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Performance of an enclosed trough EOR system in South Oman

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Abstract

Concentrating solar energy systems can serve many applications beyond electric power generation. GlassPoint Solar has introduced an Enclosed Trough Once-Through Steam Generator system that is adaptable to challenging environments and meets all requirements for Solar Thermal Enhanced Oil Recovery (EOR). In this system, troughs are enclosed in a modified agricultural glasshouse. This innovation, when combined with an air filtration system and automatic roof washers, dramatically reduces energy losses due to soiling and wind. In addition, the Once-Through design allows the use of feed-water with total dissolved solids as high as 30,000 ppm to produce 80% quality steam at 100 bar, matching typical EOR specifications. Performance during the first four months of production operation is reviewed. A dust storm during the period confirms the efficacy of the glasshouse and roofwasher in minimizing operational impacts of weather phenomena common in the MENA region. Output is determined to be consistent with the company's energy yield model. Plant reliability is monitored and 99.8% uptime is measured in the fourth month of operation.

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1. Introduction

Concentrating solar energy systems can serve many applications beyond electric power generation. Many industrial processes require thermal energy at temperatures and conditions amenable to solar, if the cost of solar

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steam can compete with existing fuels without subsidies. One application of particular interest is solar thermal enhanced oil recovery (EOR), which replaces fuel with sunshine as the energy source of steam for oilfield operations. In thermal EOR, steam is injected into an oil reservoir to heat the formation. This improves production rates and amounts, primarily by raising the temperature of the oil-bearing formation and reducing oil viscosity. Heating cubic kilometers of liquid-saturated rock by 100°C requires very large amounts of primary energy. Solar steam generators can deliver up to 80% of the oilfield steam requirement. A large market opportunity exists if solar energy can deliver steam at costs competitive with natural gas in sunny regions. Current EOR operations worldwide consume over 1.7 billion MMBTU of natural gas each year, with substantial growth forecast [1].

Using solar energy to generate steam for EOR presents unique challenges for concentrating solar energy. The area for solar collectors is limited. Initial and operating costs must compete with natural gas. High aerosol levels in dusty oilfield environments cause soiling rates that can result in average weekly optical losses as high as 30% or more [2]. Water is often scarce, and what is available contains high levels of dissolved solids and other contaminants. Boiler feedwater is usually either “produced water” separated from production oil or is pumped from brackish or saline aquifers. As it will be directly injected into the reservoir, water treatment costs must be minimized to achieve acceptable economics. Steam generators are optimized to require the least water treatment infrastructure.

GlassPoint Solar has introduced an Enclosed Trough solar once-through steam generator (OTSG) that addresses these challenges and additionally meets the requirements for the EOR application. American Petroleum Institute guidelines RP-11T, recommends design practices for oilfield steam generators. GlassPoint’s solar OTSG implements these recommendations. A pilot plant was built in a remote desert oil field in southern Oman between January and December of 2012. The GlassPoint plant began generating steam upon completion, and transitioned to full production February 1st 2013, on budget and on schedule. During the study period from February 1st to May 31st, the GlassPoint Solar EOR pilot was in daily operation, injecting a total of over 5000 tons of steam into the reservoir, consistently exceeding contract performance (Figure 1a).

2. Technology description

Enclosed Trough represents an entirely new approach to the design and construction of concentrating solar collectors. The Enclosed Trough system is protected by a glass-skinned structure, essentially a simplified agricultural greenhouse. The subject plant has a solar field footprint of 17,280 m^2 with a peak output of over 7 MW thermal. Referring to Figure 1b, lightweight parabolic troughs (4) are suspended within the glasshouse (2). The agricultural greenhouse industry has delivered over 30,000 hectares of glasshouse over the last few decades, and they are installed worldwide over a wide range of climates. They are available at low cost, and by providing structural support and isolating the solar collectors from wind and moisture, substantially reduce the total cost of the solar energy system. Total material usage in the solar field per unit of steam produced is reduced significantly compared to older CSP architectures. Total material usage per m^2 of aperture was compared to the Andasol 1 plant [3], with a reduction from 134 to 40 kg, driven by an 84% reduction in concrete and a 56% reduction in metal. Glass usage was comparable at 12 kg/m^2, but GlassPoint uses lower cost clear, flat glass for glazing, as opposed to

