describes the results of a validation of the FLAGSOL parabolic trough solar power plant performance model. The validation was accomplished by simulating an operating solar electric generating system (SEGS) parabolic trough solar thermal power plant and comparing the model output results with actual plant operating data. This comparison includes instantaneous, daily, and annual total solar thermal electric output, gross solar electric generation, and solar mode parasitic electric consumption. The results indicate that the FLAGSOL model adequately predicts the gross solar electric output of an operating plant, both on a daily and an annual basis.

INTRODUCTION

Accurate projections of solar electric plant performance are critically important in the design of such plants and as an input for strategic and cost trade-off decisions for operation and maintenance of operating plants. Performance models can be constructed with a wide range of complexity, from simple models that take only the most important variables into account to more extensive models that treat plant systems in considerable detail. Models of the latter type allow the user much greater flexibility in evaluating the effects of specific design features or plant conditions.

In addition to flexibility, the value of a performance model obviously depends on its ability to provide accurate and useful projections of solar plant output. The accuracy of performance projections from a model can be evaluated in various ways, for example, by common sense comparisons to expected output based on the plant design and the solar input, by detailed comparison with the output of other models, and by rigorous comparison with actual plant operating data. The comparison with operating data is favored but is often limited by a scarcity of adequate data for comparison, or by the ability of the model to simulate the features of a real plant in sufficient detail.

This paper presents the validation of a performance model developed by Flachglas Solartechnik GmbH (FLAGSOL) for use in feasibility studies of large parabolic trough solar electric plants. The operating data against which the model was validated were supplied by the KJC Operating Company, a subsidiary of the Kramer Junction Company, for a typical 30-MW plant of the solar electric generating system (SEGS) type. The following sections describe the model, the extent of the data, and the results of the validation comparisons.

MODEL DESCRIPTION

The FLAGSOL Performance Model is a computer code that simulates the performance of solar electric power plants that use parabolic trough solar collectors. The plant configuration typically includes a supplemental fossil fuel energy source to back up the solar field in periods of low insolation. The model accommodates normal quasi-steady-state conditions, daily startup and shutdown, and changing weather conditions during operation. The model was developed based on the experience gained from similar programs such as the Luz System Performance Model (Kearney, 1988) developed by Luz Industries Israel for the design of the SEGS plants and SOLERGY (Stoddard, 1987) developed by Sandia National Laboratories for central receiver plants. The FLAGSOL model has been significantly extended beyond a usual SEGS design to include plant configurations with combustion turbine combined cycles, thermal energy storage, and dry cooling. Furthermore, the FLAGSOL model was extended during the course of this validation to simulate more details of actual plant conditions; these improvements are discussed below.

The FLAGSOL Performance Model consists of three modules: the first defines the plant configuration; the second executes the simulation; and the third sums up the results and generates a report. The complete flow diagram of a performance calculation is shown in Figure 1.
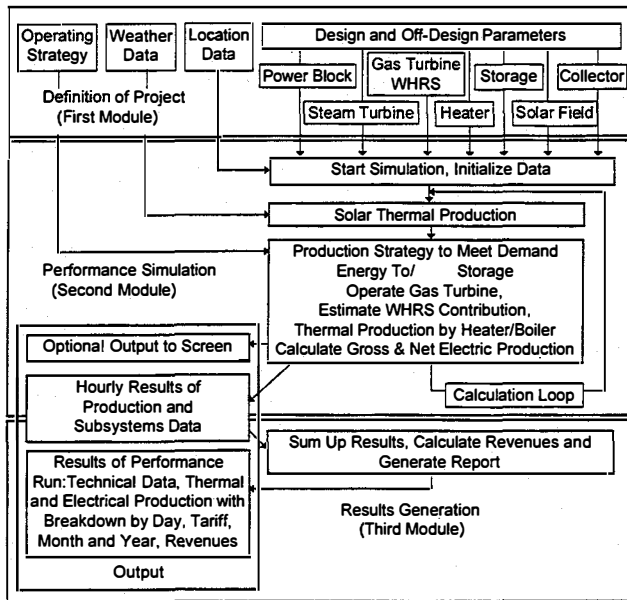
FIGURE 1. FLOW DIAGRAM OF THE FLAGSOL
PERFORMANCE MODEL.

