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ScienceDirect

Energy Procedia 49 (2014) 1756 – 1765

Energy Procedia

SolarPACES 2013

Construction 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 solar once-through steam generator (OTSG) system designed for challenging environments and to meet all requirements for solar thermal enhanced oil recovery (EOR). Parabolic trough collectors are enclosed within a modified agricultural glasshouse, which protects the collectors from wind, sand and dust common in oilfield environments, and eliminates energy losses due to wind. Automatic glasshouse washing and air filtration equipment dramatically reduce soiling and related losses. The once-through boiler process allows the use of feedwater with total dissolved solids as high as 30,000 ppm while producing 80% quality steam at 100 bar, matching typical EOR specifications. The construction of a 17,280m^2 pilot plant in southern Oman is reviewed. Construction was completed in 11 months, on time and on budget, with zero lost time injuries. This paper reports on the plant design and construction methodologies and measurements of construction labor productivity compared to long term build speed and cost objectives.

Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.

Keywords: GlassPoint; EOR; steam; solar thermal; Oman; enhanced oil recovery; Enclosed Trough

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 steam can compete with existing fuels without subsidies. One application of particular interest is solar thermal

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Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.
doi:10.1016/j.egypro.2014.03.186

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. A separate SolarPACES paper details performance measured during the first 4 months of plant operation. The plant has injected over 5000 tons of steam into the reservoir (figure 1a), consistently exceeding contract performance.

In sizing future plants to deliver significant fractions of the steam used in typical installations, requiring from 6,000 to over 36,000 tons of solar steam per day, it was determined that construction rates would need to exceed 5 hectares per week of glasshouse with associated steam systems. This paper will focus on the construction process used and key metrics that would need to be met to achieve the anticipated construction speed and cost targets.

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

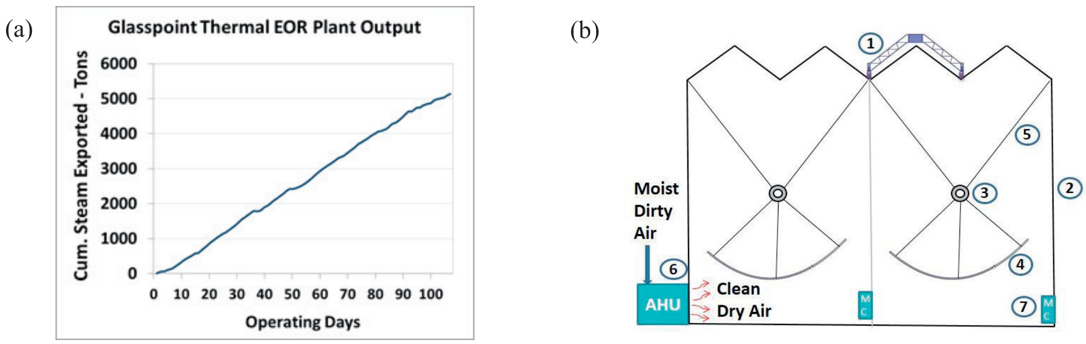

Figure 1: (a) GlassPoint plant performance, (b) Diagram of Enclosed Trough

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 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.

Figure 2: GlassPoint pilot plant, South Oman

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 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. Build objectives and strategies

The oil and gas industry has three key priorities for oil field development projects.

- Safety: Health and safety comes first, requiring compliance with many policies and procedures.
- Predictability: projects must be completed on schedule and budget. To illustrate the criticality of adherence to schedule, we can estimate the impact of a one day delay in steam production. A solar plant producing 6000 tons of steam per day at an oil field with a 3:1 Steam to Oil ratio increases production by 12,600 barrels of oil per day. At June 2013 prices of $100/barrel, the loss caused by a one day delay in output would be in excess of $1.25 million.
- Quality: The industry expects documented adherence to established protocols to ensure quality in engineering, design and execution.

