Deploying Enclosed Trough for Thermal EOR at Commercial Scale

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Abstract. Solar energy, in the form of enclosed trough direct steam generation, is now being deployed at scale to supply a portion of the energy demand for thermal enhanced oil recovery in Amal, Oman. Construction of the 1,021 MW Miraah project is well along and progress in cost reduction and labor productivity are evaluated. Results from the successful Manufacturing Verification Test and the Miraah Solar Steam Generator Project are presented and discussed. The Miraah data shows substantial reductions in material usage as a result of improved designs, increases in construction speed, and reductions in labor per unit of construction with deployment of enhanced tooling.

INTRODUCTION

The global oil and gas industry consumes over 2,800 TWh of thermal energy each year [1] in producing the world's supply of fossil fuels. The reservoirs of easily extracted light oil have been heavily depleted; two thirds of the remaining oil in place is heavy oil, which requires heating of the reservoirs to reduce oil viscosity and allow the oil to be pumped to the surface. Use of this process, known as Thermal Enhanced Oil Recovery (EOR), is increasing, increasing the energy intensity of oil production and total energy demands of the industry. Steam injection, the dominant approach in thermal EOR, requires very large amounts of thermal energy, with boiler capacity at each field typically of gigawatt (GW) scale. Solar energy, in the form of enclosed trough direct steam generation, is now being deployed at scale to supply a portion of this energy demand, lowering production costs and dramatically reducing the carbon intensity of the extraction process. Enclosed trough technology was selected for its low capital cost, low land usage, high reliability and automated cleaning in high wind, high dust environments.

In 2012, Petroleum Development Oman (PDO) deployed enclosed trough technology in a 7MWT pilot to generate steam for EOR at its oilfield in Amal, Oman [2,3]. The pilot plant has now completed over four years of daily oilfield operations. Initially operated by GlassPoint Solar, the plant has been operated by PDO since 2015[4]. The pilot's proof of performance, reliability and low operating costs led to a follow-on project at the same remote desert location. The 1021MWT (1GWT) "Miraah" Project will deliver 6,000 tonnes of steam per day (1.4 TWH/yr) and began construction in late 2015. The project is currently in construction. Over 300,000 m2 of collector enclosures are in place as of July 2017, with active construction over an area of nearly one square kilometer.

This paper reviews the reductions in material and construction costs achieved to date. Target construction rates exceeding 1,500 m2 per day have been demonstrated. Construction has proceeded on schedule despite extreme weather conditions including persistent high winds, dust storms, and high ambient temperatures. On-site

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manufacturing of the lightweight parabolic trough structure has dramatically reduced materials and shipping costs. Simple, lightweight components designed for easy assembly, along with deployment of low cost tooling for various construction operations, have been key drivers of labor efficiency. Improvements in soiling control equipment include a second-generation greenhouse, faster automatic roof washing with reduced water usage, and improved flooring methods. The partnership between GlassPoint Solar and its customer PDO has improved sourcing and construction efficiency while meeting rigorous Oil and Gas industry standards for design, construction, operational safety, and reliability.

Thermal EOR involves injecting steam into reservoirs at pressures from 40 to 120 bar. Occasionally, for deep, high pressure, reservoirs, pressures as high as 175 bar may be used. To reduce the size of transmission lines, and account for transmission losses, most oilfield steam is specified to leave the boiler flange at approximately 100 or 134 bar. At these pressures, an equivalent mass of steam, with higher specific enthalpy, can move through smaller transmission lines over long distances. For the Miraah project, outlet pressure is specified at 107 bar to maintain 95 bar pressure at the end of a 2.5km steam export line.

