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Modeling and Prediction of Clear-Sky Solar Irradiance Losses Using Meteorological and Radiative Parameters: A Case Study in Ouarzazate, Morocco

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Abstract. Understanding how to quantify loss potential due to clear-sky solar irradiance is essential for the development of enhanced Photovoltaic and Solar Energy Forecasting systems in Semi-Arid climates. In Ouarzazate, Morocco, four years (2021 - 2024) of daily weather and solar radiation observations collected by satellite and from the ground were analysed in this research through the analysis of clear-sky losses. Clear-sky conditions were isolated from all others by applying a Clearness Index threshold of ≥0.65 (KT), and Clear-sky Losses were derived from the relative differentials between All-Sky Shortwave Solar Irradiance (SSI) and Clear-Sky Shortwave Solar Irradiance (SSI). Correlation analysis between the Clear-Sky Loss and four key weather variables produced strong correlations. Three models were created to predict clear-sky losses: Linear Regression (LR), Second Order Polynomial Regression (2PR), and a Random Forest (RF) algorithm. The results indicated that the 2PR model provided the best fit (R^2 = 0.9965, RMSE = 0.0079) allowing for accurate comparisons of the 2PR model to the two better-known methods of predicting Solar Resource & Energy Potential.

Introduction

Solar energy has become a mainstay in the quest to develop sustainable and renewable energy acr oss the globe. Advances in photovoltaic technology and decreasing costs make it very important t o accurately assess the availability of solar resources to optimise system performance and improv e the forecasting of energy yields and to allow greater levels of integration into the grid[1], [2]. A ccurate forecasting of the amount of solar irradiance that will strike surfaces is critical to reducin g the potential uncertainties associated with designing and operating PV systems[3].

Ouarzazate in southeastern Morocco is home to one of the largest solar power plants in the world and provides an excellent environment for conducting research into solar energy [4], [5]. The region is known for its high levels of solar radiation, low levels of precipitation and high levels of aerosol loading due to desert dust carried by the wind from the Sahara Desert, which has caused many problems for the environment [6]. *Fig. 1* below illustrates the global distribution of dust

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intensities around the world and illustrates the impact of desert areas like southern Morocco on the global intensity of dust[7]. Dust storms, especially in the spring and summer, can have a detrimental impact on the quality of the air and the performance of PV systems [8].

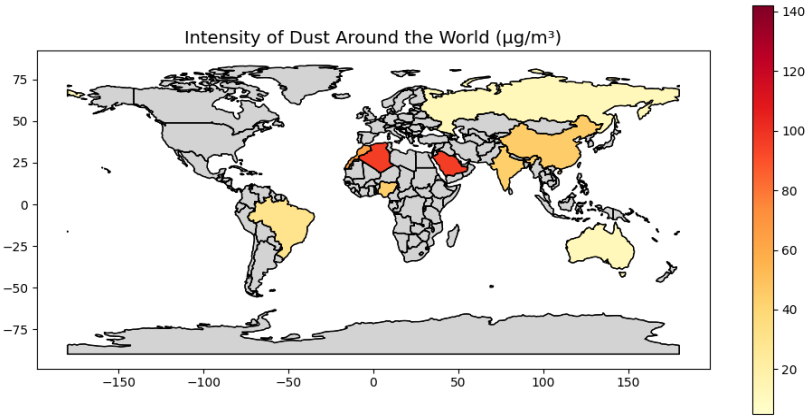


Fig. 1. Intensity of dust around the world (with some data of some country)

While there have been a number of studies that have investigated solar irradiance modeling and atmospheric attenuation effects across many regions [9], [10], little published work has been done regarding clear-sky irradiance loss associated with semi-arid environments located within Northern Africa. Many existing clear-sky models were created for other climate types and may not fully characterize the non-linear interactions between meteorological factors and irradiance loss in a semi-arid setting [11],[12] . Moreover, prior work has predominantly centred on theories of cloud-covered scenarios or theoretical clear-sky modeling, with limited long-term observational data for validation from these types of locations [13], [14].