A performance calculation starts with the definition of the plant configuration, specific subsystems, meteorological data, and load demand profiles (first module). All definitions of subsystems are stored in different files so that manifold alternatives can be easily and quickly examined. After the definition of the project, the second module takes over control and the simulation starts. It is also possible to run the model in a batch mode, in which several plant configurations are simulated successively.

At the beginning of a simulation run all necessary data are loaded and initialized. The calculation uses fixed time steps of an interval defined by the user, with a maximum length of one hour. During the simulation the calculations can be suspended at any moment to observe current values in detail. The date, time, insolation, temperatures, mass flow and energy flow in all subsystems from solar field to power block, as well as gross, net, and parasitic power can be displayed on the screen for the actual simulation time step. This feature gives the user helpful information about how the plant behaves under different operating conditions. This feature can be used to look at a single time step or successive time steps to observe trends during plant operation. This information can be printed to a file.

When the simulation is finished, the second module chains to the third, which generates a report. The standard output of the performance calculation consists of a breakdown by day, month, and electrical revenue period of the following variables: direct normal insolation, insolation to the collector and absorber, average heat losses, thermal energy produced (both solar and fossil), fossil fuel usage, electrical energy production (gross, parasitic, net, from grid), and revenues (energy and capacity payment).

A complete description of the model can be found in Flachglas Solartechnik GmbH (1994).

MODEL VALIDATION

The model validation was accomplished by simulating an operating SEGS parabolic trough solar thermal power plant and comparing the model output results with actual plant operating data. The closeness of such a comparison indicates the accuracy and applicability of the model. The eventual goal of the validation is an overall comparison of a hybrid plant—one which uses both solar and natural gas as fuel sources. The current state of the analysis includes only the solar portion of the plant. The effort to date includes comparisons among solar field thermal delivery, gross solar electric production, and solar mode parasitic electric consumption. The approach taken in this validation was to compare the *instantaneous* operation of the plant and model on selected days, and to compare the actual and projected *annual* performance of the plant.

A significant amount of actual weather data and plant operating data was required for the validation. The operator of the SEGS III-VII plants (KJC Operating Company), located at Kramer Junction in the California Mojave Desert, agreed to provide proprietary data to FLAGSOL for the purpose of validating the model with the understanding that the specific plant and the exact period of the comparison would not be disclosed because of contractual sensitivities. The comparison was made for the plant design that includes the more advanced re-heat turbine power cycle and the higher solar field operating temperature 735°F (391°C).

Accurate weather data (direct normal radiation, ambient temperature, and wind velocity) are essential for providing meaningful comparison results. The weather database used in this study was generated using data collected at the plant site. Five-minute instantaneous data recorded by the plant data acquisition system were used for all of the daily instantaneous comparisons. Gaps in this data precluded its use in the annual simulation runs. As a result, the annual simulations used hourly weather data that were an average of 10-minute data collected from several adjacent plants.

Model input parameters were set, where possible, to reflect the real plant design and actual operational conditions (for example, turbine efficiency, mirror reflectivity, number of broken mirrors and equipment availability). During the validation effort, the coding of the model was improved in a general sense to permit a more accurate description of a plant via the input parameters, as described below.

The results of actual LS-2 collector efficiency testing recently performed at Sandia National Laboratories were used as the basis for the collector model input parameters (Cohen, 1993 and Dudley, 1994). For example, the heat collection element (HCE) heat loss algorithm in the model was modified to correspond to the Sandia test results. In addition, the HCE heat losses now account for the percent of broken, lost vacuum, and clouded HCEs in the solar field. Also, the heat losses in the model are now a function of heat transfer fluid (HTF) temperature, ambient temperature, solar radiation, and in the case of HCEs with broken glass, wind speed. The collector optical efficiency, incident angle modifier, and HCE shadowing descriptors were set to match the Sandia test results for the type of collectors at the Kramer Junction plants.

In summary, the model was improved to use the as-tested collector efficiencies and allow actual monthly solar field and power block availabilities, HCE status (broken glass, lost vacuum, fluorescent glass), missing mirror status, and average mirror reflectivity to be entered as input parameters.