Supplying boiler feed water for thermal EOR at reasonable cost is a challenge, as the water produced from the oil-bearing formation is mixed with oil, solids, and dissolved minerals. Water separated from oil ("produced water") or water from saline aquifers is commonly used. To mitigate treatment costs, water is softened rather than demineralized. Hardness is removed to <1 mg/LCaCO3. If necessary, oxygen is reduced to <10 ppb using oxygen scavengers. pH typically is maintained in a range to prevent corrosion. While there is no published limit for Total Dissolved Solids (TDS) in steam generator feedwater, the American Petroleum Institute (API) Recommended Practice 11T for Installation and Operation of Wet Steam Generators recommends 60,000 PPM as the upper limit. Levels above 15,000 PPM are rarely seen, in part because softening becomes more difficult at higher levels of TDS. Note that these contamination levels are many orders of magnitude higher than in any other solar application.

To put this in perspective, a single evaporator loop in the Miraah plant produces over 13,000 tonnes of steam per annum. This quantity of the 8000-ppm water available at Amal would contain over 100 tonnes of salt, passing through a receiver with a 48mm inside diameter. To avoid accumulations of solids, it is essential that the boiler exit vapor fraction or "steam quality" is limited, such that the solids in the liquid fraction never reach a concentration in excess of the solubility limit and begin depositing on the tube walls. Depending on feedwater contamination levels at a given field, the quality limit may be set as low as 60%, or as high as 80% for all boilers, whether fuel-fired or solar. The Miraah plant operates at 80% quality. Above this level, concentration of solids becomes unacceptable.

Even with good operating practices, small amounts of solids inevitably accumulate in the evaporator tubes of all oilfield boilers. These are periodically removed with hydraulic pigs. GlassPoint's Solar Steam Generators (SSGs) boiler tubes (receivers) are of carbon steel all-welded construction with long-radius bends and fixed positions, as in conventional oilfield boiler practice[1]. This design eliminates the safety hazards and maintenance problems – ball joints and flexible connections – required by the moving receivers in older trough designs, and allows for routine pigging. The high feedwater salt concentration requires that all wetted surfaces be composed of carbon steel, as austenitic stainless alloys are susceptible to stress corrosion cracking when exposed to chloride concentrations >100 ppm. Where hydraulic pigging is not an option, "acidizing" is often raised as an alternative. In practice, the use of acid treatments for oilfield boiler scaling is rare or non-existent, as the cost of acidization would be considerably higher than hydraulic pigging and presents safety issues. Managing the large quantities of hazardous chemicals, such as hydrochloric acid, to high oil and gas safety standards is challenging, as is safe disposal of the acid mixture. The ball joints required in older trough designs pose safety concerns, and are particularly susceptible to corrosion damage. Careful monitoring of the circulating fluids by a trained chemical technician is required to avoid dissolving the boiler tubes, and degraded boiler tube lifetime would be expected.

Some oilfield operators choose to use 100% quality or "dry" steam for thermal EOR. This simplifies steam distribution, but increases operating costs and lowers boiler efficiency. Wet steam from the boiler at 60-80% quality is directed to a cyclonic separator, and the dry steam is fed to the reservoir, while the liquid fraction is often directed to a heat exchanger to heat the incoming feedwater. The resulting 120-180°C water has solids concentration 4 to 5 times higher than the feedwater, and must be disposed of carefully or treated by distillation for reuse.

[1] Once-Through Steam Generator (OTSG) and Heat Recovery Steam Generator (HRSG).

GLASSPOINT ENCLOSED TROUGH

The GlassPoint Enclosed Trough SSG was developed for thermal EOR operations. As with conventional oilfield boiler systems, it is a direct steam boiler of carbon steel construction. Parabolic troughs with an aperture of 7.64m are placed on 8m centers and focused on an all-welded receiver assembly, 61mm in diameter. All collectors are enclosed within a greenhouse, a structure similar to those used by the agricultural industry, that protects the mirrors from wind, dust and moisture, and provides for automatic washing with full recapture of the washing fluid. The greenhouse also serves as the foundation and support structure for the solar collectors. The mirrors and receiver pipes are suspended from the greenhouse ceiling and controlled by small positioning systems. Each 180m row of greenhouse contains 177m of mirror, resulting in a mirror ground coverage ratio over 93%. The high ground coverage ratio results in significant increases in annual steam production per unit of land versus older solar thermal designs.

