Proceedings of ASME 2012 6th International Conference on Energy Sustainability & 10th Fuel Cell Science, Engineering and Technology Conference
ESFuelCell2012
July 23-26, 2012, San Diego, California, USA

ESFuelCell2012-91458

LONG TERM PERFORMANCE OF THE SKYTROUGH SOLAR CONCENTRATOR

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ABSTRACT

The SkyTrough is an advanced integrated parabolic trough concentrator designed for high performance and low cost to achieve economic objectives in the market for high grade heat for industrial processes and electrical generation. To achieve low cost, a comprehensive optimization process was carried out for every component based on the choice of low cost silvered polymer film as the reflector. To verify high performance, the optical efficiency of a single module was measured at the National Renewable Energy Lab (NREL), and a demonstration loop was constructed in December, 2009 at the SEGS-II solar power plant in Daggett, CA, USA. This paper compares operating data recorded over eighteen months for the commercial demonstration at the SEGS-II plant with model predictions based on the NREL efficiency measurement. The comparison demonstrates that the SkyTrough system will perform predictably over time. Additional data illustrating the good performance of the collector in wind, and the sustained reflectance of the mirror film, are presented.

INTRODUCTION

The SkyTrough parabolic trough collector was designed from the ground up to reduce the cost of concentrating solar power (CSP). Parabolic trough technology is considered a safe prospect for financing because plants built in the 1980s in California continue to operate well, as do troughs built within the past decade in the U.S. and Spain. Thorough testing, combined with extended and regular operation of the SkyTrough at a commercial solar plant, have now demonstrated the many innovations in the SkyTrough and also provide a sound basis for product warranty. Specifically, the SkyTrough performance has matched the response predicted by optical, durability, and thermal testing for two years, and there has been no reduction in output.

The SkyTrough Solar Collector Assembly (SCA) has a 6 meter wide aperture, 656 m^2 of aperture area, and is 115 meters in length. A single SkyTrough mirror module ($82m^2$) was tested by the National Renewable Energy Laboratory (NREL), along with receivers, and performance was reported by Gawlik, et al. [1,2] as 77.3% optical and 73.7% thermal at an average operating temperature of 350°C. The incident angle modifier was also established during NREL testing. A steady state model of performance was developed based on that test data, with adjustments only for field conditions of cleanliness, shading, and blocking. No modifications for translation from a single mirror module to a complete loop were applied, nor was any change in the optical performance associated with wind included. Wind speed was included in the calculation of receiver loss, as described by Crawford, et al. [2].

FIGURE 1. SkyTrough SCAs in operation at SEGSII in Daggett, California.

A 1 MW_{th} SkyTrough demonstration loop was installed at the SEGS II commercial solar plant in late 2009, and is pictured in Figure 1. The data acquisition system was completed in June 2010. The thermal output is continuously measured, and the results are compared against model predictions based on NREL efficiency measurements. The agreement between the measured results and the model for a single day of operation was reported by McMahan, et al. [3], and is illustrated by Figure 2. Differences between measurements and predicted results in the early and late parts of the day illustrate the thermal capacitance: the system output lags in the morning and leads in the afternoon.

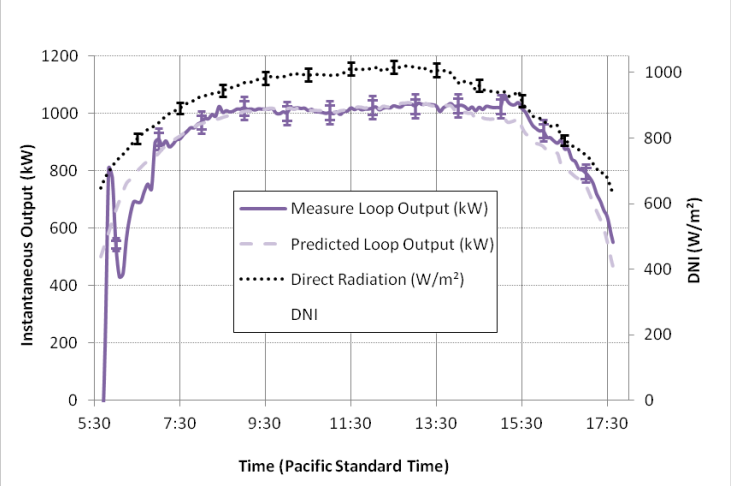

FIGURE 2. Performance of SkyTrough loop over the course of a day, measured and predicted.