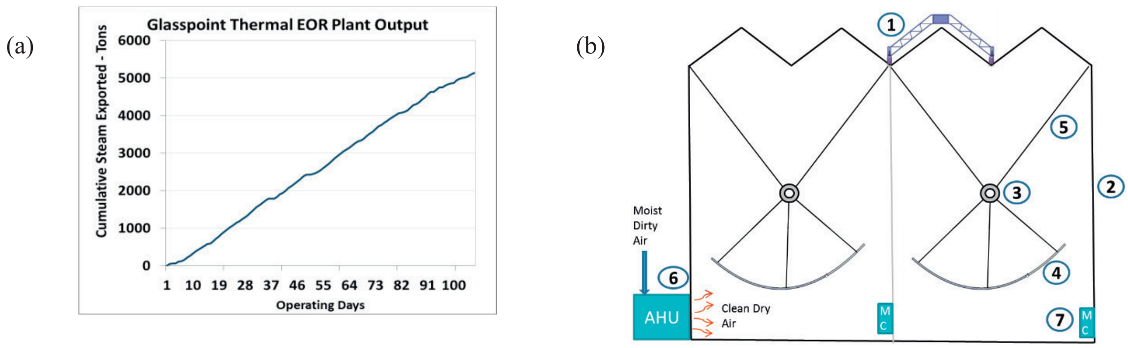

Figure 1: (a) GlassPoint plant performance, (b) Diagram of Enclosed Trough

Andasol's curved glass mirrors. GlassPoint's mirrors are of a lightweight aluminum honeycomb construction. As a result of lower material usage, and competitive conversion efficiency, the Enclosed Trough architecture is expected to offer lower cost per MMBTU of steam output compared with previous solar thermal technologies.

Ambient windborne sand, dust and humidity are substantial in many oil field environments. Overnight condensation on dust-laden surfaces results in "mud" and requires wet washing. Dust accumulation rates are high: GlassPoint has observed soiling rates resulting in a 12% per week drop in solar collection between washings at GlassPoint's plant site in California's San Joaquin Valley, while Masdar has measured up to 30% decline per week in the UAE. GlassPoint's glasshouse structure (figure 2) is fitted with an automated roof washing system (1) capable of cleaning the entire roof surface each night while the collectors are offline. The majority of wash water is returned in the gutter system and can be recovered for re-use. Dust infiltration is minimized by an air handling unit (6), which provides filtered, dried air at slight overpressure within the structure in all conditions, including dust or sand storms. These measures have proven effective in delivering consistent energy output in oilfield conditions. The small losses due to roof glass transmission and structural shading are more than compensated by the soiling control and wind protection afforded by this architecture.

Due to the absence of wind forces acting on the collectors, a lightweight reflector can deliver consistently high optical accuracy. Total weight of the mirror and frame is only 4.2 kg/m^2. The lightweight reflector enables a simple cable drive aiming system. Tracking angle is measured by inclinometers with 0.01 degree accuracy. Dedicated actuators positioned every few meters along each trough reduce collector torsion. Closed loop pointing control delivers less than 0.5 mrad pointing error at hundreds of points within the glasshouse. Pointing accuracy is maintained without regard to wind velocity, as collectors always operate in a zero-wind environment.

The low collector weight allows a simple, fully suspended installation of the entire trough system, incorporating a fixed-position receiver and a reflector that pivots about it. The fixed receiver allows for a very simple, safe high-pressure direct-steam system, free of ball joints or hoses and their costs, safety risks and maintenance requirements. The direct-steam system eliminates other costs and risks of older technologies such as heat exchangers and heat transfer fluid conditioning, storage, and fire hazard. A proprietary receiver technology is employed, using a 60mm receiver with an air stable selective absorber system and glass convection shields (3). The glasshouse structure carries the receivers and troughs. The receivers are suspended from the structure by steel rods (5). The troughs are supported from the receiver tubes using similar rods. These non-rigid links accommodate the daily thermal expansion and contraction of the receivers and troughs while maintaining precision alignment of the optical system.

The once-through steam generator (OTSG) boiler process accommodates feedwater with total dissolved solids as high as 30,000 ppm while producing 80% quality steam at 100 bar, matching typical fuel-fired OTSG specifications. Careful attention is given to outlet liquid fraction to avoid precipitating dissolved solids as scale deposits within the evaporator tubes. Even with management of solids concentrations, some scaling inevitably occurs due to excursions in water quality or chemistry. The system design incorporates features to enable receiver cleaning by pigging.

