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Solar Industrial Process Heat and Thermal Desalination

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Solar Boiler for Almond Processing

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Abstract. Since June of 2022, Sunvapor has been successfully operating the first solar boiler used for nut processing in the USA. Sunvapor engineered, managed the construction, and commissioned the turnkey solar steam generating facility for California Custom Processing ("CCP"), one of California's leading almond processors located in Madera, California. CCP takes in raw almonds and performs a range of processes, including pasteurization, that require process steam. CCP was seeking to add steaming capacity to its boiler room, which has three 500 kW_{th} (the subscript "th" means we are referring to thermal energy) gas boilers in order to raise its daytime production rate. The 2 MW_{th} solar boiler developed by Sunvapor not only satisfied the need for additional daytime steaming capacity, but in clear sky conditions has supplied 100% of all the plant steam demand - with no greenhouse gas emissions. In this paper we present all phases of the life cycle of this first-of-a-kind solar boiler for nut processing; development, construction, commissioning, and operations.

Keywords: Solar, Boiler, Almonds

1. Development

1.1 Project Background

Most of the world's almonds are produced in California's Central Valley. Almonds from California are legally required to be pasteurized either with chemicals or with steam. Only steam pasteurization is considered organic. California Custom Processing ("CCP"), a leading almond processor in the Central Valley, was seeking more steaming capacity to increase daytime production. We offered them a 2 MW_{th} solar thermal boiler so that they could achieve their steam demand with a 40% annual reduction in natural gas. The achievement of such a deep decarbonization was possible because CCP had a sufficient solar resource (P90 DNI 2,300 kWh-$m^{-2}$$year^{-1}$) and available land (~ 1.4 ha). It would not have been possible with electrification because the California grid has a higher indirect emissions factor (0.216 kg/kWh) than on-site natural gas combustion (0.181 kg/kWh), and solar photovoltaics is less than 30% as efficient at converting solar energy to heat compared with the collectors we deployed. We set the pressure of the solar boiler at 8.3 bar so that solar steam takes priority over the gas-fired boilers which turn off when the header pressure reaches 7.6 bar. The gas-fired boilers turn on when the header pressure drops to 6.6 bar. A pressure of 8.3 bar corresponds to a saturation temperature of 176.8°C. This temperature is currently inaccessible by commercial heat pumps. The maximum steaming capacity of the solar boiler is 0.8 kg/s.

1.2 Engineering Design

The engineering design involved collector selection, thermohydraulics, and controls.

1.2.1 Collector Selection

The design effort began with the selection of the collector. The project required the collector to be third-party certified by the SRCC which follows the international Standard ISO9806 [1]. In order to achieve the required steam conditions with indirect heating we needed a collector that had high (>70%) thermal efficiency at a mean fluid temperature of 205°C. Figure 1 shows the plots (orange, gray, yellow) of thermal efficiency against mean fluid temperature for three collectors that were SRCC certified in 2021 [2]. None of them had sufficiently high efficiency so we decided to assemble a Sunvapor parabolic trough collector (SPTC-3000) and perform SRCC testing at the site. From the specifications of the collector components, we predicted the thermal efficiency (blue) which achieved a value of 72% at 205°C. The collector has a 3m aperture which is easier to assemble, clean, and has lower wind loads than a 6m aperture utility-scale trough. A photograph of the SPTC-3000 collector is shown in Figure 2.