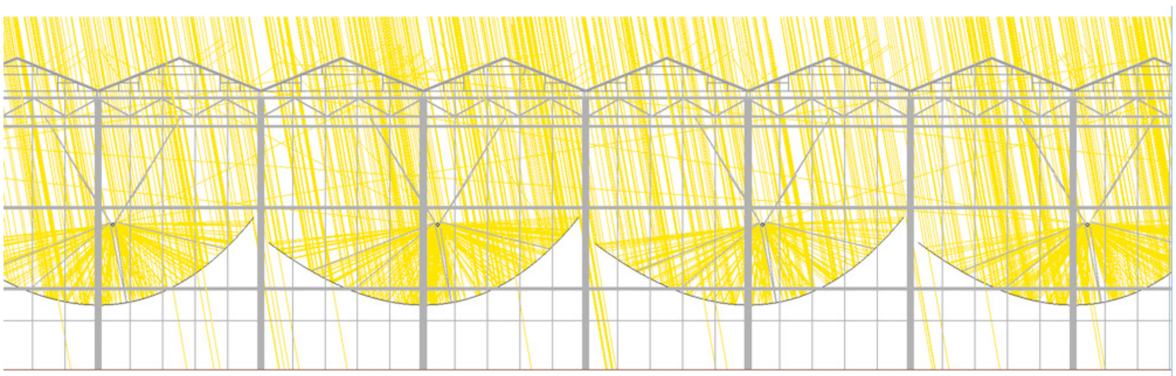

FIGURE 1. Greenhouse cross section from ray trace model

Cost

As with all solar technologies, the economic analysis of solar steam is based on its Levelized Cost of Energy (LCOE) compared to fossil fueled alternatives. Over the life of the plant, operating and maintenance costs are far lower than conventional fuel-fired boilers due to the elimination of fuel use. As a result, capital investment per unit of energy output is the principal driver of LCOE.

In calculating the capital investment, it is important that all costs be accounted for. It is common to find LCOE calculations in the literature which limit considerations only to material costs, or material and labor costs, especially in engineering and technical analysis of various design options. Fully representative plant pricing models should consider the following factors at a minimum.

- Direct project cost: For any system used for EOR, project costs must include provisions for the customer requirements for design and construction to demanding oil and gas industry standards for safety, quality, and reliability, as well as the required support of local economic development using local content, even when this results in slightly higher costs. Direct project costs include:
    - All engineering costs, including all required customer and regulatory reviews, complete construction drawing and documentation packages with data sheets and inspection test plans for each component, capture of field redlines, and back drafting to create a final as-built package. This scope also includes production of plant operating manuals, spares and maintenance management systems, and comprehensive training plans for client operations and maintenance personnel.
    - Project management, including Engineering, Procurement, Safety, Construction, Project Controls, Commissioning and Operations, and Quality
    - Logistics and shipping costs for all materials to the project site.
    - All solar collector field material costs, including mirrors, receivers, structures, aiming, and cleaning systems, including one year of spare parts.

- All balance of plant costs, including:
  - Electrical - High voltage (12kV to 38kV) switch gear, transformers, low voltage (415-480V) switch gear properly housed in air-conditioned buildings, and local AC distribution boards across the project site, as well as all power distribution wiring, including site-wide grounding grid.
  - Piping & Mechanical – All plant piping from water supply at the plant boundary to export steam at the plant boundary, including all control, isolation and relief valves, pumps, separators, blowdown pits, etc. Miraah includes an RO plant to produce wash water and an N2 plant to blanket the feed water storage tank.
  - Instrumentation and Controls – All required process measurements and controls, as well as air conditioned accommodations for operators with approved toilet, pantry, rest and prayer facilities.
  - Telecommunications – Intertie network to a customer field control room, phone service between the site and the control room, and local networks between the plant controller and all distributed control or smart devices.
  - Fire detection and suppression per client standards.
  - Commissioning and operational spares, including provision of air conditioned or shaded spares storage where needed.
- All construction costs, including:
  - Direct construction labor including site accommodations for up to 400 people, with their required visas, and travel expenses
  - Construction management, subcontractor travel for construction supervision, training and commissioning
  - Bulk materials, including concrete, rebar, gravel, etc.
  - Safety and Quality management and costs
  - Construction equipment with certified operators, rental offices, rest areas, canteens, etc., all compliant with client standards and local regulations
- Taxes and duties as applicable throughout the supply chain

