Sand and Dust Storms Impact on Photovoltaic Panels in Saudi Arabia

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Abstract:

This research aims to assess the spatial potential of solar energy in Saudi Arabia by estimating the total sum and analyzing the spatial variability of solar radiation to determine the best sites for solar energy generation that are least affected by sandstorms in the country. It also explores the effects of sandstorms on solar panels, identifies preventive measures, analyzes their impact on productivity, and recommends best practices for future development. The study utilizes time series analysis to estimate the impact of dust on productivity and identify effective ways to mitigate it. The spatial suitability of solar cell placement in different regions of the country is also analyzed. The study reveals that the Al-Ahsa region is significantly affected by sandstorms, with an average of around 25 sandstorms annually, indicating the region's vulnerability to these environmental phenomena. The western region, specifically the Tabuk station, experiences a lower frequency of about 5.5 sandstorms per year. The Al-Ahsa region shows the highest daily average rate of sandstorms, ranging from 0.4 to 0.7 sandstorms per day, with the highest rates occurring from March to May. In terms of solar energy potential, the northwestern region in Tabuk exhibits the highest average potential of about 6 watts per square meter per day, followed by the southwestern region in Asir with approximately 5.5 watts per square meter per day.

These findings provide valuable insights into understanding sandstorm patterns and identifying optimal locations for solar energy production, contributing to sustainable development efforts and climate change mitigation.

Keywords: Sand, Dust storms, Photovoltaic Panels, Solar panels, Saudi Arabia.

1. Introduction:

In today's rapidly evolving world and society, the imperative for transitioning to renewable energy and sustainable practices has never been more pressing. The global population continues to grow alongside with the demand for energy. It becomes quite evident that the reliance on fossil fuels and unsustainable practices is not only depleting finite resources but also inflicting severe environmental issues. Embracing renewable energy sources, such as solar, wind, hydro, and geothermal power, holds the key to mitigating climate change, securing a greener future, and preserving the delicate balance of our planet for generations to come. The growing interest in transitioning towards sustainable and renewable energy sources is driven by environmental challenges, climate change, and the need to reduce reliance on fossil fuels (IRENA, IEA, 2021). Renewable energy is considered an environmentally friendly and sustainable alternative to traditional energy sources, relying on renewable sources such as solar, wind, water, and biomass (IEA, 2022). Renewable energy technologies generate electricity and meet energy needs in clean and sustainable ways. Reports indicate that renewable energy could account for a significant portion of global electricity production by 2050 (IRENA, 2022). It is important to continue supporting research and development in this field and promoting policies and incentives that encourage the global adoption of renewable energy. The transition towards sustainable and renewable energy sources is necessary to address climate change, reduce pollution, and ensure a more sustainable and clean future (IRENA, 2023).

Solar energy is of utmost importance in the world due to its renewable and clean nature. It is derived from the sun, making it a sustainable and environmentally friendly solution. Solar power generation produces no greenhouse gas emissions or air pollutants, contributing to cleaner air and a healthier environment. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), solar energy plays a crucial role in mitigating climate change by reducing reliance on fossil fuels and lowering carbon dioxide (CO_2) emissions. The International Energy Agency (IEA, 2023) highlights the role of solar energy in promoting environmental and economic sustainability.

The International Renewable Energy Agency (IRENA, 2023) provides detailed analyses of the environmental and economic benefits of solar energy. The United Nations, through agencies like the United Nations Environment Programmed (UNEP, 2022), emphasizes the importance of solar energy in addressing climate change challenges and promoting sustainability. Solar energy offers energy independence, job creation, and economic growth opportunities (IPCC, 2021). It provides access to electricity for remote and underserved areas, improving living standards (IEA, 2020). Solar energy systems can be scaled up or down to meet various energy demands, and they offer long-term cost savings (IRENA, 2020). Embracing solar energy leads us towards a greener and more sustainable future. Here are some international studies that have addressed the topic of solar energy and photovoltaic panel cleaning methods, (Pravan et al., 2011) In a study focused on two 1-MW PV systems, the effects of soil type and washing technique on performance losses were examined. The results indicated that the presence of sandy soil contributed to a performance loss of 6.9%, whereas a more compact soil resulted in a lower loss of 1.1%. The study (Jiang et al., 2011) revealed that when a dust deposition layer ranging from 0 to 22 g/cm2 accumulated on the PV panels, there was a linear decrease in PV efficiency by 26%. Interestingly, the study did not find any significant difference in the effects of dust deposition on PV efficiency between different types of solar cells. In addition, the study (Zorrilla-Casanova et al., 2011) During dry seasons, the study observed that energy losses in PV systems exceeded 20% over 3-month periods. The annual average losses in PV output, even with natural cleaning by rain, were measured at 4.4%. To mitigate these losses, the study proposed implementing regular and periodic cleaning schedules for the PV modules. And, the study (Bethea et al., 1983) found that the reflectivity of PV panels is expected to decrease by 2.4% per year due to dust storm conditions. This decrease in reflectivity can significantly impact the overall performance and efficiency of the panels over time. Regular cleaning and maintenance are recommended to minimize the impact of dust storms and maintain optimal reflectivity levels. Furthermore, the study (Bowden et al., 1994) examined the effect of dust on the loss in internal reflectance of the CSP roof units and found that dust only affects the energy conversion to a small degree. The total losses attributed to dust were found to be less than 1.3%. This suggests that while dust can have some impact on the internal reflectance and energy conversion, it does not significantly hinder the overall performance of the CSP roof units. Also, the study (Kattakayam et al., 1996) The accumulation of dust and the increase in temperature of the panel can lead to a significant loss of power. Dust accumulation on the surface of the panel can block sunlight and reduce the amount of energy that can be converted into electricity.

Additionally, increased panel temperature can result in a decrease in the efficiency of the solar cells, leading to a further loss of power generation. Regular cleaning of the panels and implementing cooling measures can help mitigate these losses and maintain optimal power output.). Moreover, the study (Kobayashi et al., 2011) Changing the aspect ratio of the PV cell used for a PV module can result in a degradation of the output by 80% or less, with only 3% of spot dirt on the module area. This suggests that altering the aspect ratio of the PV cell has a significant impact on the module's performance, leading to a substantial decrease in power output. Additionally, the presence of even a small amount of spot dirt on the module area can further contribute to the degradation of output.

Solar energy is considered a crucial factor in reducing carbon emissions in Saudi Arabia. It represents a clean and renewable source of energy, contributing to environmental sustainability. By harnessing solar radiation to generate electricity, reliance on fossil fuels is reduced, thereby decreasing greenhouse gas emissions and environmental pollution. Solar power plants operate in a clean and emission-free manner, improving air quality and the overall environment. Furthermore, the use of solar energy promotes environmental sustainability by preserving natural resources and minimizing pollution. Additionally, solar energy can provide energy savings and cost reduction by installing solar power systems for local electricity generation, reducing dependence on the public grid (United Nations, 2021). This study (Hassan et al., 2005) observed reductions in efficiency of 33.5% after 1 month and 65.8% after 6 months. These reductions in efficiency indicate a significant decline in the performance of the PV system over time. Factors such as dust accumulation, environmental conditions, and aging of the panels can contribute to these efficiency losses. Regular maintenance, including cleaning and inspection, is important to mitigate these reductions and maintain optimal efficiency levels in the long term. Moreover, the study (El-Shobokshy and Hussein, 1993) found that the material, size, and deposition density of dust have a strong effect on the loss of output power in PV systems. Different types of dust, such as fine particles or larger debris, can have varying impacts on the performance of the panels. Additionally, the density of dust deposition, or the amount of dust accumulated on the panel surface, can significantly affect the power output. Therefore, it is crucial to consider the characteristics of dust and implement appropriate cleaning and maintenance practices to minimize the loss of output power in PV systems. Also, the study (Alamoud, 1993) found when exposed to the outside environment, the efficiency of PV modules can decrease by 5.73% to 19.8%, depending on the type of the module. This reduction in efficiency highlights the impact of external factors such as temperature variations, dust accumulation, shading, and other environmental conditions on the performance of PV modules. It is essential to select modules that are suitable for the specific environmental conditions and implement proper maintenance practices to minimize efficiency losses and maximize power generation. And, this study (El-Nashar, 1994) revealed that the monthly percentage decline in glass transmittance is seasonal, with a 10% decline in the summer and a 6% decline in the winter. This indicates that the transmittance of solar radiation through the glass surfaces of PV modules decreases during these seasons. Furthermore, the study found that leaving the collector without cleaning for one year resulted in a significant reduction of 70% in the collector's performance. This highlights the importance of regular cleaning and maintenance to prevent the accumulation of dirt, dust, and other contaminants on the collector surface, which can hinder the efficiency and overall performance of the system. In addition, the study (Hegazy, 2001) examined the impact of dust accumulation on the solar transmittance of vertical plates with a diameter of 1 mm. The loss in transmittance was found to be typically around 75-80% over a month's exposure. The study compared a calculated "dust factor" or correction factor to the observed reduction in transmittance, providing insights into the accuracy of the model used to estimate the effect of dust on solar transmittance. These findings highlight the significant impact of dust accumulation on the efficiency of solar panels and emphasize the importance of regular cleaning and maintenance to maintain optimal performance. Also, the study (Asl-Soleimani et al., 2001) air pollution, particularly in cities with high pollution levels like Tehran, can significantly reduce the energy output of solar modules by more than 60%. The presence of pollutants, such as particulate matter and smog, in the air can block and scatter sunlight, thus reducing the amount of solar radiation reaching the modules. This reduction in solar irradiance directly impacts the energy conversion capability of the modules, leading to a substantial decrease in energy output. To mitigate the negative effects of air pollution on solar energy generation, regular cleaning of the modules and implementing air pollution control measures are essential. Also, this study (Qasem et al., 2011) the study investigated the impact of dust densities on the performance of solar modules in both vertical and horizontal configurations. It was observed that higher dust densities negatively affected the performance of both configurations. However, the horizontal module configuration was found to have an increased risk of hotspots due to dust deposition. Hotspots are localized areas of increased temperature that can lead to reduced efficiency, decreased power output, and potential damage to the solar cells.

