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Cost and Performance Comparative Model of Dust Mitigation Technologies for Solar PV in Saudi Arabia

Samar Alqatari*, Anas Alfaris
Center for Complex Engineering Systems
KACST & MIT
77 Massachusetts Ave. E-38, Cambridge, MA 02139, USA
samarq@mit.edu, anas@mit.edu

Olivier L. de Weck
Engineering Systems Division
MIT
77 Massachusetts Ave. E-40, Cambridge, MA 02139, USA
deweck@mit.edu

***Abstract*—Solar photovoltaics are rapidly emerging as promising technologies to tackle the world's energy challenge. Certain geographic locations with high levels of insolation, while offering vast capacities for harnessing the world's available sunshine, face certain climatic challenges. The dust problem, particularly, a prevalent issue in many of these locations, has posed a serious problem for PV deployment. Module efficiency has shown to decrease by up to 70% due to dust.**

While some research has investigated potential technologies for dust mitigation, not much studied the impact of implementing them commercially, or took into account climate effects. This paper presents a dust-mitigation for solar PV model, consisting of a performance component and a financial component, to compare three main dust-mitigation technologies (electrodynamic screens or EDS; air-blowing mechanisms; and superhydrophobic nano-coatings) against each other, and against a reference based on manual cleaning. The model calculates the Levelized Cost Of Energy (LCOE) as an objective metric for comparison. Saudi Arabia is used as a case study to validate the results, given its unique combination of enormously high annual insolation and frequent dust storms.

Dust mitigation technologies show major dependence on weather patterns, and increase total power output dependence on seasonality. Different technologies increase power output disproportionally depending on the location despite the relative proximity of the test points. In some locations, the annual power production increases by up to ~17%. Overall, there is a correlation between increased energy production and decreased LCOE, showing that the increase in annual energy offsets the associated costs. The model is globally applicable, has the potential of studying additional technologies, and incorporating effects of other aerosols, making it relevant for any large-scale PV application.

Keywords— comparative model; solar photovoltaics; Saudi Arabia; dust; dust-mitigation; technologies; aerosols; module performance; levelized cost of energy

I. INTRODUCTION

Challenged by climate change and increasing global energy demand, the world is facing an intermittent energy challenge. Solar photovoltaics are rapidly emerging as clean technologies to replace fossil fuels and shift to more sustainable energy systems, creating a promising opportunity to tackle this challenge. Certain geographic locations, such as the Middle East and North Africa, provide exceptionally vast capacities of incident solar irradiation (insolation), making them attractive spots for harnessing the world's available sunshine. However, many of these locations, while receiving high amounts of insolation, face their own sets of atmospheric challenges—namely, heat and dust. The dust problem, particularly, has instigated a growing field of research [1, 2, 3], covering topics from dust characterization to its impact on solar technologies. According to one study, solar panel efficiency total reductions due to dust can be up to 70% [4].

While some research has been done to study potential technologies for dust mitigation [5], not much research has been done to study the impact of potentially implementing them commercially, or comparing their effect taking into account topological and meteorological factors. Although most of these technologies have not been commercialized yet, a targeted study of their potential industrial application, especially in regions of high insolation, is an essential missing piece in academic and industrial solar PV dust mitigation literature. Motivated by this question, this study aims to contribute to filling this gap in this meteorological-technological-economic energy nexus.

A model was created to compare different dust-mitigation technologies against a reference based on manual cleaning, which uses the Levelized Cost of Energy (LCOE) as an objective metric for comparison. The model consists of a performance component and a financial component. Although most of these technologies have not been commercialized, and the literature lacks thorough data on their effectiveness in mitigating dust or improving power output, the model uses estimates from the available literature to compare three auspicious prospect technologies: electrodynamic screens (EDS), air-blowing mechanisms, and superhydrophobic nano-coatings. The model is universally applicable and has the capacity to be refined as more technology data becomes available, and extended beyond these three technologies. It is also applicable to any location given its relevant data sets, and can further be expanded beyond a dust analysis to capture the effect of other aerosols that affect different locations disproportionally.