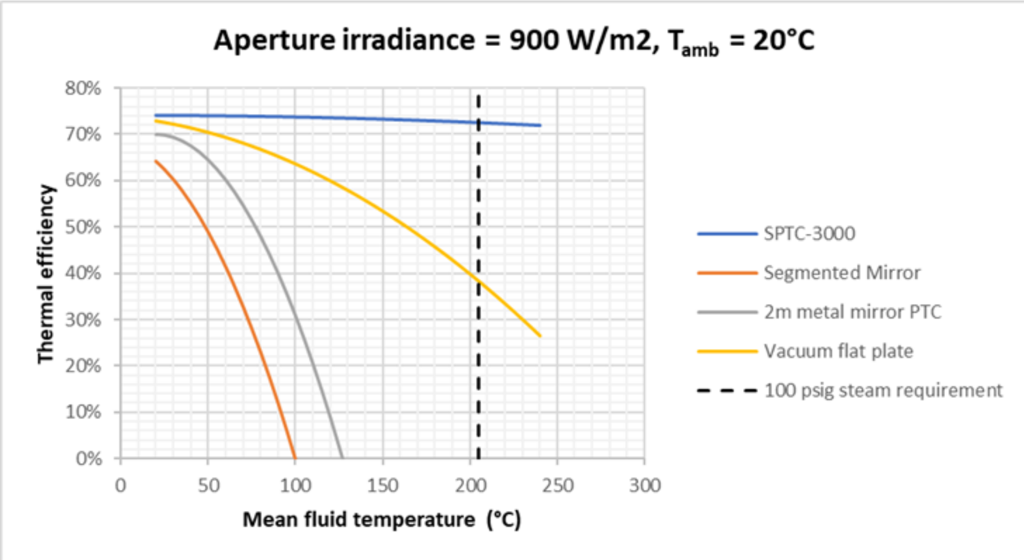

Figure 1. *Thermal efficiency as a function of mean fluid temperature*

Figure 2. *Sunvapor SPTC-3000 parabolic trough collector assembled at the site*

1.2.2 Thermohydraulics and Controls

The solar field is arranged into eight parallel loops of four collector arrays each as shown in the satellite image of Figure 3. The fluid heated in the solar field is returned to the boiler room across a pipe bridge which allows the circulation of trucks carrying almonds. Steam is produced in a 2 MW_{th} unfired steam generator (USG) that has priority over three 500 kW_{th} natural gas boilers. The heat tranfer fluid that circulates in a closed-loop in the solar field provides the heat source for the USG.

Figure 3. *Pressurized water circulates in the solar field comprised of eight collector loops. The collectors are aligned in the north-south direction. The dashed green box highlights one of the eight parallel loop, showing the flow direction within the loop. Each loop can be seen to include four collectors in series. A scale is indicated to the right of the solar field.*

We specified pressurized water as the heat transfer fluid (HTF) to avoid any risk of fire that would be possible with thermal oil. Water also poses no contamination risk due to incidental food contact in case of a leak in the heat exchanger. We use stainless steel solar absorber tubes, so we need to control the chloride concentration of the water for the avoidance of stresss corrosion cracking. We designed a master control panel to allow safe autonomous operation of the system. The control of HTF pressure, collector tracking, and pump speed ensures that the water always remains in the liquid state. The control panel also ensures that in high wind (> 61 kph) the collectors move to a safe stow position.

The project with CCP required accurate metering of the solar energy available to the plant. Our energy meter included redundant resistance temperature detector (RTD) transmitters at the inlet and outlet of the USG, and a vortex flow meter. From error propagation analysis we found that the energy measurement uncertainty was 3%. The energy data is sampled every thirty seconds and logged every fifteen minutes.

1.3 Permitting

The project was built on undeveloped land, and as condition for securing a building permit, the project was subject to environmental approval by the California Energy Commision (CEC), the lead agency, under the California Environmental Quality Act (CEQA). A detailed biological survey of the site indicated that there was no evidence of special-status plants or wildlife. However, the project was deemed by the Madera County Airport Land Use Commission to be located within an airport influence area (see Figure 4) so we were required to prove the project would not cause any visual distraction for pilots landing at the airport. During this permitting period, the Standard for Measuring the Ocular Impact of Solar Energy Systems [3] issued by the US Federal Aviation Administration (FAA) was in force.

Figure 4. *The project site is located within the Madera airport environs*

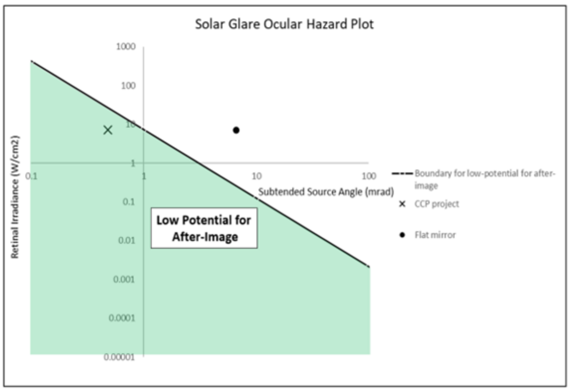

Figure 5. *With an east-west orientation, collectors could cause a visible glint with a low potential for after-image*

Under the FAA Standard it was necessary and sufficient to show that any glint or glare visible by the pilot during final approach would have a low potential for after-image. At the time of permitting an east-west orientation of the collectors was under consideration, and it was theoretically possible, though extremely unlikely, that a glint could be visible if a collector was not tracking. We therefore calculated the effective image size and brightness of such a glint and found that the pair fell within the domain of low potential for after-image as indicated by the “X“ in Figure 5.

