Wash Vehicle Fleet Sizing for Contingency Planning Against Dust Storms

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Wash Vehicle Fleet Sizing for Contingency Planning Against Dust Storms

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Abstract. Wash vehicles containing either high- or low-pressure water sprayers, a collection of rotating brushes, or a combination of these, are frequently utilized in concentrating solar power (CSP) plants to maintain a high level of optical efficiency in the solar field. In recent years, multiple modeling approaches have been developed to obtain fleet sizes and mirror-washing schedules that optimize the tradeoff of vehicle capital and use costs and labor versus lost revenues due to soiling. These planning models cover normal operating conditions well but do not consider rare events such as dust storms which can cause a significant reduction in receiver productivity, or shut down operations until most or all of the solar field's mirrors have been cleaned. To that end, we propose a methodology that evaluates whether additional capital should be deployed to hedge against these events by weighing the net present value of the expected benefits against the capital costs. The output of this method is a breakeven frequency, a metric we sue to determine whether an additional vehicle should be purchased to address the contingency of dust storms by comparing it to the expected annual storm frequency We develop a small collection of case studies using commercial-scale CSP tower plants and obtain breakeven frequencies that mostly fall between 0.1 and 1.0 storms per year, depending on the existing fleet size and storm severity.

INTRODUCTION

The reflectance of the mirrors in the solar field of a concentrating solar power (CSP) plant is a key contributing factor to optical efficiency and, in turn, the system's productivity. A mirror's reflectance may degrade due to either irreversible or reversible factors; the accumulation of foreign debris and dust on the mirrors due to wind, which we refer to as *soiling*, is the predominant source of reversible degradation, and our work focuses on the impact of this factor on profitability; see [1] for a review of studies that characterize soiling in CSP and photovoltaic applications. For most plants, regular cleaning of the mirrors mitigates the impact of soiling on revenue losses, and vehicles that utilize brushes and demineralized water are the most deployed method of maintenance in commercial-scale plants [2].

In recent years, multiple models have been developed to obtain vehicle fleets and cleaning schedules that optimize the tradeoff between lost revenues due to soiling and the costs of capital, water, fuel, labor, and vehicle maintenance. In general, the works utilize historical data as input [3], develop a stochastic process to represent soiling over time [4], or assume a linear soiling rate per day [5], and the periodic use of vehicles is consistent from year to year, whether the output is a predetermined schedule, cleaning frequency, or reflectance threshold under which cleaning begins. While these methods effectively determine the appropriate staffing levels for mirror washing under regular operations, they fail to properly account for the impact of rare events that cause heavy soiling, such as dust storms. In particular, the suggested washing policy either uses the same washing schedule before and after the dust storm, or suggests a reflectance threshold at which additional cleaning takes place, but only under the assumption of a cost rate per hour, without considering additional capital costs associated with the additional cleaning capacity.

Our work differs from the literature in that we focus on the potential benefit of purchasing additional wash trucks for contingency planning against severe soiling events. Specifically, we assume that the fleet of vehicles for regular operations has already been appropriately sized, and we develop a cost-benefit model that determines whether the cost of procuring an additional vehicle and leaving it either vacant or in rotation with other vehicles during normal operations and outweighs the benefit of reducing the lost revenue associated with deploying the truck after these rare events.

METHODOLOGY

Our contingency planning model assumes that the wash vehicle fleet has either already been purchased or planned, and analyzes the costs and benefits associated with adding a vehicle to the fleet to be used in the event of a rare, heavy-soiling event, such as a dust storm. The inputs to our model include: (i) storm severity and the seasonality of storm frequency; (ii) vehicle performance and cost information; (iii) wash vehicle scheduling and field productivity throughout the year under normal operating conditions; and (iv) expected productivity and revenue under normal operating conditions.

We use these inputs to calculate the expected loss per event, both under normal operating conditions, and when adding one or more vehicles to operate in the field only after a dust storm until the entire field is cleaned once. The loss function includes both lost revenue relative to operating conditions and the costs of operating the vehicles during the post-storm period. Using the expected loss per storm and discount rates for revenues and costs over the new vehicle's lifetime, we then estimate a breakeven frequency of storms per year at which the expected net present value of the added costs and benefits would be zero.

