Solar Thermal Field Experience at a South Oman Oilfield

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Abstract

Miraah, a 1000MW$_t$ solar thermal energy facility at the Amal oilfield in southern Oman, was announced in 2015. The project is located 800km from Muscat, with seasonal daily peak windspeeds above 12 m s^{-1} (43 km h^{-1}) and temperatures above 40°C for much of the year. GlassPoint's enclosed trough solar steam generators deliver steam at lower cost than fuel-fired steam due to reductions in capital cost, land use, and operations costs. Fully automatic system operation eliminates the need for specialist operators, and fully automatic washing with water recovery eliminates one of the largest costs in operating solar facilities in dusty desert environments. The first 110MW$_t$ phase of the Miraah project has been operating since late 2017. Solar steam is replacing a portion of the gas-fired steam required at the field. Conditions experienced during the operations period have included high average windspeeds, multiple sandstorms, and a direct hit by the most powerful cyclone ever recorded in the region. The system has consistently exceeded contract specifications for energy production and availability. This operating experience has validated the technology at large scale.

Keywords: solar thermal, concentrated solar power, CSP, industrial heat, enclosed trough, steam generation, parabolic trough, enhanced oil recovery, process heat, automatic washing, line focus, Oman

1. Introduction

According to the IEA, energy used by industry is the largest sector of world energy use, and 74% of that energy is in the form of heat, not electricity (IEA 2018). More than half of this need, over 40 EJ, is at temperatures available from current solar thermal technologies. Decarbonizing the industrial sector is critically needed as to achieve overall world emissions targets. The same study reports that the 110MW$_t$ project described in this paper is larger than all other industrial solar thermal energy facilities worldwide combined.

A new type of high-temperature solar collector, "enclosed trough", was introduced in 2011. The goal for the technology was to supply energy (steam) used in industrial processes at a lower cost of energy than fossil fuels. Many challenges to this goal associated with existing technologies were identified, including land usage (land is limited near industrial facilities), environmental conditions (sites are determined by industrial logistics or mineral resources, not cleanliness or sunshine), and cost (capital cost and operating cost). The enclosed trough architecture delivered a new lightweight parabolic trough solar collector with a fixed receiver, contained and shielded from the environment within an agricultural greenhouse which incorporated well-proven automatic agricultural cleaning systems. These elements allowed the deployment of direct high-pressure solar steam generation from oilfield water, making solar steam a "drop-in" technology for oilfield facilities.

Previous work has reported on experience and progress in building and cost-reducing enclosed trough solar systems (Bierman et al. 2017). The remote project site and the intrinsic potential hazards of working at oilfield locations made labor hour minimization a key objective. The reported results showed the importance of system design and construction processes in achieving this goal. GlassPoint's enclosed trough systems are built using a modular design which organizes large solar fields into identical independent units, and an "assembly-line" organization of construction steps and processes.

The basic architecture of the enclosed trough system is simple. A standard agricultural greenhouse is used to provide an airtight enclosure that keeps the mirrors clean. An external air handler pressurizes the interior with clean air that has been dehumidified to prevent condensation. The greenhouse not only provides protection, but provides all required structural support for the mirror and receivers within. As the mirrors are not exposed to

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wind or dust, they can be of lightweight construction. A honeycomb aluminum composite is used to reduce the full installed weight of all solar equipment to 3 kg per m^2 of collector. The greenhouse also facilitates cleaning of the only surface exposed to the environment. Automated roof washing equipment is readily available and is capable of cleaning the entire roof overnight, ensuring the plant starts each day at peak energy collection efficiency. The receiver is fixed, with the mirrors pivoting around it. As a result, there is no need for costly and leak-prone ball joints. The customer's process fluid, typically non-potable water with Total Dissolved Solids between 8000 and 15,000 ppm is directly heated in the receivers by the parabolic troughs to temperatures as high as 342 degrees C and 140 bar. As low-quality feed water may result in scaling, the entire collector is configured for periodic hydraulic pigging to remove scale.