Therefore, regular cleaning and maintenance are crucial, especially for horizontal module configurations, to mitigate the risk of hotspots and maintain optimal performance. These findings emphasize the importance of proper maintenance practices in areas with high dust densities to ensure the long-term efficiency and reliability of solar modules. And, this study (Bajpai and Gupta, 1988) found that poor efficiency in solar systems can be attributed to the scattering of incoming radiation by dust particles. Dust accumulation on the surface of solar panels scatters and diffuses sunlight, reducing the amount of radiation that reaches the solar cells and resulting in decreased energy conversion efficiency. Regular cleaning and maintenance of solar panels are crucial to mitigate the impact of dust scattering and maximize the transmittance of sunlight for optimal energy conversion. Implementing protective measures like panel coatings or anti-soiling technologies can also help minimize the scattering effects of dust particles and improve overall system efficiency.

Dust storms pose a significant challenge to the efficiency and productivity of solar panels worldwide (Alghamdi et al., 2018; Al-Kaff & Alghamdi, 2019). This issue is particularly acute in the Saudi Arabia, where frequent dust storms can cause significant damage to solar panels and lead to decreased energy production (Al-Raddadi et al., 2019). The Saudi Arabia is particularly vulnerable to dust storms, which cause dust and dirt to accumulate on the surface of solar panels, obstructing solar radiation absorption and decreasing solar panel efficiency. Furthermore, dust storms can corrode and damage solar panels, necessitating expensive repair and replacement costs. Therefore, it is crucial to study the impact of dust storms on solar panels in the Saudi Arabia to identify the best methods and solutions to deal with this problem, improve the efficiency of solar panels, and increase electric energy production (Al-Raddadi et al., 2019).

Several studies have been conducted to examine the impact of dust on the performance of solar panels. (Li et al., 2019) discuss the research status and associated challenges in this field. They provide recommendations for enhancing the performance of solar panels in the presence of dust. Building upon this research, (Li et al., 2020) specifically investigate the effects of dust on PV modules. They analyze the optical and thermal impacts of dust on solar panel efficiency and offer an overview of research and strategies employed to mitigate this challenge. Furthermore, (Alghoul et al., 2020) provide a comprehensive view of the influence of dust on photovoltaic systems. Their study explores the electrical and thermal effects of dust on panel performance and offers a review of various techniques and measures used to minimize dust accumulation and its adverse effects on performance. Additionally, (Zhang et al., 2019) focus on the impact of dust deposition on the performance of photovoltaic panels. They analyze how dust affects light transmission and heat distribution in panels and present an overview of findings and recommendations to address this challenge. And, the study (Adanu, 1994) found that the presence of dust particles in the atmosphere has a detrimental effect on solar irradiance and the energy output of PV arrays. Dust particles scatter and absorb sunlight, reducing the amount of solar irradiance reaching the PV panels. Additionally, the accumulation of dust on the surface of the panels acts as a barrier, further reducing efficiency and energy output. Regular cleaning and maintenance of the PV panels are crucial to mitigate the negative impact of dust particles. By keeping the panels clean and free from dust accumulation, the solar irradiance can be maximized, leading to improved energy generation from the PV array. These practices are essential to maintain optimal efficiency and maximize the energy output of solar systems in areas prone to dust pollution. These studies collectively contribute to the understanding of the impact of dust on the productivity of photovoltaic panels and provide valuable insights into strategies for improving their performance in dusty environments.

The objectives of this study are to analyze the effects of dust storms on the efficiency and performance of solar panels in the Saudi Arabia, identify and evaluate the effectiveness of preventive measures to reduce the impact of dust storms on solar panels, investigate and analyze the effect of dust storms on the productivity of solar panels, and identify best practices for reducing the impact of dust storms on solar panels, as well as recommendations for future system development. Achieving these objectives will help to improve the efficiency of solar panels in the Saudi Arabia, reduce the negative impact of dust storms on the environment, and contribute to the country's strategic goals of providing clean and renewable energy while reducing harmful emissions to the environment. This study is critical for identifying the best methods and solutions to deal with the problem of dust accumulation on solar panels in the Saudi Arabia. Such research can provide valuable insights into the development of novel cleaning techniques and technologies tailored to the local conditions. High-quality research in this area can also inform policy decisions related to the adoption of renewable energy and contribute to the sustainable development of the Saudi Arabia.

2. Material and Methods:

Data:

The study utilized various sources of information, including reports requested from the King Abdullah City for Atomic and Renewable Energy including data about Direct Normal Irradiance (DNI)- kwh/ m^2/ day, Global Horizontal Irradiance (GHI)- kwh/ m^2/ day, Diffuse Horizontal Irradiance (DIH)- kwh/ m^2/ day, and efficiency kwh/ m^2/ day ((Fig. 1) show you the stations locations, and the National Center for Meteorology including data about dust storms events (Day), Horizontal Visibility (HV), pressure (kPa), mean temperature (C), Wind Speed (km/h), and relative humidity (%) (Fig. 2) show you the stations locations.

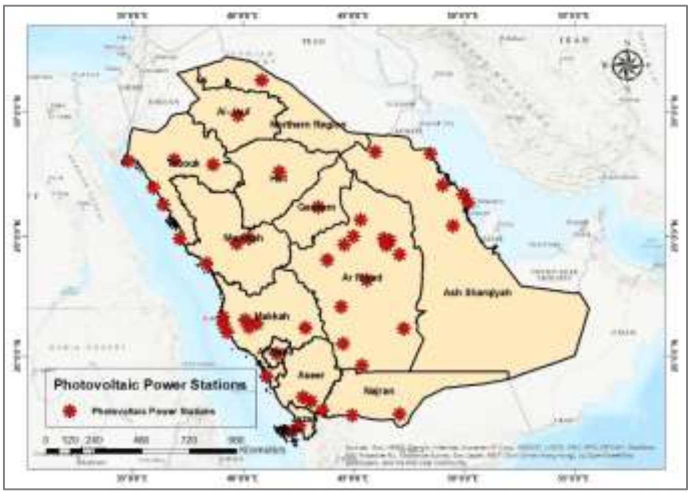

Figure 1. Map showing 49 the locations of solar stations around Saudi Arabia, the map applies to all years considered in this paper (2013-2022).

Figure 2. Map showing 26 the locations of Meteorological stations around Saudi Arabia, the map applies to all years considered in this paper (2013-2022).

Methodology:

The study employed time series to demonstrate the impact of the general trend of dust storms on the amount of photovoltaic panel productivity in the Saudi Arabia from 2013 to 2022. In the Saudi Arabia, estimate the amount of dust deposited on the surface of photovoltaic panels and its impact on productivity. Where the independent time variable (t) (study years 2013-2022) and its corresponding values are the dependent variable (Y) (the amount of electrical energy produced by photovoltaic panels), and each value in time (t) (study years 2013-2022) corresponds to the values of the dependent variable (Y) (the amount of electrical energy produced by photovoltaic panels), y is a function of time t.

In the application of time series, it relied on a number of phenomena affecting the amount of dust storms rising or falling on the productivity of photovoltaic panels, and it included 58 observations of the following phenomena: daily dust storms (DS), total horizontal radiation falling watts / day / hour / m^2 (GHI), direct vertical radiation watts/day/hour/m^2 (DNI), diffuse horizontal radiation watts/day/hour/m^2 (DHI), air temperature (AT), This time series runs from 2013 to 2022.