Since the performance model depends heavily on spatial parameters, it was tested using Saudi weather and dust data in six different locations, as well as Saudi economic metrics. Saudi Arabia is used as the case study given its unique combination of enormously high annual insolation (up to 2800 kWh/m2/y), and great levels of dust storm frequency and deposition [6, 7,8]. It is also looking to expand its renewable energy sector, with the aim of reaching 16GW target capacity from solar photovoltaics by 2032 [9]. Such an ambitious goal requires optimizing technology for maximum energy gain and minimum cost, making this analysis of dust mitigation for solar PV especially useful for the country.

II. Model Architecture

The ultimate objective of the model is to study the potential impact of incorporating dust mitigation technologies into solar photovoltaic module deployment, taking into account their effects on performance and cost. The main metric for comparison is the levelized cost of energy, which creates an objective measure of total gains (maximizing solar power potential while minimizing investment costs). The performance model depends on the performance ratio (ultimately, changes in pre-conversion and relative efficiencies of the solar modules, including or excluding application of dust mitigation technologies) and total power output over an annual period of time. The finance component includes estimates of capital investment and operation and management costs for each year.

The model is tested using Saudi-specific data: weather (solar irradiation, temperature, and humidity), and meteorological (Aerosol Optical Depth, or AOD) data sets. Since there is vast dependence on climatic and atmospheric conditions, six Saudi cities with disparate coordinates are compared. The finance model carries the analysis over a 25-year period, and uses estimates for costs associated with the various dust mitigation technologies (EDS, air-blowing, and nano-coatings).

The model can be extended in various ways:

- Comparing additional emerging dust mitigation technologies;
- Testing for any coordinate location around the world, given access to its weather and meteorological data sets;
- Comparing solar PV with other solar, renewable, or non-renewable energy sources using the LCOE.

It is worthy to note that most of the dust mitigation technologies have not yet been commercialized and limited accurate data of their performance capabilities and costs exist in the literature. This model is built with a flexibility that allows amenable refinement of the various parameters, as more data becomes available.

III. Data Description

The model uses KACST-NREL solar radiation monitoring station data for solar irradiation, temperature, and humidity data sets from 1998-2002 in Saudi Arabia. Hourly averages over the five years are calculated for six Saudi locations at various latitudes and longitudes: Abha, Al-Ahsa, Jeddah, Al-Qaisumah,

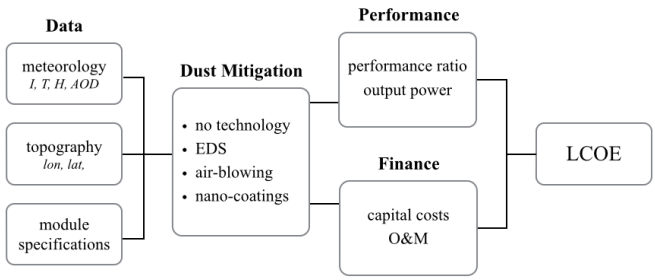

Figure 1: Model architecture

Solar Village (northwest of Riyadh), and Tabouk. For the purpose of carrying the analysis, the model allows for a choice from a number of solar modules based on different PV technologies (mono-crystalline, amorphous silicon, cadmium telluride, etc.) with initializations from different manufacturers. The results shown are using a standard mono-crystalline module, given the dominance of this type of technology in the solar PV market (comprising about 80% of total productions) [10].

Dust storm frequency was modeled using aerosol optical depth (AOD) data obtained from NASA's AERONET. AOD is a measurement of aerosols distributed within a column extended from the measurement station on earth, to the top of the atmosphere. The voltage measured is proportional to the amount of solar irradiation reflected or refracted on the sunray's path to earth, typically due to aerosols such as smoke, dust, or urban haze. In desert areas such as Saudi Arabia, dust particles comprise the major aerosols. Thus AOD provides an indication of the amount of solar irradiation that is prevented from reaching solar panels due to dust. The data used in the model is for AOD 2.0 level quality assured data for a Riyadh-based station from 1999 to 2002. The data is used to map the dust storm frequency in Riyadh over a similar historical period that the solar radiation data from KACST-NREL is collected, and daily averages over the four years are computed. The Riyadh data is used to generalize dust storm frequency over the whole Kingdom in the model, due to the lack of data for the various locations. Given the minor differences between the various locations, the results should still provide pertinent estimates for dust patterns for Saudi Arabia, while having the potential of outputting more refined results using different data sets.