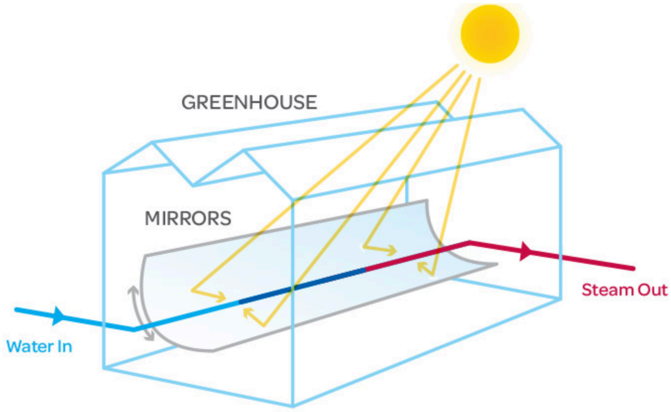

Figure 1. Enclosed Trough architecture

Figure 2 is a satellite image of the Miraah project during construction. Phase 1 began commissioning in September of 2017, and commercial operation in 2018, while Phase 2A began operation in 2019, and Phase 2B is expected to be brought online, depending on steam demand at the adjacent field in late 2019 or early 2020.

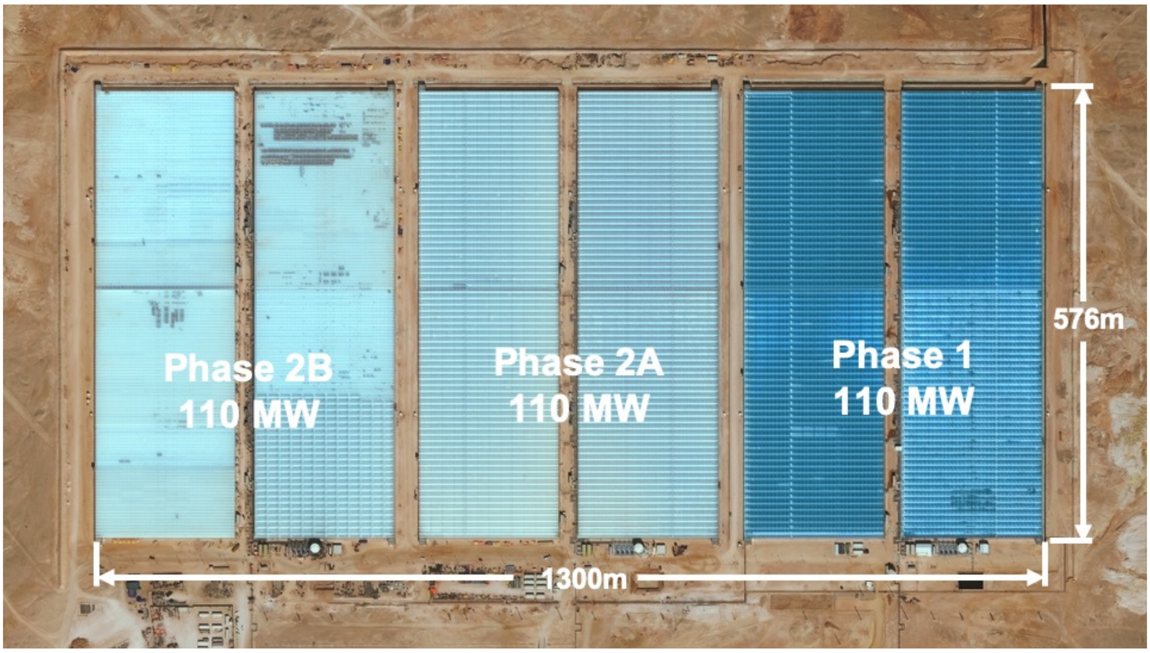

Figure 2. Miraah construction satellite photo

Solar steam generation has now been in operation for more than five years at the field, and the $110MW_t$ installation described here has been in operation since 2017. We review here the successful operations experience.