- The first stage involves testing the time series' stability using the Dickey and Fuller test (unit root test). If the test statistics are (Table-1), and it is discovered that: 0.365 2.36, as well as 0.825 2.36, then the presence of the unit root is accepted. The first differences filter is applied to the time series to make it stable.

Table 1. Summary of Dickey and Fuller test daily dust storms (DS), total horizontal radiation falling watts / day / hour / m^2 (GHI), direct vertical radiation watts/day/hour/m^2 (DNI), diffuse horizontal radiation watts/day/hour/m^2 (DHI), air temperature (AT), This time series runs from 2013 to 2022. The Dickey and Fuller test is a statistical test used to determine the presence of a unit root in a time series, which can indicate non-stationarity and the need for further analysis. The table presents the results of this test for each variable, indicating whether a unit root is present in the time series. This information is important for understanding the statistical properties of the data and for guiding further analysis of the meteorological variables over time.

Test	Module	T value	A= 0.05
D.F.	II	0.365	**2.36**
A.D.F.	II	0.825	**2.36**

- The second stage is to identify the appropriate model that represents the first differences by examining the ACF autocorrelation function for the first difference series, which leads to the MA (1) model being suggested. When the PACF partial autocorrelation function was examined, it suggested the AR model (1). When the two figures are considered, the (3,1,0) ARIMA model can be proposed.
- The third and fourth phases involve estimating the proposed models and confirming their applicability to the time series: Each of the three proposed models went through these two phases. And the models that are found to be valid for representing the time series because of the examination are compared in terms of predictive ability and the best one is chosen.

The amount of solar energy produced in the Saudi Arabia:

- To estimate the amount of solar radiation reaching the Earth's surface, several interconnected quantitative models that rely on measuring or estimating the angles of solar radiation based on the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) model that was used in the analysis of solar radiation measurements have been designed.
- The study's goal is to assess the spatial potential of solar energy in the Saudi Arabia by estimating the total and analyzing the spatial variations of solar radiation to determine which of these sites is the best for generating solar energy and is less affected by dust storms in the Saudi Arabia. In its collection and analysis, the study relied on data from King Abdullah City for Atomic and Renewable Energy and the Global Atlas of Solar Energy, where data from solar energy stations for the period 2013-2022 were entered after unifying the units measured in them, which are (watt / day / hour / m^2) so that the data is consistent. The data was entered into a geographic information system (GIS) to analyze and measure solar radiation. The process involved steps such as converting the data into point format, generalizing the data using interpolation, arranging the results into raster squares, classifying the results into levels, calculating the annual average radiation, and creating a final map of the solar radiation levels.

Development of Spatial Suitability Index for Photovoltaic Projects:

- The methodology used to develop the spatial suitability index for photovoltaic projects involved several steps to assess the energy production potential of different regions. The following paragraphs outline the key components of the methodology:

- Data Collection: Relevant data sources were compiled, including solar radiation data, geographical information, and surface terrain characteristics. Solar radiation data was obtained from meteorological stations, satellite imagery, or other reliable sources.
- Data Preprocessing: The collected data was processed to ensure consistency and compatibility. This involved standardizing units, removing outliers or erroneous data points, and conducting quality checks.
- Conversion to Point Format: The data was converted into a point format, where each data point represented a specific location within the study area. This was necessary to enable spatial analysis and interpolation techniques.
- Interpolation: Interpolation techniques, such as inverse distance weighting or kriging, were applied to generalize the data and estimate solar radiation values at locations where measurements were not available. This helped create a continuous surface of solar radiation distribution across the study area.
- Rasterization: The interpolated results were then arranged into raster squares or grids, where each grid cell represented a specific geographic area. This facilitated further analysis and classification.
- Classification: The rasterized data was classified into suitability categories based on energy production levels. These categories were determined by setting thresholds or ranges of solar radiation values associated with different energy production potentials.
- Suitability Index: A suitability index was developed by assigning numerical scores or weights to each suitability category. The scores were based on the energy production potential of a particular category, with higher scores indicating higher suitability for photovoltaic projects.
- Validation and Refinement: The suitability index was validated using independent data or ground truth measurements to assess its accuracy and reliability. If necessary, the index was refined or adjusted based on the validation results.

3. Results:

3.1. Dust storms affecting photovoltaic panel productivity:

Between 2011 and 2022, the Kingdom of Saudi Arabia experienced various dust storms across different regions, as measured by ground monitoring stations affiliated with the National Center of Meteorology. As shown in Figure 3, The data reveals that the eastern region of the Kingdom, which includes Al-Ahsa Governorate, is the most affected by dust storms, with an average of approximately 25 dust storms per year. The northern borders region, which includes Rafha and Arar stations, had an average of approximately 11 dust storms per year. The southern region, which includes Wadi Al-Dawasir, Sharurah, and Najran stations, had an average of approximately 9 dust storms per year. The average number of dust storms per year in the western region, which includes Makkah, Al-Madinah, and Tabuk stations, was approximately 5.5 dust storms. The graph provides useful information about the frequency of dust storms at the regional level in the Saudi Arabia, which can help inform decisions related to disaster management and planning.

Al-Ahsa Governorate was the most vulnerable region to dust storms during this period, recording approximately 30 dust storms in 2012, followed by 24 storms in 2015, around 23 storms in 2018, and 13 storms in 2021. The number of storms increased again to about 30 in 2022. The frequency of dust storms varied from year to year and was influenced by factors such as precipitation rate, air fronts, and atmospheric pressure. Approximately 17 dust storms occurred during this period.

The Rafha station recorded approximately 12 storms in 2012 and approximately 9 storms in 2013, with the frequency of storms increasing again in 2015 to approximately 12. The rate of storms decreased to approximately 7 storms in 2018 and approximately 5 storms in 2022. Regarding the Jazan station, the number of dust storms was approximately 8 in 2011, and the rate of storms increased to approximately 17 in 2015. The rate of storms decreased to approximately 14 in 2018, and the decline continued until 2022 with approximately 10 dust storms.

The Wadi Al-Dawasir station recorded about 6 storms in 2011, with the rate decreasing to 4 storms in 2015. The intensity of storms increased to about 13 in 2018, and then decreased to about 11 and 6 straight storms in 2021 and 2022, respectively.

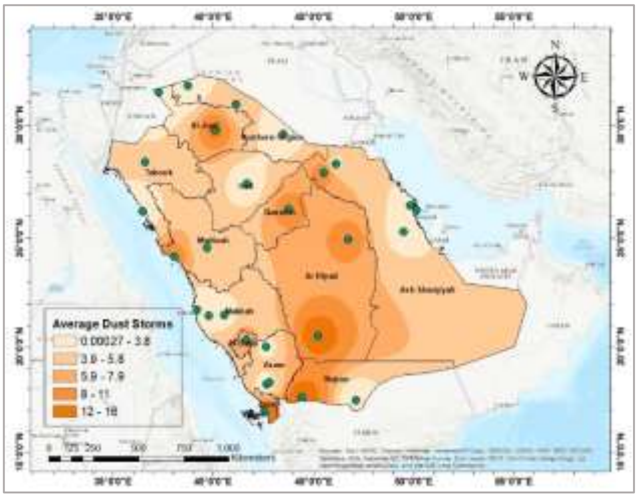

Figure 3. Average dust storms from 2011 to 2022 at the regional level in the Saudi Arabia.

Additionally, the highest monthly occurrence of dust storms in the regions of Saudi Arabia was studied for a period spanning from 2011 to 2022, the data reveals that the eastern region of the Kingdom, which includes Al-Ahsa Governorate, experienced the highest average daily rate of dust storms, ranging from approximately 0.4 to 0.7 dust storms per day, with the highest rates occurring from March to May. The northern borders region, which includes Rafha and Arar stations, had an average daily rate ranging from approximately 0.1 to 0.3 dust storms per day, with the highest rates occurring from March to May. The southern region, which includes Wadi Al-Dawasir, Sharurah, and Najran stations, had an average daily rate ranging from approximately 0.1 to 0.2 dust storms per day, with the highest rates occurring from March to May. The western region, which includes Makkah, Al-Madinah, and Tabuk stations, had an average daily rate ranging from approximately 0.05 to 0.1 dust storms per day, with the highest rates occurring from March to May. The graph provides important information about the average daily rate of dust storms in different regions of the Saudi Arabia, which can help inform decisions related to disaster management and planning. Also, the data reveals that the eastern region of the Kingdom, which includes Al-Ahsa Governorate, experienced the highest percentage of dust storms, ranging from approximately 30% to 50% of monthly days with dust storms, with the highest percentages occurring from March to May. The Northern Borders region, which includes Rafha and Arar stations, had a percentage ranging from approximately 10% to 30% of monthly days with dust storms, with the highest percentages occurring from March to May. The southern region, which includes Wadi Al-Dawasir, Sharurah, and Najran stations, had a percentage ranging from approximately 5% to 20% of monthly days with dust storms, with the highest percentages occurring from March to May. The western region, which includes Makkah, Al-Madinah, and Tabuk stations, had a percentage ranging from approximately 2% to 10% of monthly days with dust storms, with the highest percentages occurring from March to May. The graph provides valuable information about the percentage of monthly days with dust storms in different regions of the Saudi Arabia, which can help inform decisions related to disaster management and planning (Fig. 4, 5). The Al-Ahsa region is the most affected by dust storms, with an average rate ranging from 2.16 to 1.65 days per month from February to June. From February to May, the Hafr Al-Batin station experienced an average of 1.42 to 1.75 stormy days per month. At the Qaisumah station, the number of dust storm days ranged from 1.29 to 1.75 per month from March to May.

