A Framework to Reduce Dust Problems on PV Modules in the US Climatic Zones

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Abstract

The peak of energy demand, oil prices, and impending climate change are critically driving the adoption of solar photovoltaic (PV) as a sustainable, renewable and less impact energy alternative. The installation of PV systems for optimum yield is primarily dictated by its geographic location (latitude and available solar insolation), and installation design (tilt angle, orientation, and altitude) to maximize solar exposure. Once these parameters have been addressed appropriately, there are other externalities that contribute to the system performance (efficiency and output). Dust is a major factor that significantly influences the performance of the PV systems. Although substantial time and money have been invested in PV systems to increase efficiency, a far less time and money have been invested to address dust deposition on such systems.

This paper provides an overview of soiling problems; primarily those associated with dust or sand and combined dust-moisture conditions that are associated with many of the most solar-rich geographic locations in the United States. It reviews and evaluates key contributions to the understanding, performance effects, and mitigation of these problems. More specifically, the paper reviews the impact of dust deposition on the performance of solar PV and identifies challenges to further research in this area. It highlights the status of research over seven decades of effort. Based on the research studies, the research outcome presents recommendations to guide in identifying the appropriate cleaning/maintenance cycle for PV systems. This is aligned with the prevalent climatic and environmental conditions in the United States' climatic zones based on ASHRAE classification.

Keywords: Photovoltaics (PV), Performance, Dust Impact, PV Cleaning, ASHRAE US Climatic Zones.

1. Introduction

The delivery of a solar-energy system is generally associated with the sun's availability, irradiance, as well as a variety of environmental and climatic factors and component performance. Soiling represents a problem that can be an obstacle for the viability of a solar installation. The deposition of dust, bird droppings, salty water stains can degrade the efficiency of the solar PV. Moreover, it is further reduced through losses in wiring, inverters by 10-25% due to these conditions (Denholm et al., 2010)

Research has been ongoing on this subject for more than seven decades. Yet, the impact and properties of dust on energy transfer and efficiency of PV is still not fully comprehended. Till today, the most effective mitigation technique is basically washing the PV surface with water or with some specialty solutions/detergents. This method is labor and water consuming as well, it has high operating cost. In most cases in the U.S. and abroad, the abundant solar regions are usually contingent with water scarcity which makes wet cleaning not an optimum mitigation approach.

Research has aimed to study the dust deposition primarily in the context of solar PV installations. Based on the nature of investigation into the impact of dust on PV system performance, the research can be categorized into the two main topics. First, the wind effects/directions and exposure time studies, primarily investigate solar system characteristics such as tilt angle, glazing, and its impact of dust accumulation. Second, are the

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more comprehensive studies on dust particles physics and chemistry with deeper accuracy in experimental investigations.

2. Dust impact on performance: wind effects, exposure time, and tilt angle

The first studies on the effects of dust accumulation on the performance of solar collectors were conducted in the United States. Dietz (1963) tested glass samples (between 0º and 50º) and showed a reduction up to 5% of the solar radiation reaching the collector due to dust accumulation. Michalsky (1988) ran a study in Albany, NY that compared the performance of 2 pyranometers of which one was cleaned daily and the other was left un-cleaned for 2 months. The un-cleaned showed less than 1% reduction in performance. The results of these studies could not be generalized, except for these regions in the U.S. that have frequent rain and low dust. However, the industry accepted results as typical for the U.S and stopped the development till the energy crisis in early 1970s. During this period, technology and research has advanced in other critical areas where dust is more significant factor. These areas are Middle East, North Africa (MENA) and Asia as well, where desert, wind, and dusty environment are significant. Studies in these dusty areas have shown that few hours of exposure to dust can cause the same reduction in PV performance over months in more temperate areas like Northeast of U.S.

