Direct Normal Irradiance in a Changing Climate: Trends and Apparent Anomalies from 25 Years of Data in Seville

SolarPACES

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This study analyzes the long-term behavior of direct normal irradiance (DNI) in Seville (Spain) from 2000 to 2024 using ground-based monthly observations. The aim is to characterize multi-year trends and apparent anomalies that may reflect climate-driven variability relevant to solar energy planning. Backward-looking moving averages over 5, 10, 15, and 20 years confirm a persistent upward trend in annual DNI, with modest year-to-year fluctuations. Three statistical methods initially flagged a few high-DNI years as anomalies. However, when applied to residuals from the linear trend, no anomalies were detected, indicating these values align with a gradual long-term increase, consistent with the solar "brightening" phenomenon [1]. These results establish a reference for comparing observed data with synthetic datasets from Meteonorm to assess how well modeled anomalies reflect reality. The ultimate goal is to support improved solar resource projections under climate scenarios, especially for CSP applications.

1. Introduction

The availability and long-term stability of direct normal irradiance (DNI) is critical for the optimal performance and feasibility assessment of concentrating solar power (CSP) plants. Climate change introduces uncertainty into the temporal evolution of solar resources, making it essential to analyze historical trends and validate projections using robust datasets and detect early signs of instability. This work analyzes 25 years of observational data for the location of Seville to detect long-term trends and anomalies, laying the groundwork for subsequent comparison with modeled data from Meteonorm.

2. Methodology

The analysis is based on monthly DNI values from 2000 to 2024 measured at a reference station in Seville. Annual totals were computed and analyzed using backward-looking moving averages over 5, 10, 15, and 20 years to capture long-term trends. To assess potential anomalies, three statistical indices were applied to the annual data:

1. Z-score, defined as $z_i = \frac{(x_i - \mu)}{\sigma}$, where x_i is the annual DNI, μ is the mean, and σ is the standard deviation over the full period.

2. Deviation from the 10-year moving average, calculated as $d_i = x_i - \bar{x}_{i-9:i}$. A year is considered anomalous if the deviation exceeds twice the standard deviation of all such deviations, that is, when $|d_i| > 2\sigma_d$, where σ_d is the standard deviation of the d_i values.
3. Interquartile Range (IQR) method, where a value is considered anomalous if $x_i < Q1 - 1.5 \cdot IQR$ or $x_i > Q3 + 1.5 \cdot IQR$, with Q1 and Q3 being the 25th and 75th percentiles of the series and $IQR = Q3 - Q1$.

The number of anomalies identified by each method and their overlap were analyzed to assess consistency and sensitivity across approaches. In next figure we present the annual DNI with overlaid moving averages (5–20 years) on the left, and the annual DNI showing anomalies detected by each method on the right. In the extended version of this study, the methodology will also be adapted to monthly values to explore seasonal shifts in DNI behavior.

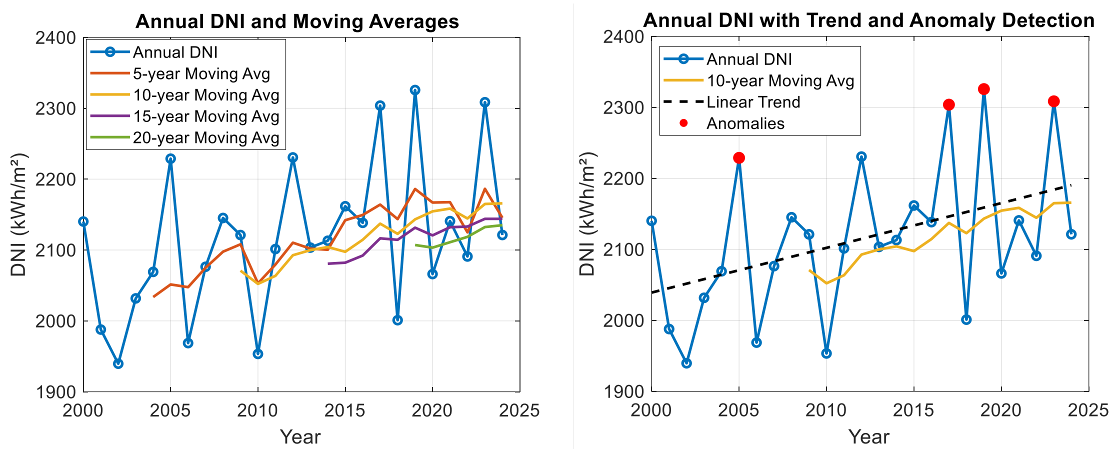

Fig. 1: *Annual DNI with overlaid moving averages in 5–20 years (left). Annual DNI showing anomalies detected by each method on the right*

3. Preliminary Results

The results show a sustained upward trend in DNI over the study period, with modest interannual variability. Anomaly detection methods applied to the raw series identified one anomalous year via Z-score, none using the 10-year moving average deviation, and four with the interquartile range (IQR)—mostly high-DNI years compared to a historical mean influenced by early low values. To better characterize true anomalies, we analyzed residuals from a linear trend fit (i.e., the difference between observed values and the fitted trend). When the same detection methods were applied to this trend-corrected series, no anomalies were found, indicating the previous outliers were part of a gradual long-term increase. A comparison of the residuals' standard deviation between 2000–2011 and 2012–2024 revealed a slight rise from 85.8 to 99.2 kWh/m², suggesting a possible, though not significant, increase in variability. These findings confirm a statistically coherent upward trend in DNI, commonly known as brightening [1], while short-term variability remains relatively stable. This highlights the importance of long-term monitoring for solar planning. The ongoing collaboration with Meteonorm developers will help assess how well modeled anomalies reflect observed behavior and improve future solar resource projections.

References

[1] Wild, M. (2009). Global dimming and brightening: A review. Journal of Geophysical Research: Atmospheres, 114(D10). https://doi.org/10.1029/2008JD011470