International Journal of Sustainable and Green Energy
2017; 6(6): 104-111
http://www.sciencepublishinggroup.com/j/ijsge
doi: 10.11648/j.ijrse.20170606.12
ISSN: 2575-2189 (Print); ISSN: 2575-1549 (Online)

Maintenance of a Small-Scale Parabolic Trough Concentrating Solar Power Plant in Louisiana

Kenneth August Ritter III, Matthew Joseph Prilliman, Terrence Lynn Chambers*, Jonathan Richard Raush

Department of Mechanical Engineering, University of Louisiana at Lafayette, Lafayette, U.S.A

Email address:

karyritter@gmail.com (K. A. Ritter III), mjprilliman@gmail.com (M. J. Prilliman), tlchambers@louisiana.edu (T. L. Chambers), jrr1239@louisiana.edu (J. R. Raush)

*Corresponding author

To cite this article:

Kenneth August Ritter III, Matthew Joseph Prilliman, Terrence Lynn Chambers, Jonathan Richard Raush. Maintenance of a Small-Scale Parabolic Trough Concentrating Solar Power Plant in Louisiana. *International Journal of Sustainable and Green Energy*. Vol. 6, No. 6, 2017, pp. 104-111. doi: 10.11648/j.ijrse.20170606.12

Received: December 15, 2017; **Accepted**: December 27, 2017; **Published**: January 16, 2018

Abstract: An accurate estimate of fixed operating costs is essential to determine the financial viability of any proposed project. Although other researchers have reported maintenance costs for large-scale concentrating solar power (CSP) plants in the United States [1 - 2], there is currently little information available specifically for small-scale CSP or solar Industrial Process Heat (IPH) plants. This paper discusses the maintenance of an operating small-scale CSP plant in Louisiana over a four year period. The results are also applicable to a small-scale IPH plant. Maintenance activities and costs are discussed for the collector field, the power block, and the cooling tower. For the collector field, a study of the degradation of mirror reflectance between washings was performed for three different types of reflective polymer thin films (3M 1100, 3M 2020, and Konica Minolta). Overall, the 3M 2020 film provided better reflectivity between washings than the other films. An optimized mirror washing schedule was determined. Optimal mirror washing schedules are very site-dependent, but for this humid subtropical location, the most economical washing schedule was found to be every 114 days, or approximately three times per year. A recommended maintenance plan for small-scale CSP and IPH plants is presented and actual maintenance costs over a four year period are provided. It was found that maintenance costs for small-scale plants are substantially larger than for large-scale plants, and that maintenance costs for small-scale IPH plants are much lower than for small-scale CSP plants, making IPH applications significantly more attractive. The average annual maintenance cost for a small-scale CSP plant was found to be approximately \$457/kWe, or \$0.27/kWhe. For a small-scale IPH plant the costs were \$3.72/m^2, \$7.81/kWt, and \$0.005/kWht.

Keywords: Solar Energy, Concentrating Solar Power, CSP, Maintenance Costs, O&M, Soiling

1. Introduction

In 2012 it was stated that dramatic reductions in cost and increases in performance must be achieved for CSP to become a major contributor to utility-scale base load power [3]. Now there is a renewed emphasis on improving of the cost-competitiveness of Concentrating Solar Power (CSP) technology, and the Department of Energy (DOE) SunShot Initiative has set a new goal to make CSP technology cost-competitive by 2030 [4], as shown in Figure 1 below.

While much emphasis has been placed on reducing the capital costs of CSP technology, it is also important to reduce soft costs such as maintenance to meet overall cost targets. Proper maintenance in solar projects can help maximize availability and extend the life of the plant. Solar power has zero fuel costs and very low maintenance costs when compared to coal, nuclear, and gas-fired power plants, and this helps the full life-cycle costs compare favorably, as the high capital costs are offset by the lower operation and maintenance costs [5]. To deliver reliable solar power, proper service is a critical component to ensure optimal performance while minimizing the risks of downtime. A well-maintained solar installation can actually perform 10% to 30% better than one that is not well-maintained [6]. The scheduling of maintenance activities depends on the expectations for the solar plant, the location and the equipment installed. The maintenance scope of work for a solar power plant typically includes the solar equipment inspections, collector cleaning, electrical testing, monitoring, facility maintenance and feedback from operations [7].

