Evaluating the Impact of Weather Factors on Solar Power Generation in Da Nang City, Vietnam

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ABSTRACT

The study focuses on evaluating the impact of weather factors such as temperature, humidity, wind speed and cloud cover on the output of solar power systems in Da Nang city, Vietnam. Weather and solar power generation data from various sources are collected and analyzed. Correlation and regression analysis methods are used to determine the relationship between weather variables and solar power generation. Among the weather factors, temperature and cloud cover are the factors that have the most influence on solar power generation. The results obtained provide important information for the effective operation of solar power systems in particular and the power grid in general. Moreover, such information will support the scheduling of mobilization of solar power for energy management based on information about weather conditions, ensuring energy security. This study also provides an important database for applying modern technologies, such as AI and machine learning, for developing solar energy management and forecasting models.

1. INTRODUCTION

In recent years, along with the encouragement of Vietnamese government to develop clean energy, the demand for renewable energy, especially solar energy, has significantly increased. This considerably affects the operation and management of power grids, as well as ensuring energy security for capacity control of solar power projects. However, performance of solar power systems not only depends on the technology used but is also affected by environmental factors, especially weather. Weather conditions, such as temperature [1]–[3], cloud cover [4]–[7], humidity [8]–[10], wind speed [11], [12], can greatly affect the output and efficiency of solar panels [13]. Therefore, carefully analyzing and accurately forecasting the effects of weather on solar power systems is necessary to optimize their performance and increase the reliability of this energy source as well as grid operation. An overview on effects of environmental factors on the performance of solar cells can be found in [14], [15].

This study focuses on evaluating environmental factors such as temperature, humidity, cloud cover, and wind speed, and analyzing their relationship with collected data on Solar Photovoltaic (PV) power output. Research is conducted for a number of solar power systems in Hai Chau District, Da Nang City. Data are scraped and processed using Python programming language.

The paper has following main contributions:

+ The main purpose of the paper is to analyze and evaluate the influence of meteorological variables on solar power output. That is, the study focuses on identifying important weather variables that affect the performance of solar power systems and analyzing the extent of their impact. This provides a more comprehensive view of how weather affects solar power systems. Research results will provide efficient support for the management and optimization of solar power systems and effective management and operation of power grids.

+ The data scrape program written in Python can automatically update and process data of weather variables and solar power output. This not only serves as a tool for the current research but also for other research in which data are a crucial factor such as applying AI to forecast solar power with weather data and generating power as input.

2. DATA COLLECTION, PROCESSING AND DESCRIPTION

2.1. Data collection and processing

In order to automatically collect data from two main sources: meteorological variables and solar power output, a scrape program written in Python is built.

Meteorological data include detailed information of temperature, humidity, cloud cover, and wind speed, are automatically collected from the website *https://www.worldweatheronline.com/*.

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Data on solar power output are collected from 5 rooftop PV sites in Hai Chau District, Da Nang City. For the sake of simplicity, they are denoted as S1, S2, S3, S4, and S5. Technical information related to the five rooftop PV sites is shown in Table 1. Both types of data were collected between January 1, 2022, and November 30, 2023, ensuring reliability and representativeness. Before making analysis, data are preprocessed to remove outliers and combine the corresponding solar power data with the meteorological data into 1 complete data file. Data are then further processed through data transformations including normalization and calculation of daily averages to minimize short-term fluctuations and highlight long-term trends.

Table 1. Technical information related to the 5 rooftop PV sites

PV site	Installed DC capacity (kWp)	Installed AC capacity (kW)	Type of Inverter	Manufacturer	Number of Inverters	Nominal capacity of Inverter (kW)
S1	3.60	3.3	UNO-DM-3.3-TL-PLUS	ABB (Fimer)	1	3.3
S2	5.92	5.0	UNO-DM-5.0-TL-PLUS	ABB (Fimer)	1	5.0
S3	5.92	5.0	UNO-DM-5.0-TL-PLUS	ABB (Fimer)	1	5.0
S4	10.60	8.3	UNO-DM-3.3-TL-PLUS	ABB (Fimer)	1	3.3
			UNO-DM-5.0-TL-PLUS	ABB (Fimer)	1	5.0
S5	4.44	3.3	UNO-DM-3.3-TL-PLUS	ABB (Fimer)	1	3.3

2.2. Data description

Data are collected and organized as in Table 2 and Table 3, in which:

- Timestamp: Time corresponding to the collected data (every 15 minutes), format: day/month/year hour:minute;
- kilowatt-hours: Solar power generated in 15 minutes;
- Power_per_kw: Solar power produced for 1 kW;
- Date: Date of data collection;
- Min: Lowest temperature of the day, in ^oC;
- Max: Highest temperature of the day, in ^oC;
- Weather: Weather on the day of data collection;
- Time: Time corresponding to the collected data (every 15 minutes), format: hour:minute:second;
- Temperature: Actual temperature corresponding to the collected data (every 15 minutes), in ^oC;
- Feel1: Feeling weather corresponding to the collected data (every 15 minutes);
- Feel2: Feeling temperature corresponding to the collected data (every 15 minutes); in ^oC; compared with actual temperature, feeling temperature takes into account wind, humidity and other factors that affect human temperature feeling;
- Rain: Rain corresponding to the collected data (every 15 minutes), measured in mm;
- RainRatio: Rain corresponding to the collected data (every 15 minutes), calculated in %;
- Cloud: Cloud cover, calculated in %;
- Pressure: atmospheric pressure, measured in mb (Atmospheric pressure increases proportionally to temperature and decreases proportionally to humidity);
- Wind: Wind speed, in km/h;
- Gust: Gust wind speed, in km/h.