IV. Performance Calculations

A. Power Calculations and Theoretical Limit

Potential solar power output was calculated using

$$P_{out} = AI\eta_{nom} \tag{1}$$

where A is the total solar panel area and η_{nom} is the nominal efficiency of the solar module, both provided by the solar manufacturer. I is the incident global horizontal solar irradiation, computed by accounting for the tilt of the panels using $I = I_0\, sin\theta_i$, θ_i being the angle of solar incidence at a given hour in the year. Theta is calculated using a set of equations that take the tilt and azimuth angles of the panel as inputs. The azimuth angle for the panel is set to be facing south,

given Saudi Arabia's location in the northern hemisphere, and the tilt angle is set to be 30˚. *PR* is the performance ratio, essentially a parameter measuring the ratio between actual electricity yield and target yield. The performance ratio, $PR = \eta_{pre}\eta_{rel}\eta_{sys}$, captures the reduction in total efficiency due to various factors. The pre-conversion efficiency, η_{pre}, is used in the model to capture the reduction in efficiency due to dust; the relative efficiency, η_{rel}, captures the reduction in efficiency due to heat; and the system efficiency, η_{sys}, captures system losses, which in the model is provided by the manufacturer.

To provide a baseline power curve for potential energy output, the "theoretical limit" is calculated. The capacity of PV systems (typically given by their installed peak power, P_k, measured in watt-peak, W_p) characterizes the nominal power output of PV modules under clear skies at Standard Test Conditions (STC). For a hypothetical solar plant with a 13.8 kW_p nominal capacity, and at a module temperature of 25˚C and solar irradiation of 1000 W/m^2, the baseline power curve is computed for the six Saudi locations. For an azimuth angle of 90˚ and a title angle of 30˚, the angle of solar incidence $\boldsymbol{\theta_i}$ and number of daylight hours are calculated for each day. The performance calculations follow the framework presented by Beckman [11]. The resulting curve is shown in Figure 2, showing a range of maximum potential energy of around 176-167 kWh over a day in midyear.

B. Power Reduction due to Dust

The pre-conversion efficiency captures reduction due to aerosols obstructing photons from reaching the solar cell. The wavelength of incoming light is calculated using

$$E = hc/\lambda \tag{2}$$

where *E* is the band gap energy [J], *h* is Planck's constant [Js], *c* is the speed of light [m/s], and λ is the wavelength of light [m]. Silicon's band gap is taken to be 1.11eV, yielding a corresponding wavelength of 1116.19nm. Thus an AOD measurement at 1020nm is chosen for the model, as it is the most suitable for the crystalline silicon module specified for the analysis. The fraction of effective insolation reaching the earth's surface is given by *exp(-AOD)* which is taken to be the dust reduction factor (DRF) for a given day, used to estimate the pre-conversion efficiency.

C. Power Reduction due to Heat

The Increase of operating cell temperature results in depleted efficiency of solar cells, essentially due to increased carrier concentrations and internal recombination rates [12]. Many studies have been conducted to study the effects of temperature on solar PV efficiency reduction, and essentially, the relative efficiency of the solar cells in large depends on the operating PV cell temperature, which in turn depends on various weather variables: ambient temperature; local wind speed; solar radiation flux and irradiation; as well as material and system-dependent intrinsic properties. Many equations that take into account all the different factors for accurately capturing effect of temperature exist in the literature. This model follows the following equations for computing the cell relative efficiency:

