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Modeling and simulation of the soiling dynamics of frequently cleaned reflectors in CSP plants

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ABSTRACT

The task of cleaning reflectors is a widely adopted strategy to handle the soiling in concentrated solar power (CSP) plants. The dynamics of the soiling of frequently cleaned mirrors is dependent on many factors such as the cleaning method, its frequency and the seasonal soiling rate. This study proposes a new approach to model the soiling of regularly cleaned reflectors instead of the inaccurate methods undermining the CSP yield by using fixed reflectance assumptions. Markov switching (MS) regime, which is a non linear time series approach where parameters are allowed to switch between the regimes, are applied on the reflectance data of second surface silvered-glass mirrors, exposed at the Plataforma Solar de Almería (PSA) in Spain during two years and cleaned biweekly using high pressure demineralized water. The nonlinearities typically exhibited by such reflectance time series are successfully modeled by accounting for two regimes, a soiled and a clean regime, and incorporating various parameters (rain, washing cycle, and lagged autoregressive terms) in the suggested MS models. Based on the information criteria and the diagnostic of the models residuals, the best model has a switching normalized reflectance mean of 0.944 during the clean regime versus 0.688 during the soiled regime, in addition to one fixed lag autoregressive term. In order to evaluate the adequacy of the proposed model versus the traditional approach, which uses fixed reflectance as input for estimating CSP plants yield, four reflectance scenarios were studied by simulating the output of a 30 MWe plant using TRNSYS© (TRaNsientSYstem Simulation) program. The first and the second scenarios used the time series of the measured and fitted model reflectance data, while the third and the forth scenarios used fixed inputs (a maximum and a yearly average reflectance). The comparison of the simulation results showed that adopting the innovative proposed concept of switching regimes results in very good performance, especially in the soiled regime during which the simplistic reflectance considerations, which ignore the soiling dynamics and the applied washing cycle, undermine the generated power.

1. Introduction

Due to their potential to produce renewable and cost effective energy, CSP projects, such as large CSP utility-scale plants (Mendelsohn et al., 2012), small-sized PTCs for industrial application (Fernández-García et al., 2015) or coupled CSP and desalination plants (Palenzuela et al., 2011), are promising options for clean energy production. Various candidate materials could be used in CSP plants, however the available supply of glass material (Pihl et al., 2012) and its high reflectance supports the deployment of glass based solar reflectors in the solar field of CSP plants.

Arid and semi arid locations with high Direct Normal Irradiance (DNI) are challenged by the degradation and persistent soiling of solar reflectors, distributed over huge areas in the solar field, which will inevitably drive down the performance of these plants. Accurate monitoring of degradation (Sutter et al., 2012) and soiling of CSP candidate materials with proper devices as demonstrated in Sutter et al. (2013) and Sansom et al. (2017) is crucial to evaluate their reflectance.

The application of anti-soiling coatings are among preventive solutions for keeping the dust away from the solar reflectors (Sarver et al., 2013). But for this technology to be effective, the performance of the mirrors should not be affected by the application of these films (Atkinson et al., 2015). To obtain a peak optical performance (Valenzuela et al., 2014), an extensive frequent cleaning must be

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Nomenclature

Acronyms

ACF	autocorrelation function
AIC	Akaike information criterion
BIC	Bayesian information criterion
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CSP	concentrated solar power
D&S	Devices and Services Co
DLM	dynamic linear model
DNI	direct normal irradiance
JB	Jarque-Bera test
LB	Ljung-Box test
ML	maximum likelihood
MS	Markov switching
MSAR	Markov switching autoregressive
MSDR	Markov switching dynamic regression
NID	normal identically distributed
PSA	Plataforma Solar de Almería
PTC	parabolic-trough collectors
SE	standard errors
TRNSYS	TRaNsientSYstem Simulation

Greek symbols

β	coefficients dependent on the identified regime
ϵ_t	the residuals of the model
μ_{s_t}	regime dependent mean
ν	coefficients independent on the identified regime
ρ	coefficients of the lagged endogenous variable
σ	variance of the Gaussian distribution
θ	parameters of the model

Roman symbols

d	order of time series differencing
L	the likelihood
M	number of regimes
n	number of data points in the dataset
p	the order of the autoregressive term
$P-value$	the value obtained to accept or reject the statistical test
p_{ij}	the probability of going from a state i to a state j
q	order of moving average
s_t	a random variable
t	the time
X	the regressors
Y_t	the reflectance time series
Z	the regressors

applied, which is considered to be the most effective and widely used solution for handling the issue of dust deposition and adhesion to solar concentrating surfaces. For benign cleaning methods, such as non contact washing using pressurized water, innovative approaches have to be investigated (Anglani et al., 2017). In order to preserve the ability of reflectors to effectively focus the direct sunlight onto the solar receiver, an acceptable specular reflectance value in the wavelength range of the solar spectrum must be maintained. It is considered that an average reflectance above 90% measured at a 670 nm must be adopted in order to produce the planned energy output and, thus, preserve the economics of the plant (Cohen et al., 1999).