Among studies in this region, Sayigh (1978) conducted a study in Saudi Arabia and found a performance reduction of 30% in flat plate collectors after only 3 days without wiping/cleaning. Another study by Sayigh et al. (1985) conducted more comprehensive experiments examining the reduction in transmittance vs. tilt angle in Kuwait desert. They found a reduction in plate-transmittance by an amount ranging from 64% to 17% for tilt angles ranging from 0º to 60º, respectively after 38 days of exposure. In addition, a reduction of 30% in useful energy gain was observed by the horizontal collector after 3 days of dust accumulation (Fig.1).

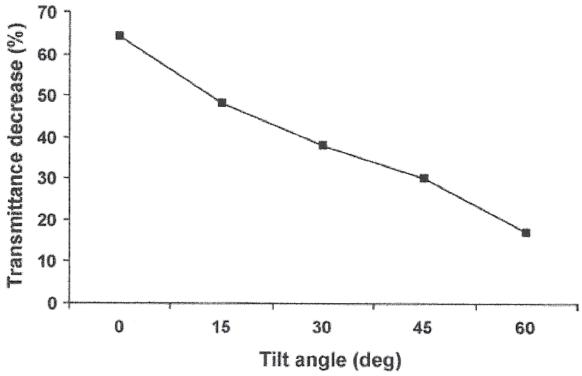

Fig. 1: Reduction in Solar Intensity for Various Particle Size Due to Dust Deposition (5)

3. Dust physical and chemical properties vs. PV performance

A critical factor to develop effective dust mitigation techniques is to understand the relationship between the physical properties of dust (size, geometry) and its chemistry (carbon, cement, limestone, etc) on performance of PV modules. This physical nature and deposition patterns vary by regions of the world. Not until early 1990s when this relationship was recognized, and research validated.

El-Shobokshy and Hussein (1993a, 1993b) investigated the physical properties of the dust accumulation and deposition density on their impact on parameters degrading PV efficiency. The experiment was entirely simulated with artificial dust (including limestone, cement, and carbon particulates) and halogen lamps. While keeping the solar (light) intensity constant and varying the different densities of dust the test was repeated several times. The study revealed the impact of cement particles to be the most significant, with a 73 g/m^2 deposition of cement dust resulting in an 80% drop in PV short-circuit voltage; atmospheric dust with mean diameter 80 mm at 250 g/m^2 was found to reduce the short-circuit current by 82%. Fine carbon particulates (5 mm) were found to have the most deteriorating effect on the PV efficiency. The study also found the impact of finer particles to have a greater impact than coarser particles on PV performance (Fig. 2), for the same dust type. In addition, while the PV fill-factor reduced with excessive dust accumulation, it was found to respond to increase in solar intensity for both cleaned and un-cleaned conditions.

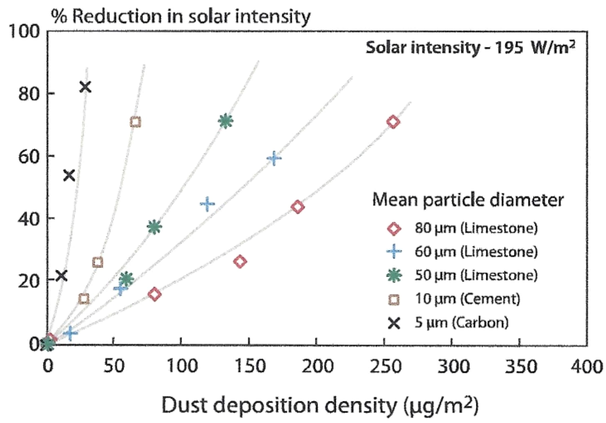

Fig. 2: Reduction in Solar Intensity for Various Particle Size Due to Dust Deposition (8,9)

Mailuha et al. (1994) conducted an evaluation on solar energy use in Kenya. Their PV module-based study focused on the impact of dust layer density, tilt angle, and solar intensity. They concluded that as solar intensity increased, PV performance due to dust accumulation decreased. As shown in Fig. 3, at 700 W/m^2, the reduction in output was almost negligible. However, when solar intensity dropped to 400 W/m^2, the loss was near 25% of initial power output (Fig. 3).