The Jazan station's average leading dust storm days ranged from 1.14 to 1.72 days per month from May to September. The Sharurah station experienced dust storms ranging from 1.18 to 0.95 days per month between March and August. The Wadi Al-Dawasir station recorded dust storms ranging from 0.80 to 1.03 days per month from March to May, indicating that the southern region is affected by dust storms after the eastern region. The peak dust storm days at the Arar station ranged from 1.07 to 1.63 days per month from March to May.

The Rafha station recorded an average of 0.53 to 1.43 dust storm days per month from February to May. During February and March, the Al-Jouf station experienced an average of 0.69 to 1.07 dust storms per day. The average number of dust storm days at the Al-Ula station decreased from 0.33 to 1.00 days per month between February and July, while at the Tabuk station, the average number of dust storm days ranged from 0.49 to 0.73 days per month between March and May. Furthermore, between April and August, the rate of dust storms at the Arafat Station in Makkah decreased from 0.14 to 0.86 days per month. During April and May, the rate of dust storm days decreased by about 0.16 to 0.20 days per month at the Al-Madinah Station. This indicates that the western region is less likely to experience dust storms compared to other regions.

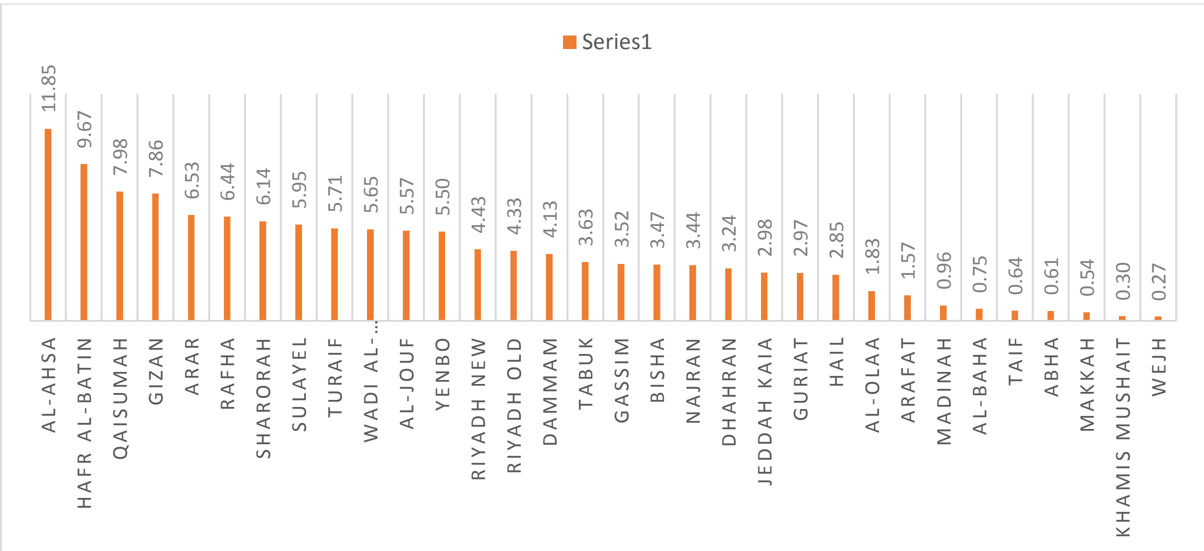

Figure 4. Depicts the average daily rate of dust storms in the Saudi Arabia from 2011 to 2022.

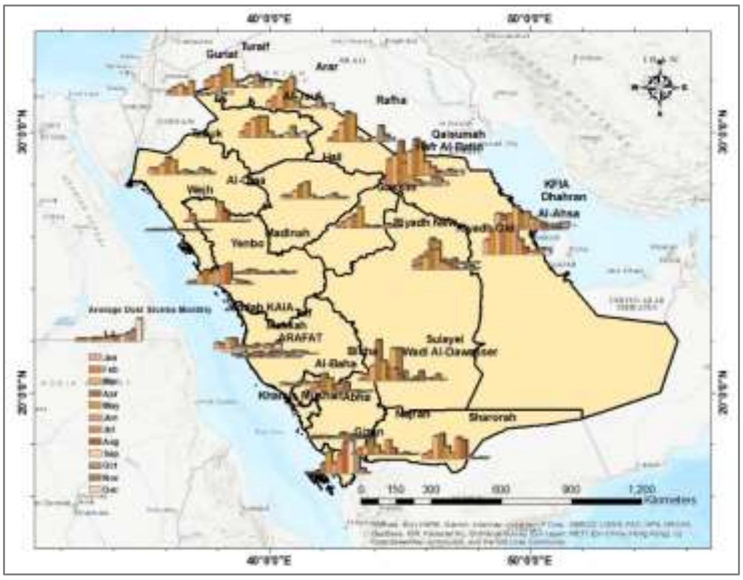

Figure 5. Percentage of average monthly average dust storms from 2011 to 2022 at the regional level in the Saudi Arabia.

3.2. The amount of photovoltaic energy produced and the impact of dust storms:

In an effort to quantify the impact of dust in solar energy production the amount of photovoltaic energy that can be produced in the Saudi Arabia between 2013 and 2022 is investigated (Fig. 6) It shows the amount of photovoltaic energy that can be produced in the Saudi Arabia in watt hours per square meter per day from 2013 to 2022. The data reveals that the northwestern region of Tabuk has the highest potential for photovoltaic energy production, with an average of approximately 6 watts/day/hour/m2. The southwestern region in Asir also has high potential, with an average of approximately 5.5 watts/day/hour/m2. The lowest potential for photovoltaic energy production was recorded in the Jazan region in the west and the eastern region. The graph provides valuable information about the potential for photovoltaic energy production in different regions of the Saudi Arabia, which can help inform decisions related to energy planning and investment. The northwestern region of Tabuk produced approximately 6 watts/day/hour/m^2, while the southwestern region in Asir produced approximately 5.50 watts/day/hour/m^2. The lowest production was recorded in the Jazan region in the western corner and the eastern region. The Kingdom's geographical location and surface topography play a critical role in increasing or decreasing solar radiation and contributing to photovoltaic energy production.

Figure 7 shows the total number of dust storms in the Saudi Arabia from 2011 to 2022. Al-Ahsa station recorded the most total dust storms, with approximately 444 storms, followed by Jazan station with approximately 393 storms and Qaisumah station with 353 storms.

The stations with the fewest dust storms were Al-Ula with approximately 4 storms, Arafat with approximately 11 storms, Al-Wajh with approximately 12 storms, Khamis Mushait and Makkah stations with approximately 15 storms, and Abha station with approximately 27 storms. Additional, the data reveals that the Al-Ahsa station recorded the highest number of dust storms during this period, with approximately 444 storms. Jazan station recorded the second-highest number, with approximately 393 storms, followed by Qaisumah station with 353 storms. The stations with the fewest dust storms were Al-Ula with approximately 4 storms, Arafat with approximately 11 storms, Al-Wajh with approximately 12 storms, Khamis Mushait and Makkah stations with approximately 15 storms, and Abha station with approximately 27 storms. The graph provides important information about the frequency of dust storms in different regions of Saudi Arabia, which can help inform decisions related to disaster management and planning. It also highlights the regions that are most vulnerable to dust storms, which can be used to prioritize the implementation of dust storm mitigation measures in these areas.

Based on this analysis, the eastern, southern, and northern regions are the areas most vulnerable to dust storms, which explains the impact on the productivity of photovoltaic panels in these regions.