The project site recently celebrated 600 days and over 200,000 hours of construction and operations effort without a lost time injury (LTI). This safety record was achieved through rigorous attention to established best practices throughout the product design, project planning, and execution phases. Safety began in the design phase with thorough adherence to hazard analysis and elimination and design for safety procedures. The design eliminates many hazards common in previous solar systems by minimizing the use of overhead lifting equipment. Lifting hazards were further reduced by designing virtually all components to be handled by workers without mechanical aids (Figure 3). No flammable liquids are used in the plant. The automatic roof washing system allows the roof cleaning to be conducted without the need for work at height. Most maintenance activities are conducted at night when temperatures are lower and the system is not pressurized. During Construction and Operations, Safety has been a high priority with daily safety discussions and the use of Task Risk Identification Card (TRIC) and Safety Training Observation Program (STOP) cards to reinforce the message to the site team.

Many aspects of the design enabled the timely completion of the project. The vast majority of the plant components, such as the glasshouse, steam systems, control system and switchgear, were well-proven, reducing schedule risk related to delivery or construction delays of new components. Thorough testing of all elements at GlassPoint's California test site, and in subsystem factory acceptance tests, ensured components worked as designed. Keeping the project on schedule avoided cost overruns related to extending staffing beyond the planned 11 months of activity. The continued high reliability has helped to keep Operations and Maintenance costs in check.

Oil and gas industry quality standards were maintained throughout the program. Detailed checklists were produced for every assembly and test step in the construction, pre-commissioning and commissioning processes.

Figure 3: Lightweight mirror installation, 3 workers, no crane, no work at height

For example, after external visual inspection, receiver welds were checked by X-ray and borescope with retained films of each weld, followed by hydrostatic testing to a proof pressure of 200 bar. The customer conducted a rigorous pre-start up audit of all quality documentation, procedures and equipment status with senior representatives from their operations, quality, safety and engineering teams.

The project construction presented a unique opportunity to study each phase of the process to develop a labor model for planned large scale deployment of the technology, in excess of one hectare per week, after the work crew has gained more than 2 years' experience. The large-scale labor model, referred to as the "2016 Model", included target labor content for each of over 40 tasks to be completed, and those tasks were grouped into phases. The primary construction phases proceeded from glasshouse erection, glazing and pressurization, to simultaneous installation of the receiver and trough system inside the glasshouse, and the modular controls and steam piping outside the glasshouse. Careful record keeping, combined with camera surveillance of the site, allowed the labor content of each task to be accurately measured. Data for three sample tasks are discussed in the results section. Note that productivity is measured as total number of operations divided by total labor hours, and is inclusive of safety training, prep time, cleanup time and any idle time during the work day. In each case, rapid improvement in labor efficiency was observed as the build team grew more familiar with the task, and tools and procedures were perfected.

4. Design for constructability

Construction of the system presented major challenges. The global expatriate construction workforce available at the site generally has limited proficiency in English, often do not share a native language, and have no prior experience with solar technology. The site location in southern Oman is several hundred km by road from any large urban center. Shortages of materials, equipment or supplies during construction would cause delays as materials were procured, often from outside of Oman, and transferred to the site. Typical elapsed time from material request to fulfillment at the site is two months. As a result, a missing tool, gasket, bolt or lubricant could delay completion of a task for weeks. The start dates for subsequent dependent tasks would be postponed as well. As workers at the site would be contracted for months of labor, the consequences would include both schedule slippage and substantial cost overruns.

These challenges were addressed in several ways. The glasshouse industry has successfully delivered structures worldwide in thousands of agricultural applications. Over 30,000 hectares of glasshouse have been built, in locations from McMurdo Station in the Antarctic to large numbers of glasshouses found in the Middle East. These structures are often built in remote areas using locally sourced labor, and are sold into a highly competitive and cost sensitive market. Their design has been refined through decades of evolution to ensure quality construction with a minimal amount of specialized equipment and worker training. Once foundations are set, the structure is bolted together, then covered with glass supported by aluminum extrusions with polymer seals. Glasshouse construction labor productivity varies. In the United States, construction typically proceeds at a rate in excess of 1.25 hectares per week with a crew of 40 working 60 hour weeks. This works out to over 5 square meters of glasshouse per construction labor hour. Projects are often larger than 25 hectares, achieving economies of scale. Based on local labor performance on other benchmark tasks, such as pipeline construction and cable trenching, GlassPoint conservatively set a goal of achieving half this labor productivity after three years of continuous build activity in the region.