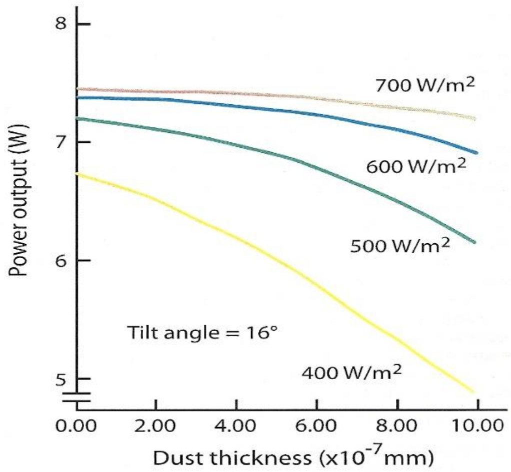

Fig. 3: Power Degradation of a PV Module for Various Intensities as a Function of Dust Thickness (10)

Hassan et al. (2005) studied the effect of airborne dust concentration on PV performance. They observed a decrease in efficiency from 33.5% to 65.8% for an exposure of 1-6 months, respectively. The study concluded that the degradation progress is dominant and proceeds rapidly during the initial 30 days of exposure to dust.

The experimental investigation conducted by Elminir et al. (2006) at the National Research Institute of Astronomy and Geophysics, Cairo, Egypt, experimented 100 glass plates with different tilt and azimuth angles. The glass transmittance was evaluated at regular intervals over a 7-month period for the prevalent wind conditions, including thunderstorms. The study revealed a reduction in dust deposition from 15.84 g/m2 (for a 0º tilt) to 4.48 g/m2 (for a 90º tilt) and a corresponding increase in transmittance from 12.33% to 52.54%. A governing equation between the dust deposition and reduction in transmittance was also derived. A critical observation revealed that differences in humidity led to the formation of dew on the PV surface which coagulated dust. Weekly cleaning cycle was recommended for moderately dusty places (Fig. 4)

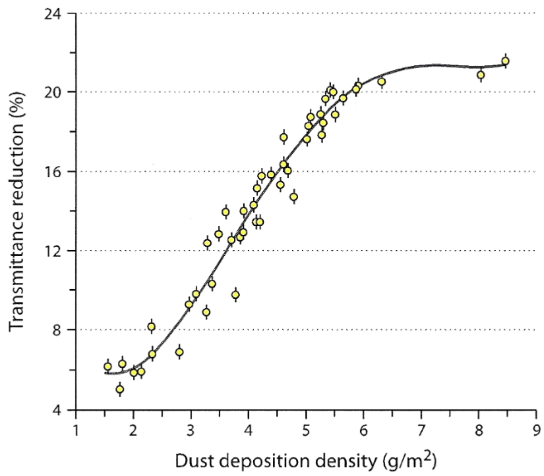

Fig. 4: Solar Transmittance Reduction as a Function of Dust Deposition Density (13)

Another study on dust physics and chemistry is conducted by Biryukov (1996) in the Negev desert. It evaluates particle size distribution using various microscopic techniques. A relationship was found between deposition rate, tilt angle, PV performance, and particle size. The study found that 90% of dust particle diameter ranges between 5 and 60 micron. The highest deposition rate per square centimeter per hour is found in particles that range between 15 and 25 micron. This supports the bigger the size, the slower the deposition rates in desert areas (Fig. 5).

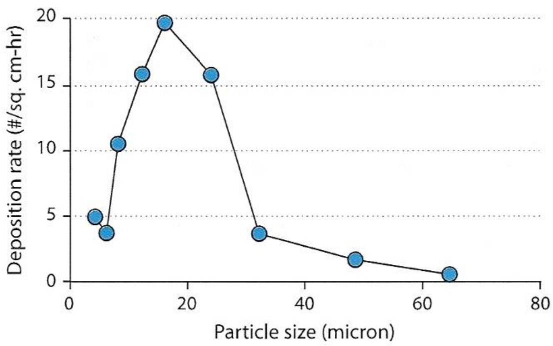

Fig. 5: Particle Size as a Function of Deposition Rate of a Solar Collector in the Desert Area.