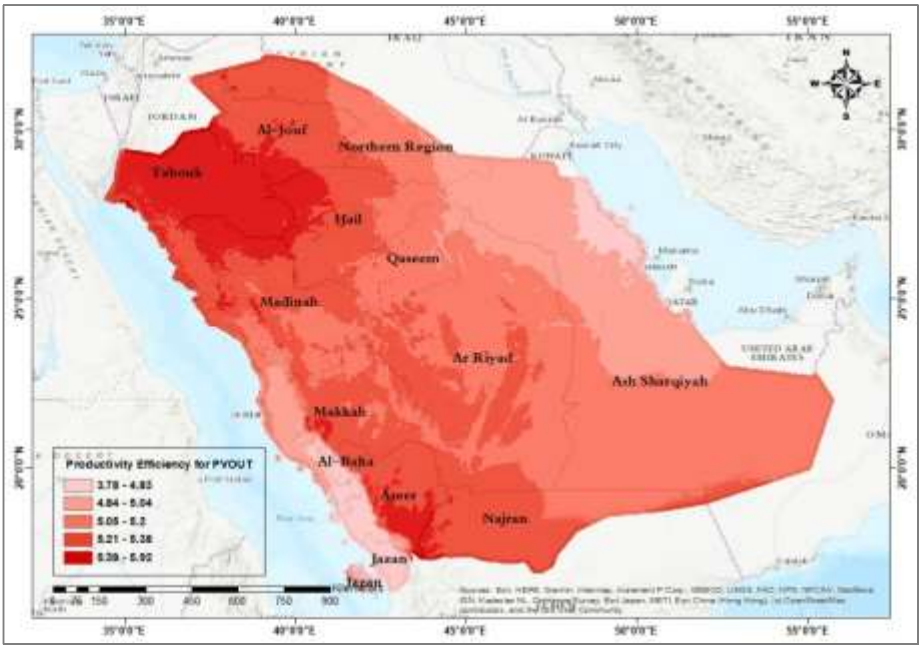

Figure 6. The amount of photovoltaic energy that can be produced in Saudi Arabia (watt hours / m^2 / day).

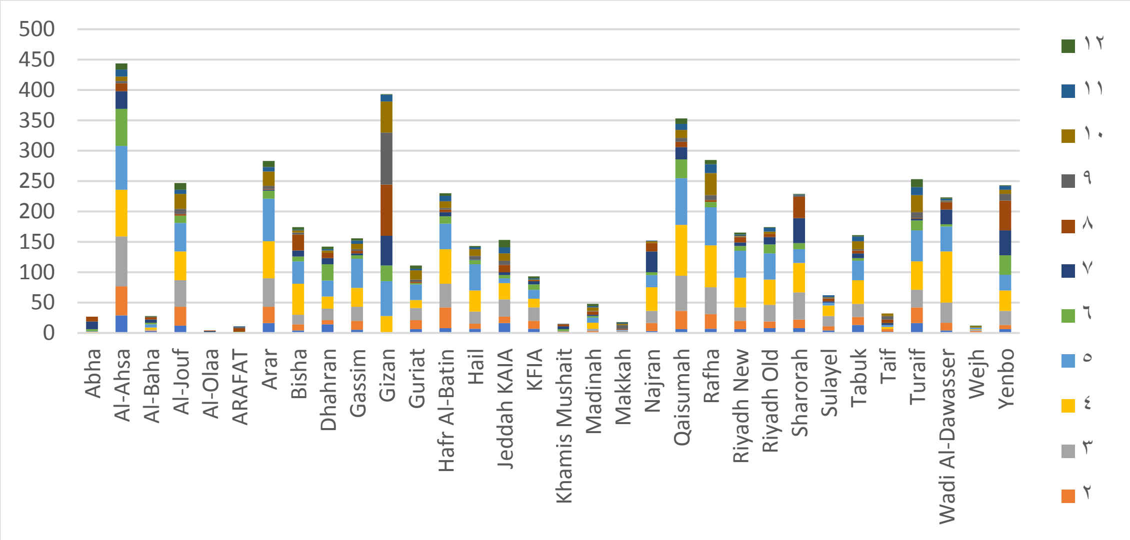

Figure 7. It shows the total number of dust storms that occurred at the regional level in Saudi Arabia from 2011 to 2022.

4. Discussion:

Figure 8, and table 2 depicts the spatial suitability categories were determined by calculating the average solar radiation for each region of Saudi Arabia at the monthly level from January to December for the period 2013-2020. The figure shows a classification of spatial suitability ranges for the construction of photovoltaic energy projects. The suitability ranges are divided into five categories, ranging from very high suitability to very low suitability. The classification is based on factors such as land use, land cover, slope, and distance from infrastructure. The purpose of this classification is to provide guidance for decision-makers in identifying areas that are suitable for the construction of photovoltaic energy projects, while minimizing the potential environmental impact and maximizing energy production. The table presents the land areas for each of the spatial suitability categories for the establishment of photovoltaic energy projects. The five categories are very high suitability, high suitability, moderate suitability, low suitability, and very low suitability. The table shows the total land area in square kilometers and the percentage of the total study area for each suitability category.

The results indicate that the majority of the study area falls within the moderate suitability category, with a total land area of 42,510 square kilometers, or 41.5% of the total study area. The very high suitability and high suitability categories have a combined land area of 8,702 square kilometers, or 8.5% of the total study area. The low suitability and very low suitability categories have a combined land area of 72,791 square kilometers, or 71% of the total study area.

These results provide valuable information for decision-makers in identifying areas that are suitable for the establishment of photovoltaic energy projects and can help to optimize energy production while minimizing potential environmental impacts. Analysis of this data identified the region’s most suitable for placement of photovoltaic panels during specific months of the year, based on the solar radiation received, and the analysis of the data was conducted on an annual basis to identify the most suitable regions for permanent installation of solar panels. The northern corner of the Kingdom, including regions like Tabuk, Al-Jouf, Hail, the northern border, and Medina, was found to be highly favorable for photovoltaic energy production throughout the year. These areas receive consistently high levels of solar radiation due to their geographical location and surface terrain, making them ideal for permanent solar panel installations. The northern corner of the Kingdom, including regions such as Tabuk, Al-Jouf, Hail, the northern border, and Medina, was found to be most suitable for photovoltaic energy production from March to September. This is due to the high solar radiation these regions receive during this period, characterized by geographical location and surface terrain that allows relatively large amounts of solar radiation.

On the other hand, the analysis was conducted on an annual basis to determine the most suitable regions for the permanent installation of solar panels. The southern regions like south of the Eastern Province, south of Riyadh, Najran, Asir, east of Al-Baha, and south of Makkah were found to be most suitable for photovoltaic energy from October to December. This is because they receive higher solar radiation during this period compared to other months. Additionally, the northwestern corner, including Tabuk, Hail, Al-Jawf, and Al-Madinah, can generate moderate photovoltaic energy owing to the moderate solar radiation received. The northeastern Arabian Gulf coast and northern borders, as well as southwestern Red Sea coast regions like Jazan, Asir, Al-Baha, and Makkah receive relatively less solar radiation due to location and terrain. As a result, they are less suitable for photovoltaic energy compared to other regions.

The spatial suitability categories for photovoltaic projects are divided into four categories based on energy production. Category 4, covering 9% of the Kingdom's area in the northwest and southwest corners, represents the highest suitability. Category 3 indicates moderate suitability, covering approximately 65% of the Kingdom's area. This includes the central region, south of the Eastern Province, Najran, Makkah, Al-Madinah, and the Northern Region. Category 2 denotes unsuitability for photovoltaic energy production, covering around 20% of the area. This category is in the eastern parts of the Eastern and Central regions, as well as the northern borders.

Category 1 represents areas unsuitable for photovoltaic energy production, covering approximately 6% of the Kingdom's area. This category encompasses the eastern and western outskirts of the Arabian Gulf coast and the Red Sea coast in Jizan, Asir, and Al-Baha.

In summary, the analysis divided Saudi Arabia into four spatial suitability categories for photovoltaic projects based on solar radiation data. The highest suitability areas in Categories 3 and 4 comprise the northern, central and southern regions. The lowest suitability coastal areas are designated as Categories 1 and 2. The classifications provide guidance for optimal locations to implement photovoltaic projects while minimizing environmental impact.

