Abstract - During the last two decades, researchers have shown an increased interest in studying renewable energy. New technologies are emerging that make the production of power from renewable sources on a large scale more efficient than ever. Solar energy is one of the largest renewable energy sources available on earth. However, areas with the most solar power potential are prone to heavy soiling. Whether it is a result of sand storms or industrial activities, soiling is a complex phenomenon involving various factors. Although research has shown that soiling has an adverse effect on the output of photovoltaic solar plants, investigating cleaning strategies and frequencies appears to be an under-explored area. This study investigates the modeling of the effect of soiling on photovoltaic solar plants through stochastic simulation. The results show that stochastic simulation can be effective in modeling the variable soiling effect on solar plant output. In addition, it can serve as a decision-support system to aid managers in scheduling cleaning tasks. Further work might explore optimizing cleaning frequency by coupling the simulation model with an optimization engine.

Keywords - solar energy; soiling; maintenance; stochastic simulation

I. INTRODUCTION

Energy is a necessary resource for humanity in modern times. The limitations of conventional energy sources will broaden the need for renewable sources in the future. During the last two decades, researchers have shown an increased interest in studying renewable energy. New technologies are emerging that make the production of power from renewable sources on a large scale more efficient than ever.

Solar power is a useful resource that can fulfill the need for efficient, reliable, and easily accessible energy. In fact, solar energy is one of the largest renewable energy sources available on Earth. The solar constant is the average amount of radiation from the Sun per unit area that reaches Earth's atmosphere for a mean solar distance of 1360 watts per square meter. In general, solar energy is linked mainly with the variability of solar radiation. The amount of solar radiation is related to different types of topography, weather, and geography. In addition, shading and radiation obstacles (such as soiling) can affect the performance of solar power plants by a large percentage [1].

Soiling refers to the accumulation of dirt on solar panels and includes different kinds of particles such as dust and bird droppings. Unfortunately, soiling is commonly overlooked or underestimated [2]. Nonetheless, it can have an effect on the output of a solar power plant as well as ongoing operations and maintenance (O&M) decisions. For example, cement particles can reduce the Photovoltaic (PV) panel output to 80% [1]. In areas prone to dust, soiling losses can be intensive in months when solar radiation is at its maximum [3]. These observations are reinforced by many studies of dust’s effects on solar power plants in dusty regions such as Saudi Arabia [2, 4].

Today the most effective approach is to clean the dust manually using water or cleaning solutions. This is labor and water intensive, especially in areas with scarce water resources. So far, there has been little discussion about modeling and optimizing cleaning schedules for PV solar plants. This research sheds new light on investigating the modeling of the effect of soiling on PV solar plants through stochastic simulation.

II. RELATED WORK

A. Soiling on PV Solar Panels

As illustrated by Figure 1, the factors influencing soiling on PV panels are many including climate, geography, particle properties, PV panel type, PV panel angle, and urbanization of the site [1, 5].

![Factors influencing dust settlement](image)

Figure 1. Factors influencing dust settlement. Source [1]
Therefore, the phenomenon of soiling on solar panels is extremely complex and challenging to model. For instance, some studies show that the efficiency of PV cells is linked strongly to the density of accumulated dust and that fine particulates deteriorate the performance of PV panels more significantly than coarser particles [6].

B. Quantifying the Effect of Soiling on Plant Efficiency

Soiling has been reported to affect the performance of solar panels in dusty regions such as the Arabian Gulf by a notable amount. For example, Sarver et al. [2] reviewed previous studies that reported losses due to dust in many places including dusty regions such as Saudi Arabia and Kuwait. These studies showed a reduction of power efficiency between 26% and 40% over a six-month period in thermal collectors and PV panels. Similar observations were reported in Kuwait, where a 17% power reduction was found over six days. Interestingly, the majority of research on the effect of dust on solar power has taken place in the Middle East, where there is promising solar potential and a desert environment [1].

In regions where rainfall is limited and the dry season lasts several months, the accumulation of soil on solar panels can have a significant impact on the performance of PV systems. However, areas with frequent rain can benefit from the natural cleaning of PV panels, reducing the soiling effect [3]. Pavan et al. [7] studied the effect of dust on a large-scale PV plant in Italy. They concluded that soiling can degrade performance by up to 6.9%. Kimber et al. [8] showed the average daily soiling loss in dry periods as 0.2%, resulting in an annual energy loss of between 1.5% and 6.2% for different locations in California and the southwest region of the United States.