The performance model, measurements, and data uncertainty for seven contiguous days were independently confirmed by Sargent and Lundy [4]. The integrated daily output for the seven days, including the day for which results are shown in Figure 2, matched the predicted performance.

This paper extends that data set by eighteen months, and demonstrates that performance has been sustained. Measured performance of the loop under high wind conditions is compared to predicted performance, and validates the integrity of the SkyTrough structural system. Direct measurement of reflectance at the SEGS II facility, combined with accelerated testing performed by NREL, have provided the basis for extended thermal performance and reflectance warranties.

PERFORMANCE OVER EIGHTEEN MONTHS

The SkyTrough has operated at the SEGS II facility for more than two years. The cumulative hours of operation for the eighteen months during which data were recorded are shown by month in the bar graph of Figure 3. Operating time is defined as the number of hours the system is actually engaged in tracking, and providing thermal output to the power plant.

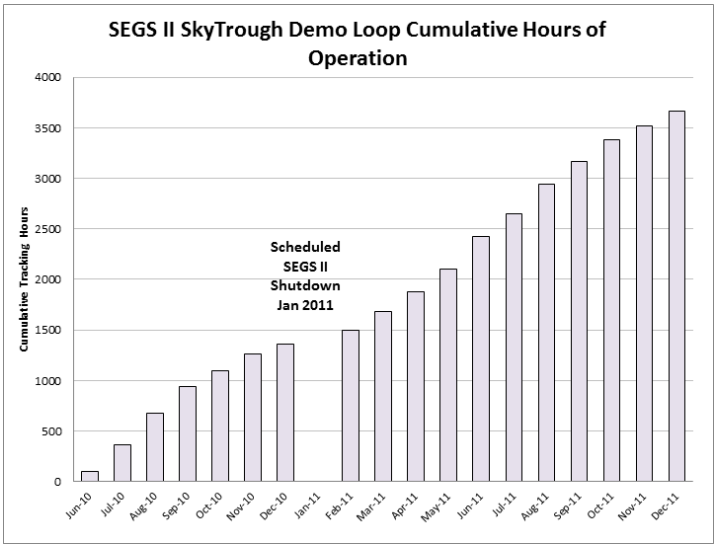

FIGURE 3. SkyTrough cumulative hours of operation, since installation of the data acquisition system.

The measured and predicted integrated loop output are plotted for the same eighteen month period and shown in Figure 4. Some variances occurred in September and October 2010, as well as January 2011. In September, communication with the data acquisition system was lost, and was restored in October. The collectors continued to operate. After a careful review of the performance, SkyFuel noted that the central control system did not send the clock synchronization signal, typically required on a daily basis, to maintain the accuracy of the tracking algorithm. This problem was immediately corrected and performance was restored.

The SEGSII facility shuts down for the complete month of January for turbine and power plant maintenance. Consequently, the collector field is taken off line for that month.

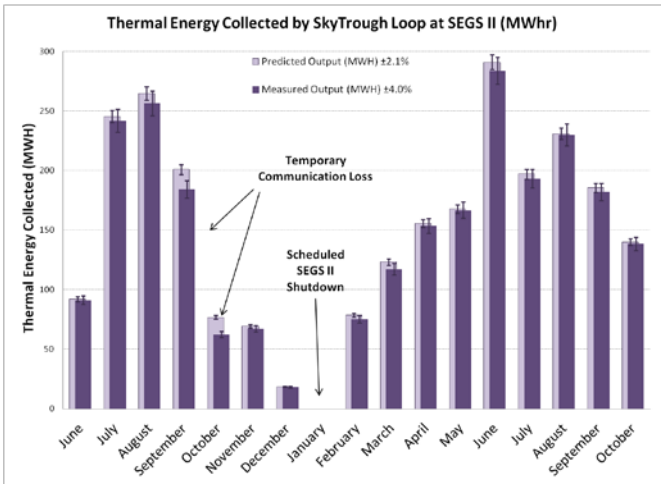

FIGURE 4. Measured compared to predicted performance of SkyTrough loop by month.