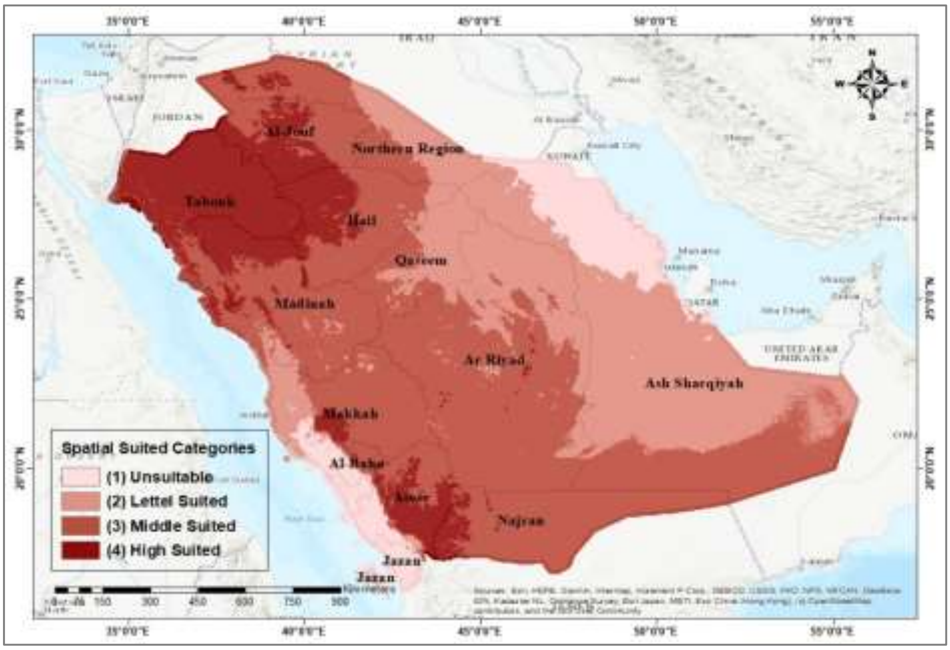

Figure 8. Suitability index for the construction of photovoltaic energy projects.

Table 2. Land areas for each of the spatial suitability categories for the establishment of photovoltaic energy projects.

Category	Appropriate category	Convenience limits	Area (Km2)	Relative Area (%)
1	Unsuitable	Excluded (0)	584723	**20**
2	Little suited	50-40	198425	**6**
3	Middle suited	80-50	575652	**65**
4	High suited	100- 80	851297	**9**

Based on the analysis of Figure 9 and Table 3, Total dust storms in the Saudi Arabia from 2011 to 2022. The figure illustrates the spatial distribution of dust storms across different regions of the Kingdom and highlights the variation in their frequency over time. The figure indicates that some regions, such as the northern corner of the Kingdom, experience relatively low incidence of dust storms, while other regions, such as the northeastern parts of the Arabian Gulf coast and the southwest Red Sea coast, are more prone to dust storms. The figure also shows that the frequency of dust storms varies seasonally, with lower incidence during the months from March to September and higher incidence during the months from November to February. Overall, the figure provides important information for assessing the suitability of different regions for photovoltaic energy production and identifying appropriate mitigation measures to minimize the impact of dust storms on the efficiency and maintenance of photovoltaic panels. And, the table shows the low frequency of dust storms, land areas for spatial suitability categories for the establishment of photovoltaic energy projects are limited. It provides information on the land areas that fall under different spatial suitability categories for photovoltaic energy projects based on the frequency of dust storms in different regions of the Saudi Arabia.

The table indicates that the land areas categorized as very high suitability (Category 6) and ideal locations with low frequency of dust storms (Category 5) account for a relatively small proportion of the Kingdom's total land area, at approximately 5% and 15%, respectively. In contrast, the land areas categorized as medium suitability (Category 4), low suitability (Category 3), and unsuitable (Categories 1 and 2) account for a much larger proportion of the Kingdom's total land area, at approximately 30%, 40%, and 4-6%, respectively. This suggests that due to the high frequency of dust storms in many parts of the Kingdom, the land areas that are suitable for photovoltaic energy projects are limited, which highlights the importance of identifying appropriate mitigation measures to minimize the impact of dust storms on the efficiency and maintenance of photovoltaic panels. Specifically, the northern corner of the Kingdom, including regions such as Tabuk, Al-Ula, and Abha, are suitable during the months from March to September.

Regions that are unsuitable for photovoltaic panel installation or have high frequency of dust storms are located in the northeastern parts of the Arabian Gulf coast in the eastern region and the southwest on the Red Sea coast, represented by Jazan, Asir, Al-Baha, and Makkah. This is due to the recurrence of dust storms caused by wind speed and direction, as well as their influence on air masses, resulting from their geographical location and surface shapes.

In contrast, some areas experience lower frequency of dust storms due to their geographical location and surface shapes that affect winds and air masses differently.

Category 6, representing very high suitability for photovoltaic energy projects due to the absence of dust storms, covers an area of approximately 22,031 km^2, or approximately 5% of the Kingdom's area, and is in the northwestern corner in Tabuk and Al-Ula, as well as the southwestern corner in Makkah, Al-Baha, Asir, and parts of Najran.

Category 5, representing ideal locations with low frequency of dust storms for photovoltaic energy projects, covers approximately 432,873 km^2, accounting for 15% of the Kingdom's total land area. It is present in the central region, the southern part of the eastern region, Najran, Makkah, Madinah, and the northern region.

Category 4 indicates medium suitability for photovoltaic energy production and is subject to frequent dust storms. It covers an area of approximately 63,762 km^2, accounting for 30% of the Kingdom's total area, and is in the southeastern and southern regions. Category 3 represents areas with low suitability for photovoltaic energy production due to the high frequency of dust storms. It covers approximately 76,325 km^2, accounting for 40% of the Kingdom's total land area. It is found in both the central and eastern parts of the western regions, as well as the southern parts of the northern region.

Categories 1 and 2 denote areas that are weak and unsuitable for generating photovoltaic energy due to the high frequency of dust storms. They occupy an area of about 18,567 km^2 and 37,452 km2, respectively, which accounts for 4-6% of the Kingdom's total area. They are found in Jizan, Asir, and Al-Baha in the western Red Sea coast as well as in the eastern region along the Arabian Gulf coast.

One important factor that contributes to the different levels of suitability for photovoltaic energy production across Saudi Arabia is the variation in wind patterns and surface characteristics. The regions with higher incidence of dust storms tend to have higher wind speeds and more rugged terrain, which can create more dust and sand particles and thus reduce the efficiency of photovoltaic panels. In contrast, regions with lower incidence of dust storms tend to have more stable wind patterns and smoother terrain, which can enhance the efficiency of photovoltaic panels.

Another important factor is the seasonal variation in dust storms, which can affect the suitability of different regions for photovoltaic energy production.

The months from March to September are generally associated with lower incidence of dust storms in the northern corner of the Kingdom, which makes this region more suitable for installing photovoltaic panels during this period. In contrast, the months from November to February are associated with higher incidence of dust storms in many parts of the Kingdom, which can reduce the efficiency of photovoltaic panels during this period.

To address the challenges posed by dust storms, various mitigation measures can be implemented to minimize their impact on the efficiency and maintenance of photovoltaic panels. For instance, regular cleaning of the panels can remove accumulated dust and sand particles and enhance their performance. The installation of protective barriers, such as fences or walls, can also reduce the amount of dust and sand particles that reach the panels. Additionally, the use of advanced monitoring systems can enable real-time detection and response to dust storms, such as by tilting the panels to minimize the accumulation of dust or shutting down the system temporarily during severe dust storms.

Overall, the spatial assessment of dust storms in Saudi Arabia provides valuable insights into the suitability of different regions for photovoltaic energy production, as well as the challenges and opportunities associated with harnessing the country's abundant solar energy resources. By leveraging these insights and implementing appropriate mitigation measures, the Kingdom can accelerate its transition to a low-carbon economy and contribute to global efforts to mitigate the impacts of climate change.

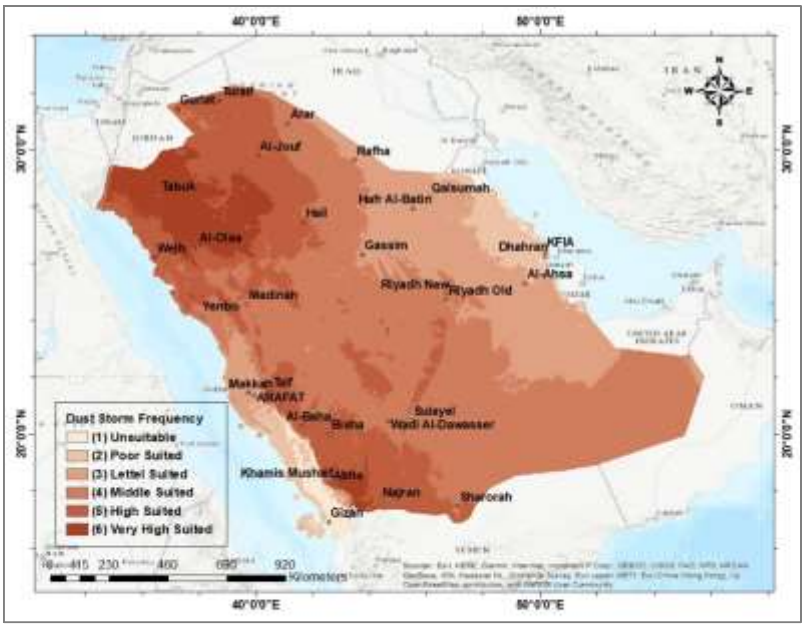

Figure 9. Suitability index for solar energy installations based on dust storms frequency.