4. United States climatic zones: ASHRAE classification

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is an American professional association seeking to advance heating, ventilation, air conditioning and refrigeration (HVAC) systems design and construction. ASHRAE has more than 57,000 members in more than 132 countries worldwide. Its members consist of building services engineers, professors, architects, mechanical contractors, equipment manufacturers' employees, and others concerned with the design and construction of HVAC systems in buildings. The society funds research projects, offers continuing education programs, and develops and publishes technical standards to improve building services engineering, energy efficiency, indoor air quality, and sustainable development (2020, Jun 1). ASHRAE has some 87 active standards and guideline project committees, addressing broad areas as indoor air quality, thermal comfort, energy conservation in buildings, reducing refrigerant emissions, and the designation and safety classification of refrigerants.

ASHRAE climate zones (2013) for the United States (Fig. 6) represents the most familiar classification for architects, builders, engineers in the U.S. It uses numbers (0-8) and 3 letter system (A, B, C) to define U.S. climate zones. The first number represents a location's main climate type (temperature data): 1: Very Hot, 2: Hot, 3: Warm, 4: Mixed, 5: Cool, 6: Cold, 7: Very Cold, 8: Subarctic/Arctic. A second letter assigned to the weather zone based on precipitation: A: Humid, B: Dry, C: Marine. The United States has 8 of the 9 defined ASHRAE climate zones. Zones 0A, 0B, and 1B do not exist in the U.S. climate zones.

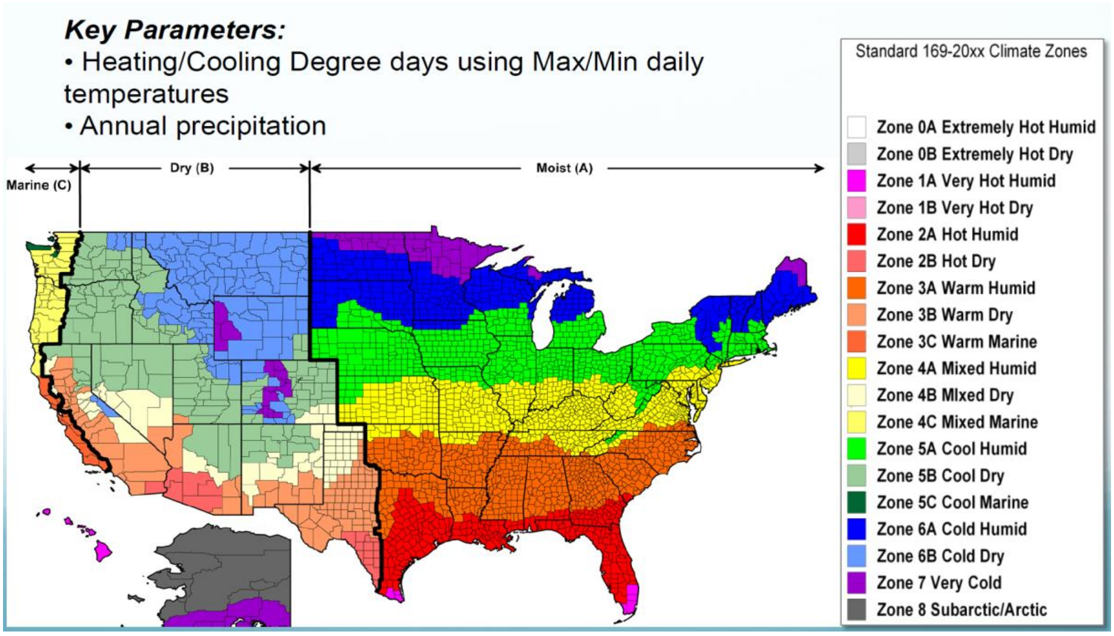

Fig. 6: ASHRAE climate zones of the United States

5. Dust reduction recommendations for U.S. climatic zones

The highest solar energy in the U.S. is located in the dry regions 2B, 3B, 4B, and southern part of zone 5B (NREL, 2018). These represent most of the southwest and west of the U.S. where solar energy exceeds 2000 kWh/m^2/year. Dust deposition is a concern in these areas to utilize this high energy output. Therefore, most research focus on such climatic zones.