As a result of this, the aim of the current research is to quantify clear-sky solar irradiance losses for Ouarzazate (Morocco) based on four (4) years (2021-2024) of daily meteorological and radiative observations. This study seeks to: 1) quantify clear-sky irradiance loss in relation to a clear index threshold (KT ≥0.65), 2) evaluate the relationship(s) between the irradiance loss and meteorological/radiative parameters, and 3) develop and validate models that will estimate clear-sky irradiance loss. Of particular interest is a second-order polynomial regression model, which has shown sufficient strength to characterize the nonlinear nature of clear sky irradiative loss when compared to the linear regression approach and other more complex machine learning techniques.

Methodology

Fig. 2 the methodology diagram (shown to the right) explains the steps that were taken within this research project. Collection of 4 years (2021-2024) worth of daily weather and solar radiation data from NASA's POWER Database was the first step. Once cleaned and processed, it was possible to analyze both the all sky and theoretical parcels to determine the rates of loss. To identify clear sky days.

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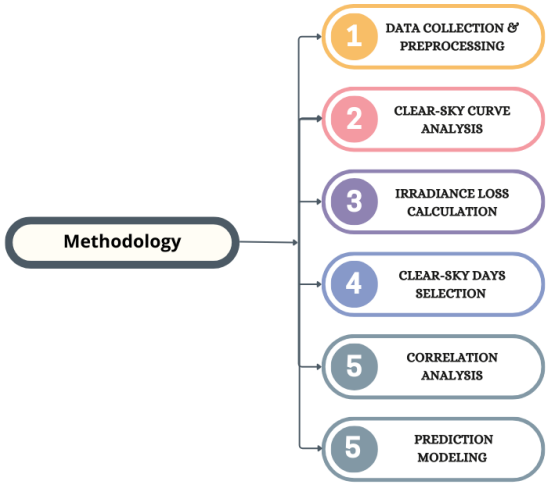


Fig. 2. Overview of the methodological workflow used in this study.

Study Area

Located in southern Morocco at approximately 1,160 meters above sea level, (30.93°N, 6.91°W), Ouarzazate has a semi-arid climate with hot and dry summer months; moderate to cool winter months and a large day-to-night temperature difference[6].. The area's location near the Sahara Desert gives it a very large amount of solar energy potential with over 2,500 kilowatt-hours per square meter of solar radiation each year, making it an ideal place for solar power production in northern Africa[15]..

Meteorological and radiation data from 2021 through 2024 were analyzed in this research study. Examples of examined variables include the following: Air and ground temperature; Relatively Humidity; Wind Speed and Direction (on many levels); Ground Pressure; and Increasing Solar Radiation shortwave, longwave and UV components.

The "clear sky" condition was determined by means of determining the clear sky clearness index (KT) - KT indicates how much solar radiation reaches the ground. Researchers previously identified a KT value of 0.65 for semi-arid climates as being suitable for determining primarily clear sky day classifications and producing the maximum usable amount of meteorological data to be evaluated on a statistical basis[16], [17]. Approximately 850-900 days met this criterion after applying this threshold to the data set.

The relative clear-sky day irradiance losses (L) were calculated using Eq. (1) for each identified clear-sky day. Pearson's correlation coefficients (PCCs) were calculated to assess the relationship between the meteorological parameters and the clear-sky irradiance losses, in order to determine the dominant atmospheric attenuation drivers in the absence of clouds.

$$L = \frac{\mathrm{ALLSKY_SFC_SW_DWN}}{\mathrm{CLRSKY_SFC_SW_DWN}} \quad (1)$$

Results

Clear-sky and Actual Irradiance Characteristics

Fig. 3 comparison of Clear Sky Irradiance (CLRSKY) to Actual All Sky Irradiance (ALLSKY), Period 2021–2024. Both timeseries are expected to exhibit strong seasonal variations with peaks during the summer months and troughs during the winter months.

