Solar Energy 157 (2017) 762–777

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Optimal condition-based cleaning of solar power collectors

H. Truong Ba, M.E. Cholette*, R. Wang, P. Borghesani, L. Ma, T.A. Steinberg

Queensland University of Technology, 2 George St., Brisbane QLD 4001, Australia

ARTICLE INFO

Keywords:
Heliostat cleaning optimization
Mirror cleaning
Concentrating solar thermal
Markov decision process
Condition-based maintenance

ABSTRACT

Cleaning costs of mirrors contribute a significant portion in operation and maintenance costs (O & M) of concentrating solar power (CSP) systems. The optimal cleaning policy is obtained from a tradeoff between revenue received from generating electricity and the costs of conducting cleaning operations (e.g. water, labor, etc.). However, this balance depends strongly on the local electricity market and weather conditions and currently available cleaning policies have not considered variation in electricity prices nor the potential for "natural" cleaning events (e.g. rain).

In this study, a Condition-Based Cleaning (CBC) policy is developed for mirrors whose degradation is stochastic and subject to seasonal variations. The optimal policy is determined by formulating and solving a finite-horizon Markov decision process whose time-varying transition matrices describe stochastic soiling, rain events, and imperfect cleanings. The optimal cleaning policy is therefore a time-varying reflectivity threshold, below which cleaning is triggered.

The methodology has been applied to a case study on a hypothetical plant in Brisbane, Australia. Using publicly available electricity price and weather data, the optimized CBC policy was found to save 5–30% of total cleaning costs compared with a fixed-time strategy. Importantly, higher CBC savings are achieved when the direct cleaning costs are high, indicating that the policy could be particularly significant for countries with high labor or resource (water, etc.) costs (e.g. Australia). Though applied to CSP in this study, the methodology is also applicable to optimal cleaning of other solar collectors (e.g. photovoltaic collectors), albeit with different efficiency models.

1. Introduction

Solar power systems are important alternatives to fossil fuel energy sources. However, the cost competitiveness of some of these technologies has been hindered by their high Operation and Maintenance (O & M) costs, particularly for Concentration Solar Power (CSP) systems. A significant contribution to the O & M cost is the cleaning of the solar collectors which are responsible for focusing the solar irradiation onto a receiver. Frequent cleanings lead to maintaining high reflectivity and generation efficiency while infrequent cleaning can save on cleaning costs (Deffenbaugh et al., 1986). An experimental comparison of solar photovoltaic (PV) technologies has indicated that though frequent cleaning can improve energy yield and Performance Ratio (PR), the corresponding Levelized Cost of Energy (LCOE) can actually increase (Fuentealba et al., 2015). Therefore, an optimal cleaning policy is required have the correct balance between revenue received from generating more electricity (cleaner collectors) and the costs of conducting cleaning operations (e.g. water, labor). A similar problem has been studied for a Heat Exchanger Network (HEN) to derive an optimal cleaning schedule with minimum total operational cost (Sanaye and Niroomand, 2007).

Most studies in cleaning of solar collectors have mainly focused on cleaning technologies (Cohen et al., 1999; Morris, 1980; Sayyah et al., 2013). The overall cleaning methods can be classified into four categories: Natural cleaning due to rain; trucks or hosing systems (Cohen et al., 1999; Trabish, 2013); sprinkler-like systems with fixed nozzles; and robotic cleaning systems (Schell, 2011). Additionally, a particle-charging based method was proposed with the benefits of being self-cleaning and water saving (Mazumder et al., 2014). To automate cleaning, a GPS-based system of mirror washing machines (MWMs) was developed by BrightSource to optimize cleaning tasks including the location and density of stopping points, the cleaning order and the heliostats' orientations (Alon et al., 2014).

Among the few studies focusing on cleaning schedules, most have focused on setting time-based cleaning intervals considering average degradation rates. Deffenbaugh et al. (1986) and Bergeron and Freese (1981) suggested optimal cleaning frequencies which balance the daily reflectivity degradation and the annual performance of solar collectors.

---

* Corresponding author.
E-mail address: michael.cholette@qut.edu.au (M.E. Cholette).

http://dx.doi.org/10.1016/j.solener.2017.08.076
Received 23 March 2017; Received in revised form 31 May 2017; Accepted 28 August 2017

Nomenclature

N	number of states
K	number of decision epochs
Δt	discretization interval for the decision epoch
k	index of time period (decision epochs), $l = 1,2,\ldots,K$
i,j	indices of states of a certain mirror, $i,j = 1,2,\ldots,N$
Δs	discretization interval for the states
$p^D(s_j\|s_i,\text{no rain})$	transition probability from state s_i to state s_j given no cleaning and no rain at time epoch k
$p^R(s_j\|s_i,\text{rain})$	transition probability from state s_i to state s_j given rain event in epoch k
$p_k(s_j\|s_i,a)$	transition matrix in epoch k with action a
$H(t_k)$	revenue per square meter with maximum reflectivity (potential revenue)
$L(S_k,t_k)$	degradation cost per square meter with state S_k at time epoch t_k
$C_k(S_k,A_k)$	cost per square meter when state is S_k and action A_k is taken in epoch k
S_k	reflectivity loss of the field at time t_k

Kattke and Vant-Hull (2012) applied a similar methodology to establish the optimal balance between average field reflectivity and excess capacity in the design phase of the solar field.