Model Assumptions and Notation

We adopt the following assumptions for our contingency planning model. We assume that we know: (i) the capital and operating costs of each wash vehicle under consideration; (ii) each vehicle's operating speed and cleaning efficiency; (iii) the rate of reflectance degradation due to soiling, which we assume is constant under normal operating conditions for simplicity and zero after a dust storm; (iv) the plant productivity by month under normal operating conditions, which we assume is deterministic but varies by month; (v) the relative dust storm frequency by month; and, (vi) the severity of the dust storms, i.e., the field's reflectance after such an event. For simplicity, we assume that the time elapsed between consecutive cleanings, which we refer to as the *cleaning period*, is identical for all mirrors in the field in a particular month, and that it may vary from month to month. We assume that if an extra vehicle is purchased for contingency analysis, it may be placed in a rotation with the other wash vehicles to prevent degradation due to lack of use, and that maintenance and materials costs are similar to those of the other vehicles. Additionally, we assume that once a single cleaning of the entire field has occurred with or without additional vehicles, the cleaning schedule under normal operations resumes immediately. Finally, we assume that while storm frequency may vary by month, a storm is likely to occur at any point in the month with equal probability.

Table 1 displays the notation we employ for our methodology, including the units of each parameter and calculated value. Because all the equations that follow directly use assumed inputs, we do not distinguish calculated parameters from user-defined inputs; rather, each of the equations that follow have a calculated value on the side as input and either user-defined inputs or calculated values from earlier equations on the right-hand side.

TABLE 1. Summary of notation for contingency planning model

Sets	Description
$m \in M$	months; M={1,…,12}
$h \in H_m$	hours in which receiver operates in month *m*

Parameter	Description	Units
c	mirror reflectance after cleaning	[fraction]
d	solar field soiling rate	[1/hour]
t_m	time between consecutive mirror cleanings, normal conditions	[hours]
$\hat{t}$	time between consecutive mirror cleanings, using all vehicles	[hours]
r_m	average field reflectance under normal operating conditions in month m	[fraction]
$\hat{r}$	average field reflectance whem all vehicles are operating	[fraction]
a_h	average DNI in hour h	[W/m^2]
η_h	solar field efficiency in hour h	[unitless]
q^s	field reflectance immediately after a dust storm	[fraction]
q_m	average field reflectance during first post-storm cleaning	[fraction]
$\underline{\boldsymbol{a}}$	DNI threshold for receiver operations	[W/m^2]
v_m	average field reflectance during period of disruption	[fraction]
f_m	dust storm frequency in month m	[unitless]
b_m	expected revenue in month m under normal operating conditions	[$]
δ	discount rate	[fraction]
ℓ	vehicle lifespan	[years]
w	cost rate for vehicle operations during post-storm cleaning	[$/hour]
x	expected loss per dust storm	[$]
y	net present value of additional vehicle for dust strom contingencies	[$]
z	wash vehicle capital cost	[$]
g	dust storm frequency	[storms/yr]
u_m	mirror washing costs in month *m*	[$]
y^w	net present value of additional vehicle for added wash fleet availability	[$]

Calculating Expected Loss per Dust Storm Event

The first collection of calculations in the methodology we adopt determines the expected loss per dust storm event, which includes both the lost revenues due to soiling and the additional costs of wash vehicle use in post-storm operations. Given the assumption that the soiling rate is constant, the average reflectance of the field is the post-cleaning reflectance minus half of the product of the soiling rate and the cleaning period. Equations (1) and (2) calculate the average field reflectance under normal operating conditions and when all vehicles are in operation, respectively:

$$r_m = c - \frac{d \cdot t_m}{2}, \forall m \in 1, \dots, 12, \tag{1}$$

$$\hat{r} = c - \frac{d \cdot \hat{t}}{2}, \forall m \in 1, \dots, 12., \tag{2}$$

We note that although additional vehicles may be utilized during these events, the cleaning period after a dust storm may be longer than during normal operations due to the additional time required to clean heavily soiled mirrors.

