Renewable and Sustainable Energy Reviews 82 (2018) 2218–2234

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Modeling and analysis of dust and temperature effects on photovoltaic systems' performance and optimal cleaning frequency: Jordan case study

Bashar Hammad[a], Mohammad Al–Abed[b], Ahmed Al–Ghandoor[c,d,*], Ali Al–Sardeah[e,f], Adnan Al–Bashir[c]

[a] Department of Mechatronics Engineering, the Hashemite University, Zarqa, Jordan
[b] Department of Biomedical Engineering, the Hashemite University, Zarqa, Jordan
[c] Department of Industrial Engineering, the Hashemite University, Zarqa, Jordan
[d] Energy Center, the Hashemite University, Zarqa, Jordan
[e] Department of Mechanical Engineering, the Hashemite University, Zarqa, Jordan
[f] King Abdullah II Design and Development Bureau (KADDB), Amman, Jordan

ARTICLE INFO

Keywords:
Photovoltaic systems
Dust accumulation
Ambient temperature
Multivariate linear regression
Artificial neural networks
Optimal cleaning frequency
Modeling
Simulation

ABSTRACT

This paper provides a regionally focused review of work conducted in the Middle East and North Africa (MENA) region related to the effects of dust accumulation and ambient temperature on PV performance. It proposes models to simulate these effects, and suggests a financial methodology to determine cleaning frequency for a case study in Jordan. Two models have been developed; the first utilizing Multivariate Linear Regression (MLR), and the second utilizing Artificial Neural Network (ANN), to estimate PV system conversion efficiency based on experimental data of exposure time to natural dust and ambient temperature. The methodology of building the two models is demonstrated and a comparison between them is made to discuss their validity and accuracy. In addition, estimating the losses due to dust accumulation and, consequently, optimizing cleaning frequency are presented. It is found that both models can predict conversion efficiency closely, with R^2 values close to 90%. The two models are employed in calculating losses (represented in losses in system efficiency, η, and the monetary value of these losses) due to dust accumulation only; thus, finding an optimal cleaning frequency of the systems. During the 192 days spanning the duration of the study, the average efficiency reductions due to dust are 0.768%/day and 0.607%/day using MLR and ANN models, respectively. Consequently, energy losses for the duration of the study are 10.282 kWh/m^2 and 8.140 kWh/m^2, and economic losses are 3.76 US$/m^2 and 2.98 US$/m^2 using MLR and ANN models, respectively. The optimal cleaning frequency is calculated to be 12–15 days depending on the model and length of exposure time adopted in analysis. This is the first reported optimal cleaning frequency in Jordan, and agrees with most recommendations of other already published works by other researchers and techniques in the MENA region.

1. Introduction

Photovoltaic (PV) systems became one of the main suppliers of electricity generated from Renewable Energy (RE) resources in the last decade, as the price of components and installation decreased by an average of more than 85% since the 1990s [1,2]. Deployment of the technology reached wide locations around the world with the most significant potential in the Middle East and North Africa (MENA) region, due to the region location at the core of the sunbelt countries [3]. Conversely, climatic conditions (semi–arid, desert, or urban locations) and environmental conditions (dust accumulation, mud–rain soiling, or smug), in addition to geographical localities, play a vital factor of overall energy yield for such systems. Dust accumulation and soiling, among the most important location–dependent characteristics, have attracted researchers worldwide aiming at better understanding and mitigating their effects on PV performance, with the goal of maximizing the energy yield and minimizing the power losses due to these factors. It is worth mentioning that MENA region has the highest dust emission and deposition flux in the world [4]. Moreover, this region controls dust distribution in other parts of the world [4,5]. Being part of the sunbelt countries and having the highest dust activity regions, research devoted to investigate effect of dust on PV perfor-

* Correspondence to: Director, Energy Center, Professor of Industrial Engineering, Department of Industrial Engineering, The Hashemite University, P.O. Box 330127, Zarqa 13133, Jordan.

E-mail addresses: ghandoor@hu.edu.jo, gandoor2002@yahoo.com (A. Al–Ghandoor).

http://dx.doi.org/10.1016/j.rser.2017.08.070
Received 18 April 2017; Received in revised form 22 July 2017; Accepted 18 August 2017
Available online 25 August 2017
1364-0321/

mance in MENA region becomes an intuitive and a necessary requirement for PV designers, operators, policy makers, and investors.

Since the mid–nineties, large amount of work has been done in the PV field [6]. However, the number of papers published discussing effect of dust and soiling on PV systems increased rapidly, reaching 80 publications in 2015, responding to the need of lowering PV costs and establishing markets in solar–abundant, but dust–rich, countries [7]. This paper aims at achieving the following: Firstly, to provide a review of the dust effect reviews, with a regional–focused review of work conducted in MENA region related to effect of dust and temperature on PV performance. Secondly, to demonstrate a case study for the MENA region investigating two modeling and simulation techniques of the combined effect of temperature and dust on PV system's performance, recommending cleaning frequency based on economic analyses of these techniques.