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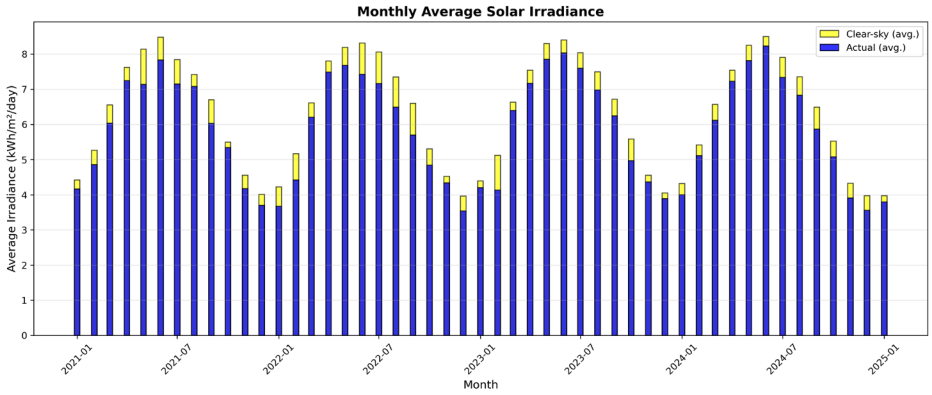


Fig. 3. Clear-sky vs actual irradiance

The year June 2024 saw the highest clear sky irradiance measurement of 9.23 [kWh/m²]. The lowest recorded number was from December 2021 at 3.47 [kWh/m²]. Along the same lines, actual irradiance (ALLSKY) peaked in June 2024 with a similar number of 9.22 [kWh/m²], which matches the annual solar production cycle, and dropped to a low of 0.62 [kWh/m²] in February 2023, signifying a day with considerable air pollution attenuation to that day's solar generation.

Daytime all-sky irradiance averaged during this period accounted for an average of 5.89 [kWh/m²] ($\sigma = 1.71$) as opposed to 6.37 [kWh/m²] ($\sigma = 1.58$) experienced on days with clear skies. The differences experienced on the two average irradiances represent the systematic reduction in available solar energy created by the effects of clouds, aerosol particles, and atmospheric variability.

Temporal Evolution of Irradiance Losses

Fig. 4 this graph shows how much daily irradiance was lost by looking at the difference in actual irradiance and that that would occur under a clear sky (irradiance) as a percentage of the actual irradiance.

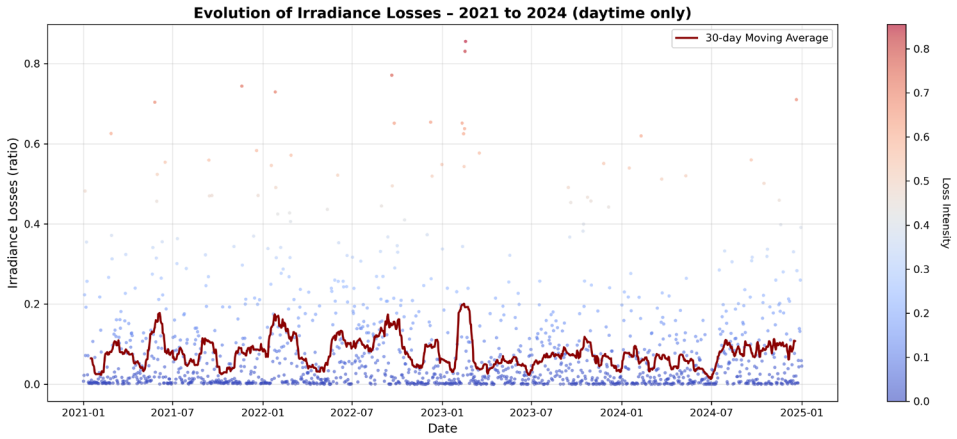


Fig. 4. Daily irradiance losses

Although at times instantaneous losses may exceed 80% (e.g., February 2023). However, their overall trend reflects that for the majority of days there were moderate, generally below 20%, instantaneous losses.