The CEC concluded from our biological findings and airport impact analysis that the project would cause no adverse impacts to the environment, and issued a Notice of Exemption from further CEQA studies. Ironically, after the building permit was issued, and with further experience from pilots, the FAA determined that their safety assesssments of solar systems should be focused on their impact on Airport Traffic Control Tower (ATCT) cabs [4]. The Madera airport did not have an ATCT. Furthermore, the project settled on a north-south collector orientation which we showed could not produce a glint visible from the final approach path under any circumstances.

2. Construction

Sunvapor managed multiple California licensed construction contractors for the grading, collector assembly and erection, concrete foundations, piping, and electrical work. The total construction period was approximately seven months. Parts of the piping installation adhered to Section B31.1 while other parts adhered to Section B31.3 of the ASME Code for Pressure Piping [5]. There were no reports of any safety incidents during construction.

3. Commissioning

Before we could commercially operate the system, we needed SRCC certification for the SPTC-3000 collectors. We also sought to demonstrate to CCP before commercial operation that the transition from solar steam to backup natural gas steam would cause no interruption to their pasteurization process.

3.1 SRCC Testing

3.1.1 Durability Testing

We used 17 kg sand bags to simulate the highest wind loads the collector would see during operation. Loads were applied to the convex and concave sides of the mirrors (Figures 6a, 6b) to cover the full range of motion. No permanent deformation of the collector was observed. We tested (Figure 6c) the full solar field piping network under 150% of the design pressure which was 37 barg. This closed-loop solar field design pressure is intended to maintain the pressurized water heat transfer fluid in the liquid state. The isolated piping network held pressure for a test duration of 2 hours, exceeding the 15-minute duration required in the ISO9806 Standard. We subjected the receiver to thermal shock using a 17°C water spray while the heat transfer fluid was flowing at 205°C. No damage or loss of vacuum was observed.

Figure 6a. *Convex load*

Figure 6b. *Concave load*

Figure 6c. *Internal pressure*

Figure 6d. *Thermal shock*

3.1.2 Performance Testing

The purpose of SRCC performance testing is to determine the collector's thermal efficiency coefficients defined in the ISO9806 Standard by fitting to the measured quasi-dynamic collector heat gain. The heat gain was measured for one of the eight loops in the solar field. The loop was instrumented with its own vortex flow meter, and RTDs at the inlet, middle, and outlet of the loop. This way, we had individual heat gain measurements for each of the two rows (#5, 6) in the loop. Beam irradiance was measured by the difference in the signals from two pyranometers located as outriggers in the tracking aperture plane. A shadow band covered one of the pyranometers (see Figure 7); otherwise, they both saw the same portion of the sky during the collector's range of motion.

***Figure 7**. Tracking pyranometers. The shadow band is seen in the foreground.*

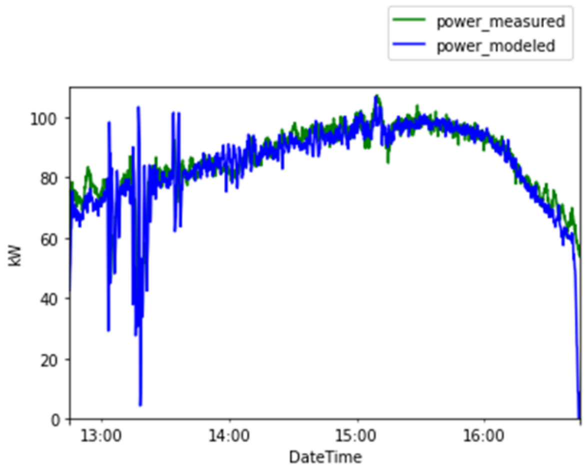

***Figure 8**. Heat gain for row #5 on February 23, 2022.*

An example of one of the performance test trials in shown in Figure 8. The extracted coefficients are used to plot the modelled row power (i.e., heat gain). Row #5 uses the inlet and middle temperatures of the test loop. The results of fitting the efficiency coefficients to measurements of the heat gain performed over four days are as follows:

$\eta_{0b} = 74\%$, a_1 = 1.02e-2 W/°K-m^2 , a_2 = 3.4e-4 W/°K^2-m^2, a_5 = 3,460 J/°K-m^2 , b_0 = 0.46; where η_{0b} is the optical efficiency, a_1 is the linear heat loss coefficient, a_2 is the quadratic heat loss coefficient, a_5 is the effective thermal capacity, and b_0 is the incidence angle modifer coefficient as defined in the ISO9806 Standard. The receiver absorber tube has a solar absorptivity >96%.