- One year operating costs after completion of all commissioning work, including staffing, services, transportation, etc.
- All required overheads, including
  - Selling, General and Administrative expenses
  - Research and Development costs to support continuous improvement in plant performance while reducing cost, as well as development of configurations to serve new applications
- Reasonable profit for sustainable business and growth

It is important that all of the above are considered when calculating project pricing. Most of these costs are driven by, and scale with, the cost of the solar field, the balance of plant, and the construction costs. Thus, cost reduction efforts can be focused in these three areas.

Scale effects are significant. Economies of scale accrue from spreading one-time engineering, project management and procurement expenses across a larger project. Higher procurement volumes allow negotiation of lower material costs, as well as allowing investments in tooling and manufacturing techniques that are only cost-effective at high volumes. GlassPoint's experience has shown that these factors alone account for a 10% reduction in cost as project size increases from 100 to 300 MWt.

Product Development Drives Cost Reduction

The Miraah solar field is similar to the pilot built in 2012, but virtually every facet of the design has been improved to reduce materials, construction and operating cost, increase specific output, and improve already high reliability and serviceability. The design changes had to be conducted in a way that minimized risk and ensured that any new, unanticipated problems would be identified and resolved prior to field deployment, whether such problems arose in the manufacturing, shipping, installation, performance, or reliability of the new equipment.

Achieving significant cost reduction often requires significant design changes; scale alone could not support the target cost reductions for Miraah. For instance, in the mirror support and aiming systems, the 36-fold increase in volume between the pilot and the early construction years of the Miraah project would allow 10% to 20% cost reductions without design change, but evolutionary design changes allowed many subsystems to be cost reduced by over 50%.

As labor is a key cost element in component manufacturing and plant construction, industrial engineering methods have been integrated into all product and tooling design. Approaches are evaluated and adjusted to first and foremost ensure the safety and ergonomics of each operation. Next, labor productivity is evaluated and improvements are developed in component design, tooling, fixturing, training and quality assurance processes. A goal was set for construction operations to complete each step for one 180m row in an 8-hour work shift. This goal was achieved as construction proceeded; efforts then focused on achieving higher build rates while simultaneously reducing the number of workers assigned to each operation.

GlassPoint uses a phase-gate process for the release of new or improved designs. New solutions go through a Concept and Feasibility stage where small scale lab tests quickly screen new ideas. Viable solutions are moved to a Prototype phase where full scale working prototypes are lab tested. Refined designs go through an Engineering Verification Test, where components are deployed to the field for testing in small volumes and performance and reliability are confirmed. Finally, a Manufacturing Verification Test (MVT) is conducted at full scale with significant volume, to ensure that parts produced on production tooling match the performance and reliability of engineering prototypes, and that the packaging, installation tooling, quality checklists, and other details are finalized. Out of an extended pipeline of design and sourcing improvements, only design changes ready for MVT in mid-2015 were considered for the Miraah project. Less mature concepts are road-mapped for future release.