Daily Comparisons

The main purpose of the daily comparisons were to evaluate the ability of the model to reproduce the real plant performance on an instantaneous basis (i.e., 5-minute data) throughout the day. Daily solar-only comparisons were done for typical sunny summer, fall, and winter days to see how the model responds to seasonal effects. Daily comparisons were also made on a high wind day and a partially cloudy day. For each of the days, the instantaneous solar thermal output, solar electric output, and parasitic electric loads were compared. This type of comparison allows plant startup and other timing considerations to be evaluated. In addition, the cumulative integrated performance for each day was also calculated and is summarized in Table 1.

In general the model tends to slightly over-predict solar thermal output, gross solar electric output, and on-line parasitic electric consumption. Using design input assumptions, the model under-predicts the off-line parasitic load. Actual solar output is matched fairly closely during the summer day, but seems to be less accurate on the fall and winter days. However, it is useful to look at the instantaneous output for a better understanding of the fit between the model and the actual plant data. Figure 2 shows the daily instantaneous comparisons between the model and the actual plant data for gross solar electric output on typical summer, fall, and winter days. Much of the discrepancy during the fall day is caused by an equipment problem resulting in a 30-minute start-up delay in the morning. Adjusting for this availability delay, the model reasonably predicts the actual solar electric output of the plant. During the winter, losses have a larger impact on the total daily output, making it is more difficult to accurately predict the performance of the plant.

The instantaneous parasitic electric consumption of the plant is slightly overestimated by the model while the plant is producing
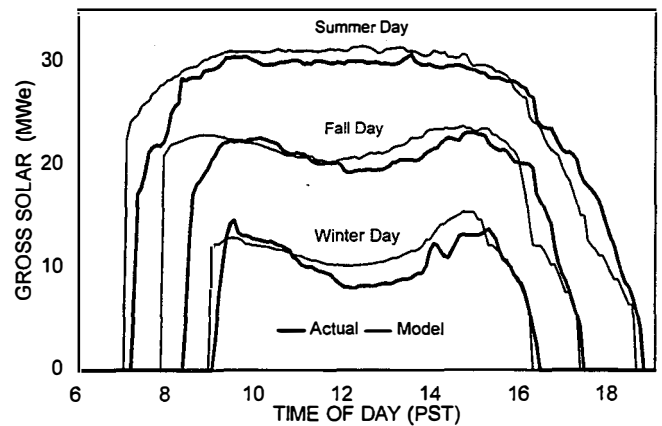
FIGURE 2. ACTUAL AND PROJECTED GROSS SOLAR ELECTRIC OUTPUT FOR SUMMER, FALL, AND WINTER DAYS

power, and underestimated when the plant is off-line. The modelled plant parasitic loads need to be fine-tuned to better reflect the actual equipment operating loads.

The new HCE heat loss algorithms allowed the model to reproduce the performance impacts resulting from high-wind conditions experienced by the operating plants.

The model had more difficulty reproducing the exact operating profile of the plant on partially cloudy days. Figure 3 shows the daily comparisons between the model and the actual plant data for gross solar electric output on a partially cloudy day. This discrepancy is most likely caused by a number of factors. The solar radiation data used is measured at a single location at the edge of the plant. Multiple instruments located throughout the solar field would be required to get a more accurate average solar radiation level on partially cloudy days, because clouds may cover part of the field at any given time and leave the rest of the field in direct sunlight. Also, 5-minute average insolation data would probably be better than the 5-minute instantaneous data used. The model