In a typical application, to maintain steam injection around the clock, solar steam is injected during the day and steam produced by natural gas is injected at night. If the rate of steam injection is held constant, gas consumption is reduced by up to 25%. By injecting more steam during the day and less at night, gas consumption can be reduced up to 80% without the need for costly thermal storage. The heating and pressurization of the subterranean reservoir

Figure 2: GlassPoint pilot plant, South Oman

typically transpires over a period of many months, and is not sensitive to the timing of steam injection. Thus, the reservoir itself acts as a primary thermal storage medium.

3. Forecasting performance

System performance is measured as tons of steam delivered to the outlet per day. The subject system has a design peak output of 14.8 tons of steam per hour and an average output of 50 tons of steam per day. An outlet steam separator is used to ensure accurate measurement of saturated steam and condensate production. A performance model is used to forecast output based on measurements of Direct Normal Irradiance (DNI) derived from an on-site meteorological station. System output over the study period will be reviewed and compared to forecast performance.

GlassPoint uses both optical modeling and thermal modeling to predict performance. For the optical model, available DNI is measured and expected optical collection is modeled. Optical modeling for the system is complicated by the need to account for the effects of the glass roof and walls, and to calculate shadowing effects from the glasshouse structural elements. A proprietary Monte Carlo ray tracing program (Figure 3) was developed to characterize the solar field. The solar field—metal structure elements, glass, reflectors, receiver tubes, and receiver convection shields—is modeled in detail, taking into account both physical location and optical properties: reflection, transmission, and absorption. The model was verified by comparing results to NREL's ray tracing program SolTRACE [4] and analytical models, as well as by running special, extreme cases. Final verification is based on actual results from operation.

The optical model calculates an optical efficiency -- that fraction of incoming solar energy which is delivered onto and absorbed by the receiver. The thermal model then accounts for energy losses due to radiation, conduction and convection, and calculates the net energy available to heat water and produce steam.

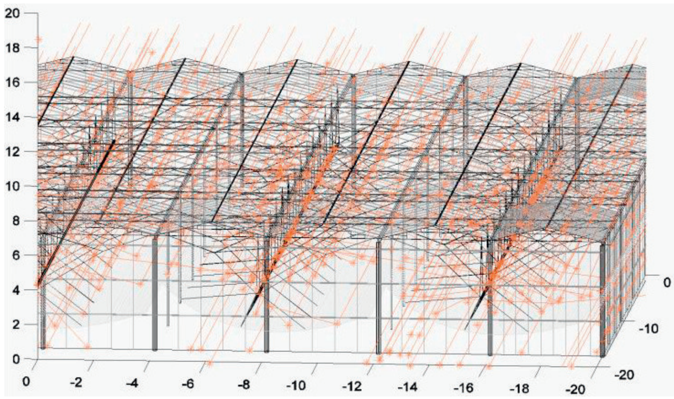

Figure 3: Ray trace diagram

The model also includes other variables that affect performance. First, the system's thermal mass and the amount of energy it takes to warm the system to working temperatures must be taken into account. Similarly, the starting water temperature and the final steam quality and pressure determine the resulting steam flow rate for a given input thermal power. For these, measurements are taken at the site to establish operating parameters. A final key variable is soiling of the glasshouses. In the model, a constant soiling loss of 2% is used, and has generally provided a good fit to the data. With basic enthalpy calculations, it is possible to calculate a mass flow of steam with a particular quality and pressure from the thermal energy and input feedwater temperature and mass flow. Through this sequence of operations, the model predicts the start of steam export and the steam output in tons based on the average DNI recorded for each minute of plant operation.

4. Performance benchmarking

With the performance model, we can compare forecast plant output to that of the EuroTrough system, whose performance model is publicly available on NREL's System Advisor Model (SAM). Two assumptions are worthy of comment. First, the SAM model baseline assumptions included 5% soiling on mirrors and 2% average soiling on the receiver envelope. Given the high soiling rates at the site, very frequent cleaning would be needed to maintain this level of soiling. Second, the EuroTrough design optical losses increase with wind speed [5], and the project site winds during peak solar production hours are significant. Between the hours of 10 and 3pm, the site weather station reports average peak wind speeds of 25kmph. Figure 2 of [5] suggests that in these conditions the Eurotrough output would be reduced by approximately 15% versus the the SAM model due to collector twisting.