Based on experience at remote sites, the glasshouse industry has also established practices of kitting all required materials and tools, and minimizing reliance on tools, supplies, or hardware sourced by local contractors. This not only eliminates delays and quality issues related to improper materials or equipment, it allows the construction process to be executed in exactly the same manner, regardless of build location.

GlassPoint's receiver and trough assembly, known as the "Solar Package" are the newest portions of the system design. Significant effort was devoted to ensuring the same fast, defect free construction. The systems were designed for rapid, correct assembly, by unskilled workers. Based on repeated design reviews, visual assembly instructions were produced, rich in photographs and 3D graphics, with minimal reliance on written communication, as shown in Figure 4a. Multiple test builds were carried out at a test glasshouse in GlassPoint's facility in Shenzhen, China by non-English-speaking factory staff. Once part quality and assembly speed met targets, a constructability review was held at GlassPoint's test site near Bakersfield, California. In a 3 day period, 80 meters of receiver, troughs and controls were installed by a team with no prior knowledge of the system design. The review was attended by representatives of the customer and more importantly, the Omani construction contractor. The effort not only validated the design and procedures, it allowed the attendees from Oman to clearly visualize each step and identify and proactively resolve any potential issues. Dozens of small projects were launched to address valuable learning. For instance, component packaging changes were made to reduce unpacking labor, and nut plates and captive nuts replaced loose hardware. As with the glasshouse, every required part, tool or supply needed to complete a task was kitted together, so that a crew could quickly obtain the supplies they needed for a shift and get to work, rather than hunting for missing items.

Specialized fixtures and tooling were developed to for rapid accurate installation of the solar package. Aids were developed for nearly every step of the operation. Lifting fixtures, receiver weld alignment fixtures, carts to allow easy movement of the mirrors through the glasshouse, and simple tools to laser-align the receiver tubes, all contributed to build speed and quality (Figure 4b).