TABLE 1. DAILY COMPARISON BETWEEN MODEL AND ACTUAL PLANT

Case	Solar Thermal % of Actual	Gross Solar Electric % of Actual	On-Line Solar Parasitics % of Actual	Off-Line Parasitics % of Actual
1. Sunny Summer	103	103	118	50
2. Sunny Fall	113	109	116	50
3. Sunny Winter	113	108	109	40
4. High Wind	102	108	110	50
5. Partially Cloudy	114	127	118	60
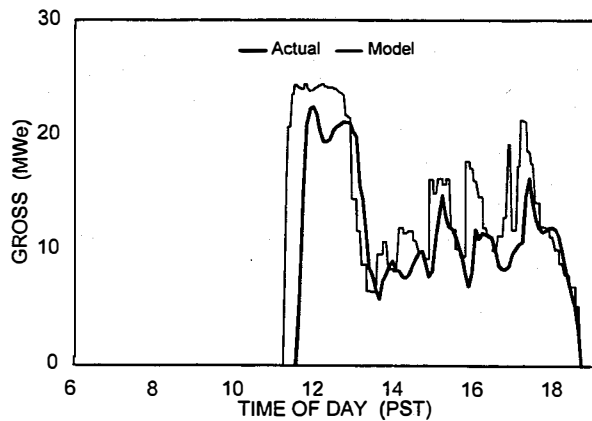
FIGURE 3. ACTUAL AND PROJECTED GROSS SOLAR ELECTRIC OUTPUT FOR A PARTIALLY CLOUDY DAY

operates in a quasi-steady-state mode that responds more quickly to solar radiation transients than does an actual plant. It takes time for the heat collected in the solar field to return to the power plant heat exchangers, generate steam, and reach the turbine. In addition, it takes different lengths of time for the heated oil to return to the power block from different portions of the solar field. In a real plant, this results in a mixing of various oil temperatures, accompanied by a smoother variation in solar field outlet temperature. The solar field and power plant also have thermal capacitance which tends to damp out the spikes produced by the model. Finally, operator actions can have a significant effect on the plant output on a partially cloudy day. However, on an annual basis, the lower performance on some partially cloudy days tends to cancel out the higher than projected performance on other partially cloudy days.

Annual Comparisons

The purpose of the *annual* comparison is to evaluate the ability of the model to reproduce the real plant performance for an entire year. The main measures were actual versus projected comparisons of solar thermal output, gross solar electric output, and parasitic electric consumption.

The comparisons between projected and actual gross solar electric production were very good on an annual basis. Table 2 shows the comparison of actual and projected gross solar electric production by month and for a full year. The table shows data for three cases: *all days*, *excluding outage days* (meaning only the days during which the plant actually operated), and for *solar-only* operation *days* (when no gas-firing, which can have a secondary effect on solar-generated electricity, was used). The *all-days* comparison shows the model to be within 5% of the actual on an annual basis. On a monthly basis the deviation is larger because of plant outages. The large error in January is caused by the planned 2-week annual maintenance outage. The second case,

TABLE 2. GROSS SOLAR ELECTRIC PRODUCTION- ACTUAL AND PROJECTED FOR ALL DAYS, INCLUDED DAYS, AND SOLAR ONLY DAYS (BY MONTH)

	All Days Model % of Actual	Excluding Outages Model % of Actual	Solar Only Days Model % of Actual
Jan	229.3	84.7	123.5
Feb	93.9	93.9	109.8
Mar	113.5	106.5	105.9
Apr	108.6	107.2	107.2
May	102.0	100.7	101.4
Jun	98.0	97.4	95.0
Jul	103.9	103.7	102.2
Aug	102.5	101.7	99.8
Sep	100.0	100.0	105.2
Oct	111.4	102.2	111.1
Nov	111.7	111.7	112.3
Dec	108.0	108.0	120.8
Year	**104.5**	**102.1**	**104.3**

excluding outages, removes all days from the comparison where plant outages impacted solar operation. The annual comparison is within 2%. On a monthly basis, the model very closely predicts the summer performance, but has more difficulty with winter projections. During the winter, small variations can have a much larger effect on total performance because of the generally lower solar production levels at that time of year. The solar-only case compares days where there was no fossil operation during hours of solar operation. This shows essentially the same results as the prior case, but eliminates any bias resulting from fossil operation. This shows a higher monthly variation, however, there are substantially fewer days included in the comparison.