Table 2. Data structure

```
RangeIndex: 335328 entries, 0 to 335327
Data columns (total 17 columns):
 #   Column          Non-Null Count   Dtype
---  ------          --------------   -----
 0   Timestamp       335328 non-null  object
 1   kilowatt-hours  335328 non-null  float64
 2   Power_per_kw    335328 non-null  float64
 3   Date            335328 non-null  object
 4   Min             335328 non-null  int64
 5   Max             335328 non-null  int64
 6   Weather         335328 non-null  object
 7   Time            335328 non-null  object
 8   Temperature     335328 non-null  int64
 9   Feel1           335328 non-null  object
 10  Feel2           335328 non-null  int64
 11  Rain            335328 non-null  float64
 12  RainRatio       335328 non-null  object
 13  Cloud           335328 non-null  object
 14  Pressure        335328 non-null  int64
 15  Wind            335328 non-null  int64
 16  Gust            335328 non-null  int64
```

3. DATA ANALYSIS METHODS

After preprocessing, data are analyzed using a variety of statistical and data analysis methods:

- Correlation analysis: Use the Pearson correlation coefficient to evaluate the level and direction of the relationship between weather factors (temperature, feeling temperature Feel2, humidity, cloud cover, wind speed) and solar power output. The correlation coefficient provides an index of the degree to which one variable is correlated to the other.

Table 3. Data information

Timestamp	kilowatt-hours	Power_per_kw	Date	Min	Max	Weather	Time	Temper-ature	Feel1	Feel2	Rain	Rain Ratio	Cloud	Pressure	Wind	Gust
1/2/2022 0:00	0.0	0.0	1/2/2022	22	23	Heavy rain at times	0:00:00	22	Moderate rain at times	22	0.6	0%	90%	1019	11	31
1/2/2022 0:15	0.0	0.0	1/2/2022	22	23	Heavy rain at times	0:15:00	22	Moderate rain at times	22	0.6	0%	90%	1019	11	31
1/2/2022 0:30	0.0	0.0	1/2/2022	22	23	Heavy rain at times	0:30:00	22	Moderate rain at times	22	0.6	0%	90%	1019	11	31
1/2/2022 0:45	0.0	0.0	1/2/2022	22	23	Heavy rain at times	0:45:00	22	Moderate rain at times	22	0.6	0%	90%	1019	11	31
1/2/2022 1:00	0.0	0.0	1/2/2022	22	23	Heavy rain at times	1:00:00	22	Moderate rain at times	22	0.6	0%	90%	1019	11	31

- Analysis of Variance - ANOVA: A statistical method that separates an observed aggregate variability found inside a data set into two parts, i.e., systematic factors and random factors.
- Kruskal-Wallis test: An extension of the Wilcoxon rank sum test that can be used to test for differences in the distribution of more than two samples.

Data analysis is an important step in solar technology research and development. It contributes to improving the efficiency and sustainability of this energy source, while minimizing negative impacts on the environment, thus promoting the development of clean and renewable energy sources.

3.1. Correlation analysis

Pearson correlation coefficient is used to evaluate the degree and direction of the relationship between meteorological factors in numerical format (temperature, feeling temperature Feel2, humidity, cloud cover, wind speed) and solar power output. The correlation coefficient provides an index of the degree to which one variable is correlated to the other. The Pearson correlation coefficient helps to understand whether an increase or decrease in weather factors will make an increase or decrease in solar power output. Identifying weather factors that have a strong relationship with solar power output can help us identify the most important factors to optimize output and to invest effectively.

The Pearson correlation coefficient is calculated as follows [16]:

$$\rho_{xy} = \frac{Cov(x,y)}{\sigma_x \sigma_y} \tag{1}$$

in which,

ρ_{xy} : Pearson correlation coefficient
$Cov_{(x, y)}$: Covariance of variables x and y
σ_x : Standard deviation of x
σ_y : Standard deviation of y

Metrological elements with a categorical format (weather, Feel1) are converted into numeric form through one-hot encoding technique before evaluating the correlation in the relationship between these factors and solar power. One-hot encoding will create new columns for each unique value in the "Weather" and "Feel1" columns. After coding, we will calculate the correlation coefficient between these new columns and the "Power_per_kw" column to determine the influence of "Weather" and "Feel1" on solar power.

3.2. Analysis of variance ANOVA

Analysis of Variance (ANOVA) is an analytical tool used in statistics that separates the aggregate observational variation found within a data set into two parts: systematic components and random components.

Systematic components have a statistical influence on a given data set, while random components do not. ANOVA testing is used by analysts to determine the influence of independent variables on the dependent variable in a regression study.