Next, we calculate an effective average field reflectance during the first post-storm cleaning for each month $\boldsymbol{m}$, which we refer to as $\boldsymbol{q_m}$, as follows. Using a typical meteorological year format file from the EnergyPlus database [6] as input, we obtain the observed direct normal irradiance (DNI) for every hour in month $\boldsymbol{m}$. Then, we multiply each DNI observation by both the field efficiency and the ratio of post-storm to normal operating reflectance. Finally, we remove entries below a cutoff threshold for plant receiver operations, before summing the hourly results. This quantity is divided by an analogous summation of hourly DNI observations without any post-storm multiplier, but using the same cutoff, to obtain the effective average field post-storm reflectance in month $\boldsymbol{m}$ in equation (3):

$$q_m = r_m \cdot \frac{\sum_{h \in H_m}\left[\frac{q^s}{r_m} a_h \cdot \eta_h \cdot I\left(\frac{q^s}{r_m} a_h > \underline{a}\right)\right]}{\sum_{h \in H_m}\left[a_h \cdot \eta_h \cdot I(a_h > \underline{a})\right]}, \forall\, m \in 1, \ldots, 12, \tag{3}$$

in which $I(\cdot)$ is an indicator function. This calculation assumes that a severe drop in reflectance can preclude the plant from conducting any receiver operations; if no cutoff point is assumed, then the equation (3) is reduced to $q_m = q^s$. We note that the post-storm reflectance, $\boldsymbol{q^s}$, is highly uncertain and may be subject to precipitation events that may naturally clean the field or cause reflectance to degrade further, as is the case in the "red rain" events described in [7,8]. For simplicity, we present this as an expected value of post-storm reflectance, but if the distributions of both the frequency and the cleaning efficacy of precipitation events are known, then $\boldsymbol{q_m}$ may be estimated via simulation.

Next, we calculate the average effective field reflectance during the total period of time in which the solar field's average reflectance differs from normal operations, which requires two full cleanings; the first takes place after the dust storm, and the second takes place under normal operations until the typical average reflectance is reached. We refer to this two-cleaning time interval as the *period of disruption*. The average field reflectance during the period of disruption is weighted according to each cleaning period's length in equation (4):

$$v_m = \frac{\left(\hat{\boldsymbol{t}} \cdot \frac{q_m + \hat{r}}{2} + t_m \cdot \frac{r_m + \hat{r}}{2}\right)}{t_m + \hat{\boldsymbol{t}}}, \forall\, m \in 1, \ldots, 12. \tag{4}$$

Next, we calculate the fraction of lost revenue for a storm in month m as the product of (i) the fraction of lost reflectance during the period of disruption and (ii) the fraction of month m covered by the period of disruption. The result is multiplied by the expected monthly revenue and the monthly relative storm frequency, and then washing costs are added to obtain the expected loss per storm in equation (5):

$$x = \sum_{m=1}^{12}\left(f_m \cdot b_m \cdot \frac{r_m - v_m}{r_m} \cdot \frac{t_m + \hat{\boldsymbol{t}}}{|H_m|}\right) + w \cdot \hat{\boldsymbol{t}}. \tag{5}$$

Analysis Metric: Breakeven Storm Frequency

Using the procedure above, we can make all the computations necessary to calculate the expected loss per storm for any vehicle fleet size. We calculate the expected per-storm benefit of a vehicle by comparing the expected loss with the current fleet to that of the fleet plus one vehicle. Let x_i and x_{ii} be the left-hand result of equation (5) after using the procedure above to obtain losses for the current vehicle fleet and with one additional vehicle, respectively. Then, the assumed number of dust storms per year, difference in loss per storm given by $(x_{ii} - x_i)$, discount rate, and vehicle lifespan can be converted to an expected net present value via equation (6):

$$y = g \cdot (x_{ii} - x_i) \cdot \frac{1 - (1 - \delta)^{\ell}}{\delta}. \tag{6}$$

The metric we use for this analysis, which we term the *breakeven storm frequency*, is the annual storm frequency for which the net present value of the benefit of the additional vehicle is equal to its capital cost, i.e., $y = z$, as shown in equation (7):

$$g^* = \frac{z \cdot \delta}{(x_{ii} - x_i) \cdot (1 - (1 - \delta)^{\ell})}. \tag{7}$$

If the actual storm frequency exceeds g^*, then an additional vehicle should be purchased for contingency planning. The metric g^* may be calculated for any starting fleet size to assess the potential benefit of purchasing more than one additional vehicle.