Figure 4 shows the projected gross solar electric output plotted against the actual gross solar electric output. Note that the scatter falls fairly evenly on both sides of the line (which represents the case where the model exactly predicts the actual plant output). Based on this figure, there are often +/-30 MWhe per day variations between actual and projected gross solar output, but on average the model gives good agreement with actual output. This day-to-day variation is likely caused by variations in daily solar field and power block availability, operator interaction, and inaccuracies in the weather database (hourly data).
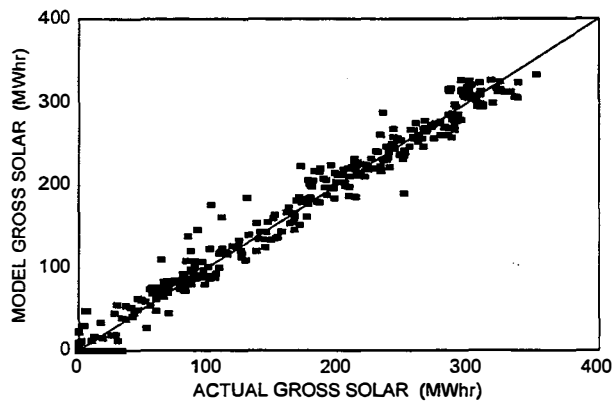
FIGURE 4. ACTUAL VS. PROJECTED DAILY GROSS SOLAR ELECTRIC OUTPUT

Solar mode parasitic loads were evaluated on days when there was no gas boiler operation. When the boiler is operated, it is difficult to determine which parasitic loads are attributed to the boiler operation and which are attributed to solar or balance-of-plant operation. The daily total results show the same trend as in the instantaneous comparisons. The model tends to slightly over-predict the actual parasitic loads while the plant is on-line and under-predict the parasitic load of the plant when it is off-line.

DISCUSSION

A number of factors have a significant effect on the accuracy of this analysis. The first is the quality of the weather and insolation data. Accurate direct normal radiation data is difficult to maintain. A small error in the calibration of instruments or transmitters translates to errors in the measured radiation. Also shadowing, alignment of the instruments and the need for cleaning are additional concerns. On sunny days a single instrument can generally provide acceptable insolation data. However, on partially cloudy days a single instrument or multiple instruments at the same location will not necessarily give a representative value of what the plant experienced. More instruments dispersed through the solar field would be required to get a better representative value. Also the weather instruments are located at the edge of the solar field; the location could have impacted the accuracy of the model on the cloudy days.

This evaluation used 5-minute instantaneous data whereas 5-minute average data would probably have improved the simulation. Because 5-minute radiation data were lacking during the first half of the year, the annual simulation was done using hourly averages of 10-minute radiation data collected from several of the plants. Ideally the analysis would have been done using 5- or 10-minute average data from the plant in question.

Wind data also affected the plant. From a modelling standpoint both the maximum and the average wind speed are important. The average wind speed is used to determine the heat losses from the broken HCEs, and the maximum wind speed is used to evaluate whether the solar field must be shut down during high-wind conditions to protect it from damage.

Although this validation made every attempt to accurately reflect the actual status of the plants in the input, this is a difficult task, especially for an annual analysis. For example, mirror reflectivity varies from day to day. It is possible to accurately measure the reflectivity of a point on a mirror, but it is a more difficult task to determine the average reflectivity of 200,000 m^2 of mirror surface. For purposes of this analysis, monthly average mirror reflectivities were used. These are based on a fairly small sample of points, often taken only a few times during a given month. As such, fairly large errors in the monthly values are possible, and day-to-day variations are likely even larger.

HCE and mirror status are accounted for on a monthly basis. The model was modified to reflect the actual heat losses of HCEs as tested on the rotating collector test platform at Sandia National Laboratory. However, only one pair of HCEs were tested, first with vacuum intact, then with holes drilled through the metal bellows allowing air in the vacuum space, and finally with the glass broken. A statistical sampling of tubes would have been required to get a more accurate value. Also, degradation of the optical properties of the black chrome HCE tubes with broken glass occurs over time as a result of surface oxidation. This impact was not accounted for in this analysis.

The actual plant data used in this analysis for comparison with the model results also had its limitations. Some uncertainty exists in the calculated solar field thermal energy delivery, the gross electric output, and the parasitic electric loads. The calculation of the solar field thermal energy delivery requires accurate flow and temperature instrumentation and accurate property data for the heat transfer fluid. Although operators at this plant spend a significant effort keeping the instrumentation calibrated, it is likely that the severity of the environment (high temperature), the heat transfer fluid used, and the quality of the instrumentation cause the accuracy of the thermal calculation to be in the ±10% range. In addition, the property data used to calculate thermal energy and the HTF specific heat and density are based on the manufacturer's data. These properties for HTF fluids often vary with time (reference Solar One Study, Faas and Thorne). Density can be easily measured, but it is difficult to get accurate specific heat data. The electric meters used to monitor the plant gross electric generation and parasitic loads are not high precision meters, and are probably ±2% at best.