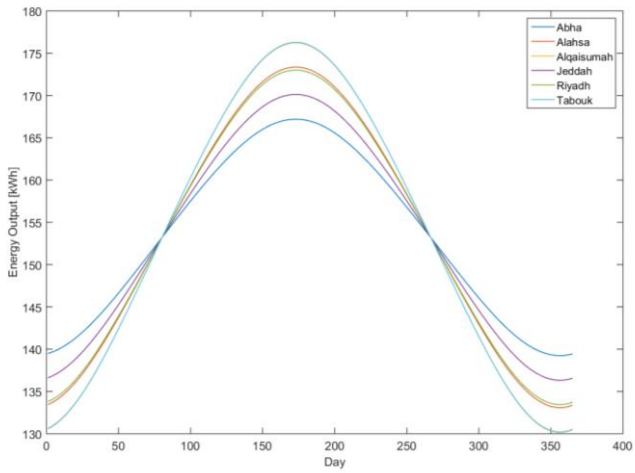

Figure 2: The power potential for various Saudi cities under STC conditions.

$$\eta_{rel} = \eta_{T_{ref}} \left[1 - \beta_{T_{ref}}\left(T_c - T_{ref}\right)\right] \tag{3}$$

$$T_c = T_a + \left(\frac{T_{NOCT}-20}{0.8}\right) G \tag{4}$$

Where η_{rel} is the cell relative conversion efficiency, $\eta_{T_{ref}}$ is the efficiency of the cell at T_{ref} and 1000 W/m [13], $\beta_{T_{ref}}$ is the temperature coefficient (provided by the manufacturer), T_c is the cell temperature, T_{ref} is the reference temperature of 25˚C, T_a is the ambient temperature, T_{NOCT} is the nominal operating cell temperature, and G is the global incident solar irradiation. Due to the shortage of wind data in this particular case, the increase in efficiency due to convective heat transfer was not captured. Since Saudi Arabia does not experience vast winds; for the purposes of this model, this shortage is negligible.

V. Dust Mitigation Modeling

Self-cleaning (or dust mitigation) technologies can be broadly classified under active and passive technologies. Active technologies employ methods to actively repel dust particles off of solar panel surfaces. Two of the most popular active technologies are electrodynamic screens (EDS) and air-blowing mechanisms, which are modeled here. Passive self-cleaning technologies do not actively repel dust particles or other pollutants, but generally serve to make the manual cleaning process (using water and soap detergent) more efficient and effective [14]. These technologies are typically thin film or layering materials exhibiting self-cleaning behavior, coating solar panels. One of these technologies, super-hydrophobic nano-coatings, which unlike the other two active technologies modeled, has actually been commercialized. The performances and costs of these technologies are modeled while keeping their functional differences in perspective.

A. Electrodynamic Screens (EDS)

The development of EDS was first instigated by research on dust mitigation for solar panels in space, and the first application was carried out by NASA with promising results – the ability to repel 95% of dust particles, both charged and

uncharged, in less than two minutes [15]. In this technology, two electrodes, coated with a dielectric film for protection, are deposited on the cover glass place of solar panels. Voltage is then applied and an electric field activates the electrodes, charging the dust particles, and running an electromagnetic wave that helps repel the dust particles off the solar panels. The dust particles are then collected using a Farady Cup. The process requires less than 0.1% of the energy produced by the solar panel [16]. Although research on EDS had started some time ago, the technology has yet to be commercialized, with a patent only published in late 2013 [17]. EDS is an active self-cleaning mechanism that does not require water or manual labor. It does, however, require a dry ambient temperature and cannot work under wet conditions. The technology was modeled such that with each 10% increase in humidity levels, the effectiveness of the technology would degrade, and would stop working for humidity levels higher than 60%. This is based on the testing conditions indicated in the literature for this technology. Although negligible, the 0.1% of module power production requirement was captured.

B. Superhydrophobic Nano-coatings

This technology is fabricated using materials with super-hydrophobic (or water-repellant) properties, such as TiO_2 or ZnO. Solar panels are coated with super-hydrophobic thin films that make the cleaning process using water more efficient. When a hydrophobic coating is applied, the water spreads over the panel's surface more easily, forming intricately into particulate drops that easily slide off the (tilted) solar panel, carrying with it dust and other dirt accumulated on its surface. Typically these materials have higher reflective or refractive indices than the semiconducting material used for conversion, hindering the amount of total potential insolation. Applying these coatings have shown an increase in power output of ~27% [18], although their effectiveness depends on weather patterns. Regions with higher patterns of rain and humidity will witness a more drastic increase in energy output than those with drier climates. Furthermore, the costs of water and frequency of cleaning required will also be less for wetter locations. Saudi climate is generally hot and dry, except for occasional rain in the winter and high humidity levels along the coasts. Potential power output was modeled in correlation with humidity levels.