The average ratio of measured to predicted output for the eighteen month period is greater than 96%, and exceeds 98% if the clock update event is removed. The loop performance has remained substantially the same for the entire period. These field measurements support the conclusion reached by McMahan, et al. [3]: NREL test results for a single SkyTrough mirror module accurately predict the response of a complete loop.

The continuous operation of the SkyTrough in a commercial environment, with performance that is both predictable and sustained, supports SkyFuel's guarantee of thermal output for the collector system based on measured Direct Normal Insolation. The output of a SkyTrough collector system is now warranted for several years in direct response to the performance of the SEGS II commercial demonstration.

PERFORMANCE DURING WIND EVENTS

The SkyTrough is designed for two types of wind events:

- peak winds are defined as a three second gust of 38m/s - 84 mph - at a 10m reference height, and
- operational winds, with maintained speeds below 18m/s - 40 mph at the reference height.

The structural design point wind speed was selected to match the twenty-five year Mean Recurrence Interval event for most of the Southwestern United States. Calculation of the peak collector loads was based on comprehensive wind tunnel testing [5]. These peak loads are the structural design criterion for the space frame support, the mirror panels, and the support pylons of the SkyTrough. The collector control system forces all of the SCAs in a collector field to a downward-facing stow position to reduce load during a peak wind event.

The stiffness of the SkyTrough must be sufficient to maintain adequate performance in any tracking position during operational wind conditions. Clear solar days with high wind speeds are rare; however, Figure 4 illustrates a clear day operating event where the wind speed ranged from 2 to 11 m/s(5 to 25 mph), and a stow event occurred near 17:00 when maintained wind speed exceeded 18 m/s (40 mph). There is no apparent correspondence with the ratio of measured to predicted performance. That ratio remained high during operation; specifically, above 99% for the integrated daily performance.

SkyFuel has reviewed many days, both clear and partly cloudy, to evaluate the change in performance as a function of wind speed. Only a couple of operating days with partly cloudy conditions and wind speeds above 11 m/s (25 mph) are available from a data set of eighteen months. These days are difficult to interpret with a steady state model and relatively few samples; however, the variation of performance in wind remains below the uncertainty (<4%) of the measured data.

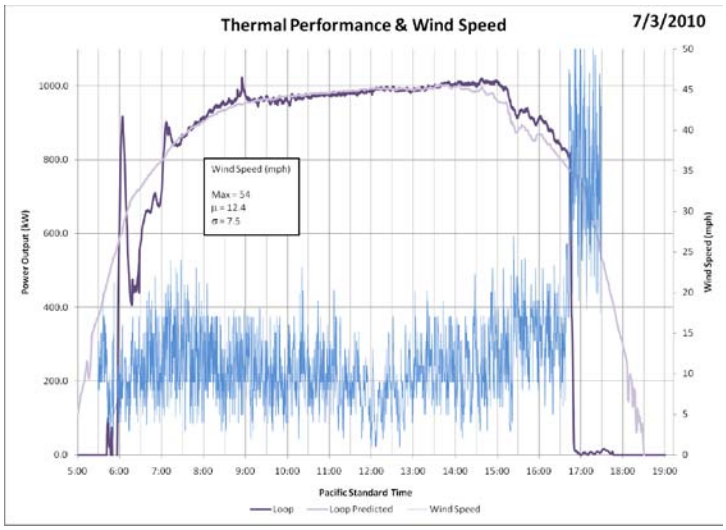

FIGURE 4. Thermal performance, predicted and measured, with wind speed for a single day.

Our examination of wind speed and performance of the SkyTrough in a commercial environment indicates that there is no measurable impact on thermal output at operating wind speeds of 11 m/s (25 mph).

REFLECTANCE OF REFLECTECH MIRROR FILM

The highly reflective surface of the SkyTrough is a silvered polymer called ReflecTech mirror film, laminated to an aluminum sheet substrate for shipment to the site as a mirror panel. These panels slide into place, span the entire aperture width, and are used in place of traditional glass mirrors. The monolithic panels can be seen in Figure 1.