The first new iteration of the design was to be deployed across 432 rows of greenhouse and collector. The total greenhouse footprint for these collectors is approximately 622,000 m2. To conduct an adequate MVT, a full row of greenhouse and collector was added to the existing Solar Steam Generator Pilot (SSGP) in Amal. Steam from one row of the existing plant was rerouted to allow the MVT to provide the final pass of the direct steam process at approximately 110 bar and 300°C, with peak steam flows of approximately 7 tons per hour. The plant started in this new configuration in June of 2016 and has operated routinely since. Construction and operation of this 1440 m2 structure allowed sufficient scale to verify construction labor estimates, performance, and reliability. Lessons learned were recorded, and minor design, packaging, tooling, and construction process improvements were identified prior to the final production release of materials for the Miraah project.

Selected Design Improvements

A structured process was utilized to capture and prioritize lessons learned from construction and operation of the pilot plant. These led to a large number of design improvement projects.

As the mirrors operate in a controlled, wind free, environment, design efforts focused on minimizing the mass of the mirror structure. The mass of aluminum used to form the front and back sheets of the composite mirror itself was reduced by 18%, from 550 to 450 microns thick. GlassPoint's inline metrology system for mirrors uses machine vision to evaluate aiming accuracy. In figure 2, mirror performance before and after the reduction in material usage are compared for 2,500 mirrors or approximately 25,000 m2 of reflector.

GlassPoint's figure of merit (Fig. 2) calculates the percentage of the sun's reflected rays that would strike the receiver, assuming a properly positioned and aimed reflector. As a result of a large number of improvements to the mirror manufacturing process, mirror precision improved despite the reduction in mirror face material mass to about 1.2 kg/m2.

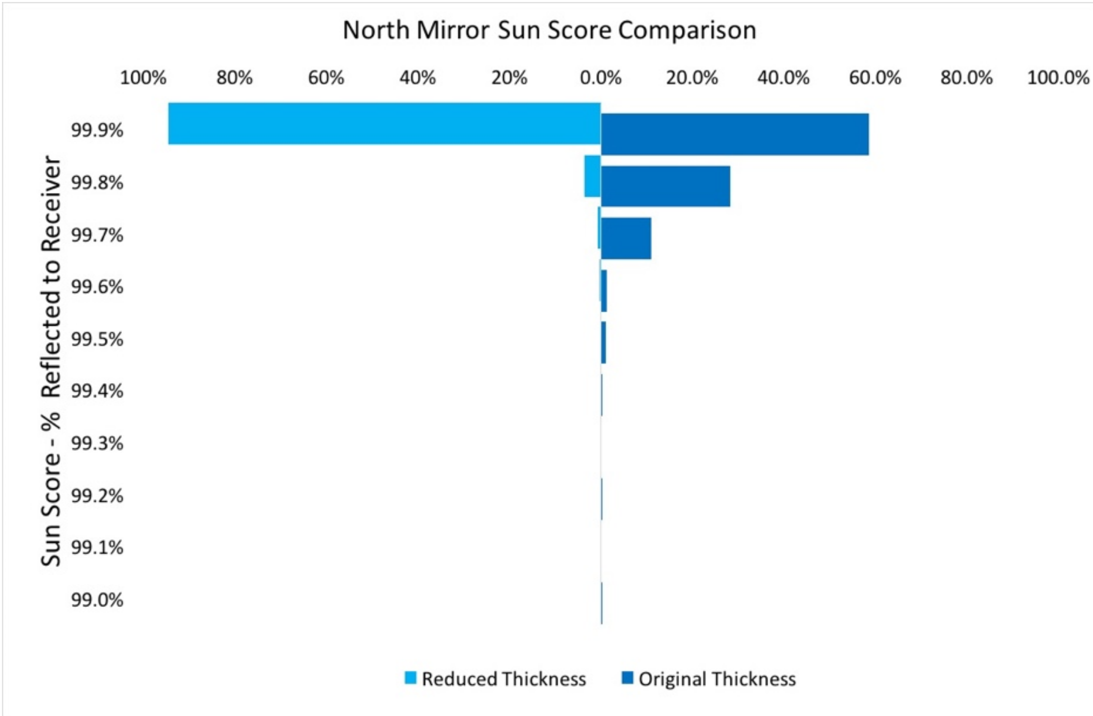

FIGURE 2. Mirror thickness reduction qualification data

Reflector support structure cost was reduced by replacing the previous hydraulically formed and hinged ribs with a rigid space frame designed for field fabrication. Figure 3 compares the previous design to the current structure configuration. Analysis showed that savings from eliminating the hinged section more than compensated for the cost of increasing greenhouse interior height to accommodate the monolithic structure.