C. Investigating Cleaning Frequency

The soiling effects can be mitigated by scheduling frequent manual or automatic cleaning. Frequent cleaning results in additional costs that include human resources, water, and detergent. Therefore, the trade-off between the cost of cleaning and the losses that result from soiling should be considered.

Although a large body of literature has reported on maintenance simulation and optimization, little research has been conducted regarding the maintenance of solar plants [9]. Mani and Pillai [1] compared soiling effects in several regions around the world and suggest cleaning guidelines for each region. For example, they recommend daily cleaning for solar panels in desert environments.

More recently, Jones et al. [10] presented a study for optimizing the cleaning interval for a large simulated PV plant in Saudi Arabia. The soiling data collected over a year showed a strong seasonality pattern. A soiling-loss function was constructed using a simple exponential model. The optimization was achieved by mathematical means assuming no variability exists in the model.

Although research has shown that soiling has an adverse effect on the output of PV solar plants, the subject of cleaning strategies and frequencies appears to be under explored. This study investigates the modeling of the effect of soiling on PV solar plants through stochastic simulation.

III. METHODOLOGY

A. Input Data

The main input data for the model were obtained from recent studies [10, 11]. One advantage of using published data is to allow the comparison of results. The loss attributed to soiling was estimated based on experiments [10]. The loss can be represented by an exponential function:

\[ L_s(t) = 1 - e^{-at} \]

where \( a \) is the loss coefficient.

It was found that the percentage of loss varies significantly by both the PV technology and the month as seen in Figure 2. The PV technology considered in this research is poly-Silicon.

![Figure 2. Monthly soiling loss coefficients for poly-Si PV panels (adapted from [10])](image)

The solar power plant output was obtained using PVsyst simulation software [10]. The plant is located in Rumah, Saudi Arabia, near Riyadh, and has a capacity of 100 MW. The average hourly output was found to be 22,885 kWh.

The average hourly plant output over a year was distributed monthly according to the distribution of the Global Horizontal Irradiance (GHI) in Riyadh [11]. As Figure 3 shows, GHI differs significantly on a monthly basis, which in turn affects the power generated by the plant.

![Figure 3. Distribution of monthly Global Horizontal Irradiance (GHI) in Riyadh (adapted from [11])](image)
Two different cleaning methods are considered in this study. Both cleaning methods have the same efficiency in removing the soiling from PV panels. The cleaning costs below are obtained from [10].

For manual cleaning, where panels are cleaned by hand using water, the costs include labor, water, and other consumable materials. The total cost for a single cleaning cycle is SAR 72,433.

For assisted cleaning, where special equipment (such as washing tractors) is used, the costs include labor, water, other consumable materials, and equipment depreciation over eight years. The total cost for a single cleaning cycle is SAR 12,294.

B. Simulation Modeling

In order to account for variability in the power generated by the PV plant, the weekly output in kWh was fit into a Triangular distribution with the minimum, mode, and maximum parameters as follows: (-0.1(Plant_Output), Plant_Output, 0.1(Plant_Output)), where Plant_Output is the weekly power generated from the simulation as described in sub-section A. The benefit of stochastic simulation lies in its ability to model plant-output variability caused by unpredictable weather and operating conditions.

The simulation explored the effect of changing both the cleaning method and the cleaning frequency on the plant output and maintenance costs. Ten scenarios were run for each cleaning method while increasing the cleaning frequency gradually from 1 week to 10 weeks, totaling 20 different scenarios. Because stochastic simulations require the use of replication to obtain an accurate estimate of responses [12], each scenario was run for 15 independent replications where each replication used a different stream of random numbers to sample from the statistical distributions.

The model was constructed using WITNESS V 20.0, a commercial software for Discrete Event Simulation (DES). In DES, the modeled system evolves over time as state variables change at discrete points in time [12]. It is one of the most popular simulation techniques in modeling and optimizing maintenance systems [13]. The simulation was conducted on a computer with i7 processor CPU @ 2.20 GHz and 8.00 GB of RAM. The total simulation time was 24:19 minutes.

The model was validated using both white-box and black-box techniques [14]. In black-box validation, the output of the model is compared to the expected results. In this case, it includes the power plant output and the cleaning costs for different configurations. White-box validation includes checking the logic of the model by following both the code and the animations to ensure the model behaves the way it was intended to. In this case, various interactive plots of the plant output (both with and without the soiling effect) were monitored during the simulation, as were the individual and accumulated cleaning costs and soiling losses.