The mirror panel reflectance has a direct impact on trough performance; consequently, it is measured with a repeatable sampling method on a regular basis at the SEGSII facility. These reflectance measurements are taken with a Devices and Services specular reflectometer at a single wavelength (660 nm), with a 25 milliradian instrument aperture. All measurements are taken at the same four points of each mirror module: 600mm from the east and west rim and 600mm from the north and south edge of exterior panels. A data set includes 72 measurements which are averaged to provide a single indication of reflectance. The standard deviation of the measurement set typically ranges from 0.3 to 0.5 reflectance points. Measurements are always taken immediately following a high pressure wash of the collectors. A complete discussion of reflector specularity for parabolic trough concentrators can be found in Gee et al. [6].

In September 2010, the collectors were manually rotated to the zenith position during a rainstorm (not recommended practice). The rain was short and light, resulting in a layer of contamination. Reflectance was measured after the typical plant-wide high pressure wash with deionized water in early

October, and found to be lower than expected. In late October of 2010, the reflectance measurement set was repeated after a second high pressure wash. The reflectance was restored.

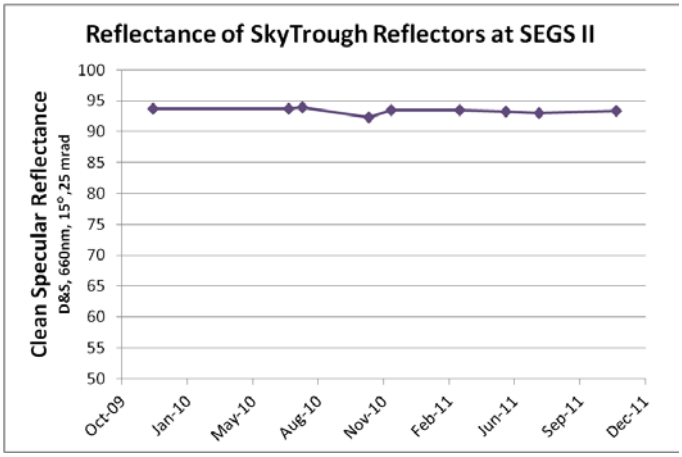

FIGURE 5. Specular reflectance of the SkyTrough at SEGSII.

The clean reflectance of the SkyTrough, installed at the SEGS II commercial power plant, is shown in Figure 5. The average reflectance is 93.4%. The reflectance of SkyTrough mirror panels at the SEGSII commercial plant has been maintained, without loss, within the uncertainty of the measurement data sets.

ReflecTech mirror film has passed accelerated and durability testing including

- ASTM G155 2x UV at 30 and 60°C, 5 and 60% relative humidity for 12,000 hours,
- ASTM G90 outdoor tests at 5x sunlight and hourly water spray for 7,500 hours,
- ASTM D870 thirty day water immersion tests,
- ASTM D4587 cyclic condensation testing at 30 and 60°C, 100% relative humidity for 100 cycles,
- ASTM D522 bending tests at 25mm radius,
- ASTM E822 hail tests, front and back, 1 inch diameter, and
- The Ultra-Accelerated Weathering Station (UAWS) operated by NREL. After receiving an equivalent cumulative UV dose of over 25 years outdoor exposure on the UAWS, no degradation and no loss in reflectance were measured in three replicate samples.

Details of these tests are described in DiGrazia et al. [7]. The combination of these tests with the experience gained in a commercial facility supports SkyFuel's offer of a 20 year reflectance warranty on the ReflecTech mirror film.

CONCLUSIONS

The continuous operation of the SkyTrough at the SEGS II power plant facility has demonstrated that the thermal performance is both predictable and sustained at high levels. There is no measurable impact on thermal output at operating wind speeds of 11 m/s (25 mph). Reflectance measurements of ReflecTech mirror film have shown no degradation after more than two years of operation in a commercial environment.

SkyFuel now provides warranted thermal output based on Direct Normal Insolation for several years, and guarantees the reflectance of ReflecTech mirror film for twenty years as a direct result of the performance of the SEGS II commercial demonstration loop.

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