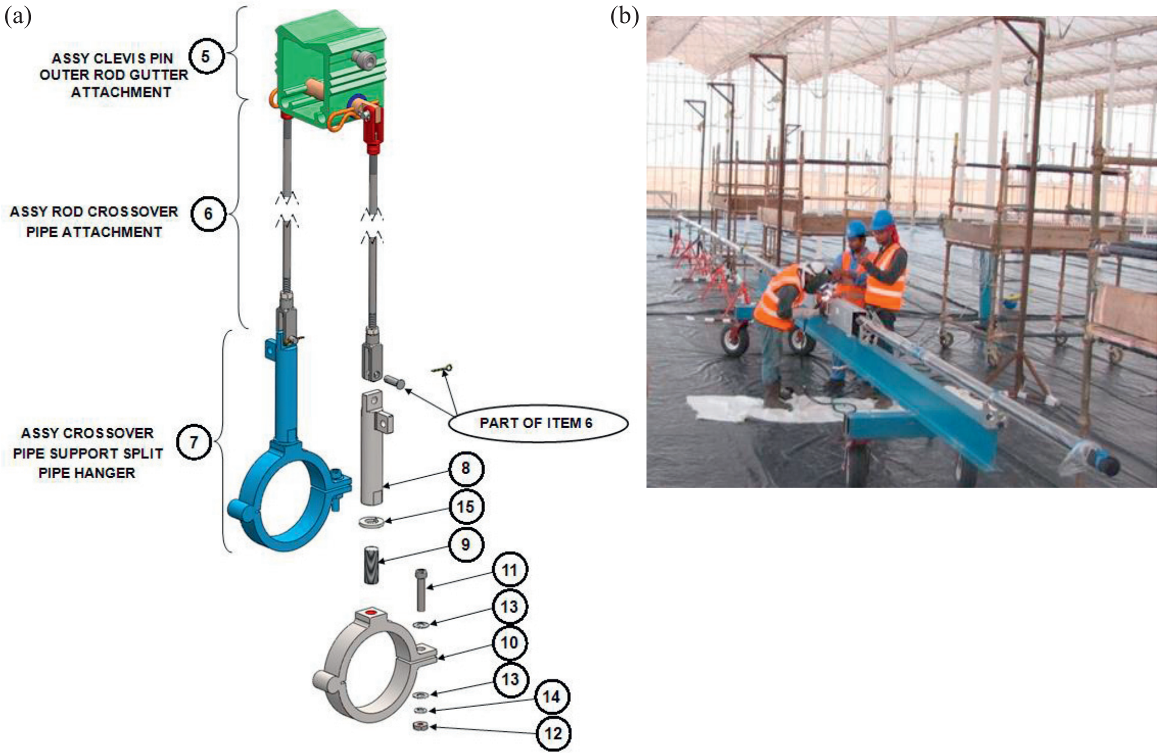

Figure 4: (a) Highly visual assembly documentation, (b) Receiver Weld Fixture and simple lift fixtures. 30m sections of receiver were welded and then hoisted into position and attached to overhead hangers

The design and execution plan focused on minimizing work at site, especially work with novel systems and technologies. Subsystems such as the roof washer, air handler, controls and steam handling equipment were completely built and tested at specialized facilities, then containerized and transported to site (figure 5). The system control room was staged with the steam handling skids for integrated testing in the US before shipment to site. Pre-shipment acceptance testing of roof washing and air handling equipment was carried out in Europe. The control room and the air handler arrived as pre-packaged containerized modules. The steam handling equipment was delivered on skids that were shipped to site in standard containers. The balance of the exterior system elements, including cables, switchgear, water and steam lines used common oilfield EOR components. The construction team was able to handle this part of the project with minimal training or tooling.

Figure 5: Containerized modules—(a) Control Container; (b)Air Handler with field assembled filter baghouse; (c) Positive displacement pump skid; (d) Separator/valve/instrumentation skid

5. Results

Construction was completed on schedule during an 11 month period. In several instances, material deliveries to the site were delayed by either late shipments or longer than planned transit times. As the plan was conservative, the local construction team was able to maintain schedule despite these delays (Figure 6).

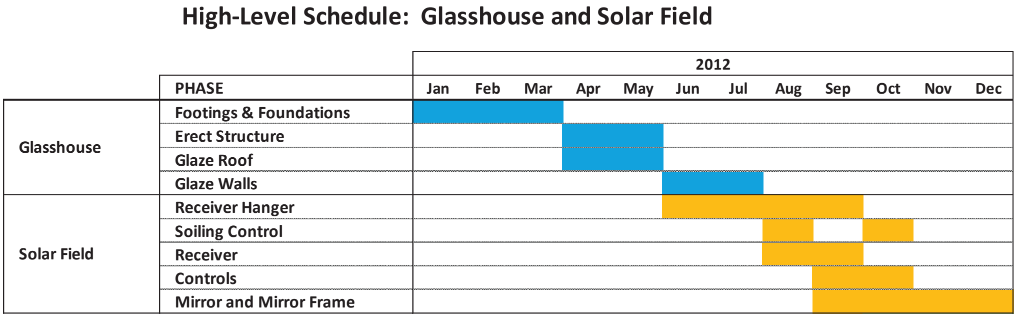

Figure 6: Construction timeline

Construction began on January 17th, 2012 with surveying of the foundations. Next, a specialized rig drilled holes in the leveled site provided by the customer. Steel bases were set in the holes for the roughly 500 columns, and concrete was poured to secure them in place. The columns and roof trusses were installed, and then the roofing system of aluminum extrusions and glass was set in place. The roof was immediately covered with a chalk solution. The resulting white surface helped reduce daytime heating of the glasshouse interior. Work paused to allow for trenching and installation of power and control cables for the solar aiming system, and installation of the overhead receiver suspension and mirror aiming drives. Finally, the walls were glazed to create a pressurized environment. At this point, in late July, the glasshouse was complete.