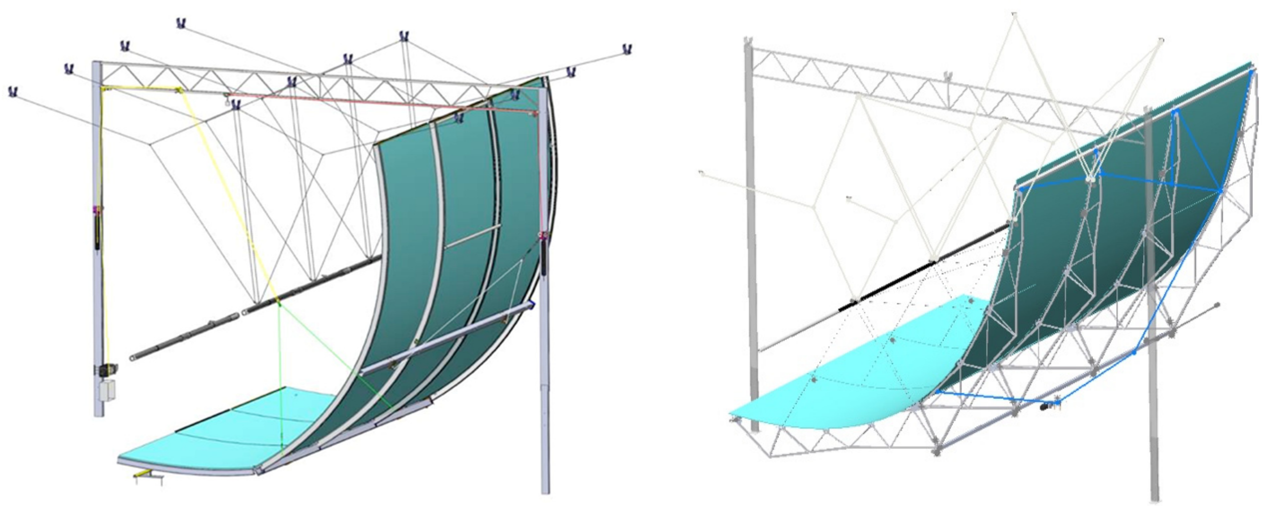

FIGURE 3. Mirror structure and aiming system evolution

Structural aluminum usage per m2 of aperture was reduced 30% from 1.14 to 0.8 kilograms. At current prevailing extrusion costs of approximately $3.00 (USD) per kg, the mirror structure materials now cost $2.40 per m2. Finite element analysis showed the new, monolithic space frame structure was five times stiffer than the previous design. The switch from offsite to on-site manufacturing reduced the number of shipping containers required for collector structure by more than 50%. The construction costs of a temporary factory were avoided, as careful review of the construction schedule and night-time interior temperatures showed that the greenhouse interior could be used for this operation. Thus, the incremental cost of shifting the operation on-site is limited to differences in labor rates.

The resulting reduction in weight and improvements in stiffness of the mirror assembly enabled a new aiming drive system that reduced installation and maintenance costs associated with the previously used overhead pulleys. The new design uses 33% fewer motors to position each 180m row of mirrors, paired with an absolute inclinometer to control aiming with a precision of 0.01 degrees or 0.2 milliradians. The 33% reduction in motor count, combined with increased manufacturing volume and simplifications to cables that connect the mirrors to the motors, have resulted in a total cost reductions in the aiming system of over 60%. Note that all of the savings listed, in mirror, rib and aiming drive materials, are attributable to the support and protection from wind and dust provided by the greenhouse enclosure.