C. Air-blowing Mechanisms

Air blowing is not as prominent as EDS or nano-coatings in the solar PV dust mitigation academic discourse or industrial applications. The model in this paper is based on a solar array self-cleaning air-blowing system developed in the UAE [19]. The technology is applicable on all-roof, roof-integrated, or façade-integrated PV systems, and capitalizes on cold exhaust air-conditioning air to blow off dust from- and cool solar panels. This technology is unique for its tackling both pre-conversion and relative efficiencies of solar modules, since it both cleans off dust and removes thermal energy through convection. Given proximity of climate and weather conditions between the UAE and Saudi, this technology was modeled using the empirical results obtained in the study of efficiency improvements.

VI. FINANCIAL CALCULATIONS

The Levelized Cost of Energy (LCOE) is used as a measure to compare the finances of applying the different technologies (or lack thereof) in the model. The life-cycle assessment is carried for the period of twenty-five years. The following equations are used to compute the LCOE [20]:

$$LCOE = TLCC \div \{\sum_{n=1}^{N}[Q_n \div (1+d)^n]\} \quad (5)$$

$$TLCC = \sum_{n=1}^{N} \frac{C_n}{(1+d)^n} \quad (6)$$

$$(1+d_n) = (1+d_r)(1+e) \quad (7)$$

where *LCOE* is the levelized cost of energy, *TLCC* is the total life-cycle cost, Q_n is the energy output in a year, d is the discount rate, N is the analysis period, C_n is the cost in period n, d_n is the nominal discount rate, d_r is the real discount rate (rate in the absence of inflation), and e is the inflation rate. The real discount rate is set as 7% and the inflation rate is taken as the current Saudi inflation rate of 2.4% [21]. The capital investment cost estimates are outlined in table 1, and are modified from values obtained from the renewable energy modeling software SAM [22]. The operations and management estimate costs used in the model are outlined in table 2. Values in tables 1 and 2 represent the costs associated with the reference scenario based on manual cleaning.

The following cost adjustments are made to model the incorporation of the dust mitigation technologies:

A. Electrodynamic Screens (EDS)

The integrated EDS system with a solar cell includes a cover plate; a layer of front electrodes; a semiconductor layer; a reflection enhancement layer; and a back electrode. The semiconductor layer is the crystalline silicon solar module. The model assumed a borosilicate glass plate substrate for the cover plate, and indium tin oxide (ITO) electrodes for good deposition on the glass panel. The reflection enhancement layer was modeled as a TiO2 255nm thin film. The approach for modelling the costs of the EDS system was bottom up, where typical values for the costs for the various components making up the system were added individually. Production and installation costs were estimates, mostly as ratios of general solar module installation prices. This active self-cleaning technology does not require (in fact, cannot function with) water or detergent, which decreases annual organization and maintenance costs.

B. Superhydrophobic Nano-coatings

The lifetime of this technology is five years; thus a reinstatement of capital costs is renewed every five-year period. A 250ml of the nano-coating material, costing about $61.3, would be enough to cover a typical 3kW installation, so a multiplier is added to adjust for the scale of the model.

C. Air-blowing Mechanisms

Costs of exhaust ducts, installation, labor, and miscellaneous materials and supplies required for implementing the system were modeled. The system is fairly

TABLE I: CAPITAL INVESTMENT COSTS FOR YEAR 0

Capital Investments	*Costs [$]*
Module direct costs	90,930
Balance of system equipment	5,547
Installation cost	2,534
Installer margin and overhead	5,479
Total	**1, 044, 905**

TABLE II: OPERATIONS AND MANAGEMENT COSTS FOR YEAR 1

O&M	*Costs [$]*
Wages for four workers	51,200
Wages for one supervisor	16,000
Detergent	960
Water flow	2,880
Maintenance	600
Miscellaneous	1,920
Total	**73,560**

expensive, coming at an average of ~$80 per meter of duct extensions, with an additional ~$76 per meter on material costs.