3.2 Gas Boiler Backup Testing

If the plant steam pressure should fall below the required set point (6.6 barg) the almonds must be reprocessed for pasteurization, resulting in lost productivity. We demonstrated during commissioning that the plant steam pressure is maintained above the set point through the transition from solar steam to gas boiler backup. Figure 9 shows a plot of the steam pressure in the USG as a solid blue line, the plant steam header pressure in the dashed line, and the consumed solar steam mass flow for that period in orange. Before the USG check valve (CV) is closed the USG pressure and plant steam pressure are the same. As the solar steam pressure begins to drop from 120 psi (8.3 barg) at sunset, the gas boilers which were off, started up when the pressure reached a set point of 96 psig (6.6 barg). As soon the gas boiler and solar boiler pressures were equal, the CV of the USG closed and the plant steam was supplied by the gas boilers. At no point does the plant steam pressure fall below the setpoint, and there is no interruption to the pasteurization process.

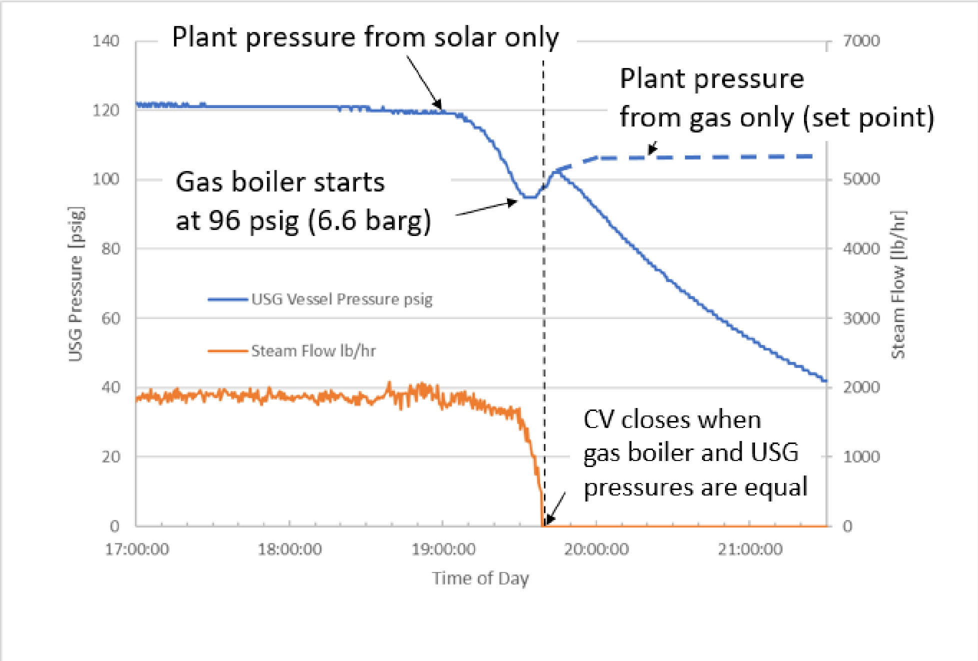

Figure 9. *The plant steam pressure never falls below the set point during the transition from solar steam to gas boiler backup*

4. Operations

The performance of the plant has been measured every day since June 1, 2022 and compared with the model. An example of the full solar plant performance during a summer day is shown in Figure 10. The model uses the coefficients of Table 1 for the collector characteristics and there is only one free parameter – the soiling loss - which is adjusted to find minimum error for the daily energy. The drop of the modelled heat gain at 18:00 is an artifact of the temporary shading of the pyranometer that measures the total hemispherical irradiance.

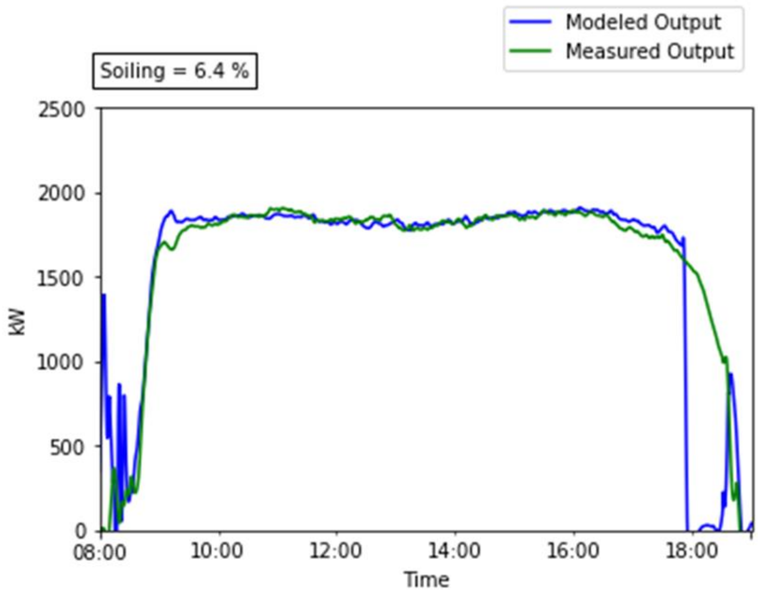

Figure 10*. Solar plant performance for 8/14/2023. The plant capacity was approximately 2 MW_{th} and the soiling loss was 6.4%.*

We have kept the mean soiling rate to approximately 14% during the life of the plant. This has required monthly washing of the mirrors during the summer months and no washing at all during the winter months. During the summer months the soiling rate is approximately 1%/day.