Construction Conditions

Site conditions in Amal, Oman present significant challenges. Figure 4 shows the wind data from a typical year weighted by the available solar energy. Approximately 30% of the energy is delivered at times when the wind ranges between 8 and 16 m/s (29-58 km/hr). Construction work is typically limited when wind speeds exceed 30 km/hr due to concerns about blowing dust and sand, and difficulty handling materials, although steam generator operation is unaffected by these conditions.

Figure 5 shows the average high and low temperatures measured at the site for each month. The highest temperature measured was 45°C. In the summer months, work hours are shifted to avoid the hottest portions of the day. The impact of the summer heat was mitigated by using night shifts for solar collector construction, with peak night shift temperatures usually remaining below 35°C.

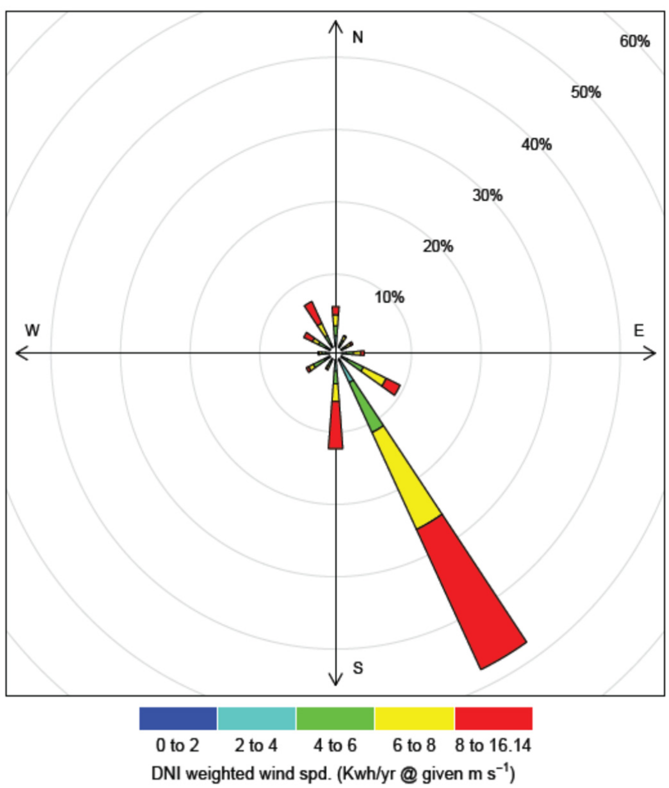

FIGURE 4. Amal solar-rated wind rose

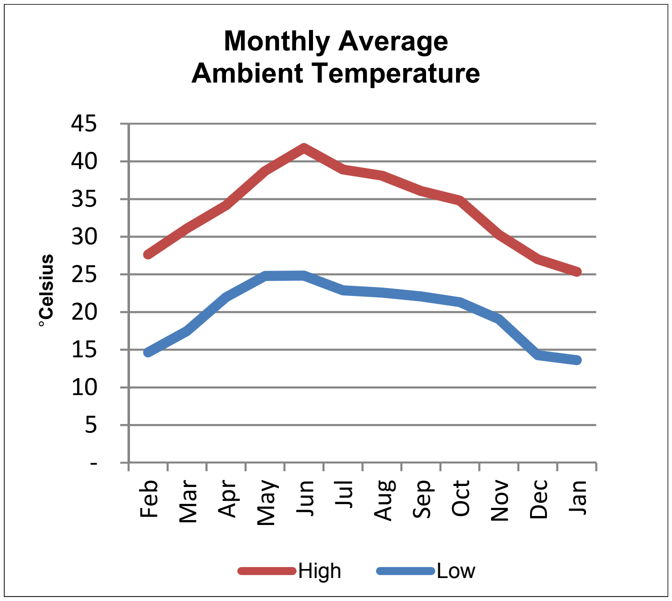

FIGURE 5. Amal average monthly temperature extremes

Labor Reductions

During construction, labor productivity for each construction operation was carefully monitored. This data was then normalized to labor hours per m2 of greenhouse footprint. Due to the high ground coverage ratio, this metric is sufficiently close to the labor hours per m2 of collector aperture.