IV. RESULTS AND DISCUSSION

The annual plant output was found to be comparable for both manual and assisted cleaning. As Figure 4 illustrates, the plant output peaks in the shortest cleaning frequency (1 week) and decreases gradually as the time between cleaning intervals increases. In other words, the longer PV panels are left without cleaning, the more soiling accumulates, contributing to the soiling loss. The slight variation between the two cleaning methods is due to the variability of input sampled from statistical distributions. The plant output ranged from around 197,000 MW to around 183,000 MW, implying a power loss due to soiling of 1.6% to 8.6%.

As can be expected, the difference in cleaning cost between the cleaning methods is significant (Figure 5). The cost difference increases substantially as the cleaning frequency decreases. For the exception of the substantial capital cost, assisted cleaning is the preferred choice since it is the more economical cleaning method in all scenarios.

Figure 6 shows a plot of the two responses in the simulation experiment, cleaning costs versus plant output. From this data, we can see a number of non-dominated solutions [15], where a group of solutions exist without a dominant solution that is best in both responses. For example, in manual cleaning, the solution with the highest plant output has the highest maintenance cost (cleaning the panels every week). The solution with the second-highest plant output has a lower maintenance cost than the solution with the highest plant output. Therefore, the first solution
dominates the second solution in plant output, but the second solution dominates the first solution in maintenance cost. It is not possible to decide which solution is better without further data.

Nonetheless, assisted cleaning outperforms manual cleaning since all assisted-cleaning solutions are better in both cleaning cost and plant output. This chart gives flexibility to the decision maker, especially if prices are dynamic or the power plant is established for objectives other than monetary benefits.

Assuming an electricity tariff of 0.26 SAR/kWh, which is the current commercial tariff in Saudi Arabia, the optimum cleaning cycle can be obtained. This is achieved by calculating the income generated by the power plant and subtracting the maintenance costs. Figure 7 presents the results for both cleaning methods and all cleaning frequencies. The maximum revenue while using assisted cleaning can be realized when the panels are cleaned on a weekly basis. This amounts to a 1.6% power loss due to soiling. The total revenue steadily decreases as the cleaning frequency increases.

For manual cleaning, however, the revenue rises sharply as the cleaning frequency increases. This is followed by a gradual decline that matches the pattern of the assisted cleaning line. In this case, the maximum revenue is realized when the panels are cleaned every three weeks. Although cleaning weekly would minimize power loss due to soiling, the cleaning cost would not be justified since it is higher than the potential loss of income. The power loss due to soiling in this case would be around 3.6%.

These results are in agreement with Jones et al. [10], who found the optimum cleaning cycle to be 8.4 days and 19.85 days for assisted cleaning and manual cleaning respectively. The slight differences in the findings are likely to be related to the variability considered in our approach in addition to the choice of time unit, weeks, in this research.

Investigating the cleaning frequency relies primarily on the method of modeling the soiling loss. Current research tends to assume that soiling loss is a function of time since last cleaning rather than the soiling weight or density. It has been shown that the effect of soiling can be reduced significantly by external factors such as rain or wind [1, 3]. Furthermore, the amount of soiling loss depends on the soiling accumulation rate, material, and characteristics. This differs substantially from one area to another. The availability of such data may present a challenge to future research attempts.

Notwithstanding these limitations, these findings suggest that stochastic simulation is an effective method for investigating the cleaning frequency of PV solar plants prone to soiling. In contrast to mathematical approaches found in earlier studies, stochastic simulation allows the modeling of variability that affects PV solar plants as a result of weather and operating conditions.

In addition, plotting the results of main responses—in this case, power plant output and cleaning costs—provides the decision maker with better flexibility. A solution can be dynamically selected from a number of non-dominated solutions.

It would be interesting to utilize the ability of stochastic simulation to model complex operations in simulating additional aspects of solar plants maintenance. Adding more decision variables such as the number of maintenance technicians, number of cleaning equipment, dynamic cleaning schedules might require coupling the simulation model with an optimization engine [16].

V. CONCLUSIONS

The purpose of the current study was to investigate the modeling of the effect of soiling on PV solar plants through stochastic simulation. The results show that stochastic simulation can be effective in modeling the variable soiling effect on solar plant output. In addition, it can serve as a decision-support system to aid O&M managers in scheduling cleaning tasks.

Further work seeking to utilize the ability of stochastic simulation to model complex operations might explore optimizing the cleaning frequency by coupling the simulation model with an optimization engine.

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