2. Project Success Criteria

A number of objectives were established for the Miraah project. The overarching goal was to prove the suitability of the enclosed trough technology for Industrial Process Heat applications. Success criteria were as follows.

First, cost of energy needed to be competitive with fossil fueled alternatives. The energy delivered by the plant reduces demand for steam generated using natural gas fired boilers. Levelized cost of energy for the completed plant could not exceed the costs of operating these boilers using natural gas at US$4.75 MJ^{-1} ($5 per MMBTU). Achieving this goal required high efficiency conversion of solar energy to high pressure steam delivered at approximately 10 MPa (100 bar) and 310°C. The steam is produced by from low-quality feed water with over 8000 ppm of dissolved solids, primarily salt, very different from the ultra-pure water or specialized heat transfer fluids commonly used in CSP plants built to generate electricity. Designing for such high mineral content water is a critical factor in reducing total cost of energy, as no costly water treatment plant is required beyond basic water softening to remove calcium compounds. These capabilities must be provided at exceedingly low capital expense. The details of this effort have been previously published (Bierman et al. 2013, 2017).

Industrial users of solar energy, particularly those in remote locations, require automatic, robust systems that support their daily operations with minimal attention, allowing their operations and engineering staff to focus on their core business. To substitute solar heat for fossil fuels, users expect systems with reliability that matches or exceeds that of their existing energy sources. The minimum dispatch reliability target for this facility was established at 99%. Output predictability is also critical; users are willing to accept the variability of solar energy to achieve cost reduction and carbon emissions reduction goals but need to be able to plan for average monthly output, as well as expected output for the next 24-hour period, with high confidence. Easy curtailment of energy production is also required, as facilities at the site which supply electricity and water and downstream consumers of energy may all experience planned and unplanned interruptions. Users seek a robust unit that can be turned on and off at will, delivering any amount of output from a small fraction of rated output to 100%.

Staffing in remote environments is a constant challenge for energy and mining customers. Often the customer must take responsibility for housing, feeding and providing medical care to every worker on their site. As a result, operating staff requirements must be minimized. Successful solar plants will limit the number of workers required to operate and maintain the plant and will not require substantial specialized training for new staff. Field workers often work intermittent schedules, returning home every 4-12 weeks for extended periods. Turnover is inevitable, and new staff will inevitably be added to operating teams over time.

Concentrated solar energy plants for electric power generation are usually sited after conducting extensive studies to optimize location for the best solar resource, least soiling, access to good roads and utility interconnection. Solar thermal facilities used for industrial applications does not enjoy this luxury, as they must be collocated with the industrial facilities they serve. Most industrial locations in the sunbelt are in harsh desert locations, usually remote from large cities and infrastructure, and sited based on the availability of oil, gas, or metals. As a result, any solar plant for industry must be exceedingly robust. Three criteria of particular importance are resistance to seismic and wind loads, as well as the ability to operate in areas with heavy soiling due to windblown dust.

3. Results

In September of 2019, the 110MW$_t$ Miraah Solar Steam Generation Phase 1 plant had completed 21 months of commercial operation and celebrated 2 years since the plant first produced steam. A second 110 MW$_t$ module, part of Phase 2 of the Miraah project, came online in 2019 and is showing similar operating results to Phase 1. Enclosed trough technology beginning with the Solar Steam Generation Pilot (SSGP) (Bierman et al. 2013), has been in continuous operation at PDO's Amal Gathering Field in the remote Omani desert for nearly 7 years, with over 220 MW$_t$ now in daily operation. This operating experience has proven the suitability of the design for industrial processes anywhere in the global sunbelt. For the purposes of this discussion, we compare conditions with those near the city of Calama in Chile's Atacama Desert, which has excellent potential for deployment of solar industrial process heat.