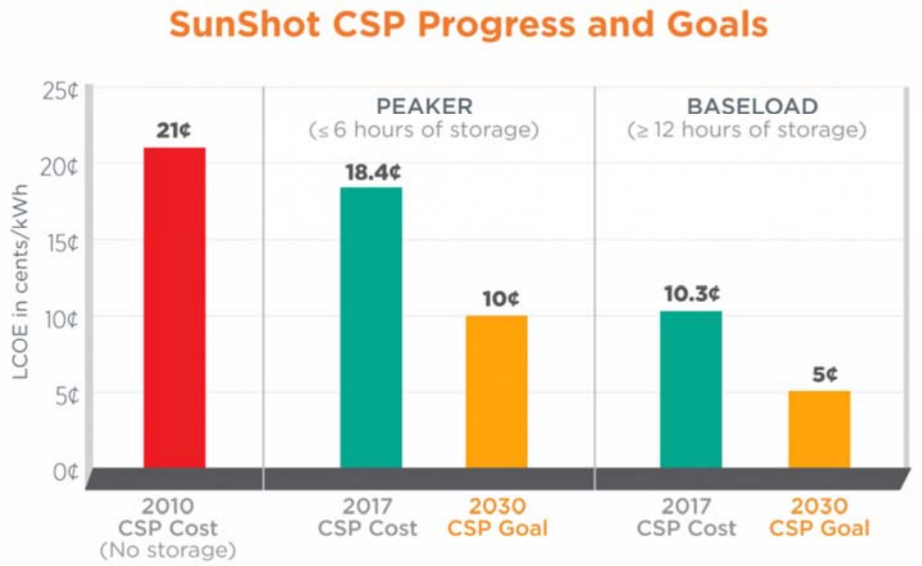

***Figure 1.** Falling cost of CSP and 2030 SunShot Goal [4].*

The solar specular reflectance in the collector field should naturally be kept at its highest level to ensure high global yield, but keeping the solar collectors clean in an economical manner is the biggest maintenance challenge for CSP technology [8, 9]. There are many issues related to CSP performance due to soiling, and technologies are continually being developed to keep the reflectors clean with minimal use of water [10]. With over 300 publications generated in the last five years alone, the effects of soiling and particle accumulation on solar collectors is a high interest topic and a large part of the current maintenance study presents the optimization of collector reflectivity in the Louisiana climate by means of an optimal collector washing schedule.

Cleco Power LLC and the University of Louisiana at Lafayette (UL Lafayette) completed the installation and commissioning of a pilot-scale concentrating solar thermal power plant, the first of its kind in Louisiana, in December 2012 [11 - 14]. All components in the system are commercially available and have proven to be successful in other states, but prior to this installation there was no data available to determine whether the technologies would be effective in the Louisiana area. Therefore, the pilot plant provides Louisiana-specific performance and price information regarding the use of CSP technology in Louisiana. The plant is also being used to study innovative new CSP technologies [15]. The pilot plant was installed at the UL Lafayette Energy Research Complex, which includes the Cleco Alternative Energy Center and the UL Lafayette Solar Technologies Applied Research and Testing (START) Lab, as shown in Figure 2 below.

The pilot project objectives are to test a CSP system under actual conditions in Louisiana, to gain experience in maintaining and operating such a system, to determine the scalability of the technology, and to determine the overall feasibility of the installation. The pilot concentrating solar power plant uses reflective parabolic solar troughs to generate roughly 500 kWt for process heat or 35 kWe of electricity using an Organic Rankine Cycle (ORC) turbine-generator system as a power block. The system consists of three main components: (i) the solar collector field, (ii) the power block, and (iii) the cooling system. Explanations of these components and the required maintenance for each are presented, along with costs and an overall recommended maintenance schedule.