The average loss per month demonstrates strong seasonal variability; the loss rate increases during the winter months and some transitional months as a result of higher cloud cover and

increased atmospheric instability within the winter months. In addition, during the summer months, loss rates are typically lower and more stable.

Annual Statistics of Irradiance Losses

Table 1 summarizes the annual statistics of irradiance losses. The average annual losses vary between 4.5% and 9.7%, with 2022 showing the highest mean loss (0.0972), followed by 2021 (0.0768) and 2024 (0.0730).

Table 1: Annual Statistics of Irradiance Losses (2021–2024)

Year	Mean Loss	Max Loss	Month of Max Loss	Min Loss	Month of Min Loss
2021	0.0768	0.7440	November	0.0003	August
2022	0.0972	0.7712	September	0.0000	November
2023	0.0688	0.8555	February	0.0000	January
2024	0.0730	0.7103	December	0.0000	March

Once we established a value of KT (clear-sky index) of 0.65 or higher, of the 1,462 daytime days in which clear skies existed based on our criteria, 1,073 clear-sky days met our definition of a clear-sky condition. Upon filtering these data according to criteria for calculating day-to-day changes in irradiance losses (due primarily to particulate matter/humidity as opposed to clouds), we found substantial variation in the amount of irradiance loss from clear-sky days. On average, the amount of irradiance loss was 0.0249, which will generally mean a low level of attenuation on verified clear-sky days. However, there were isolated secondary peaks of irradiance loss likely due to short-duration atmospheric conditions such as dust storms and episodes of rapid changes in humidity.

Correlation Analysis

There are a number of correlations between meteorological and radiative input variables and clear sky irradiance losses. An inverse correlation was found between relative loss and clear sky irradiance that suggests increased loss sensitivity in reduced clear sky conditions. The strongest relationships among all of the variables were seen with respect to the radiative input variables, which included ALLSKY SFC SW DWN, ALLSKY KT, and PAR components and indicate their importance for atmospheric transparency. The meteorological input variables had a weaker, but moderative relationship with loss and would therefore be viewed as an indirect influence on the loss through atmospheric stability and scattering interactions. The information gathered from this study aided in the selection of input variables that were used as predictors for both polynomial regression and machine learning–based models for estimating losses.

Predictive Modeling Performance

Using all meteorological and radiative variables, three predictive models were created: Linear Regression, Second Degree Polynomial Regression (Ridge), and Random Forest.

Table 2: Performance Comparison of Prediction Models

Model	R^2	RMSE
Linear Regression	0.9949	0.0095
Polynomial Regression (Degree 2)	0.9965	0.0079
Random Forest	0.9735	0.0218

Of these three models, the Second Degree Polynomial Model produced the most accurate predictions with the least amount of error; however, Random Forest performed worse than both Regression models. Therefore, we can infer that clear-sky irradiance attenuation in semi-arid

climates can be accurately predicted with the integration of radiative parameters and a moderate amount of non-linear modelling. Clear-sky irradiance losses are better described as a smoothed non-linear function than an extremely complex or erratic one.