For each step in the glasshouse build process, a rapid improvement in labor productivity was observed as the build team became more familiar with the task and tools. In many cases, the local contractor found ways to re-organize the work for greater efficiency. As the glasshouse was quite small by agricultural standards, a decision was made to work with locally available scissor and forklifts, instead of importing specialized equipment normally used in the glasshouse industry. Adjusting for these factors, glasshouse construction productivity met expectations. In future projects at greater scale, task scheduling can be optimized, teams will have months to perfect their skills at a given task, and will be equipped with specialized machinery that will dramatically reduce the effort associated with erecting columns, installing trusses, and glazing the structure.

With an air and water tight glasshouse in place, the air handler was installed to pressurize the structure with clean air. The design objective static test pressure was measured and achieved, ensuring that positive pressure could be maintained in the structure even in windy conditions. To ensure safe temperatures inside the glasshouse, work shifted from days, with ambient temperatures of 40 to 50 degrees C, to nights, with temperatures in the 20's and 30's. The high reflectivity of the chalked roof significantly improved the effectiveness of lighting. Workers reported higher comfort, and higher productivity was observed, as a result of the lower temperatures. No safety or productivity issues were encountered with night work, and the percentage of night work will likely increase in future projects.

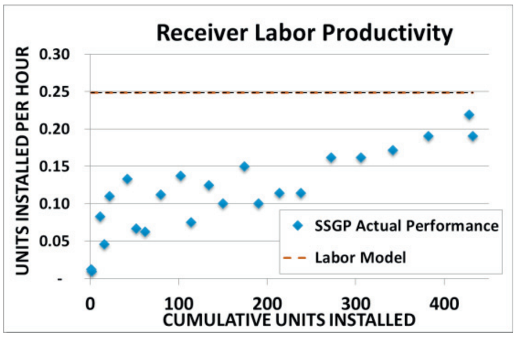

Figure 7: Receiver labor productivity

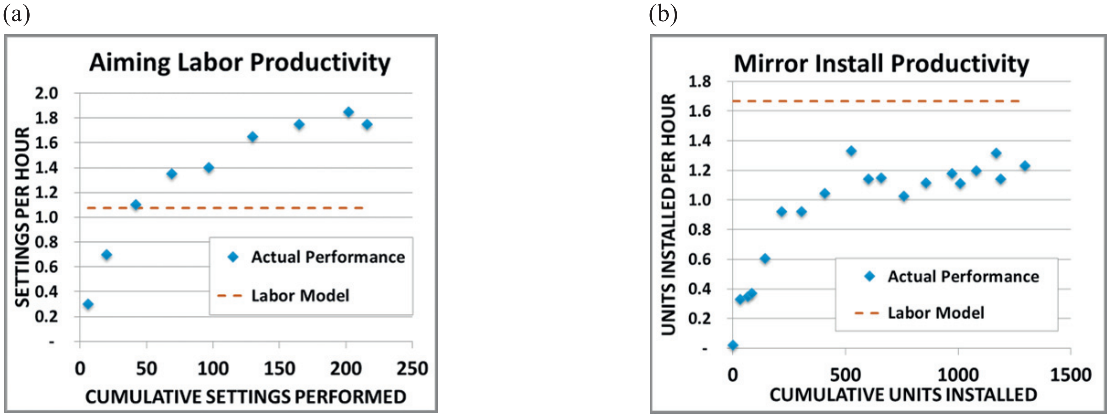

Figure 8: (a) Aiming drive labor productivity, (b) Main mirror installation productivity

The interior was then pressure washed with demineralized water, and the membrane flooring system was installed to isolate the glasshouse environment from the compacted soil floor of the glasshouse. The membrane, an engineered two-layer system of fiber reinforced polymer sheeting with flame retardant and UV resistant properties, augmented by a heavy gauge fiber reinforced polyolefin perimeter walkway, provided a durable, low cost surface that held up well under foot and light vehicle traffic. Within this clean envelope, the 5m long receivers were unpacked, welded and installed on the overhead hangers. This operation was executed over a 3 week period with rapidly improving technique, eventually exceeding a labor productivity of 0.2 units per labor hour (Figure 7). Little incremental work must be done to ensure achievement of the 0.25 unit per hour model goal for large scale deployments. An additional opportunity exists to dramatically reduce the number of welds by manufacturing 10m long receivers in the future, reducing the number of welds to be completed and inspected by half.