***Figure 2.** Cleco Alternative Energy Center and UL Lafayette START Lab.*

2. Solar Collector Maintenance

2.1. Solar Collectors

The solar collector field consists of 12 reflective parabolic Large Aperture Troughs (LATs), which sit on approximately 1 acre of land, as shown in Figure 3. Each trough is roughly 12 m long by 7.3 m wide, and has an effective reflective area of

87.6 m^2. The reflectors consist of thin film polymer technology provided by 3M and Konica Minolta. Schott PTR70 heat collection element (HCE) tubes with 70 millimeters outside diameter are employed which, when combined with the large aperture, results in an industry leading concentration ratio (the ratio of the area of collected radiation to the area of concentrated radiation) of 104.

Soiling, or degradation of the reflectiveness of the concentrating reflectors, has a direct impact on the performance of CSP plants [16]. The soiling effect lowers the optical efficiency of the reflectors, which results in less of the available solar radiation being reflected onto the absorber tube. This results in a smaller energy output and an increase in the levelized cost of electricity or heat. An economic analysis was performed at the Kramer Junction solar power park located in Boron, California and indicated that maintaining an average field reflectivity above 90% is cost-effective [1]. Frequent reflector washing is therefore required, and the effectiveness of the washing was found to vary with location and time of year.

2.2. Reflector Washing

In a previous study of different cleaning methods, the most effective was found to be using deionized water and a brush resulting in an average cleaning efficiency of 98.8% in rainy periods and 97.2% in dry seasons [17]. In a recent study a soft cleaning brush and small amount of water was found to be the most effective way to clean the thin film polymer without inflicting surface damage or reducing specular reflectance [18].

Figure 3. *Reflector Washing.*

The washing procedure currently employed at the Louisiana plant involves using a pressure washer with deionized water and a microfiber cloth attached to a pole brush designed by 3M. This brush consists of a long pole attached to a brush head that clamps the microfiber cloth down on a sponge that has running water flowing to it to reduce surface friction. Shown in Figure 3, the reflector washing procedure consists of an initial spray of water with a pressure-washer, followed by wiping with the brush before the reflectors are sprayed again.

Reflector washing was completed following approximately one year of deployment of the facility. In 2015, a full washing of the East Solar Collector Assembly (SCA) was conducted, however the West SCA was not washed for test purposes. The complete washing of the system (1050 m^2) required approximately 16-man hours and used about 30 gallons of deionized water. This cleaning method returned the overall reflectivity of the aperture to a value near that of the original performance specification of 95.5% [19].

2.3. Measurement of Reflectivity

Since the start of plant operation, a micro-TRI-gloss glossmeter by Byk-Gardner has been used to measure reflectance of the solar reflectors. This device reports a derived reflectivity value rather than a direct measurement [20]. This glossmeter offers easy one-time calibration versus a reference, and allows the entire collector field (1050 m^2) to be measured in less than 1 hour. The data collection method used in this study is unique from that of large-scale power plants in that measurements are taken of the entire reflector field rather than just a representative sample.

Measurements taken of the specular reflectance showed that following washing, the reflectors returned to original performance specifications for reflectivity (> 95%) after having been reduced to less than 80%. The gloss measurements can be correlated to specularity of the reflectors, a major factor in optical efficiency. The degradation rate of the reflectors from particle accumulation continues to be monitored continuously.

2.4. Experience on Collector Reflectivity

The Cleco Alternative Energy Center's location in a humid subtropical region of the United States presents unique issues related to soiling, and subsequent thermal losses, of the solar reflectors. More specifically, its location in southern Louisiana offers much less soiling in the form of sand and dirt debris when compared to the Solar Electric Generating Stations (SEGS) plants on the west coast [1], while the higher humidity of the area also serves to reduce the effects of soiling. The amount of rainfall can also have a variable impact on soiling, with this impact potentially being magnified by planned SCA rotations to maximize rainfall on the reflector surfaces. As such, it is essential to determine the optimal reflector washing schedule and procedures to maintain near-ideal operating conditions and to reduce thermal losses without incurring redundant O&M costs from cleaning efforts that provide little gain in system efficiency.

2.5. Soiling Rate

Following the May 2017 reflector washing, the glossmeter was used to take weekly reflectivity measurement of the entire collector field. The three types of reflective thin film tested in this study were: 3M 1100, 3M 2020, and Konica Minolta. Two measurements were taken per panel, so 480 measurements were taken each week. One goal of this maintenance study was to determine whether the current bi-annual reflector washing is cost effective. This determination is based on a calculated correlation between the drop in average reflectivity and thermal efficiency of the reflectors as a function of time.