The subject pilot plant was developed in 2011. GlassPoint is currently planning construction of a new system in 2014 with slightly higher performance, and this is included in the comparison. For a projected aperture area at a zenith angle of 0^o, and DNI of 950 W/m^2, the 2011 plant achieves an peak efficiency of 66%, while the 2014 plant should reach 68%, both with 2% soiling losses, versus the 71.8% EuroTrough efficiency used in the SAM model. Efficiency is slightly lower than the EuroTrough design, likely as a result of roof structure shadowing, glazing losses and the use of an air-stable selective absorber coating and non-evacuated receiver (Figure 4a). Note also that since the average operating temperatures of EuroTrough is approximately 100^oC higher than for the EOR application, we can anticipate that the EuroTrough efficiency would be slightly increased at the lower EOR operating temperature. However, an external heat exchanger would be needed to boil the low grade feedwater using the Heat Transfer Fluid it is designed for, as this system is not designed for the required 200 bar proof pressures or hydraulic pigging.

As previously noted, the oil field environment is characterized by space constraints. Typically, existing roads, pipelines and wellheads constrain the available space. Long steam pipelines to remote areas that will not be developed in the future add cost and operational complexity, while lowering efficiency. Potential future drilling plans further limit siting options for an asset expected to operate for over 25 years. Thus energy yield per unit area is a critical figure of merit. Comparing the Enclosed Trough solar field, with its 94% ground coverage, to the EuroTrough design with 32% ground coverage assumed (17m spacing), the Enclosed Trough system has 109% higher annual energy yield per unit area of solar field. Perimeter areas outside the solar field for the Enclosed Trough system are also significantly smaller, providing an additional benefit of up to 10% in total energy density (Figure 4b).

(a) (b)

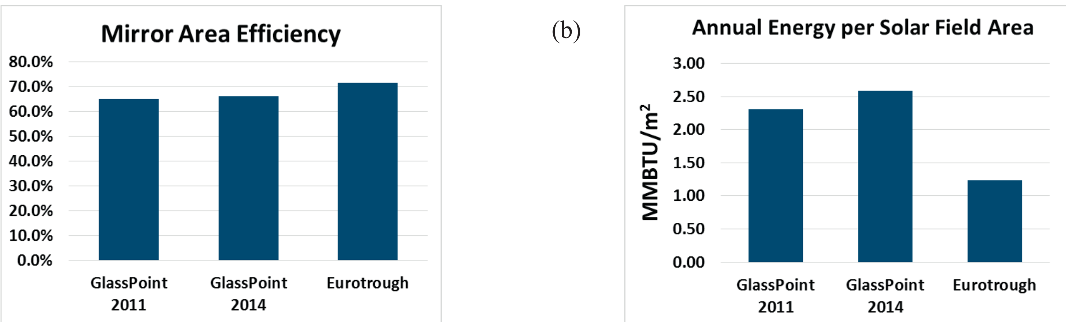

Figure 4: (a) Mirror area efficiency, (b) Energy per solar field area

5. Measuring DNI

Accurate DNI measurements are required as inputs to both the performance model and the plant control algorithm. GlassPoint's pilot plant uses two rotating shadowband radiometers (Irradiance RSR2 units)—one primary and one redundant—to measure and calculate DNI. To verify the accuracy of this data, the RSR2 units are periodically tested against a Kipp and Zonen CHP 1 pyrheliometer aimed on a two axis tracker. Comparing the CHP 1 pyrheliometer readings with RSR2 readings, they have been shown to match averaged daily values within 1.0%.

Work is currently under way to collect and summarize DNI comparison data at the pilot site in Oman but so far has shown that the RSR2 is performing well within its specified accuracy. The uncertainty for DNI measurements taken with a rotating shadowband unit such as the RSR2 is estimated to be +/- 4.76% with 95% confidence level based on analysis completed at the National Renewable Energy Labs. [6]

6. Measuring output

GlassPoint utilizes the ASME Performance Test Codes (PTC) as guidance for design, construction, commissioning, and performance evaluations. PTC 46, Overall Plant Performance, is the primary test code. Test boundaries were established accordingly, as shown in Figure 5a. Test duration is set at a full operating day to account for startup and shutdown behavior.

The primary control interface at the site is a Supervisory Control and Data Acquisition (SCADA) PC on which all operating data is recorded in one minute intervals. All performance information including process set points, process values, alarms, warnings, error messages, and operator messages are stored on this machine, but data from only six sensors is required for performance evaluation. These sensors were calibrated during plant commissioning following PTC and industry best practices. GlassPoint analyzes and reviews process data daily to make sure the system is operating correctly. Figure 5b shows a simplified schematic of the steam generation system including the six evaluation sensors.

