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Automated, robotic dry-cleaning of solar panels in Thuwal, Saudi Arabia using a silicone rubber brush

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ABSTRACT

The challenge of mitigating power loss in solar photovoltaic (PV) systems—due to dust—is critical to the economical deployment of solar in arid regions. These areas suffer from high aerosol concentration levels and frequent sand storms that lead to an accumulation of a layer of dust on the surface of solar arrays. The dust stays in place due to only slight and occasional rain fall. This paper presents the results from a study conducted on the effectiveness of dry cleaning solar panels, using an automated robotic cleaning system. The robotic cleaning system is part of a research program related to robotic dust mitigation technologies for solar panels, and includes a new type of brush, which uses silicone rubber foam flaps mounted onto an aluminum core. The study found that the robotic system, using this silicone rubber foam brush, was able to effectively minimize the impact of dust on the solar panels' power output, providing an increase in power output versus the weekly-cleaned controls. This new brush shows promise for use in solar panel dust mitigation due to its effective cleaning performance and low cost, and does not induce any damage to the surface of the solar panels.

1. Introduction

1.1. Importance of solar power generation

As the effects of climate change intensify across the globe, significant efforts are being made to better understand the implications of various energy policies and their wide ranging effects—from their impact on economies to their effects on biodiversity (Sturm et al., 2017). While the issue is global in nature, the impact of climate change differs on a regional basis, as well as on various time horizons, and thus the importance, value, and costs of various mitigation efforts are not uniformly perceived. Therefore, it is difficult to determine the single best long-term strategy that represents the best method of addressing climate change on a global scale, and is in the best interest of all concerned parties (Lempert et al., 2004). Science can inform these decisions by clarifying the likely costs and benefits of various actions (Hallegatte et al., 2016). The current belief is that a reduction in CO_2 concentrations via a shift toward renewables for primary energy production, is an appropriate and prudent insurance policy against the potential impacts of climate change (Chu et al., 2016). The need for green energy sources becomes more significant in light of the fact that global energy demand is expected to increase by approximately 50% by 2040 (IEA, 2016). Through the continuous improvement of technology and exploration of possibilities, it is possible for the scientific community to guide policy decisions toward promising avenues for mitigating climate change, while minimizing any negative consequences of the mitigation strategies.

Renewable power generation technologies include a diverse class of technologies that are critical in addressing the growing primary energy demand without accelerating the release of CO_2 and other greenhouse gases. The impact of renewable energy sources in reducing CO_2 emissions is, at this point, being outpaced by the global growth in primary energy demand associated with increasing per capita income in developing countries (Lempert et al., 2004), meaning that deployment of renewable energy generation needs to accelerate more rapidly if the impacts of CO_2 (and other greenhouse gas) emissions are to be mitigated. While many of the traditional renewable power technologies, such as hydro-electric, have reached relatively high deployment saturations. For example, the U.S. currently captures about 50% of viable hydroelectric potential (Kao et al., 2014), and remaining opportunities are generally related to smaller projects (Krause et al., 2016) that cannot significantly decrease CO_2 emissions due to primary power generation alone, and also introduce other potentially negative environmental impacts that must be considered (Kelly-Richards et al., 2017). Solar power stands out (along with wind power) as having significant potential (Wadhawan and Pearce, 2017) for competitive growth in share of the energy sector, with some models indicate that solar power has the potential to provide as much as 50% of total

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primary power generation in competitive markets (Creutzig et al., 2017). Low deployment in the past has primarily been due to the high cost of solar power production, coupled with challenges related to storage and load regulation, due to the variability of production associated with wind, hydro and solar power production (Jacobson et al., 2015).

In the last year, however, solar power generation has actually reached price parity with conventional power sources in many countries (Karneyeva and Wüstenhagen, 2017), opening up the possibility to significantly expand solar power production in many regions of the world in a cost-effective manner (Kang et al., 2017). The advancements in technology and optimizations in processes, enabling the low prices in the field of solar power production, now grant a tool that could allow for the reduction in generated CO_2 without a negative economic impact. As such, solar power generation appears to be a critical technology in the global effort to minimize the impact of climate change.

1.2. Impact of dust on solar power generation

Dust remains a significant challenge for the solar industry at the operation and maintenance level, as dust accumulation on panels can significantly reduce the power production of those panels (Adinoyi and Said, 2013; Al Shehri et al., 2016). There is a strong alignment between regions of optimal solar insolation and the presence of climactic conditions that lead to dust deposition on solar panels (Deb and Brahmbhatt, 2017). As such, dust deposition is a critical challenge that will impact the economic viability of solar power in many regions if the deposition is not mitigated.