1.1. Soiling and dust reviews

Several review papers have been published with the aim at classifying and categorizing the large amount of work accomplished in the field. A review on the review papers published since 2010 is presented in [7]. Mani and Pillai reviewed the research done in two periods; before and after 1990, and made general recommendation for different climatic zones, temperature ranges and annual precipitation [8]. For the Mediterranean climate (Jordan is part of this climate), they recommended cleaning once a week or every two weeks depending on the rate of dust accumulation. A comprehensive review of the research and challenges to dust issues including dust effects on glass transmittance of PV modules, physics and chemistry of dust particles, restoration and preventive mitigation is summarized in [9]. A list of the recently published work in this field is presented in [7] and is classified based on their focus into the following subjects: performance, modeling/simulation, composition/morphology, transmission/reflection, cost/economics, mitigation/cleaning, ambient conditions/effects, instrumentation, spectral effect, and tilt/orientation. A more recent review examining works that study the influence of dust scattering and deposition, and partial shading due to deposition on efficiency degradation in addition to other factors affecting dust deposition on PV panels is presented in [10]. The factors that affect the operation and efficiency of the PV systems are reviewed in [11]. It was concluded that, in addition to cell technology and selection of required equipment, ambient conditions including temperature and dust have a significant impact.

A review focuses on mechanisms of dust accumulation; addition, rebound, and resuspension is presented in [12]. The effects of air velocity and direction, tilt and azimuth angles, and humidity, in addition to best mitigation strategy for each mechanism, are also discussed in [12]. It was stated that soiling depends greatly on panel module tilt angle, and resuspension mechanism is the most sensitive to wind velocity and the highest dependent on particle size. The existing theoretical models for dust life cycle; generation, deposition, adhesion, and removal, are reviewed in [13] with special focus on the interface between particles and solar collectors' surfaces. The aim of [13] is to help workers in solar field find a balance between dust losses and cleaning expenses. A review that integrates all external, internal, operational and economic factors affecting performance of PV systems is presented in [14] including dust, soiling, and cleaning cost, aiming at providing an overall idea about positive and negative effects on PV performance in one paper.

PV output power, and its effect on power grid, necessitates the need to develop models to predict the inherently variable power output. A systematic and comprehensive review of these models is presented in [15]. It was reported that the regression models have the advantage of correlating meteorological variables, whereas the intelligent learning techniques (such as artificial neural networks, ANNs) can be applied in a dynamic environment and offer improved nonlinear approximation performance utilizing better training data and algorithms. In [16], degradation due to two major environmental factors; high ambient temperature and high concentration of atmospheric dust, on performance of solar plants based on the type of solar collectors, geographical location, local climate, and exposure period of the collectors is reported in this review. This review shows that frequency of cleaning is critical, as the adhesion of dust increases with time on the collectors. More importantly, they reported a number of experiments supporting the conclusion that a linear approximation is valid for the efficiency drop versus the dust concentration, up to a certain range of surface dust density.

Characteristics of monitoring of PV systems, monitoring parameters, measurement of monitoring parameters, major instruments used in PV monitoring system, data acquisition (DAQ) system, and methods of data transmission, storage and analysis are reviewed in [17]. They reported that harsh environmental conditions, such as dust and sand storm, could reduce sensors reliability, increase instances of malfunction, or render the information they gather obsolete. A review, presented in [18], discussed effects of dust property, wind velocity, surface property, tilt angle and orientation, ambient temperature and humidity on the settlement of dust on PV modules. In addition, they studied soiling mitigation methods based on their classification into manual and self–cleaning. They further divided the self–cleaning methods into active and passive techniques. The advantages and disadvantages and comparison of the mitigation techniques were also explained and summarized to serve as a guide in selecting the most suitable method for soiling mitigation [18].

The effects of humidity and air velocity, in addition to dust, were reviewed in [19]. The authors of that review concluded that humidity affects the incident irradiance and dust accumulation. However, increasing air velocity decreases the cell temperature and increases the dust accumulation. But in the same time, as air velocity increases, the humidity level decreases.

1.2. Temperature effect on PV performance

Other published research papers focused on the effect of operating and ambient conditions on performance of PV systems with and without considering dust accumulation. Correlations of solar electrical efficiency and power dependence on temperature were reviewed in [20], and it was concluded that both efficiency and power of PV modules decrease linearly with the operating temperature. [21] stated that in general the power of PV modules drops by 0.5%/°C and the efficiency reduces by 0.05%/°C with increase of ambient temperature. The simulation of varying ambient temperature and its effect on PV performance and studying the influence of fins on the backside of the modules were shown in [21]. It was found that maximum power decreases as ambient temperature increases. A statistical model, to predict performance of PV systems based on probability density functions of solar irradiance and temperature developed from real measurements, was presented in [22]. The simulated results aiming at minimizing network losses were verified by comparison to actual behavior of 3.6 kWp grid–connected PV system. It was emphasized that the accuracy of the model depends significantly on long term meteorological data for any site [22].

Experimental and theoretical investigations of effect of ambient temperature on the performance of a thin film PV module were presented in [23]. The study demonstrated that ambient dry bulb has a significant effect on open circuit voltage and less effect on short circuit current. Another work aiming at understanding how temperature influences PV cells conversion efficiency was presented in [24] by describing the heating process of a polycrystalline PV cell and the correlation between temperature increase and efficiency drop. It was found that the efficiency drops by 0.0608%/°C as module temperature increases.

Investigating the influence of ambient temperature and wind speed