The rate of soiling over the summer season of 2017 for the three different types of thin-film is shown in Figure 4.

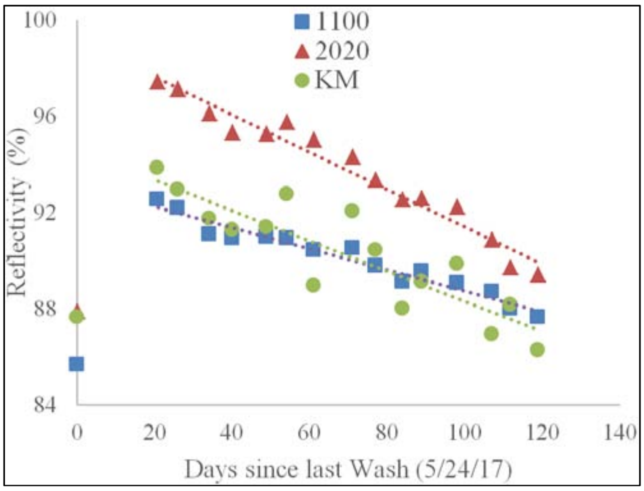

Figure 4. *Soiling Degradation Rates for 3M 1100, 3M 2020, and Konica Minolta film.*

Analysis of the data shows that the rate of soiling is approximately linear for each of the three films. The soiling rates of the 3M 1100, 3M 2020, and Konica Minolta films are 0.07, 0.06, and 0.1 percentage points per day, respectively. These rates are all significantly lower than those measured for the CSP plant in Kramer Junction during a similar study [1]. This appears to be due to the decreased severity of soiling factors for the Louisiana plant due to its location and climate.

Further analysis of this graph shows that the 3M 2020 film offers a higher initial reflectance value when clean, and although it degrades at a higher rate than the other films, its higher initial reflectance means that after four months it still had higher reflectance values than the other films. Based on this analysis, the 3M 2020 is the film with the best reflectance properties tested. The soiling degradation rates of the 3M 1100, 3M 2020, and Konica Minolta films are shown in Table 1.

Table 1. *Soiling Degradation Rates.*

Film Type	Degradation Rate (%/day)	Reflectivity when New (%)	4 Months Post-Wash (%)	Reflectivity after Wash (%)
3M 1100	0.044	94.4	87.6	92.5
3M 2020	0.078	98.9	89.4	97.4
Konica Minolta	0.063	95.3	86.3	93.8

The soiling rate is one of several parameters that go into the equation for determining the optimal cost-effective cleaning schedule for concentrating reflectors [21]. This equation can be expressed by:

$$N_C = \left(\frac{2W}{A_0 I_0 DC}\right)^{\frac{1}{2}} \tag{1}$$

Where N_C is the ideal number of days between reflector washing, W is the cost of this cleaning per square meter of surface area, A_0 is the optical efficiency of the reflectors, I_0 is the average daily solar energy available per square meter of surface area at the location in question, D is the soiling rate of the reflector surface as a percentage of the restored reflectivity value, and C is the energy price, expressed in dollars per kilowatt-hour, at the specified location [21].

For the Louisiana site the following values were used: W = \$0.78/m^2; A_0 = 0.62; I_0 = 4.5 kWh/m^2/day; D = 0.000467; and C = \$0.092/kWh, based on the U.S. Energy Information Administration's commercial pricing data for July 2017 [22]. As a result, the optimal interval for washing the collectors, *Nc*, was calculated to be 114 days, or about 3 times per year. Louisiana has one of the lowest electricity cost in the country, which makes it cost effective to allow the collectors to go longer between washings. By way of comparison, keeping all other values constant, states with higher electricity prices such as California (\$0.177/kWh) and Hawaii \$(0.265/kWh) would have washing intervals of 82 days and 67 days respectively, to minimize cost.