However, such fixed-time interval cleaning strategies neglect the influence of the stochastic and time-varying factors inherent in cleaning optimization. The stochastic nature of the soiling process makes an "average"-based fixed-time approach suboptimal when compared to a condition-based approach, which can exploit direct on-site measurements of soiling and/or optical efficiency to adapt the cleaning policy to the current condition. Moreover, the seasonality of weather and electricity-price statistics play a key role in the economics of solar collector cleaning. In particular, the soiling process is strongly affected by local weather conditions (e.g. wind, rain, humidity, (dew)-temperature, airborne dust concentration and type) and varies seasonally (Bergeron and Freese, 1981; El-Nashar, 2009; Ghazi et al., 2014; Guan et al., 2015; Maghami et al., 2016; Sayyah et al., 2013). In addition, rain and wind events may also lead to natural cleaning events which are free of charge (Bethea et al., 1981; Ghazi et al., 2014; Guan et al., 2015; Sayyah et al., 2013; Vivar et al., 2010). Thus, both the stochastic soiling rate and the seasonal properties of weather and price should lead to cleaning policies that vary accordingly. Intuitively, high electricity prices and Direct Normal Irradiation (DNI) mean that cleaner collectors (high optical efficiency) are preferred to take advantage of the high potential revenue. In contrast, when prices are low, revenue loss due to soiling will be lower.

Despite the promise of newly developed online measurement technologies (Wolfertstetter et al., 2014a, 2012; Zhu et al., 2014), no cleaning studies have yet considered soiling/optical efficiency measurements and seasonal variations in weather/electricity price in their optimization. In this paper, a reflectivity-based cleaning policy is developed for the particular case of CSP heliostats (but applicable to other solar collectors) under the well-known paradigm of Condition-Based Maintenance (CBM) (Liu et al., 2003; Prajapati et al., 2012), called in this case Condition-Based Cleaning (CBC). The cleaning optimization problem is formulated as a finite-horizon Markov Decision Process (MDP) with the aim of minimizing the sum of cleaning costs and lost revenue due to reflectivity degradation. In contrast to the existing work, cleaning decisions are made by comparing the reflectivity with a time-varying threshold which has been set considering seasonal variation in the weather factors such as DNI and rains as well as electricity prices. Furthermore, a numerical study is performed with the aim of assessing the profit impact of the new CBC policy compared to a traditional time-based cleaning schedule and to test the sensitivity of this benefit to delays between the cleaning decision and the actual cleaning event.

The remainder of the paper is structured as follows. Section 2 discusses the optimization problem setup and details the objective function and necessary statistical models. Section 3 describes how to use commonly available data to estimate the necessary probabilities and model parameters for the optimization model, while Section 4 discusses how the quality of the cleaning policy is evaluated using Monte Carlo simulation. Section 5 presents a case study on a hypothetical CSP plant in Brisbane, Australia and the proposed strategy is compared with a time-based cleaning schedule. Finally, Section 6 presents the conclusions of the study and suggests avenues for future work.

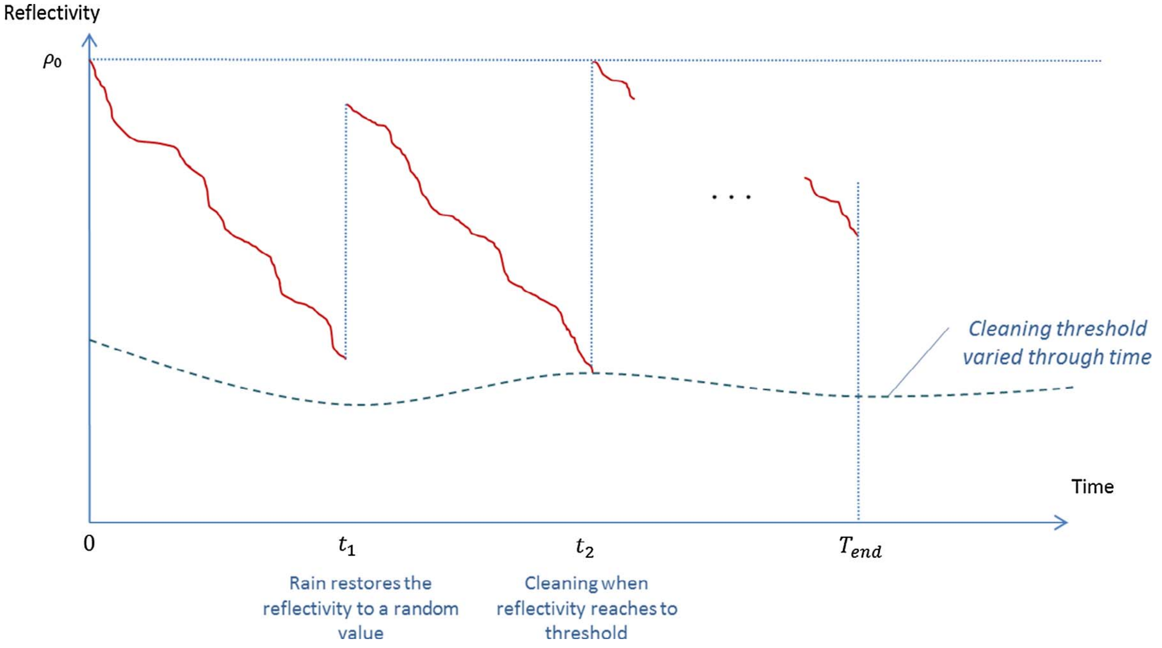

Fig. 1. Reflectivity degradation and cleaning threshold.