Additional Benefit: Increased Fleet Availability

A second benefit associated with an extra vehicle's presence in the fleet is reduced loss of washing capacity due to vehicle maintenance. While we do not present detailed data for this in the case studies that follow, the added benefit could be approximately determined as follows. Let k and $\hat{k}$ be the vehicle fleet availability without and with an extra vehicle, respectively, i.e., $\hat{k} > k$. If we assume that the fleet's wash rate is directly proportional to its availability in months that required use of the entire vehicle fleet, then the reflectance of the field in that setting is increased to r_m^v as shown in equation (8):

$$r_m^v = c - \frac{d \cdot t_m \cdot k}{2 \cdot \hat{k}}, \tag{8}$$

as the wash period is multiplied by a factor of $k/\hat{k}$. Then, using the same discount rate as in equation (5) and allowing for the increased wash costs, the net present value of the revenue benefit associated with the increased availability is the difference between added revenue and incremental costs, multiplied by the annuity factor, as given by y^w in equation (9):

$$y^w = \sum_{m=1}^{12} \left(b_m \cdot \frac{r_m^v - r_m}{r_m} - u_m \cdot \frac{\hat{k} - k}{k} \right) \cdot \frac{1 - (1 - \delta)^{\ell}}{\delta}. \tag{9}$$

To account for increased vehicle availability in the breakeven frequency as calculated in equation (7), z may be redefined as the difference between the capital cost and the net present value from equation (9), i.e., $z \leftarrow (z - y^w)$.

RESULTS

We develop three case studies for to demonstrate the use of this model. In the first, we create a contrived central receiver plant in Daggett, CA using SolarPILOT [9] for which the vehicle fleet and schedule has already been optimized using an existing planning model from the literature [10], and we assume storms occur in each month with equal probability. The second case uses most of the assumptions from the first case but assumes that storms occur with 25 percent probability each in May, June, July, and August. The third case uses publicly data available from the NOOR III plant in Ouarzazate, Morocco with some additional cost assumptions from the literature, and assumes that storms occur at the same relative frequency as in Case 1. All cases assume a DNI threshold of 200 W/m^2 for operations to take place per equation (3). **Table 2** displays a summary of the inputs to each case study. We assume that the initial cleaning after the dust storm starts immediately after the event, uses all available trucks, and cleans continuously at half the normal wash rate until the entire field is cleaned, after which normal operations resume.

TABLE 2. *Summary of inputs to contingency planning model*

Parameter	Units	Cases 1-2	Case 3	Source	Notes
Location		Daggett, CA (US)	NOOR III (MOR)		
Annual Output	GWh	500	500		
Revenue Rate	\$/MWh	135	150	[11] (MOR)	Crescent Dunes PPA applied to Cases 1-2
Vehicle Cost	\$	200,000	200,000	[12]	2x multipler applied
Vehicle Lifetime	yr	10	10	[12]	
Vehicle Operating Cost	\$/hr	54	30	[10]	Relative labor reduction from [3] applied to Case 3
Discount Rate	%	6	6	[13]	
Heliostats		10500	7400	[11] (MOR)	
Heliostat area	m^2	115	178	[11] (MOR)	
Wash rate	m^2/hr	3680	3680	[3]	
(Clean/new) mirror reflectance		0.986	0.986	[2]	
Soiling rate	fraction/day	0.027	0.036	[14]	San Leandro, CA test

For each case, we start with the inputs in **Table 2**, then use the methodology section above to obtain the breakeven storm frequency for a collection of instances in which we vary (i) the storm severity, i.e., the field reflectance after a dust storm takes place, and (ii) the number of vehicles in the fleet to start. Specifically, we evaluate breakeven frequencies for post-storm reflectance levels between 25 and 75 percent in 5-percent increments, and for all vehicle fleet sizes ranging from one to eight vehicles. **Fig. 1** displays a heat map of the results from each case.