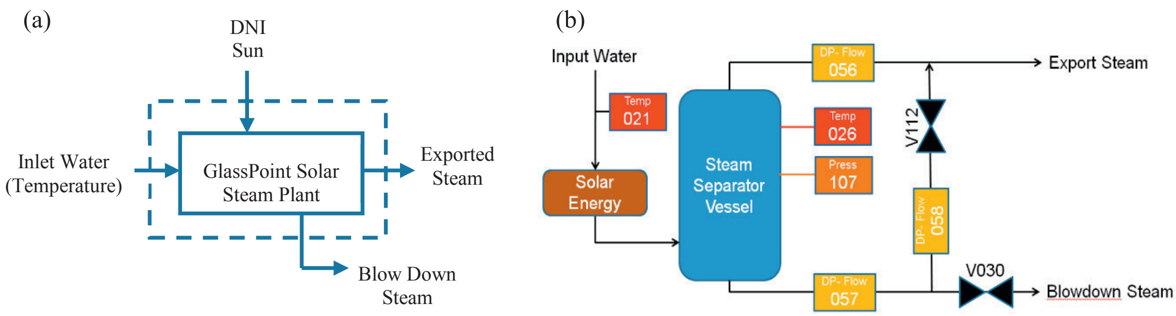

Figure 5: (a) Test boundaries, (b) Simplified schematic

The process flow diagram for the system is simple, as a pump directly pressurizes the feedwater, which is boiled in the solar field, then metered from a separator vessel. No heat exchangers or heat transfer fluids are used. The evaluation sensors indicate temperature of feedwater and output steam (Temp 021 and 026), output pressure (Press 107), and water and steam flows (056, 057, and 058). The flows are measured by differential pressure flow sensing devices that measure pressure drop across a fixed orifice primary element placed in fluid and steam lines. Accuracy of these pressure sensors are +/- 0.4% of the reading. Differential pressure is converted to flow rate using a standard equation and was verified by comparison of flows between these sensors, and other sensors in the system. As output steam must be maintained at 80 quality (80% vapor and 20% liquid), the control valve V030 is opened as needed to maintain level in the steam separator vessel when the plant output is at less than 80 quality. The excess water is determined by subtracting the flow at DP058 from the total condensate output measured at DP057.

7. Actual performance and comparison to model

Using 2011 reference year weather data from an onsite weather station, daily output in tons of steam was calculated using the GlassPoint performance model (Figure 6a). As can be seen, significant variation in output is expected as a result of variations in the solar day and weather conditions. Near-zero output days between day 100 and 250 are often a result of dust storms. Low output in other periods is associated with cloud cover or haze.

(a) (b)