A number of weaknesses exist in the model that reduce its ability to accurately reproduce the normal operation of a SEGS plant. A fairly simplistic approach is used to model the turbine start-up, based on an assumed time delay and thermal energy delivery requirement. Then the model immediately ramps up to the maximum output achievable based on the thermal delivery of the solar field. This approach can be used, but the parameters that match the actual plant start-up vary somewhat throughout the year. A more accurate start-up model that reflects the actual start-up requirements and the maximum ramp rate of the turbine would be more desirable. The steepness of the model ramp rate as opposed to the actual plant start-up can be seen in data in Figure 2.

A second weakness of the model is the part-load operation of the plant. The model corrects for turbine efficiency at part-load; however, the model does not reflect the actual operating conditions of the plant. The model assumes that the plant continues to operate at design solar field outlet temperature and design turbine inlet and outlet steam temperatures and pressures. In practice the solar field and turbine are operated at reduced temperatures and pressures at part load conditions. This affects heat losses and efficiencies of both systems. Also, the time lags and the thermal capacity of the plant could be added to the model. These are less relevant when the model is run using hourly data, but could help to more closely reflect actual plant output when finer time steps are used.

Finally, because the SEGS plant cycle on a daily basis and many of the systems are manually controlled, the normal day-to-day and even moment-to-moment operational decisions impact the comparison. This point is most obvious during the winter daily data shown in Figure 2. The small peak and subsequent valley in actual gross electric generation between 1400 and 1430 hrs is an example. The model projection shows a fairly smooth increase in power output during this time, which is common during this part of year for east/west tracking parabolic trough collectors. The likely scenario was that the HTF flow to the solar field was not increased fast enough to keep up with the increasing solar conditions. As a result the solar field slowly began to increase outlet temperature. The flow was then increased to cool the solar field down resulting in an increased surge of hot HTF to the heat exchangers and increased steam production. The power output momentarily increased until the cooler oil resulting from the increased flow through the solar field started reaching the heat exchangers, then the power level dropped. Although this is not the optimal control mode for the plant, it probably had minimal impact on the daily output. However, this example shows the impact that normal plant operations can have on electric output. The plant's influence is most significant during plant startup and hybrid operation.

CONCLUSION AND RECOMMENDATIONS

A comparison was made between the projected performance and actual performance of a 30-MW SEGS plant for data gathered over a full year of operation by the KJC Operating Company at Kramer Junction, California. As a result of evaluating daily and annual comparisons, it can be concluded that the FLAGSOL solar plant performance model adequately predicts the gross solar electric output of an operating plant, both on a daily and an annual basis. On an annual basis, accuracies on the order of ±5% seem to be possible given the correct input assumptions. On a day-to-day basis, the deviations between the model and actual output can be higher as a result of operator interaction, transient weather, and system availabilities. Ideally 5- or 10-minute data should be used to evaluate plant performance, however even hourly data can be used to obtain reasonably accurate performance projections.

A model of this type is valuable for projecting the expected output of existing and future solar thermal electric power plants.

The model also proves useful in understanding which areas are contributing to under-performance of the plant. This is a useful tool for an operator to help prioritize operation and maintenance efforts to improve daily and annual performance.

Improvements to this validation would include improving the quality of the solar radiation and plant data, improved accuracy of plant status, and minor upgrades to the model. In addition, further analysis of solar field and power plant efficiencies, losses, and parasitic loads would be necessary. A more detailed understanding of the actual operating modes and practices would also be useful.

Finally, it seems that it is not possible to create a model that exactly models the performance of an operating solar thermal power plant. There are too many unknown parameters, often caused by the sheer size of a real solar thermal electric power plant. Such parameters include mirror reflectivity, optical properties, heat losses, component efficiencies, and even solar radiation resource data. In addition, transient effects are often too complex to be exactly modeled.

Equipment availability and human intervention add additional difficulties to the process. However, given proper assumptions, a reasonable model can be developed that, on average, reasonably predicts the performance of a solar thermal electric power plant.

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