3. Power Block Maintenance

The power block for the system is the Green Machine, manufactured by ElectraTherm, which operates on the thermodynamic cycle called the organic Rankine cycle (ORC). It works in a manner similar to a steam turbine generator system, except that the working fluid for the power block is an organic refrigerant, R245fa, which has a much lower boiling point than water. The refrigerant working fluid picks up thermal energy as it passes through a liquid-to-liquid heat exchanger, where hot water from the solar collector field is on one side of the heat exchanger, and the refrigerant is on the other side. The hot refrigerant is allowed to expand and create vapor in a boiler, and then the refrigerant vapor is converted to mechanical energy by expanding it through a twin-screw expander system. After the working fluid is expanded through the expander, it is condensed by passing through another heat exchanger. This time the hot refrigerant is on one side of the heat exchanger, while cold water from a cooling tower is on the other side. The refrigerant is condensed as it passes through the heat exchanger and it is pumped back to the boiler, and the cycle starts again. The twin-screw expander turns an AC generator that produces three-phase electrical power at 480 V and 60 Hz, which is synchronized to the grid. Figure 5 shows the major components in the power block.

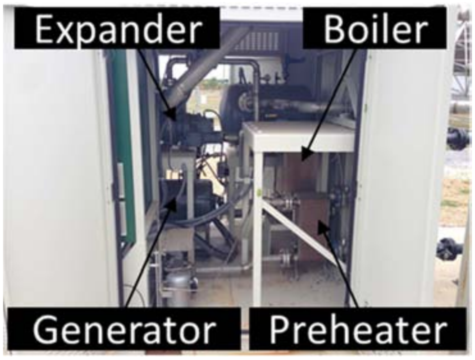

Figure 5. *Power block components.*

The Green Machine power block has a maintenance schedule that is dependent on the hours the system has operated [23], as shown in Table 2 below.

Table 2. *Green Machine Maintenance Schedule [24].*

Maintenance Task	Interval (Hours)
Inspect all plumbing, flanges, and valves for leaks	4400
Inspect hardware for wear/damage	4400
Gates 37mm belt tension/inspection	4400
Check oil drain catch bottle	4400
Grease pump motor bearings	4400
Inspect and grease generator bearings	4400
Clean air vents on generator	4400
Clean cabinet filters, verify fan operation	4400
Inspect for electrical wear/damage	4400
Check for non-condensable gases (NCGs)	4400
Check operation of compressed air system	4400
Gates 37mm belt replacement	8800
Check HX water-side pressure difference	8800
Clean enclosure	8800
Verify operability of safety equipment (buttons, lights, labels)	8800
Replace PRVs.	17600
Replace PLC and HMI batteries	17600
Howden expander rebuild	22000
Replace VFD internal cooling fan	26400

4. Cooling Tower Maintenance

The cooling tower maintenance consists of weekly circulation, monthly water tests and inspection, and yearly deep cleaning and inspection. To keep the equipment running trouble free, the following maintenance procedures are followed in the time frames indicated. Figure 6 below shows the cooling tower with the condensing flat plate heat exchangers in front.

Figure 6. *Cooling Tower.*

4.1. Weekly Circulation

Due to weather events and down times, every week the cooling tower is autonomously run for 130 minutes. The more the water in the cooling tower is circulated the lower the deposition rate of silt buildup in the cold water collection basin. Using the Wonderware Supervised Control and Automated Data Acquisition (SCADA) system, the cooling tower is set for regular circulation as part of the maintenance schedule.

4.2. Monthly Tests and Inspection

A monthly test and inspection is performed by a commercial water treatment company and a report of water contaminants and actions required is filed. For the water treatment plan every month the water in the cooling tower is treated with corrosion inhibitor and biocides to ensure that bacteria levels are low. As part of the preventative maintenance plan, all components including nozzles, basins, and drains are inspected for algae growth and corrosion.

4.3. Yearly Deep Cleaning and Inspection

Particulate matter from the air that flows through the cooling tower is deposited and accumulates over time, therefore must be periodically cleaned [24]. A deep cleaning of all interior surfaces of the tower is performed once a year. This process involves flushing out the cooling tower, cleaning out the basin, and circulating water for several hours. The exterior and basin is also pressure washed to clean out any algae growth and silt buildup. Mechanical and electrical components are checked, cleaned, and replaced if needed.