VII. RESULTS AND DISCUSSION

A. General Observations and Patterns

Results display major dependence of energy output on weather patterns, elevation, and seasonality. Although solar irradiation generally follows a bell curve symmetry throughout the year in most locations, this pattern almost demolishes in power production curves, as seen in figure 3. A similar symmetry follows for temperature levels, and dust storm season tends to correspond with the summer. Saudi Arabia's climate conditions result in enormous potential solar energy losses in its sunniest months.

Another observation is that different locations exhibit different solar capacities despite their relative spatial proximity. The city of Abha (having the highest elevation of all cities) yields a total of 15.47 MWh over the year, while Jeddah, a coastal humid city, yields 8.67 MWh, about 54% of Abha's total energy production. It is to be noted that the AOD data for the years corresponding to the KACST-NREL solar irradiance data used in the model, was available for Riyadh city. This analysis could (and most likely will) yield different results as more reliable data becomes available. Nonetheless, the model provides accurate results for Riyadh, and bears the flexibility of expanding as more accurate data becomes available for the rest of the cities and for more recent time periods.

B. Model Validation

To validate the model, the results were compared with those obtained from the European Solar Test Installation's (ESTI) Photovoltaic Geographical Information System (PVGIS). Using Riyadh's latitude and longitude (24.91 and 46.41,

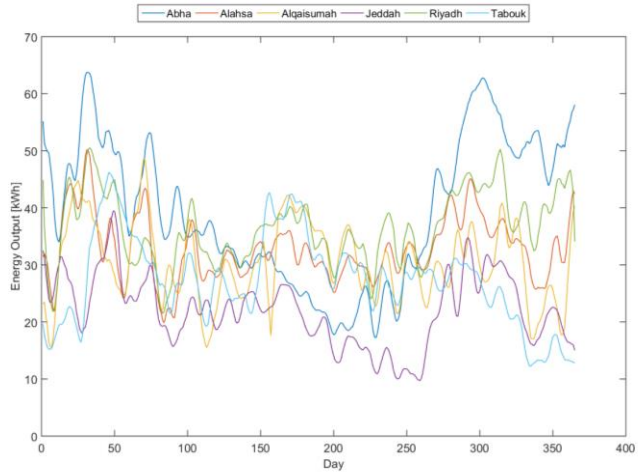

Figure 3: Daily changes in energy production for each of the six Saudi cities.

respectively) and the same initializations as those used in the PV model presented in this paper, the PV Estimation calculations result in a 58.3 kWh average daily and a 1770 kWh average monthly electricity production. The model presented here gave a total of 45.7 kWh average daily, and 1391 kWh average monthly, energy production for the same coordinates. The PVGIS calculations may not take into account the effect of dust, as the numbers of this model under the no-dust scenario result in more comparable numbers (55.6 kWh average daily and 1691 average monthly).

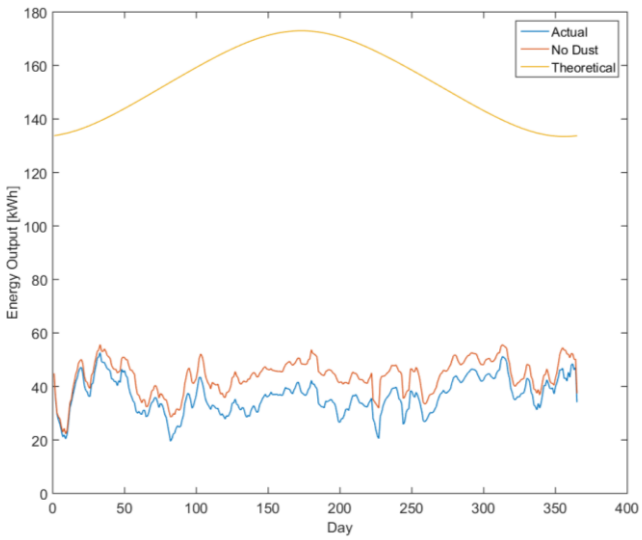

Figure 4: Three scenarios for Riyadh: actual power production, a no-dust scenario, and a theoretical power potential.