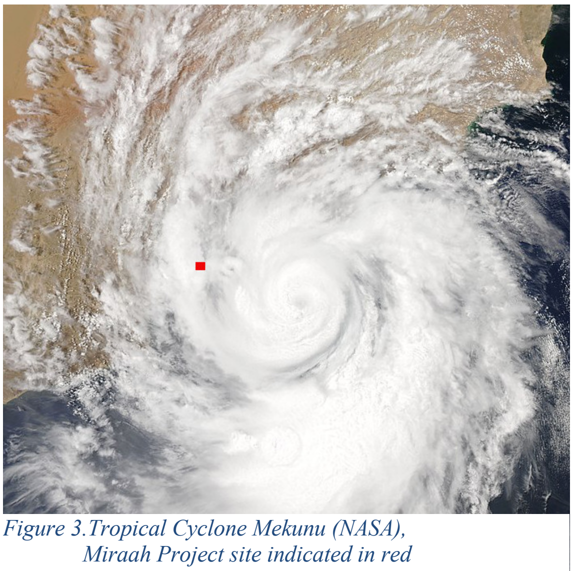

Figure 3.Tropical Cyclone Mekunu (NASA), Miraah Project site indicated in red

While tropical cyclones have been known to occasionally strike the region where the plant is sited, they have historically been rare and generally mild. This pattern was broken in 2018, Miraah's first year of operation, when tropical cyclone Mekunu struck the site on May 25th followed by tropical storm Luban on October 25th.

Mekunu was the largest cyclone to strike the region since 1959, with windspeeds of 50 m s^{-1} (180 km h^{-1}) over the Indian Ocean. At landfall, nearby meteorological stations recorded winds reaching 33 m s^{-1} (120 km h^{-1}). Mekunu brought over 48cm of rain to the Miraah site in 48 hours. Figure 1 shows the plant location plotted on a satellite image of Tropical Cyclone Mekunu. The plant was robust both in energy production and in its structure.

Figure 4 demonstrates the success and robustness of energy output in the face of these conditions. The Miraah Phase 1 plant consists of 4 independent solar steam generators or “blocks”, two with a nominal capacity of 146.7 metric tons of steam per day and two larger units with 183.3 tons capacity, for a total average daily output of 660 tons of 10 MPa (100 bar) steam. Customer demand for steam has varied periodically, so steam output of the total facility has had periods of limitation (curtailment). One of the blocks, Block 4, was designated as a reference block and operated as frequently as possible with minimal curtailment. Data from days with good solar radiation from before and after Mekunu, and after Luban, is presented in Figure 4. The performance data shows that both before and after the storm passages, the plant measured performance closely matches the performance forecast model for the plant.