5. Costs

The yearly costs for the major components including labor are presented in Table 3. The major components include the solar collectors, the power block and the cooling tower. The solar collectors consist of two rows of six Large Aperture Troughs (LATs) each, with evacuated tube collectors (ETC) and a single-axis tracking system. The power block includes the boiler, expander, generator, condenser, and pre-heater. The costs shown below include parts plus labor for all repairs in each of the three categories.

Table 3. *Materials and Labor Costs for Major Components per Year.*

Year	Collectors	Power Block	Cooling Tower	Total
2013	$8,043	$0	$9,030	$17,074
2014	$3,166	$14,270	$1,216	$18,652
2015	$2,985	$1,323	$5,432	$9,741
2016	$1,415	$15,526	$1,623	$18,564
Total	$15,609	$31,120	$17,301	$64,030
Average	$3,902	$7,780	$4,325	$16,008

Several large expenditures caused variability in the yearly maintenance costs for each plant component category. For example, in 2013 an evacuated tube collector was repaired at a cost of $4069. In 2014 three hundred pounds of refrigerant were added costing over $7,000, including labor. In 2016 an electrical issue caused several electrical components to be replaced costing near $2,000. Also in 2016 two hundred pounds of refrigerant were added costing over $4,000. The variable costs for each plant component tend to average out over all components, however, such that the cost in each year has been relatively constant over the four year period studied, at an average overall maintenance cost of $16,008/year.

In order to make these cost numbers scalable and comparable to other technologies, it is helpful to express maintenance costs in terms of normalized values, such as cost per kWe and cost per collector field area. Previous research [14, 25] has determined that at this location there is an average of 273 days per year when the Direct Normal Irradiance (DNI) is high enough (400 W/m^2) to operate the plant. On those days there is an average DNI of 679 W/m^2 for an average of 6.3 hours per day, for a total of 1,720 hours of production per year. The collector area is 1050 m^2 and the solar to thermal efficiency is approximately 70%. Thus the collector field provides a nominal 500 kWt. The Organic Ranking Cycle (ORC) power block has an efficiency of approximately 7%, resulting in a nominal electrical power output of $35kWe. Normalized annual costs in various units are shown in Table 4 below.

Table 4. *Normalized Annual Maintenance Costs for Small-Scale CSP Plants.*

Overall Costs	
Annual Cost/kWe	$457.36
Annual Cost/kWhe	$0.27
Collector Field Costs	
Annual Cost/m^2	$3.72
Annual Cost/kWt	$7.81
Annual Cost/kWht	$ 0.005

Note that the collector field costs are based only on maintenance to the collector field, not to the power block or cooling tower, which would be appropriate if one were designing a plant to provide Industrial Process Heat (IPH) for a process such as desalination, rather than electricity. These results show that the maintenance costs for a small-scale IPH facility would be substantially less than for a small-scale CSP plant. This is partly due to the low efficiency of the ORC (7%) when producing electricity at this scale, and it is also partly due to the fact that for process heat, the maintenance costs for the power block and cooling tower do not apply. Even at a small scale, however, the annual cost of $7.81/kWt found in this study compares favorably to the current default value of $5/kWt provided in the System Advisor Model (SAM) for large-scale IPH plants [26], which is provided free of charge from the National Renewable Energy Laboratory (NREL).

6. Maintenance Schedule

As noted by Eaton [27], general inspection and evaluation of the CSP plant should be conducted on a regular basis that is consistent with system use and local environment. A maintenance schedule for the Louisiana plant has been developed, which may be helpful when planning future plants. Table 5 shows the maintenance tasks with the corresponding frequency the maintenance should be performed.