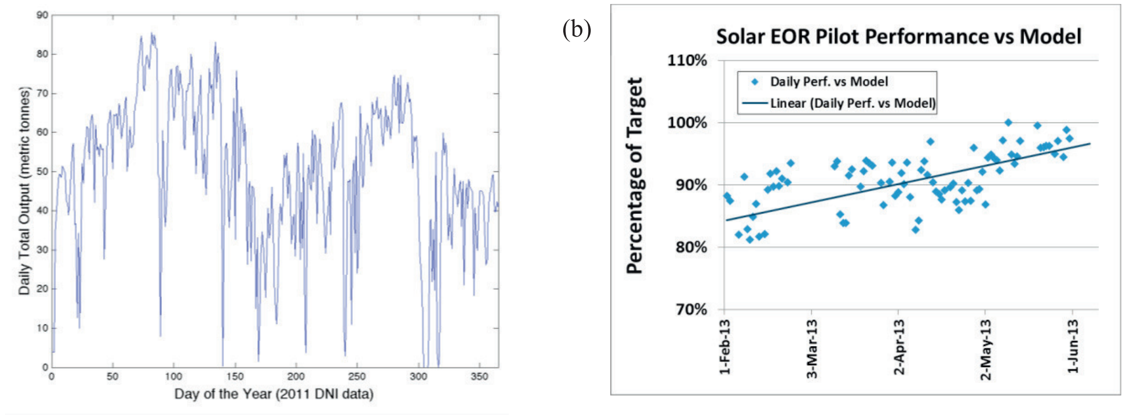

Figure 6: (a) Daily output forecast, (b) Pilot performance vs. model

The project is similar to earlier designs, but was an order of magnitude larger and had many advancements in detail design and controls. As a result, initial performance at system commissioning was expected to be less than model forecast. GlassPoint planned a series of actions to bring plant performance to modeled levels over a period of 180 operating days. Performance commitments for the first year of operation were adjusted to allow for these improvement activities. GlassPoint expects the plant to exceed its nominal output targets within the first 180 days of operation. Performance improvement efforts first focused on the tracking algorithm, and ensuring the sun remained focused on the receiver throughout the day. Next, water flow control algorithms were optimized to maximize the conversion of available energy into exported 80% quality steam, in addition to handling rapid changes in DNI caused by passing clouds. Currently, efforts are focused on fine tuning the shape of the parabolic troughs. After over 100 days of operation, the plant is operating at an average of more than 97% of the theoretical output, exceeding expectations for this stage of operation and the performance commitments made to the end user. Examination of actual versus modeled performance over the study period shows rapid progress, as shown in Figure 6b. Figure 7a shows a comparison between modeled and actual performance for a clear, cloudless day. 82.7 tons of steam were exported, versus a theoretical output of 84.7 tons. Note that the output is not symmetrical about noon, as it takes between 40 and 70 minutes each morning to heat the system to its 310^{o}C operating temperature and establish level in the steam separator drum before steam can be exported to the reservoir at the requisite pressure and quality. Fit to model is slightly better in the morning than the afternoon; this is due in part to the accumulation of soiling on the

(a) (b)

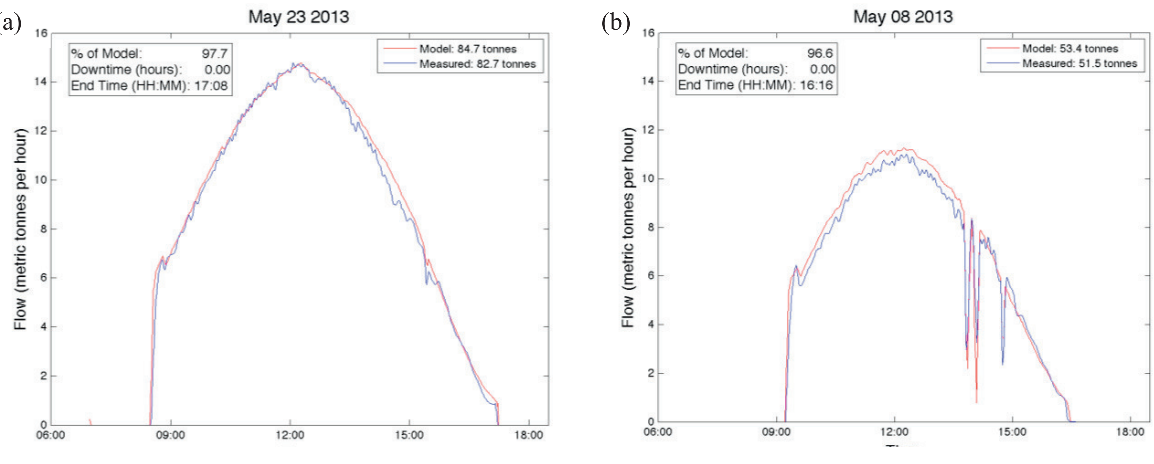

Figure 7: (a) Clear day, model vs. actual; (b) Typical day, model vs. actual

glasshouse roof over the course of the day. The roof is washed each night, so transmission through the roof is highest in the morning and decreases over the course of the day. Daily cleaning of at least half of the roof surface is required to maintain average soiling losses at 2% or less.

Figure 7b shows performance versus model for a more typical day, with scattered clouds passing over the site. This phenomenon presents control challenges, as feed water flow must be rapidly reduced, and then increased to match the available energy. Failure to reduce flow as solar input drops will result in lost output, while failure to rapidly increase flow as solar input increases could result in higher than target steam quality in the lines. This can cause scaling in the evaporator tubes, or in extreme cases, overheating of the tubes and superheating of the steam. To address this problem, a feed forward loop modulates water flow to the plant based on incident DNI and modeled efficiency based on the current position of the sun. As a result, output steam quality has been consistently maintained at the 80% target through rapid variations in available energy.

8. Soiling studies

GlassPoint has performed preliminary soiling studies, both on the reflectors and on the glasshouses at a test site near Bakersfield, CA. For reflective material, as with similar studies [2], mirror stands were used to hold the material at 0°, 45°, and 90°, and these were placed both inside and outside of a glasshouse. Reflectivity of the mirrors and transmission properties of the glasshouse were then tested with Surface Optics 410 Reflectometer and Filmetrics aRTie spectrophotometer. The data showed that the reflectors outside the glasshouse experienced soiling rates as high as 12% per week, while those inside the glasshouse had a soiling rate averaging 0.2% per week, though a longer study is needed as this is near the resolution limits of the instruments. We can conclude that the glasshouse reduced mirror soiling by more than 95%. A significant qualitative difference in soiling was also noted. Daily cycles of condensation on the outside mirrors caused caking of the deposited dust. This deposit was impossible to remove without the use of large amounts of water, a method which will likely result, over the long term, in degradation of the reflective surface. Inside the glasshouse, a non-condensing environment is maintained at all times. As a result, accumulated dust is easily removed with a dry cleaning cloth. Figure 8a shows weekly soiling rates for aluminum mirrors, both inside and outside the glasshouses.