C. *Theoretical Potential of Power Output and Effect of Dust*

Figure 4 shows the energy output for Riyadh under three scenarios: actual energy production, a hypothetical scenario neglecting the effect of dust, and the potential energy production under STC conditions for daylight hours. The total energy production over a year under the 'no-dust' scenario comes down to 17.33 MWh, and 'actual' scenario to 14.42 MWh – a decrease of 16.79%. In the field of solar energy where developers yearn for the slightest increase in efficiency, a substantial amount of potential solar energy is lost due to atmospheric externalities. Power production under a no-dust scenario would be 28.8%, and actual energy production is 24.1%, of the potential theoretical limit.

D. *Impact of Dust Mitigation Technologies on Performance*

Since the performance of dust mitigation technologies depends on climate conditions, and was modelled as such, their resultant impact on solar module performance is location-dependent. Table 3 shows the percentage change in annual energy output for each of the cities employing the different dust-mitigation technologies. The two cities with the largest disparity in percentage employing different technologies, Alahsa and Jeddah, are highlighted. The model shows that applying EDS to solar modules in Alahsa would yield a 17.32% increase in annual energy production, while applying it to modules in Jeddah would increase energy production by 6.61%. The highest increase, 18.23%, would occur in Tabouk. Inversely, applying nano-coatings to solar modules would increase annual energy production by 16.75% in Jeddah and 5.97% only in Alahsa.

Figures 5 and 6 demonstrate the difference in performance employing each of the dust-mitigation technologies for Alahsa and Jeddah, respectively. The increase in potential power output varies for cities with different climates. In Jeddah, where the annual average humidity level for the 1998-2002 period of the datasets is 61.15% (with a 78.19% high in September), nano-coatings perform best. The technology works in Jeddah's favor, as the super-hydrophobicity increases the efficiency of water dispersion in the cleaning process, and the self-cleaning properties help the panels capitalize on the humid climate. In Alahsa, where the average humidity is 25.58%, no-coatings perform worst in increasing power production in comparison

TABLE III: THE PERCENTAGE INCREASE OF TOTAL ANNUAL ENERGY PRODUCTION FOR EACH CITY & DUST-MITIGATION TECHNOLOGY IN %. THE TWO HIGHLIGHTED CITIES HAVE THE LARGEST DISPARITY IN PERFROMANCE CHANGE EMPLOYING DIFFERENT TECHNOLOGIES (AND THEY HAPEEN TO BE BETWEEN EDS AND NANO-COATINGS FOR BOTH ALASHA AND JEDDAH).

City	Dust-Mitigation Technology		
	EDS	***Nano-coatings***	***Air-blowing***
Abha	11.8	11.5	6.3
Alahsa	17.3	6.0	10.2
Alqaisumah	14.9	9.1	9.9
Jeddah	6.6	16.8	9.2
Riyadh	16.1	8.0	9.9
Tabouk	18.3	7.1	9.2