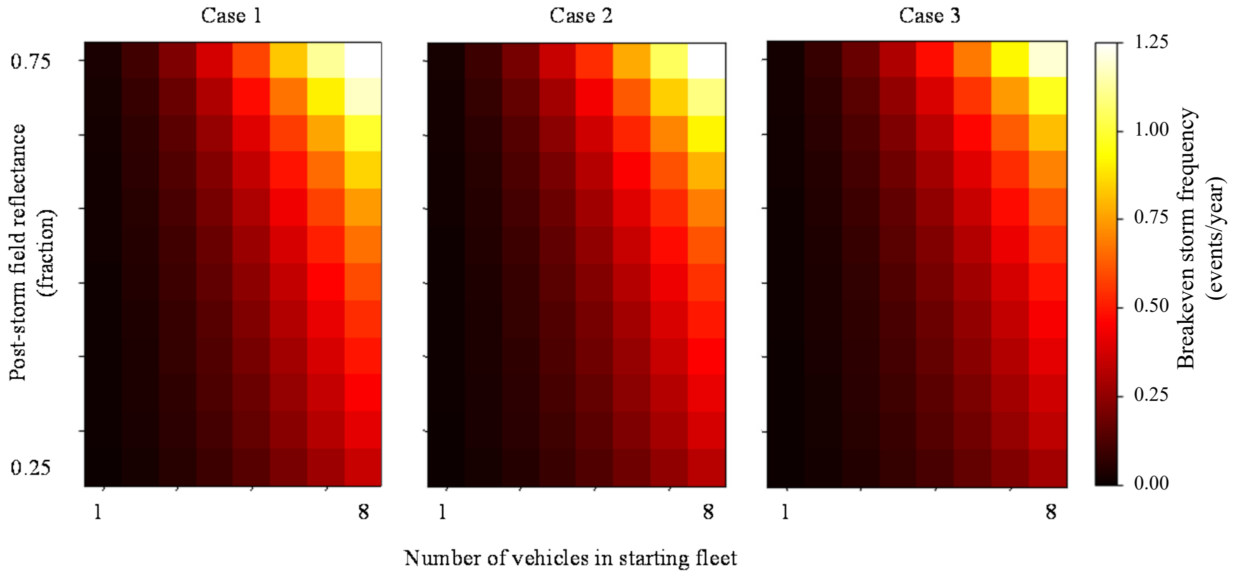

FIGURE 1. Heat map of breakeven storm frequency (events/year) for contingency planning case studies

The optimization model from [9] recommends a starting vehicle fleet of four vehicles for each plant used in these case studies; we find in all three cases that an additional vehicle is justified if a severe dust storm reducing field reflectance to 75% occurs approximately every three years, with less frequent events justifying a purchase if the storm severity is higher. This indicates that currently deployed CSP plants in locations with annual (or more frequent) dust storms are exposed to sufficiently high losses to warrant further consideration of capital deployment for wash vehicles to use in the event of a dust storm. The revenue and loss assumptions that vary between the two plants had little impact on the breakeven frequencies, and the similarity between Case 1 and Case 2 show that the timing of the storms have a reduced impact on contingency planning decisions when compared to storm severity, fleet size, and storm frequency. We note that the capital cost of a wash truck is directly proportional to the breakeven frequency, i.e., doubling the cost to $400,000 per truck would double the scale guiding the heat maps in **Fig. 1**, with the individual results otherwise unchanged. Similarly, if we assume that the vehicle fleet availability increases by 1% when an additional vehicle is added, and we assume that a total of 1,200 operating hours take place per month using four vehicles in Case 1's operating schedule, then the procedure using equations (8)-(9) yields an NPV of about $62k due to the additional vehicle fleet availability; thus, the breakeven frequencies in the column representing 4 vehicles in Case 1 would be reduced by 31%.