Measurements were also made of roof soiling and the effectiveness of the automatic roof-washer at the California site. It was found that the automatic roof washing system restored transmission of glass to within 0.5% of complete cleanliness after repeated soiling cycles that reduced transmission by over 10%. In a separate study, the roof was exposed to 2300 wash cycles in a single location, simulating over 12 years of two-day cleaning cycles. No loss of glass transmission was detectable (Figure 8b). As with the reflector soiling studies, further study is needed to test for any long-term effects missed by these short term and accelerated tests.

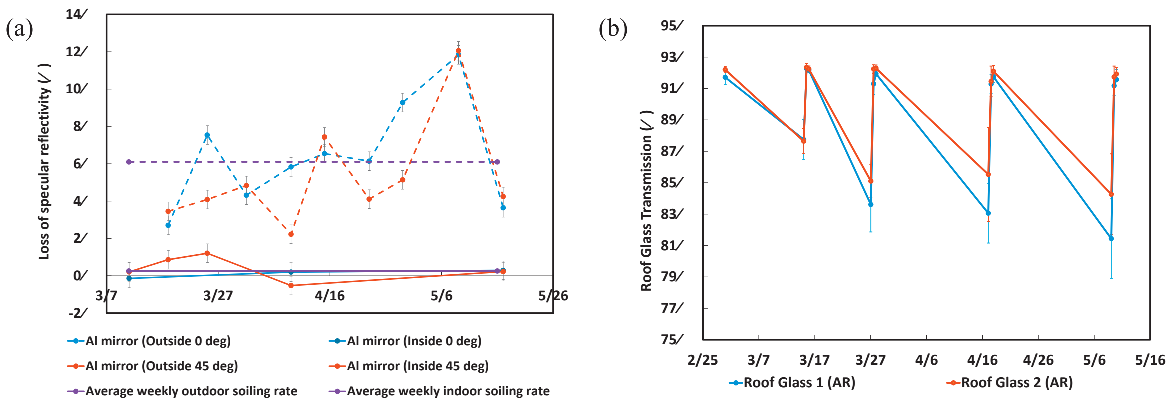

Figure 8: (a) Soiling rates for aluminium mirrors, (b) Roof soiling and recovery after washing

The Oman site has different soiling characteristics than the California site. Average soiling rate is expected to be similar to UAE [2] which was measured at around 15% per week and as high as 30% per week. The Arabian Peninsula and the MENA region are subject to high average aerosol levels and dust storms (Figure 9).

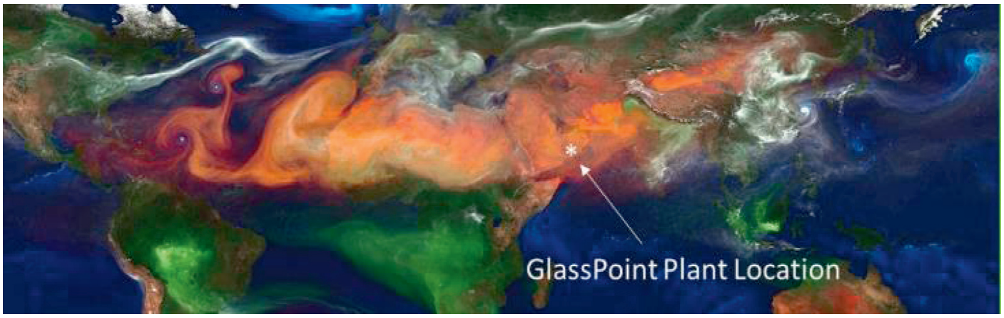

Figure 9: Dust (red), sea salt (blue), smoke (green), sulfate particles (white). Source – NASA/Goddard