Research on the impact of dust on solar panel yields has been ongoing in the Middle East, to better understand the phenomena and learn how to best mitigate its impact. The number of research articles has been increasing steadily for the past 7 years. While there were generally less than 10 articles/year related to the impact of dust on solar power generation prior to 2009, there were over 80 published articles in 2015 alone (Costa et al., 2016). It has been observed that the loss in power generation due to dust accumulation can exceed 40%, and that daily losses due to atmospheric dust deposition can exceed 6% (Saidan et al., 2016). Annual losses in power production due to dust deposition could be as much as 10% with weekly cleaning, as indicated by experiments showing an 11% decline in power generation after one week of exposure to dust (Saidan et al., 2016). Despite the exigence of the problem as demonstrated by the emerging literature, and the many studies focused on measuring the impact of dust in reducing solar power generation, there has been little *in situ* work done to assess the impact of emerging dust mitigation technologies, especially related to automated systems for dust mitigation in the harsh desert environments in which solar resources are often located. Notable exceptions include a review on mitigation methods that includes mechanical systems (Jamil et al., 2017), and a proposed mechanical cleaning system tested in India (Deb and Brahmbhatt, 2017). Based upon a 2014 analysis of technologies available for mitigating the impact of dust accumulation on solar power generation (Alshehri et al., 2014), the authors decided to investigate and develop an installed robotic cleaning solution, as the analysis indicated that installed robotic cleaning systems represented the most promising technology investigated.

With this in mind, after many laboratory-based tests leading towards the development of a specialized robotic platform for dry-cleaning solar panels, this paper presents the results of a 3-month field study of the robot's performance in Thuwal, Saudi Arabia. The study was conducted with the aim of addressing the effectiveness of the technology, specifically the silicone rubber foam brush, which showed promise in an earlier lab-based study (Al Shehri et al., 2017). In these earlier lab-based studies, the silicone rubber foam brush, which is considerably cheaper to manufacture than most alternatives, demonstrated a number of key benefits, including: resistance to the collection of dirt/debris on the brush, resistance to the absorption of water, lack of impactful damage to the panel surface and high cleaning efficiency. This technology is now under patent proceedings and is published. The data presented in this current paper corresponds to a relatively short period of time in comparison with the 20-year guaranteed life of a solar panel. The timeline for the experiment was gauged to balance the need for knowledge-sharing with repeatability, as the experimental design involved the comparison of the effectiveness of the cleaning robot as opposed to traditional manual cleaning on a weekly cleaning schedule, and was thus able to cover multiple full cleaning cycles for comparison purposes.

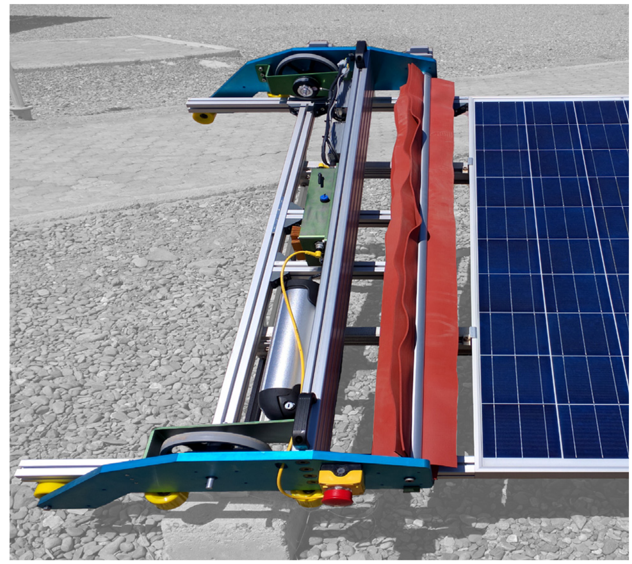

Fig. 1. The robotic cleaning system as installed in the test field. (Background in grayscale to emphasize system.)

2. Methods

2.1. Field experiments for assessing cleaning effectiveness

The field experiments discussed in this paper were conducted with the intention of gauging the effectiveness of using a silicone rubber foam brush on an automated robotic cleaning tool (shown in Fig. 1) in mitigating the impact of deposited dust on solar power generation. A 10 kW PV system was used in the experiment. Commercially available modules (240 W) were installed at an angle of 25 deg (optimal solar angle for Thuwal area) and distributed in three rows. Each row was monitored using a 3 Sunny Boy 3000TL inverter. The system was commissioned in December 2013, and our tests were conducted from March until June of 2016. Full data collection was available between the end of April and the beginning of June, yielding 37 days of high accuracy results. Additional, lower resolution data was collected from April 1 to May 24. The area where the panels are installed has paved walkways and gravel, to minimize dust generation from personnel movement. The site is located near one lightly used road, and there are no significant industrial sites nearby. Groundwork was being done on a construction site that was about 700 m south-west of the testing site, with prevailing winds coming from a north-westerly direction. Additionally, the site is located on the coast of the Red Sea, which also will impact the quantity and composition of the dust being deposited on the panels.

Current-voltage data was planned to be obtained from the online portal provided by SMA technologies, which is enabled through the Sunny WebBox, which collects the data from the inverters and uploads it to the SMA servers. Due to problems with the 3G connection during the experimental timeline, data in the latter part of the experiment was gathered using an SD card that serves as a backup data collection