Based on the literature research provided earlier, Table 1 provides a basic guide to reduce dust deposition for U.S. climatic zones. It lists the characteristics of the weather in each zone and states that represent that zone (column 2). It provides the conditions that affect the PV installations in these specific zones (column 3), and recommendations for dust reduction as a rule of thumb for such zones (column 4). Nevertheless, dust deposition and soiling of PV modules remains a problem in search for better alternatives especially in the desert and arid climate in the U.S. and the world. These areas combine the best solar energy potential that unfortunately come with the worst dust accumulation conditions.

Table 1: Dust Reduction Recommendations for U.S. Climatic Zones

Climate Zone	Characteristics Location within the U.S.	Conditions Affecting PV Performance and Dust Deposition.	Cleaning Frequency Framework
1-A VERY HOT HUMID (TROPICAL)	Tropical climate: without frost, coolest month is warmer than 65ºF (18ºC) e.g. Extreme Southern FL, FL Keys, West Palm Beach area, Miami	Mostly low latitudes and require low tilt in PV systems to maximize energy Lower tilt angles tend to accumulate more dust deposition, therefore, tilt PV modules higher than latitude is recommended to reduce dust accumulation High annual rainfall minimizes dust accumulation	- Periodic washing by continuous annual precipitation reduces dust accumulation - Cleaning is recommended of a weekly/biweekly basis during dry season - Frequency depends on intensity of dust accumulation
2-A HOT-HUMID Warm winter	Wet- tropical: without frost, coolest month is warmer than 65ºF (18ºC) e.g. FL, Southern of GA, AL, MS, LA, SE of TX	Mostly low latitudes and require low tilt in PV systems to maximize solar energy PV systems with higher tilt angle are recommended in subtropical areas to reduce dust accumulation Utilize wind during the dry season to blow dust from the panels.	- Periodic washing by continuous annual precipitation reduces dust accumulation - Cleaning is recommended weekly for moderate dust accumulation in the dry season.
2-B HOT-DRY (ARID) Desert Mild/warm winter	Arid climate: evaporation exceeds precipitation Arid (desert): minimal annual rainfall Many regions: SW of TX, Southern AZ	Dusty desert environments and frequent dust storms reduces PV efficiency Low humidity and rainfall contribute to the problem High temperature reduces PV performance Has the max available, and intense solar radiation than any other regions	- Cleaning to respond to intensity of dust accumulation-at least a weekly cleaning is recommended - Immediate cleaning following dust storms is required - Application of dust-repelling coatings is highly recommended as preventative approach
3-A WARM-HUMID Mild/warm winter	Wet- semi-tropical: without frost, coolest month is warmer than 50ºF (10ºC) e.g. NC, SC, GA, AL, MS, LA, AR, OK	Mostly low latitudes and require low tilt in PV systems to maximize solar energy PV systems with higher tilt angle are recommended in subtropical areas to reduce dust accumulation Utilize wind during the dry season to blow dust from the panels.	- Periodic washing by continuous annual precipitation reduces dust accumulation - Cleaning is recommended weekly for moderate dust accumulation in the dry season.
3-B WARM- DRY Tundra (Savannah) Semi Desert Cool winter	Arid climate: evaporation exceeds precipitation Semi-arid (steppe): low annual rainfall Many regions: West TX, Parts of AZ, Southern and middle CA (away from ocean)	High latitudes require high tilt angle in PV system; a lower fixed tilt angle is recommended to optimize year-round solar gain Dust generally tends to fall off with an increased tilt angle Areas with higher rainfall would aid in cleaning the PV panels	- With low rainfall and high tilt angle, a moderate frequency cleaning cycle (weekly) is recommended - More frequent cleaning cycle is recommended with lower tilt angle (to maximize solar gain) - A less intense (weekly or biweekly) cleaning cycle is adequate for above 40^{o} N