One such dust storm was observed in early April. During this event, winds exceeded 40km per hour for over 24 hours, with peak gusts over 60km/hour. Surface visibility was reduced to less than 100 meters. The plant continued to operate during this storm, producing 48 tons of steam. It was noted that although the windblown dust forced a shutdown of outdoor activities, at the 6 meter level of the glasshouse roof, there was sufficient direct sunlight to continue normal plant operation. Others have observed a relationship between airborne dust and elevation. A Desert Research Institute study of windblown dust from vehicular traffic, a common oil field soiling source, found a 55% reduction in dust at 4.6m elevation compared with a 1.8m elevation, and an 87% reduction at 9.1m. [7]

Comparing system performance before, during, and after the storm provides another confirmation of the efficacy of the glass enclosure (Figure 10). During the storm, with strong wind, but dust primarily near the ground, DNI was only slightly affected. Performance dropped by 6% as measured by fit to model. When operation resumed after the storm, performance had degraded by nearly 12%. After measuring the performance with the soiled roof for a full day, the roof was cleaned overnight using the automatic roof washing system and performance was measured again. Performance had returned to the pre-storm baseline. Several conclusions can be drawn from this data. First, that the automatic roof washing system effectively removes soiling due to airborne dust. Second, that there was no significant soiling of the mirrors during the storm. Third, that the enclosure allows normal operation in high winds, with negligible attenuation from airborne particles or loss of optical alignment.

Results for soiling studies at the southern Oman site are preliminary at the time of writing, but initial data is consistent with the California data. As the Oman glasshouse has improved leak integrity and added a superior air handling system, the ultimate performance of the system with regard to mirror and receiver soiling control is expected to be superior. Trends appear to be consistent with those seen in California. Enclosing the reflectors in a glasshouse results in dramatically reduced soiling rates, and the automatic roof washing system effectively removes dust deposits from the glass without reducing transmission of the glass.

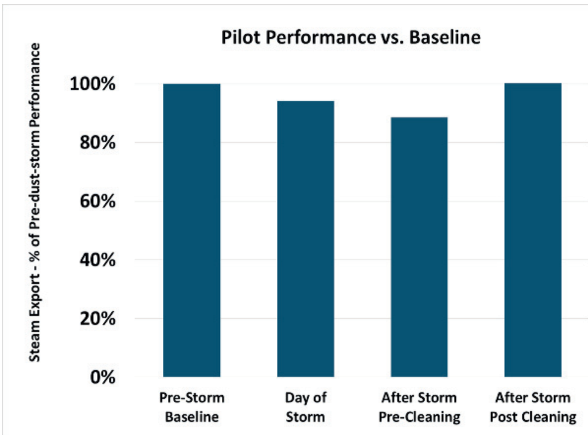

Figure 10: Performance vs. baseline, weather event

9. Dispatch reliability

As a production system, the pilot plant is subject to rigorous daily reporting of uptime and downtime, with root cause and corrective actions required for any lost production. Substantial effort was devoted to ensuring system reliability in the oil field environment. For instance, the mirror positioning electronics were of particular concern. These off-the-shelf electronics operate inside the glasshouse at temperatures as high as 70^{o}C. Highly Accelerated Life Testing was conducted at operating temperatures as high as 100^{o}C to ensure their reliability. Similar endurance testing was conducted for all high stress or critical components or systems.

For the first four months of operation, the plant has been available to run during 98.5% of the potential operating hours. Most downtime has been related to various plant safety protections causing nuisance shutdowns in response to sensor inputs that exceeded conservative operating limits. As these issues were addressed, availability reached 99.8% in May, 2013.

10. Conclusions

After four months of production operation, initial operating metrics for the Solar EOR Pilot are encouraging, indicating the project has met all design objectives.

- The Optical and Thermal models developed to predict system performance based on weather data have been shown to conservatively predict plant output on a minute by minute basis.
- Measured performance is approaching modeled performance, is exceeding performance commitments, and should exceed model forecast within the first year of operation.
- Frequent scattered clouds present a significant challenge at the site, but model-based feed-forward control based on measured Direct Normal Irradiance has allowed fully automated operation in all use cases.
- The glasshouse enclosure has been demonstrated to reduce mirror soiling by more than 95%, and to alter the nature of mirror deposits, allowing them to be easily removed with a dry cloth.
- The automatic roof-washing system has demonstrated its effectiveness and reliability in the solar application. Full recovery from a 12% soiling event was accomplished in 12 hours after a major dust storm, confirming the benefit of this technology.
- Dispatch Reliability has been excellent; after a few short weeks of commissioning, the plant was placed in daily production operation, and has achieved 99.8% uptime in its 4th month of operation.

Areas for further study include continued monitoring of long-term performance and reliability, as well as receiver fouling studies based on pigging results.

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