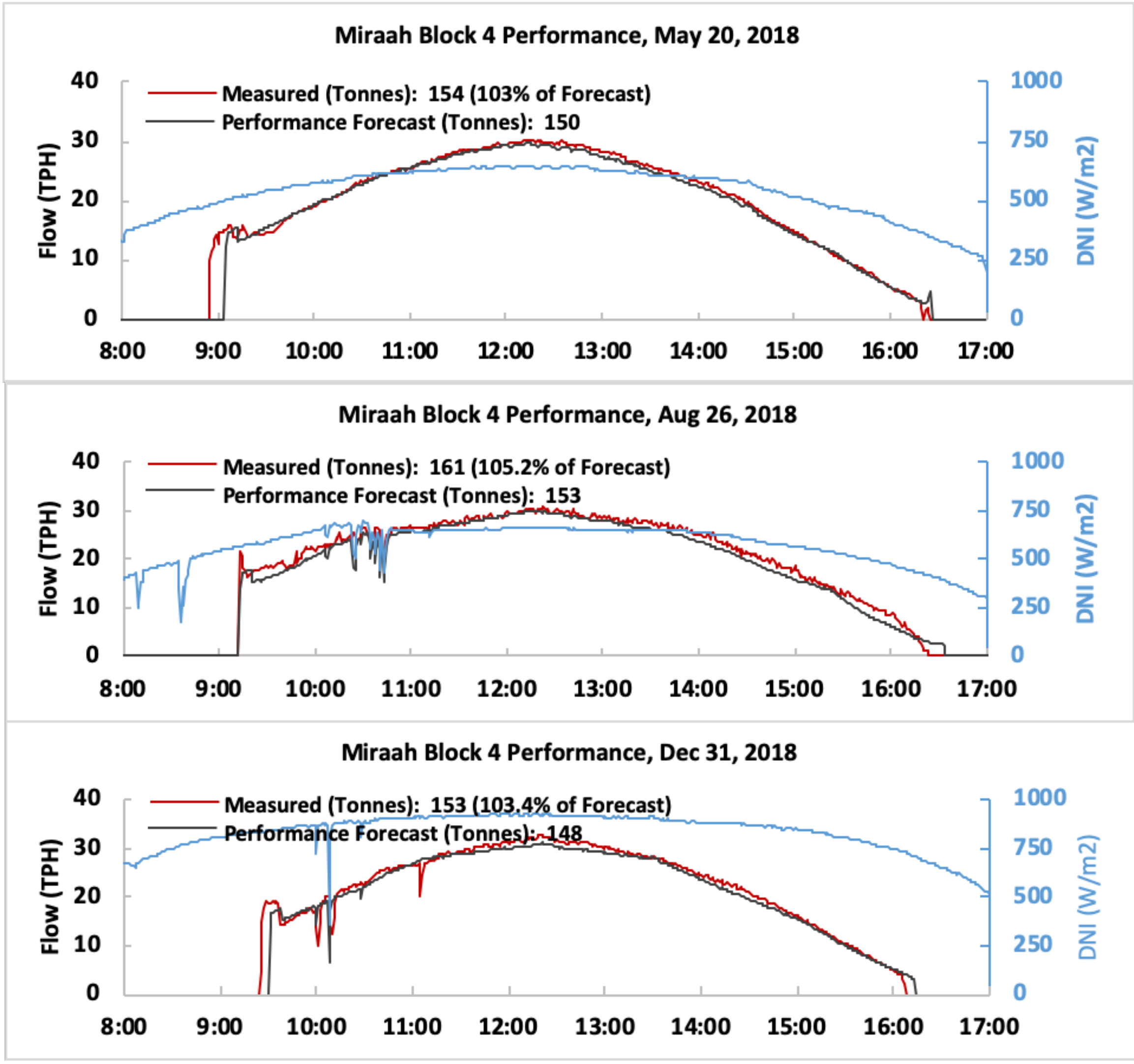

Figure 4. Miraah Phase 1, Block 4 performance vs. forecast

Some operational factors are visible in Figure 4. First, notice that the peak Direct Normal Irradiance (DNI) in May and August only reaches approximately 600 W m^{-2}. This is common in the region, as high levels of airborne dust and haze reduce DNI. Even in December, the peak DNI just slightly exceeds 900 W m^{-2}. The same solar plant would have far higher energy output in the Atacama, where typical peak and total annual radiation are on the order of 50% higher. Note also in the August and December plots the passing clouds which reduce the DNI for brief periods between 10 and 11 AM. Such transient events are common, and the plant must operate smoothly as incoming solar energy varies, often from more than 800 W m^{-2} to zero for periods of several minutes.

A contractual performance test for the entire plant was carried out during the second half of the first operating year. The key tests included availability, automatic operation, and energy production. Energy production was measured as weather-adjusted, curtailment-adjusted tons of steam delivered. Performance for all blocks was compared to contractual performance targets on a monthly basis. Performance for the period averaged 104.6% of target. Note that the low output in October and November was the result of curtailment, not weather; the customer was unable to accept steam from the plant for part of this period.