Construction began with minimal special tooling. Additional equipment was delivered and developed over the course of the project. In addition to tools and fixtures, specialized tooling included electric tugs and trailers to facilitate material movement through the greenhouse, permanent mobile scaffolds to facilitate each task performed at height, and improved lighting for night work.

An example of the effectiveness of the improvements is shown in fig. 6. Installation of Mirrors and Receivers initially took over 0.6 labor hours per m2 of greenhouse. As the number of cumulative rows installed grew, proficiency increases and specialized tooling reduced this to less than 0.2 hours.

Improvements continue to increase productivity and substantial improvements are anticipated as the number of rows installed climbs into the hundreds.

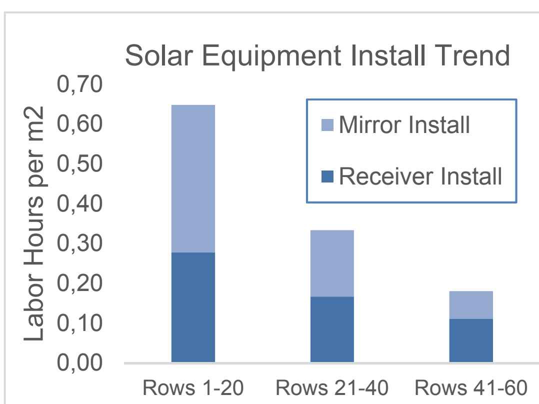

FIGURE 6. Solar equipment install labor

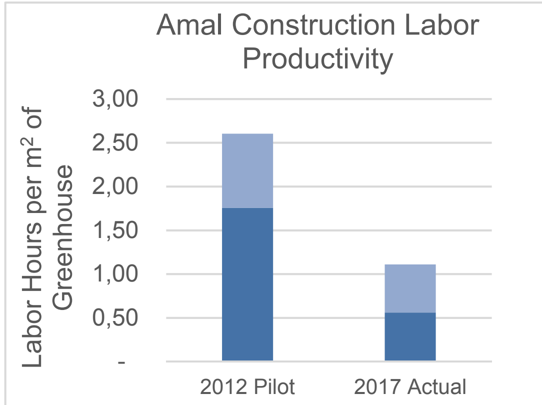

FIGURE 7. Total solar field construction labor

The results are summarized in the chart above. Greenhouse construction labor was reduced 68% from 1.75 to 0.56 hours per m2 of greenhouse. Solar collector installation labor was reduced 35% from 0.85 to 0.55 hours per m2 of greenhouse. As a structured process continues to identify many opportunities for further improvement, labor productivity is forecasted to improve significantly as we complete the Miraah project.

It should also be noted that return on investments in labor reduction is region-dependent. Compared to the relatively low-wage environment for Middle Eastern construction projects, in higher cost regions, such as the United States, different design and construction tradeoffs would be made to further reduce labor at the expense of slightly higher material and tooling costs.

CONCLUSIONS

Over four years of safe and successful operation, the enclosed trough solar steam generation pilot has operated using feedwater with a Total Dissolved Solids concentration of 8,000 ppm with energy output and availability above contract requirements, demonstrating the safety and effectiveness of solar steam generation in real-world oilfield conditions. The GW-scale Miraah plant will operate using the same feedwater and deliver large-scale reductions in operating costs and carbon emissions at the field.

A structured product development effort has resulted in substantial reductions in material and labor costs. The Miraah data shows increases in construction speed, and reductions in labor per unit of construction. These savings result from deployment of improved designs, enhanced tooling, and growing workforce experience with solar construction. Solar field construction labor costs of approximately $10/m2 have been achieved with an identified path to further reductions for future construction.

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