4-A MIXED-HUMID (TEMPERATE-HUMID) humid, no dry season warm summer cool winter	Temperate, subtropical climate: 8 months or more of average warmer than 50ºF(10ºC), rainfall all year MD, DE, VA, WV, KY, MO, KS.	A lower fixed tilt angle is recommended to optimize year-round solar gain in temperate areas. High latitudes require high tilt angle Dust generally not a problem unless combined with heavy moisture Heavy rainfall aids in cleaning the PV panels	- The least intense cleaning required- a monthly or bi-weekly cleaning cycle is adequate - Intense rainfall washes off the dust from the panels and maximize benefits of nature
4-B MIXED-DRY (TEMPERATE-DRY) tundra/dry warm summer cool winter	Temperate, subtropical climate: 8 months or more of average warmer than 50ºF(10ºC), Dry summer (Mediterranean) Northern TX, NM	High latitudes require high tilt in PV system; a lower fixed tilt angle is recommended to optimize year-round solar gain Dust generally tends to fall off with the increase in the tilt angle	- Recommended cleaning weekly or bi-weekly depending upon the rate of dust accumulation on the surface. - Regions with higher dust accumulation may need a daily cleaning
5-A COOL-HUMID 6-A / 7-A COLD/VERY COLD-HUMID humid, no dry season mild summer cool summer	Cool to Cold, temperate, moist, and forest: 4-8 months of average warmer than 50ºF (10ºC), rainfall all year **5-A**: PA, OH, MI, IL, IA, NE **6-A**: ME, NH, VT, WI, MN, ND, SD	Dust is less critical factor in comparison to maximizing solar gain in these regions Sun movable tracking may be needed to harness solar energy Colder temperature improves PV performance Dust generally tends to fall off at near-vertical tilt angles	- Weekly cleaning cycle is adequate - A less intense biweekly cleaning cycle is adequate for above 40^{o} N - Intense rainfall washes off the dust from the panels and maximize benefits of nature - Removing snow accumulation needs to be frequent and immediate after snowstorms
5-B COOL-DRY 6-B VERY COLD-DRY mild summer cool summer	Cool to cold, mountain climate, changes rapidly, has same seasons of wet and dry periods of the immediate surrounding climate. e.g. Higher latitudes. 5-B: CO, UT, ID 6-B: MT, WY	High latitudes require high tilt angle closer to vertical Sun movable tracking may be needed to harness solar energy Colder temperature reduces PV cells heat and improves performance Dust generally tends to fall off at near-vertical tilt angle	- Weekly cleaning frequency is adequate - Removing snow accumulation needs to be frequent and immediate after snowstorms

6. How to clean and prevent dust

In areas of low-soiling conditions and/or periodic rain in the U.S., dust represents no major problem. Naturally, rain, or snow, would clean the surfaces periodically. This is valid in most of the United States except the south-western regions where some other cleaning methods would take place. In areas of high moisture and heavy morning dews, performance is affected by compounding the dust problem. Light rain can collect particles and form a residue that stick to the collectors. This requires continuous cleaning and wash off the PV surface. These specific 2 cases (desert, heavy dew) require more advanced technology such as automated cleaning devices and robots to mitigate dust and keep the PV at its best efficiency performance.