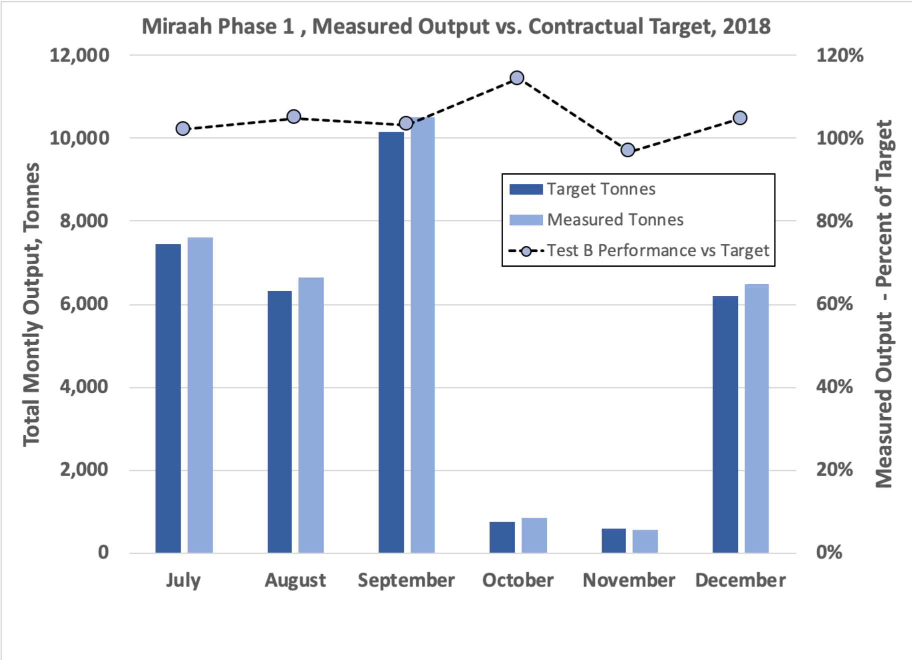

Figure 5. Miraah Phase 1 2018 performance vs. contractual target

Achieved plant availability was very high. Regardless of what dispatch regime the customer requested (full output, partial output, or no output), availability was measured based on the plant's readiness to operate as required during the period where available solar energy allows operation. By this metric, availability for the July-December period was 100%. All required maintenance activity that could have caused plant downtime was conducted at night or during planned periods of curtailment in the daytime; all the required work could have been performed at night if necessary, which would keep the same availability with 100% dispatch.

In considering the plant's performance, it's important to note that no solar specialists were present at site. Plant operators and maintenance technicians were recruited from the available workforce that normally operates other oil and gas assets at the oilfield. Engineering staff were either located nearly 1000 km away in Muscat, Oman, or in California. Plant operators and technicians all worked rotating schedules such that the mix of staff at site changed constantly during the test period.

Resistance to wind loads was amply demonstrated during Mekunu, which delivered estimated gusts of 30 m s^{-1} (108 km h^{-1}) or more. Other enclosed trough solar installations in California's San Joaquin valley have been designed for peak wind speeds of 38 m s^{-1}. For comparison, the peak wind speed recorded since 1939 in Calama is 28 m s^{-1} (101 km h^{-1}). Structural wind loads increase as roughly the square of the wind speed, so the structural impact of wind in Calama would be approximately 45% lower than the design loads in California.