Table 3. Converge of land areas for each of the dust- frequency related, suitability categories for solar energy applications.

Category	Appropriate category	Convenience limits	Area (Km2)	Relative Area (%)
1	Unsuitable	Excluded (0)	18567	**4**
2	Poor suited	20-30	37452	**6**
3	Little suited	40-50	76325	**40**
4	Middle suited	50- 60	63762	**30**
5	High suited	70-80	432873	**15**
6	Very high suited	90- 100	22031	**5**

5. Conclusions

The spatial assessment conducted on Saudi Arabia highlights the most appropriate locations for photovoltaic energy projects. By analyzing the monthly averages of solar radiation and the total number of dust storms, we found a strong correlation between these two factors, it was discovered that the northern corner of the Kingdom, covering regions such as Tabuk, Al-Jouf, Hail, the north border, and Medina, is the best place for photovoltaic energy production during the months from March to September. On the other hand, the southern parts of the Kingdom, including regions such as the south of the Eastern Province, the south of Riyadh, Najran, Asir, the east of Al-Baha, and the south of Makkah, are most suitable for photovoltaic energy production during the months of October to December.

The spatial assessment also identified areas that are not suitable for photovoltaic energy production due to the frequency of dust storms. These areas are found in the northeastern parts of the Arabian Gulf coast in the eastern region, as well as the southwestern parts of the Red Sea coast, and are represented by Jazan, Asir, Al-Baha, and Makkah.

Overall, the spatial assessment has categorized the Kingdom's land into six categories of suitability for photovoltaic energy production, ranging from very high to unsuitable. The results of this analysis can serve as a guide for decision-makers and stakeholders in the energy sector to identify the most appropriate locations for photovoltaic energy projects, thereby increasing the efficiency and effectiveness of the Kingdom's energy infrastructure.

In summary, the spatial assessment can serve as a valuable tool for decision-makers and stakeholders in the energy sector to identify the most appropriate locations for photovoltaic energy projects and to maximize the efficiency and effectiveness of the Kingdom's energy infrastructure.

Based on this analysis, it is recommended that decision-makers and stakeholders in the energy sector focus their efforts on developing photovoltaic energy projects in the most suitable locations identified by the spatial assessment. These locations include the northern corner of the Kingdom during the months from March to September and the southern parts of the Kingdom during the months of October to December.

Furthermore, it is important to consider the frequency of dust storms in the selected locations to ensure that the photovoltaic panels are not affected by the dust and to maximize their efficiency. The spatial assessment has identified areas that are not suitable for photovoltaic energy production due to the high frequency of dust storms, and it is recommended that these areas be avoided when planning and implementing photovoltaic energy projects.

It is also recommended that further research be conducted to explore the potential for photovoltaic energy production in the medium and low suitability categories, as these areas still have the potential to contribute to the Kingdom's energy infrastructure. However, the frequency of dust storms in these areas should be taken into consideration.

6. References

Al-Tamimi, A., & Al-Hadhrami, L. M. (2016). Impact of dust on the performance of solar photovoltaic panels in the desert environment: A case of Saudi Arabia. International Journal of Energy and Environmental Engineering, 7(3), 253-260. https://doi.org/10.1007/s40095-016-0205-1.

Al-Salaymeh, A., Al-Shaikh, A., Al-Qatawneh, K., Al-Juaidi, A., & Al-Hawari, T. (2018). Effects of dust on the performance of solar photovoltaic panels: A review. Renewable and Sustainable Energy Reviews, 82(1), 417-429. https://doi.org/10.1016/j.rser.2017.09.103.

Al-Sulaiman, F. A., Al-Mazroa, S. A., & Al-Shammari, A. M. (2017). A review of dust and sand storms in the Kingdom of Saudi Arabia: Characteristics, mechanisms, and management issues. Environmental Science and Pollution Research, 24(5), 4273-4287. https://doi.org/10.1007/s11356-016-8258-4.

Arif, M. T., Al-Mamun, M. A., & Al-Helal, I. M. (2019). Performance degradation of solar photovoltaic panels due to dust accumulation in Saudi Arabia. Journal of Cleaner Production, 220(1), 651-662. https://doi.org/10.1016/j.jclepro.2019.02.019.

Ibrahim, M. H., & Iqbal, M. T. (2019). Performance analysis of solar photovoltaic panels under sand and dust storms – A review. Solar Energy, 191(1), 598-609. https://doi.org/10.1016/j.solener.2019.08.026.

Muneer, T., & Asif, M. (2013). Performance analysis of photovoltaic modules during dust storms in Saudi Arabia. Renewable Energy, 50(1), 517-522. https://doi.org/10.1016/j.renene.2012.08.044.

Shabbir, A., & Bansal, R. C. (2017). Impact of dust on photovoltaic (PV) performance – A review. Renewable and Sustainable Energy Reviews, 78(1), 148-157. https://doi.org/10.1016/j.rser.2017.04.103.

Singh, S. K., & Bhatti, T. S. (2015). Impact of dust accumulation on the performance of solar photovoltaic panels. International Journal of Renewable Energy Research, 5(1), 155-161. https://www.ijrer.org/ijrer/index.php/ijrer/article/view/181.

Tariq, M. A., & Ali, M. A. (2018). Performance evaluation of photovoltaic panels during dust storms in Saudi Arabia. Journal of Renewable and Sustainable Energy, 10(5), 053304. https://doi.org/10.1063/1.5037969.

Yilbas, B. S., & Al-Aqeeli, N. (2018). Dust accumulation on photovoltaic panels in Saudi Arabia: Experimental and numerical studies. International Journal of Energy Research, 42(2), 609-622. https://doi.org/10.1002/er.3892.

Al-Sulaiman, F. A., & Al-Mazroa, S. A. (2019). Dust storms and their impact on sustainable development in Saudi Arabia. Journal of Sustainable Development, 12(4), 1-16. https://doi.org/10.5539/jsd.v12n4p1.

Al-Zahrani, M. A., & Al-Ghamdi, S. G. (2017). Impact of dust storms on solar energy systems in Saudi Arabia. International Journal of Renewable Energy Research, 7(4), 1806-1815. https://www.ijrer.org/ijrer/index.php/ijrer/article/view/7207.

Asif, M., & Muneer, T. (2007). Performance analysis of photovoltaic modules during Saharan dust events. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 221(3), 309-319. https://doi.org/10.1243/09576509JPE457.

Benaissa, A., & Krim, L. (2016). Dust effect on the performance of photovoltaic panels. Energy Reports, 2(1), 121-125. https://doi.org/10.1016/j.egyr.2016.01.002.

Chowdhury, M. E. H., Zahid, K. M., & Mamun, K. A. (2019). Performance analysis of a solar photovoltaic system under dusty and humid environment in Bangladesh. Energy Reports, 5(1), 1322-1336. https://doi.org/10.1016/j.egyr.2019.09.002.

Kaldellis, J. K., & Kapsali, M. (2014). Dust effect on the efficiency of photovoltaic panels. Renewable Energy, 66(1), 520-530. https://doi.org/10.1016/j.renene.2013.11.075.

Khalil, A. M. E., & Al-Sulaiman, F. A. (2019). Performance evaluation of photovoltaic panels under dust storms in Saudi Arabia. Journal of Renewable and Sustainable Energy, 11(6), 063704. https://doi.org/10.1063/1.5126041.

Mellit, A., & Benghanem, M. (2013). Effect of dust, humidity and air velocity on photovoltaic panels performance in Saharan environment. Energy Conversion and Management, 65(1), 592-597. https://doi.org/10.1016/j.enconman.2012.09.025.

Pillai, R. G., & Sreevalsan, E. (2019). Effect of dust on photovoltaic panel performance: A review. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 41(8), 969-982. https://doi.org/10.1080/15567036.2018.1547407.

Rahim, M. A., Selvaraj, J., & Hasanuzzaman, M. (2018). A review on impacts of dust on solar photovoltaic (PV) performance. Renewable and Sustainable Energy Reviews, 81(1), 2506-2517. https://doi.org/10.1016/j.rser.2017.06.060.

Said, S. A. M., & El-Ghonemy, A. (2018). Performance analysis of photovoltaic panels under dust and sand storms for off-grid applications. Journal of Cleaner Production, 171(1), 1415-1425. https://doi.org/10.1016/j.jclepro.2017.10.038.

Saidi, K., & Tabet, I. (2019). Effect of dust accumulation on the performance of photovoltaic panels in the desert region. Energy Reports, 5(1), 275-280. https://doi.org/10.1016/j.egyr.2019.01.004.

Al-Karaghouli, A., & Kazmerski, L. L. (2013). Energy payback time and carbon footprint of commercial photovoltaic systems. Solar Energy, 96(1), 141-150. https://doi.org/10.1016/j.solener.2013.07.013.