The monthly performance of the system for the past 16 months is shown in Figure 11. For each month, the supplied (i.e., metered) energy, and the energy losses due to soiling and lack of availability is plotted. The unit of energy is natural gas equivalent therms (one therm is equal to 29.307 kWh), accounting for the 82% boiler efficiency. In the initial months of operation, we had difficulties with flexible hose leaks which resulted in an average availability of 90% for 2022. After the leak issue was substantially solved in 2023, the system has had an average availability of 97%. There was a planned plant shutdown in September, 2022. In May and September of 2023 there was insufficient maintenance staff responsiveness to leaks that impacted availability.

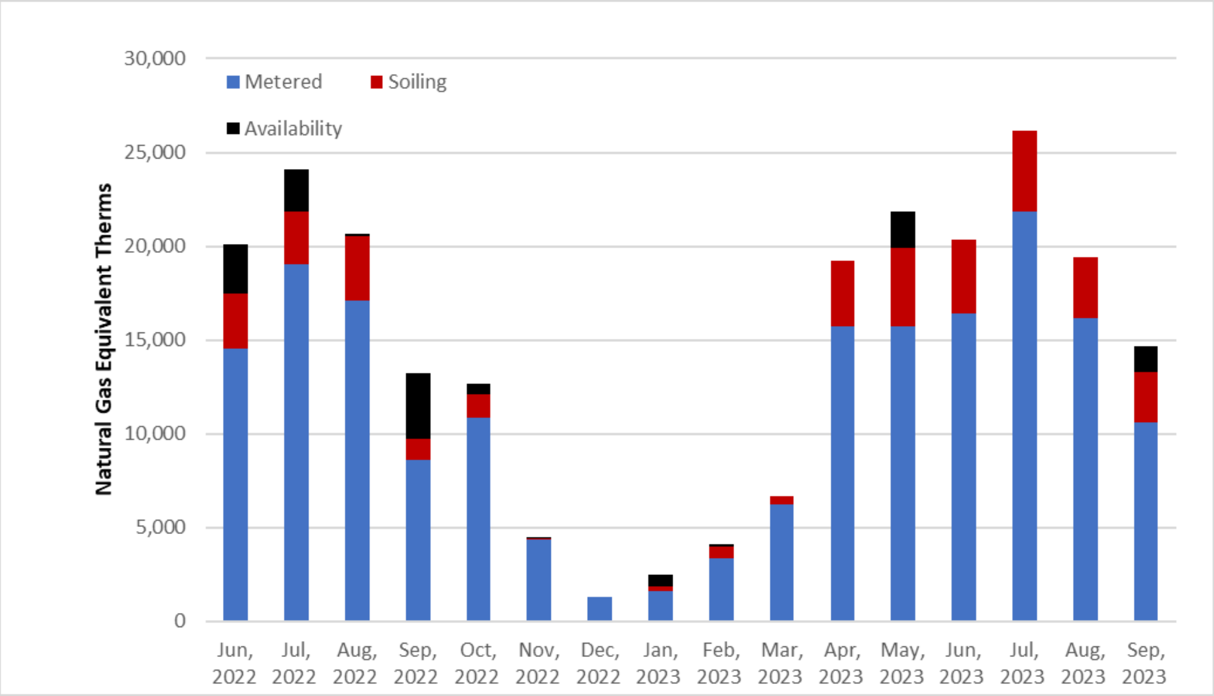

Figure 11. *Monthly solar plant performance since the beginnng of operations in June, 2022*

There have been no reports of any safety incidents since the commencement of commercial operations. This first-of-a-kind solar boiler for nut processing has become a successful reference case for future industrial solar boilers across a wide range of industries.

Data availability statement

The availability of the logged sensor data from which the figures are derived is restricted by third-party constraints.

Author contributions

Philip Gleckman contributed conceptualization, formal analysis, funding acquisition, methodology, and project administration. Brandon Hathway contributed conceptualization, data curation, formal analysis, investigation, and methodology.

Competing interests

The authors declare that they have no competing interests.

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