In some instances, nature can be the most effective and least costly solution for dust problems in zone 3C and 4C of Pacific coast marine climate on the map (Fig. 6), where heavy rain washes off any dust deposition. Sandia National Labs and the solar thermal industry were among the first to develop mitigation techniques for dust and soiling problems in the United States

7. Conclusion

This paper reviewed the research development, challenges relating to the dust deposition on PV installations. It provides analysis on the environmental impact (wind, exposure) on dust deposition, and the dust particle analysis (physical and chemical properties) and how it affects PV performance. It analyzes United States climatic zones based on ASHRAE classification and discusses the characteristics of each zone. It provides conditions affecting PV performance and dust deposition for each zone (Table 1). It highlights the problems associated with desert climate in regions like the southwest of the U.S. (2B, 3B, 4B, and southern part of zone 5B on the map). These areas have growing potential in interest and investment but need to mitigate the dust accumulation problems associated with it. The paper finally provides a framework of recommendations for cleaning PV modules in each of the U.S. climatic zones based on variations of weather and precipitation conditions pertinent to each zone.

8. References

ASHRAE, 2020. https://en.wikipedia.org/wiki/ASHRAE, accessed June 1, 2020

ASHRAE 169-2013, Climatic data for building design standards, www.ashrae.org, accessed Jun 1, 2020.

Biryukov S., 1996. Degradation of optical properties of solar collectors due to the ambient dust deposition as a function of particle size. Journal of Aerosol Science: 27: p 37–8.

Denholm P, Drury E, Margolis R, Mehos M., 2010. Solar energy: the largest energy resource. In: Sioshansi FP, editor. Generating electricity in a carbon-constrained world. California: Academic Press, p. 271-302.

Dietz A., 1963. Diathermanous materials and properties of surfaces. In: Zarem A, Erway D, editors. Introduction to the Utilization of Solar Energy. New York: McGraw-Hill; p. 59–86.

Elminir H, Ghitas A, Hamid R, El-Hussainy F, Beheary M, Abdel- Moneim K., 2006. Effect of dust on the transparent cover of solar collectors. Energy Conservation and Management 2006; 47:3192-203.

El-Shobokshy M., Hussein F., 1993a. Degradation of photovoltaic cell performance due to dust deposition on its surface. Renewable Energy 1993; 3:585–90.

El-Shobokshy M., Hussein F., 1993b. Effect of dust with different physical proper- ties on the performance of photovoltaic cells. Solar Energy 1993; 51:505–11.

Hassan, A., Rahoma, U., Elminir, H., Fathy, A., 2005. Effect of airborne dust concentration on the performance of PV modules. Journal of the Astronomical Society of Egypt, 2005; 13 (1), 24–38.

Mailuha J., Murase H., Inoti I., 1994. Knowledge engineering-based studies on solar energy utilization in Kenya. Agriculture Mechanization in Asia, Africa, and Latin America 1994; 25:13–6.
McKnight, Tom L; Hess, Darrel, 2000. "Climate Zones and Types". *Physical Geography: A Landscape Appreciation*. Upper Saddle River, NJ: Prentice Hall.

Michalsky J, Perez R, Stewart R, LeBaron B, Harrison L., 1988. Design and development of a rotating shadow band radiometer solar radiation/daylight network. Solar Energy 1988; 41:577–81.

National Renewable Energy Lab (NREL), 2018. Solar Resource Data, Tools, and Maps. https://www.nrel.gov/gis/solar.html, accessed Jun 1, 2020.

Sarver et al., 2013. A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches. Renewable and Sustainable Energy Reviews 2013 (22): 698-733.

Sayigh A., Al-Jandal S., Ahmed H., 1985. Dust effect on solar flat surfaces devices in Kuwait. In: Proceedings of the international symposium on thermal application of solar energy. Hakone, Japan ; 1985. p. 95–100; Furlan C, Mancin N, Sayigh A, Seraphin B, editors. Proceedings of workshop on the physics of non-conventional energy sources and materials science. ICTP, Trieste, Italy. 1985. p. 353–67.

Sayigh A., 1978. Effect of dust on flat plate collectors. Sun, mankind’s future source of energy. In: Proceedings of the international solar energy society congress; 1978. p. 960–4.