While the results in **Fig. 1** show the impact of the vehicle fleet size and storm severity on the breakeven frequency for which the net present value of an additional vehicle purchase is zero, several parameters in our economic analysis may vary from case to case or are uncertain in nature. To that end, we conduct a sensitivity analysis by varying several key inputs by 50% in each direction and calculating the expected net present value of adding a vehicle to the fleet for dust storms only. Our baseline case uses the inputs from Case 1 with four vehicles in the starting fleet, and assumes that one storm occurs each year that brings the field reflectance to 50%; the net present value in this baseline instance is ~$196,000. The tornado diagram in **Fig. 2** displays the results of this sensitivity analysis with bars denoting the change in net present value from the baseline; the results show that while vehicle cleaning speed, solar field size, and average revenue per unit energy produced offer significant changes to the net present value, changing a single parameter by 50% in either direction consistently yields a positive net present value if a single severe storm occurs each year on average.

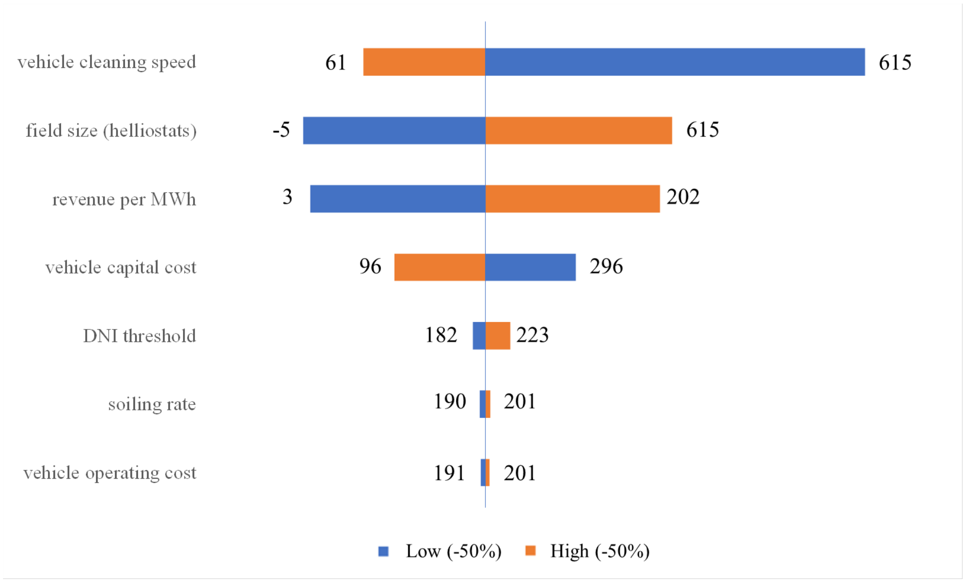

FIGURE 2. Tornado diagram displaying the expected net present value (in thousand USD) of an additional vehicle for contingency against dust storms as key inputs vary, assuming one storm per year occurs; the baseline case denoted by the center line yields a net present value of $196,000

CONCLUSIONS

This paper presents a methodology for contingency planning against infrequent but severe dust storms that can significantly reduce or preclude receiver operations until a full cleaning of the mirrors in the solar field has taken place. We propose a breakeven storm frequency as a metric for determining whether the expected benefit of an additional vehicle purchase specifically for dust storms is greater than the capital cost if the storm frequency and severity are known or can be estimated. We develop a small collection of case studies using information on deployed plants, as well as from other case studies in the literature. The results show that additional vehicle purchases may provide a sufficient return on investment to warrant a purchase specifically for dealing with these events; moreover, the positive expected net present value is robust to a large collection of changes to key inputs when assuming a frequency of one storm per year for a commercial-scale case study.