Resistance to seismic loads is also important in many locations. Solar facilities in California and in the Calama area must be designed for peak ground accelerations on the order of 5 N kg^{-1} (0.5 g). The largest force that the greenhouse foundations must resist is vertical uplift caused by wind. Mekunu's extreme conditions caused no structural damage and validated the foundation and structure designs. The enclosed trough design is inherently resistant to seismic loads, as the structure is lightweight, flexible, and very similar to agricultural greenhouses. As of 2019, such agricultural greenhouses covered 500,000 ha worldwide (Hortidaily 2019), including many thousands of hectares in seismic zones. The framing system for a greenhouse is flexible and this results in a fairly high fundamental period for the building. The anticipated earthquakes in the region near Calama are intense seismic events with short period shaking. These short period earthquakes do not couple well with a long period building. The building is essentially de-tuned from the dynamic motion of the earthquake. Seismic design building codes recognize this de-turning effect and specify lower seismic design forces for buildings with long fundamental periods. The masses of greenhouse buildings are much lower than in older CSP trough and tower designs. This results in proportionally lower seismic design forces. These lower forces can easily be accommodated with standard structural systems which utilize commonly available building materials and construction methods. The glass covering of the greenhouse is organized as independent panes which each are free to move in their mounting channels, allowing the structure to flex and move without glass breakage. The enclosed troughs themselves are suspended by flexible members which accommodate both structural movements and the dilation associated with daily thermal cycling without misalignment or damage.

Soiling resistance was the final success criterion. The Omani desert is subject to seasonal dust storms with far higher frequency than major dust events in the Atacama region (Reyers et al. 2019). Major dust storms occur several times each year in Oman, reducing specular transmission of glass surfaces by up to 20%. Figure 6 shows the beginning of a typical storm. Within the dust cloud, visibility is reduced to less than 50m and airborne dust driven by 8-17 m s^{-1} (30-60 km h^{-1}) winds forces suspension of all outdoor activity until the storm passes. GlassPoint has repeatedly measured the impacts of such events, measuring system efficiency before and after cleaning the enclosure roof. The results show full recovery of system output (corresponding to 98% or higher clean glass) after a single automated wash cycle, which takes less than 24 hours. Chronic daily soiling has greater impact on total energy production than dust storm events. The Oman desert has high quantities of fine dust, similar to the Chusca dust found in the Atacama. Soiling reduces specular transmission at a rate of about 2% per day. Specular transmission studies of soiling are not common in the literature, but PV soiling studies provide a good relative comparison of soiling rates. PV performance loss due to soiling in Oman has been reported at 35-40% for 3-month periods (Kazem and Chaichan, 2016) while such loss rates at Calama have been reported at 15% in two months (Cordero et al. 2018). We can conclude that soiling in the Atacama is similar to that experienced in Oman, though of slightly lower intensity.

Figure 6. Typical Amal dust storm, photographed within 1km of project site

The SSGP and Miraah plants have operated successfully in this soiling environment for 7 years. Automatic roof washers are operated nightly and return the roof glass to greater than 98% of its original specular transmission each morning, regardless of whether the soiling is the usual 2% daily soiling, or a sudden 20% loss brought on by dust storms. The common high wind conditions occasionally limit cleaning, as the washers are not designed to operate in winds in excess of 10 m s^{-1} (36 km h^{-1}). In the Atacama, nightly cleaning can be even more reliable than in Oman due to the much lower wind speeds typically encountered there.

Figure 7. Automated Roof Washing Equipment, Roof during cleaning

4. Conclusions

Enclosed trough technology has been proven an effective solution for large scale industrial process heat requirements. The enclosed design is inherently resistant to high wind loads, soiling due to airborne dust and seismic forces.

The Miraah operation to date has been an unqualified success. Performance, measured in tonnes of steam produced each day, has exceeded forecasts. The plant has withstood dust storms, tropical storms and cyclones, and routinely operated in soiling conditions that would reduce output by 2% per day if not for the integrated automatic cleaning system. The conditions experienced in Oman, including soiling rates and events, wind loads, and temperatures, are more extreme than those in other locations such as Chile's Atacama desert.

The operations results at the Amal field support the premise that the enclosed trough technology can deliver reliable, low-cost supply of solar thermal energy at industrial sites anywhere in the world, without degradation due to soiling, mechanical failure, or system integrity.

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