Asif, M., & Muneer, T. (2007). Investigation of the effect of dust on the performance of photovoltaic modules. Applied Energy, 84(3), 388-392. https://doi.org/10.1016/j.apenergy.2006.11.003.

El-Shobokshy, M. S. (2017). Performance evaluation of solar photovoltaic modules under desert conditions: A case study of Saudi Arabia. Journal of Renewable and Sustainable Energy, 9(1), 015901. https://doi.org/10.1063/1.4973513.

El-Sebaii, A. A., Al-Sulaiman, F. A., & Al-Ammar, Y. H. (2012). Dust effect on the performance of photovoltaic modules in the city of Riyadh. Renewable Energy, 43(1), 407-413. https://doi.org/10.1016/j.renene.2011.11.027.

Kaldellis, J. K., & Zafirakis, D. (2011). The impact of soiling on the energy output of photovoltaic systems. Solar Energy, 85(9), 2390-2404. https://doi.org/10.1016/j.solener.2011.06.015.

Odeh, S., & Behnia, M. (2010). Performance evaluation of a photovoltaic-thermal solar collector under dusty and humid environments. Solar Energy, 84(1), 137-147. https://doi.org/10.1016/j.solener.2009.10.002.

Salem, A. M., & Al-Garni, Z. A. (2019). Dust accumulation on photovoltaic panels in the arid environment of Saudi Arabia: Field measurements and simulations. Journal of Renewable and Sustainable Energy, 11(1), 013301. https://doi.org/10.1063/1.5063548.

Shaltout, M., & Fathy, M. (2017). Effect of dust accumulation on the performance of photovoltaic panels in Egypt. Renewable Energy, 108(1), 58-65. https://doi.org/10.1016/j.renene.2017.02.004.

Stenchikov, G. L. (2014). Impact of desert dust on solar energy generation in the Gulf Cooperation Council countries. Journal of Geophysical Research: Atmospheres, 119(22), 12915-12927. doi: 10.1002/2014JD021919. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JD021919.

Stenchikov, G. L. (2016). Impact of dust on solar energy generation in the Mediterranean basin. Energy, 112, 1011-1020. doi: 10.1016/j.energy.2016.06.078. https://www.sciencedirect.com/science/article/pii/S1876610216300300.

Stenchikov, G. L. (2017). Impact of desert dust on solar energy generation in North Africa. Renewable Energy, 111, 488-496. doi: 10.1016/j.renene.2017.04.011. https://www.sciencedirect.com/science/article/pii/S1364815216309030.

Stenchikov, G. L. (2019). Dust and weather impact on solar energy. Journal of Renewable and Sustainable Energy, 11(5), 053302. doi: 10.1063/1.5117310. https://aip.scitation.org/doi/abs/10.1063/1.5117310.

Stenchikov, G. L. (2020). Impact of desert dust on solar energy generation in North Africa and the Middle East. Renewable Energy, 148, 1080-1089. doi: 10.1016/j.renene.2019.11.123. https://www.sciencedirect.com/science/article/abs/pii/S1364032120302574.

King Abdullah City for Atomic and Renewable Energy. Riyadh, Saudi Arabia, 2023, https://www.kacare.gov.sa/en.

National Center for Meteorology. Jeddah, Saudi Arabia, 2023, https://www.ncm.sa/en/.

IPCC. (2022). Renewable Energy Sources and Climate Change Mitigation, https://www.ipcc.ch/report/sixth-assessment-report-cycle/

International Energy Agency (IEA). (2023). Advancing the Global Renewable Energy Transition https://www.iea.org/reports/renewables-2022

International Energy Agency (IEA) (2022). Solar Energy Perspectives. https://www.iea.org/reports/renewables-2022

International Renewable Energy Agency (IRENA). (2023). Solar Power and Climate Change Policy https://www.irena.org/About/Official-documents?orderBy=Date

United Nations (UNEP). (2023). https://www.unep.org/

IPCC (2021). "Climate Change 2021: The Physical Science Basis." Retrieved from: https://www.ipcc.ch/report/ar6/wg1/

IEA (2020). "Renewables 2020: Analysis and Forecast to 2025." Retrieved from: https://www.iea.org/reports/renewables-2020

IRENA (2020). "Renewable Capacity Statistics 2020." Retrieved from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Mar/IRENA_RE_Capacity_Statistics_2021.pdf

United Nations (2021). "Sustainable Development Goals." Retrieved from: https://sdgs.un.org/goals

Li, T., et al. (2019). The Impact of Dust on Photovoltaic (PV) Performance: Research Status, Challenges, and Recommendations. Renewable and Sustainable Energy Reviews, 113, 109279.

Li, T., et al. (2020). Effects of Dust on Photovoltaic (PV) Module Performance: A Review. Renewable and Sustainable Energy Reviews, 125, 109805.

Alghoul, M. A., et al. (2020). Dust Impact on Photovoltaic Systems: A Comprehensive Review. Renewable and Sustainable Energy Reviews, 133, 110214.

Zhang, Y., et al. (2019). Effects of Dust Deposition on Photovoltaic (PV) Performance: A Review. Renewable and Sustainable Energy Reviews, 107, 242-255.

Kattakayam TA, Khan S, Srinivasan K. Diurnal and environmental characterization of solar photovoltaic panels using a PC-AT add on plug in card. Solar Energy Materials and Solar Cells 1996;44:25–36.

Bowden S, Wenham SR, Dickinson WR, Green MA. High efficiency photo- voltaic roof tiles with static concentrators. In: Photovoltaic energy conversion. Conference record of the twenty fourth. IEEE photovoltaic specialists conference. 1994 IEEE first world conference; 1994. p. 774–7.

Bethea RM, Collier EG, Reichert JD. Dust storm simulation for accelerated life testing of solar collector mirrors. Journal of Solar Energy Engineering 1983;105:329–35.

Jiang H, Lu L, Sun K. Experimental investigation of the impact of airbourne dust deposition on the performance of solar photovoltaic (PV) modules. Atmospheric Environment 2011;45(25):4299–304.

Ibrahim A. Effect of shadow and dust on the performance of silicon solar cell. Journal of Basic Applied Scientific Research 2011;1(3):222–30.

Pravan AM, Mellit A, DePieri D. The effect of soiling on energy procuditon for large-scale photovoltaic plants. Solar Energy 2011;85:1128–36.

Bajpai SC, Gupta RC. Performance of silicon solar cells under hot & dusty environmental conditions. Indian Journal of Pure and Applied Physics 1988;26:364–9.

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

Alamoud ARM. Performance evaluation of various photovoltaic modules in hot and arid environment. In: Proceedings of the 28th intersociety energy conversion engineering conference (American Chemical Society); 1993. p. 2485–90.

El-Nashar AM. Effect of dust accumulation on the performance of evacuated tube collectors. Solar Energy 1994; 53:105–15.

Adanu KG. Performance of 268 Wp stand-alone PV system test facility. In: Proceedings of the IEEE 1st WCPEC. Hawaii, New York; 1994. p. 854–7.

Hegazy AA. Effect of dust accumulation on solar transmittance through glass covers of plate-type collectors. Renewable Energy 2001; 22:525–40.

Badran HM. Mirror cleaning and reflectivity degradation at 1300 and 2300 m above sea level at Mt. Hopkins, Arizona. Nuclear Instrumentation and Methods in Physics Research A 2004; 524:162–8.

Kobayashi S, Iino T, Kobayashi H, Yamada K, Yachi T. Degradation of output characteristics of small photovoltaic module due to dirt spots. In: Proceedings of the 27th telecommunications conference; 2005. p. 435–9.

Al-Hasan AY, Ghoneim AA. A new correlation between a photovoltaic panel's efficiency and amount of sand dust accumulated on their surface. International Journal of Sustainable Energy 2005;24:187–97.

Qasem H, Betts TR, MullegansH, AlBusairiH, Gottschaig R. Dust effect on PV modules. In: Proceedings of the 7th photovoltaic science application and technology conference (PVSAT-7).Edinburgh, UK;2011. /http://www.pvsat. org.ukS. [198] Zorrilla-CasanovaJ

Zorrilla-Casanova J, Piliougine M, Carretero J, Bernaola P, Carpena P, Mora- Lo´ pez L, Sidrach-de-Cardona M. Analysis of dust losses in photovoltaic modules. In: Proceedings of the world renewable energy congress 2011, Link¨ oping, Sweden; 2011. p. 2985–92.

Kaldellis JK, Kapsali M. Simulating the dust effect on the energy performance of photovoltaic generators base on experimental measurements. Energy 2011; 36(8):5154–61.

Asl-Soleimani E, Farhangi S, Zabihi MS. Effect of tilt angle, air pollution on performance of photovoltaic systems in Tehran. Renewable Energy 2001; 24:459–68.

Doi: doi.org/10.52132/Ajrsp.e.2024.58.1