The soiling rate depends greatly on the prevailing weather conditions (Bergeron et al., 1981; Heimsath et al., 2010; Fernandez-Garcia, 2012; Burgaleta et al., 2012; Bouaddi et al., 2017). For example, the combined effect of light rain and wind severely pollutes the surface of the mirrors (King and Myers, 1980), while strong rainfalls effectively eliminate the adhering dirtiness. The adopted cleaning frequency may change seasonally as in Jones et al. (2007), where the reflectance obtained during winter with no artificial cleaning applied is almost equivalent to the reflectance obtained by applying frequent artificial cleaning during summer. Also, as concluded by Roth and Pettit (1980), the state of a mirror influences the dust accumulation rate. The authors pointed out a sharp drop of 0.0085 reflectance units/day for newly exposed mirrors, but as dust accumulation increases the soiling rate slows down. The possible reason for this might be that the probability for a particle to settle on a mirror surface is lower when the surface is covered with other dust particles than when the mirror is totally clean.

To obtain accurate energy production estimations under real outdoor conditions, Deffenbaugh et al. (1986) incorporated a soiling factor in the calculation of reflector's optical efficiency. For simulation purposes, reflectance is usually treated as a constant input, annual average, as in Blair et al. (2014) and Quaschning et al. (2001). When deciding on the best cleaning frequency to adopt in CSP plants, reflectance dynamics and various other variables (such as rainfall) should be taken into account. To determine a suitable cleaning frequency, Jones et al. (2007) proposed a formula where variables such as the constant annual soiling rate, the number of natural cleaning, and the effectiveness of the cleaning are considered. On the other hand, Bergeron (1982) used a simplified reflectance formula, which relies on the assumption that the reflectance evolves over time as a constant daily reflectance loss until reaching a plateau level. A different method was followed by Kattke and Vant-Hull (2012), suggesting a time-average reflectance based on film growth assumption. A time series approach was adopted in Bouaddi et al. (2015), where dynamic linear models (DLM) were applied to model the cumulative soiling of mirrors in Agadir (Morocco).

Unlike cumulative soiling, which is characterized by a continuous decreasing trend with some stochastic variation unless a strong natural cleaning event brings back the reflectance to high levels, regularly cleaned mirrors exhibit various swings (gains and losses of reflectance) and follow completely different dynamics dictated by the seasonal soiling, the frequency and efficacy of the artificial cleaning and the effectiveness of natural cleaning. By adopting a regular cleaning frequency (2, 6, and 12 days), Roth and Pettit (1980) showed that the reflectance oscillates around a long term average. However, this is not necessarily the case when the time between successive cleaning of reflectors is not equally spaced (Burgaleta et al., 2012), or when heavy soiling causes the overall average reflectance to severely drop during a dusty season. Since it could be advantageous to alternate between different cleaning methods (Jones et al., 2007) with each washing method having its own frequency of use, the resulting reflectance level may change over many cleaning cycles. In their work, Ba et al. (2017) proposed a modeling tool based on a finite horizon Markov decision process to decide on the optimal cleaning decision. However, the reflectance data used in their work does not build upon real site data.

This paper proposes a set of models based on Markov regime-switching (MS), which introduce the idea of changing regimes, to describe the reflectance dynamics of cleaned reflectors in CSP plants. This approach was applied on frequently cleaned CSP mirrors exposed for two years in Almería, Spain. This period of measurement is long enough to capture the seasonal aspects of reflectance change under the adopted washing frequency and the prevailing weather conditions. Key elements affecting the soiling, such as the rainfalls and the implemented cleaning frequency as well as the dustiness state of the mirror, are incorporated into the proposed models. To evaluate how this new modeling approach of reflectance works compared to simplistic approaches, it was tested against three other reflectance scenarios using the simulation results of