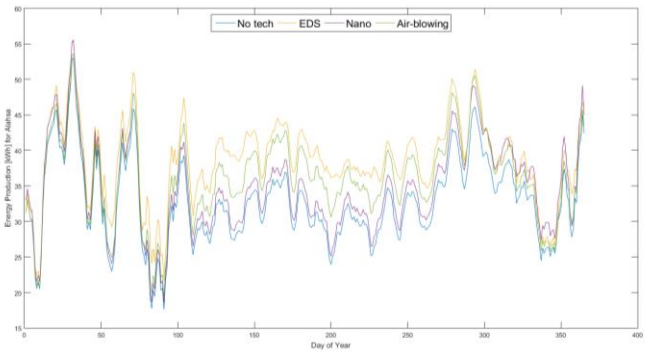

Figure 5: Impact of dust mitigation technologies on energy output for Alahsa

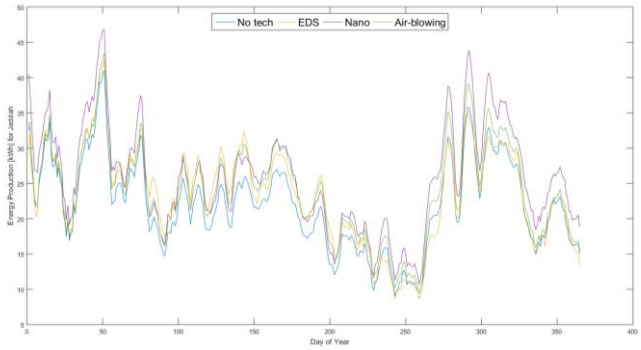

Figure 6: Impact of dust mitigation technologies on energy output for Jeddah

with the rest of technologies. Inversely, EDS has the least increase in Jeddah. Geared more towards dusty and dry climates, EDS is not designed for humid areas and thus has a smaller increase in power output for Jeddah. The technology will fail to achieve its self-cleaning function, and will decrease the solar module efficiency due to the high band gap of TiO_2 used for electro-conductivity.

E. *Financial Results*

Table 4 displays all results of localized costs of energy for all regions and technologies generated using the model. The LCOE differs for the different cities significantly. Abha, producing the most energy over a year has the lowest base (no dust-mitigation technologies applied) LCOE of 0.2760 $/kWh. This is 44% lower than the LCOE in Jeddah, which has the least potential for energy production. This shows that in the field of solar energy, higher efficiencies and optimal conditions for solar energy offset costs of solar modules.

Overall, the LCOE correlates with change in performance. The locations that yield the highest increase in performance, or energy output over a year, also have the lowest LCOE. While the dust-mitigation technologies may increase capital and/or operations and management costs, the resultant energy increase offsets the increases in cost, and lower the overall LCOE. In Alahsa for instance, EDS increases annual energy production by 17.3%, highest of all dust-mitigation technologies, decreasing total LCOE by 8.8% than using traditional cleaning methods (the no-technology case). Similarly, the highest energy output increase for Jeddah is with employing superhydrophobic

TABLE IV: LCOE FOR ALL REGIONS AND TECHNOLOGIES IN $/KWH.

City	Dust-Mitigation Technology			
	No technology	*EDS*	*Nano-coatings*	*Air-blowing*
Abha	0.2760	0.2644	0.2559	0.2832
Alahsa	0.3293	0.3002	0.3208	0.3254
Alqaisumah	0.3544	0.3299	0.3355	0.3254
Jeddah	0.4942	0.4940	0.4353	0.4911
Riyadh	0.2962	0.2729	0.2830	0.2937
Tabouk	0.3974	0.3594	0.3831	0.3965

nano-coatings, which decreases total LCOE by 11.6%.

The financial analysis carried by the model is relatively simplistic, and used mainly as a measure to compare the various technologies than to assign a monetary value to the investment and produced energy costs of employing the dust-mitigation technologies. However, the metric is useful in verifying the performance analysis, given the comparability of technology costs and the correlation of their implementation between cost and performance. Additionally, a more complex financial analysis could take into account the reductions in cost if environmental considerations were to be factored into the analysis.

VIII. CONCLUSION

A model was developed to compare three promising dust-mitigation technologies for solar PV, and was tested using Saudi Arabian datasets for six locations across the country. The model looks at changes in performance and total energy output of PV modules applying the technologies, and shows substantial dependence of their impact on local climate and topology. The model also calculates the LCOE for the different technologies as an objective metric for comparison, balancing energy output with technology cots. It shows that increases in total energy output correlate with decreased LCOE, indicating that the increase in energy output outweighs the increased initial investment costs of the technologies. Self-cleaning dust-mitigation technologies are worthwhile investments for optimizing solar PV technologies in locations poses a serious problem. This model is useful in estimating potential increases in energy production applying each of the dust-mitigation technologies, and using its outputs as indicators for matching the technologies with specified locations.

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