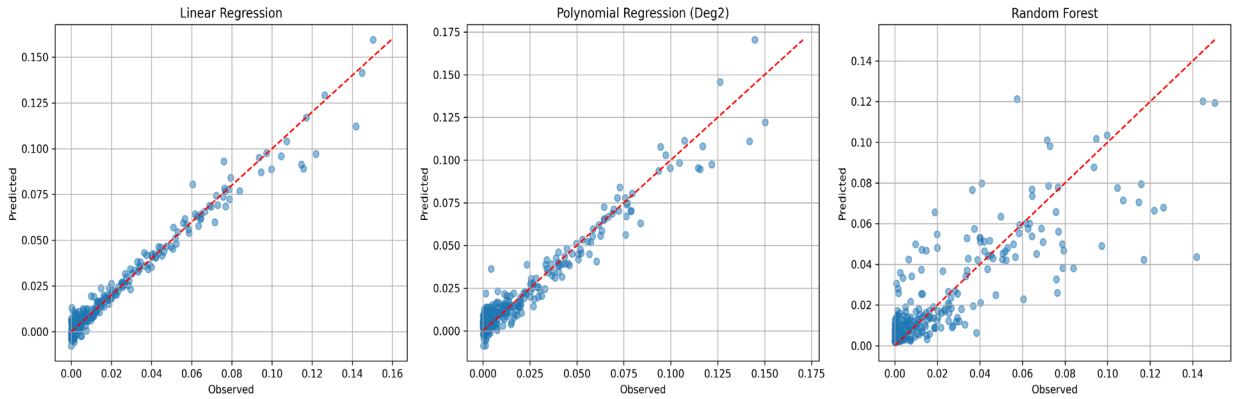


Fig. 5. Observed vs. predicted clear-sky irradiance losses for three models (Linear, Polynomial deg-2, Random Forest)

Fig. 5 a comparison of the observed and predicted clear-sky irradiance losses from three different models, namely Linear Regression (on left), Polynomial Regression of degree 2 (in the center), and Random Forest (on right) illustrate that both linear and polynomial models cluster very close to the ideal 1:1 agreement indicated by the dashed red line, confirming that linear and polynomial models have similar accuracies in predicting clear-sky irradiance losses.

Discussion

The research from 2021 to 2024 focused on the losses of clear-sky irradiance occurring throughout the year. Researchers studied both the drivers of clear-sky irradiance losses in Ouarzazate and identified the causes of those losses as atmospheric events like aerosol and water vapor. Researchers concluded that there are many factors that cause the amount of solar radiation received on Earth to vary, and some of these factors can increase or decrease the amount of solar radiation received[18], [19].

Less clear-sky irradiance losses were observed during the summer months than in all other seasons, due partly to high moisture levels in the air, which also caused greater attenuation of solar radiation during both winter and transitional seasons. In addition, the presence of Saharan dust events also caused significant increases in the total number of clear-sky irradiance losses throughout the year, especially in winter and transitional months.[6], [7], [8].

Based on this model comparison, although the Random Forest model achieved a lower overall accuracy than the second-degree polynomial and linear regression models, the polynomial and linear regression models still provided very high accuracy levels (R^2 = 0.9949 / 0.9965) compared to the Random Forest model (R^2 = 0.9735). The results of the research also refute some of the previous research by suggesting that the second degree polynomial regression models predict clear-sky irradiance losses based on the ability of the models to show smooth and well-behaved nonlinear relationships. This finding suggests that the second degree polynomial regression model provides a robust way of predicting clear-sky irradiance losses using only radiative and meteorological variables, providing ease in the computational capacity needed to produce valuable results.[9], [12], [14] .

Conclusion

The authors analysed clear-sky solar irradiance losses in Ouarzazate, Morocco. They analysed daily meteorological and solar data obtained from NASA/P.O.W.E.R. between 2021 and 2024. They calculated a clearness index (K T = 0.65) to identify 1,070 clear-sky days, which provided the basis for estimating the atmospheric attenuation due to clouds. The authors reported that even though the region has a high solar potential, there were considerable losses of solar irradiance caused by aerosols, water vapour and dust. The authors also identified the second degree polynomial regression model as having the highest R2 value (0.9965) and the lowest RMSE value (0.0079). The authors concluded that the attenuation of clear-sky solar irradiance in semi-arid areas can be described using a smooth, nonlinear relationship. The authors recommend using polynomial regression for quantifying photovoltaic resources and predicting energy output from photovoltaic systems in areas with a similar atmosphere. In the future, the authors recommend using tomorrow's data to create better estimates, monitoring actual ground radiometric measurements, and performing detailed characterizations for aerosols.

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