Table 5. *Solar Power Plant Maintenance Schedule.*

Component	Required Maintenance	Times Per Year	Every 2 Yrs	Every 5 Yrs
Collectors	Reflector Washing	3		
	Tube Pressure Wash	2		
	Repairing Film	2		
	Soap/Pressure Wash Pillars	1		
	Inspect Frame and Brakes	1		
	Gloss Measurement/Recording	52		
Hydraulics	Change Filters		X	
	Change Gaskets		X	
	Fluid Level Check	12		
	Change Fluid			X
Power Block	Soap/Pressure Wash Casing	4		
Cooling Tower	Check chemicals	12		
	Flush, scrub, refill			
Radiometer	Levelling Legs	52		
	Wipe Lenses, Bulbs	365		
	Calibrate		X	
Reporting	O&M Report	4		
Grounds	Cut Grass	52		
	Spray Weeds	4		
SCADA	Check clock synchronization	365		
	Backup all data	12		

The reflector washings have previously been conducted twice per year, but the recent soiling study described above indicates that three times a year is the most cost effective for this site. When checking the hydraulic fluid in the East Stow position, when the cylinders are retracted, the upper site glass should show full [26]. The monthly cooling tower maintenance is handled by the commercial water treatment company. The radiometer devices were calibrated in the fall of 2017.

7. Summary and Conclusions

A study of maintenance activities and their associated costs has been performed for a small-scale CSP facility in

Louisiana. Maintenance activities are divided into the three main components of the CSP plant: the collector field, the power block, and the cooling tower. For the collector field, a soiling study was conducted for three different types of thin films, and reflectivity degradation rates were calculated for each type. Even though it has a higher degradation rate than other films, the 3M 2020 film proved most effective overall due to its higher initial reflectivity. It was found that the current washing procedure, using a pressure washer with deionized water and a brush with flowing water and a micro-fiber cloth attached, restores reflectiveness to near original specification values with no long-term degradation shown. An optimal mirror washing schedule for this site was calculated and the optimal interval between washes was determined to be 114 days, which is approximately three times per year. Although this result is very site-specific, the same method could be used to calculate the optimal cleaning schedule for other sites.

Actual maintenance costs for each of the three major plant components over a four year period were recorded. The average annual maintenance cost for this facility was $16,008/year. Normalized cost figures were also calculated and it was determined that maintenance costs for solar IPH plants are significantly lower than for CSP plants, especially at the small scale when using an ORC-type power block. The annual maintenance cost for a small-scale IPH applications were found to be only slightly higher than similar large-scale IPH plants.

8. Future Work

8.1. Auto-Wash by Rain System

Future work will investigate the use of light rainfall as a supplementary reflector washing technique. To gain a better understanding of the potential benefits of such a practice, there are plans to experiment by setting the parabolic trough control system to automatically turn to an angle of 90 degrees (reflectors facing skyward) when rainfall with low wind speed is detected. Implementing such a system will require accurate weather data, specifically rain rate and wind speed data, and re-programming the WonderWare SCADA system. The installation and integration of a Davis Instruments Vantage Pro2 weather station is planned for this purpose. The results of the planned research will be considered alongside the results of the current study to determine whether this automatic washing improves plant profitability. Once this system is in place the optimal cleaning schedule will need to be recalculated.

8.2. Soiling Testbed Design

This study also revealed the need for a separate apparatus designed exclusively for soiling studies. A rendered image of a preliminary design for a soiling study station, which will be used in future experiments, is shown in Figure 7.

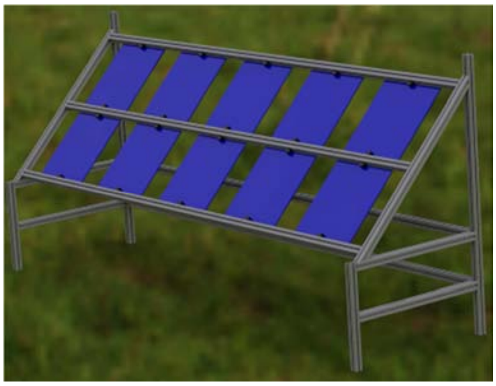

Figure 7. *CSP soiling testbed setup.*

The fixed tilt rack can study 5 different reflector types quickly and simultaneously, with an clean control reflector for each type of film. The same deionized water and micro-fiber cloth cleaning procedure currently used will be conducted for each of the 15” X 15” panels. These additional experimental considerations will further define the standards of reflectivity maintenance for CSP plants.

Acknowledgements

This study was supported by Cleco Power, LLC, under the grant entitled, “UL Lafayette/CLECO Solar Thermal Power Plant Supplement,” and the U.S. DOE and the Louisiana Department of Natural Resources under the “Empower Louisiana – Renewable Energy Program,” grant number RE-06.

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