While we propose a brief analysis of the benefits associated with an extra wash truck's availability, e.g., greater fleet availability after accounting for maintenance when full fleet usage is recommended according to a schedule produced from a model like those in [3,4,5,10], this analysis can be further incorporated using reliability data. Additionally, the study could be extended to cover the relative benefit of alternative cleaning methods, such as the self-cleaning technologies discussed in [15], when compared to the use of wash vehicle fleets with respect to these rare events.

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REFERENCES

1. Sarver, T., Al-Qaraghuli, A., & Kazmerski, L. L. (2013). A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches. Renewable and Sustainable Energy Reviews, 22, 698-733.
2. Fernández-García, A., Álvarez-Rodrigo, L., Martínez-Arcos, L., Aguiar, R., & Márquez-Payés, J. M. (2014). Study of different cleaning methods for solar reflectors used in CSP plants. Energy Procedia, 49, 80-89.
3. Wolfertstetter, F., Wilbert, S., Dersch, J., Dieckmann, S., Pitz-Paal, R., & Ghennioui, A. (2018). Integration of soiling-rate measurements and cleaning strategies in yield analysis of parabolic trough plants. Journal of Solar Energy Engineering, 140(4).
4. Truong Ba, H., Cholette, M. E., Wang, R., Borghesani, P., Ma, L., & Steinberg, T. A. (2017). Optimal condition-based cleaning of solar power collectors. Solar Energy, 157, 762-777.
5. Ashley, T., Carrizosa, E., & Fernández-Cara, E. (2019). Heliostat field cleaning scheduling for Solar Power Tower plants: A heuristic approach. Applied Energy, 235, 653-660.
6. Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., Strand, R.K., Liesen, R. J., Fisher, D. E., Witte, M. J., & Glazer, J. (2001). EnergyPlus: Creating a new-generation building energy simulation program. Energy and buildings, 33(4), 319-331.
7. Conceição, R., Merrouni, A. A., Lopes, D., Alae, A., Silva, H. G., Bennouna, E. G., Collares-Pereira, M., & Ghennioui, A. (2019, July). A comparative study of soiling on solar mirrors in Portugal and Morocco: preliminary results for the dry season. In AIP Conference Proceedings (Vol. 2126, No. 1, p. 220001). AIP Publishing LLC.
8. Azouzoute, A., Merrouni, A. A., Garoum, M., Bennouna, E. G., Ghennioui, A., & Ydrissi, M. E. (2019, July). The impact of optical soiling losses on the electrical production of CSP power plant. In AIP Conference Proceedings (Vol. 2123, No. 1, p. 020090). AIP Publishing LLC.
9. Wagner, M. J., & Wendelin, T. (2018). SolarPILOT: A power tower solar field layout and characterization tool. Solar Energy, 171, 185-196.
10. Wales, J., Zolan, A., Newman, A., & Wagner, M. (2020). Optimizing vehicle fleet and assignment for concentrating solar power plant mirror washing. Under Review.
11. Relloso, S., & Gutiérrez, Y. (2017). SENER molten salt tower technology. Ouarzazate NOOR III case. In AIP Conference Proceedings (Vol. 1850, No. 1, p. 030041). AIP Publishing LLC.
12. Kolb, G. J., Jones, S. A., Donnelly, M. W., Gorman, D., Thomas, R., Davenport, R., & Lumia, R. (2007). Heliostat cost reduction study. Technical Report SAND2007-3293, Sandia National Laboratories.
13. Röger, M., Lüpfert, E., Caron, S., & Dieckmann, S. (2016). Techno-economic analysis of receiver replacement scenarios in a parabolic trough field. In AIP Conference Proceedings (Vol. 1734, No. 1, p. 030030). AIP Publishing LLC.
14. Deffenbaugh, D. M., Green, S. T., & Svedeman, S. J. (1986). The effect of dust accumulation on line-focus parabolic trough solar collector performance. Solar Energy, 36(2), 139-146.
15. Costa, S. C., Diniz, A. S. A., & Kazmerski, L. L. (2018). Solar energy dust and soiling R&D progress: Literature review update for 2016. Renewable and Sustainable Energy Reviews, 82, 2504-2536.