The mirror frames pivot around the receiver pipe on bearings that are part of the receiver assembly. Hanger rods were installed, followed by the mirror frames. As mirror frames were completed in each row, the aiming drives were installed and powered up, and each 10m section of mirror frame was moved through its full range of motion. The 2016 labor model set a goal of 1.07 drives aligned per labor hour. This objective was met after three nights of work. At completion of the effort, productivity exceeded the goal by a wide margin (Figure 8a).

After control functionality was verified, the main trough mirrors were installed. A cart allowed two workers to move up to 24 mirrors at a time to the current work zone. Then, three workers would place the mirrors on the frames and secure them. The mirrors weigh between 18 and 28 kg and are easily handled without mechanical aids. The installation rate increased quickly to approximately 80% of the model rate and stabilized at about 1.3 per labor hour (Figure 8b). The gap to model was studied and a variety of small design and procedural improvements were identified to ensure that the long term model goal would be met.

The steam handling and balance of plant installation was completed concurrently with the solar field and was operational by the time that the solar field was complete; space constraints prevent a more detailed discussion. Commissioning of the integrated system was completed on December 11th, and on December 12th, 2012 the system produced steam for the first time. Over the following month, many system failures were simulated to ensure a safe shutdown in all eventualities, including power failures, water leaks, motor failures, loss of water supply and many other scenarios. By January 24th 2013, all integrated system commissioning was completed, and operational testing began. The first phase of acceptance testing, in which peak performance was measured, was completed in three days, exceeding specification on each day of the test. The one-year operating test is now under way and has been successful to date. The results of this testing are reviewed in a separate SolarPACES paper.

With steam production performance meeting expectations, focus shifted to smoothly integrating the solar steam into the daily field operations. Solar steam was injected directly into a production steam header charged at 88 to 100 bar by the customer's gas fired steam generators. No issues were encountered with this hybrid operation.

One objective was to confirm the viability of a variable rate steaming strategy for this field. While variable rate steaming is used in EOR, the most common approach when using fuel fired OTSG's is to run at a constant rate over the course of the day. Since solar thermal production rates vary with the available solar energy, the highest solar fraction is achieved when injection rates are allowed to increase during the day and drop to a lower rate at night. Over many weeks of testing, with solar steam increasing injection rates by up to 50%, no issues were encountered. It was necessary to adjust injection flow control valves to accommodate the higher daytime injection rates. An injection network optimized for solar would accomplish this with remotely controlled motor operated valves. Such designs are already common in the industry to give operators better control and more flexibility in how the steam is delivered to various wells.

6. Conclusions

The construction of the solar EOR pilot plant met project objectives for safety, schedule, quality, and cost. The project validated GlassPoint's future project construction cost model, and proved that variable-rate solar steam could be smoothly integrated with fuel fired steam generators.

- Construction and initial operation was completed with zero lost time injuries
- Pre-deployment testing succeeded in minimizing delays and costs related to field learning
- The project was completed on schedule and has met or exceeded all contractual performance commitments.
- Careful measurement of construction labor productivity indicates GlassPoint's modeled labor costs for high volume construction are achievable.
- The project cost met projections
- No significant issues were encountered integrating solar steam with the existing oil field EOR operation. Daily increases in steam injection flow as high as 50% were successfully demonstrated.

Monitoring of plant performance continues. GlassPoint is currently working on minor design and procedural improvements, based on the over one hundred lessons learned that were recorded during the pilot construction. This will ensure that future systems can be built at the required rate and at target cost.

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