ANOVA coefficient is calculated as follows [17], [18]:

$$F = \frac{MSE}{MST} \tag{2}$$

in which,

F: ANOVA coefficient

MST: Sum of squares of studied factors

MSE: Sum of squares of other factors

P-value: Probability of the data occurring if the null hypothesis H_0 is true. That is, which percentage of the data satisfies the value P. Suppose P = 2%, then 2% of the data in the data set satisfies a certain condition.

3.3. Kruskal-Wallis test

Kruskal-Wallis test [19] is a non-parametric statistical test method used to compare the medians of three or more independent groups.

This method makes it possible to test for differences between groups without having to adhere to the assumptions of normal distribution and equal variance between groups.

Conditions for applying Kruskal-wallis test:

▪ *Data types:*

Kruskal-Wallis test applies to both qualitative and quantitative data.

Qualitative data must be converted into digital format so that it can be calculated.

▪ *Indepence:*

Samples belonging to one group must be independent of each other and be selected independently randomly.

Samples are not taken in pairs or unpaired, each sample belongs to only one group.

▪ *Distribution:*

The distribution of independent variables for each group must be non-normal.

The groups do not have to have the same distribution, there is not a large difference between the variances of the groups.

▪ *Correlation:*

Samples are chosen independently and there is no correlation between them.

4. ANALYSIS RESULTS

Research has been conducted on 5 PV sites in Hai Chau District, Da Nang City (denoted as S1, S2, . . . , S5). Collected data are scraped, processed and analyzed in Python. Data analysis is performed by applying the three popular data analysis methods: Correlation analysis, analysis of variance ANOVA, and Kruskal-Wallis test. It is noted that all five solar power systems considered are located in the same area (Da Nang city) so the weather conditions are relatively similar for these systems. They are all types of rooftop solar power systems with capacities from 3 kW to 10 kW. Their inverters are all from the same manufacturer, i.e., ABB (Fimer). Therefore, the analysis results for them have some similarities with each other. Specific results are shown as follows.

4.1. Results of correlation analysis

Correlation analysis evaluates the strength and direction of the relationship between numerical meteorological variables (temperature, feeling temperature Feel2, humidity, cloud cover, wind speed) and solar power generation "Power_per_kw" of the PV sites.

In this study, it should be noted that we use “Power_per_kw” instead of “Power_per_kwp” for solar power generation. “Power_per_kw” is evaluated according to the nominal capacity of the Inverter (Inverter output) while “Power_per_kwp” is evaluated according to the battery panel (Inverter input), so in principle these two parameters are similar to each other. In the study, the actual data are being taken at the Inverter, so “Power_per_kw” is used to evaluate the output of the Inverter.

The correlation can be clearly seen in Fig. 1 and Fig. 2.

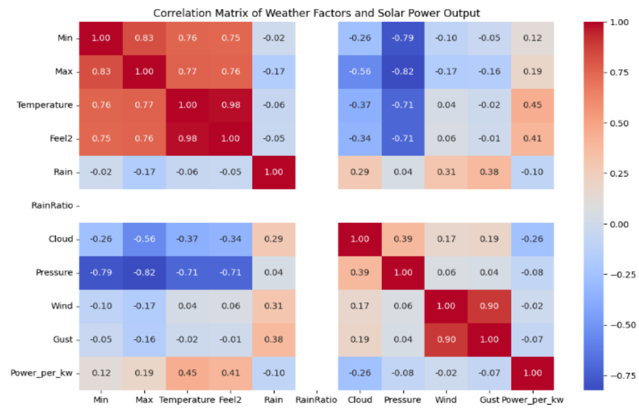


Fig.1. Correlation matrix between meteorological factors 'Min', 'Max', 'Temperature', 'Feel2', 'Rain', 'RainRatio', 'Cloud', 'Pressure', 'Wind', 'Gust' and solar power generation 'Power_per_kw'.

As shown in Fig. 1 and Fig. 2, the comprehensive correlation between weather factors and solar power generation shows certain characteristics:

▪ Temperature: Has a positive relationship (although not very strong) with solar power generation with the correlation coefficient equal to 0.45. This can be explained by the fact that high temperatures are often accompanied by strong sunlight, creating favorable conditions for solar power production.

▪ Feeling temperature (Feel2): Similar to temperature, feeling temperature can also affect solar power generation. However, this relationship needs to be examined and analyzed more thoroughly.

▪ Humidity (Pressure): Appears to have a negative relationship with solar power generation (correlation coefficient equal to -0.08). High pressure is often associated with bad weather or high clouds, which reduces the efficiency of solar energy collection.

▪ Rain (Rain) and Rain ratio (RainRatio): As expected, rain and rain rate have a negative relationship with solar power generation. Rain reduces the efficiency of solar panels by reducing direct sunlight.

▪ Cloud: Similar to rain, clouds also have a negative effect on solar power generation (correlation coefficient equal to -0.26). Clouds reduce the amount of sunlight reaching the solar panel surface.

▪ Wind (Wind) and Wind gust (Gust): Although not clear, there may be a relationship between wind and solar power generation. However, this relationship needs to be further examined.

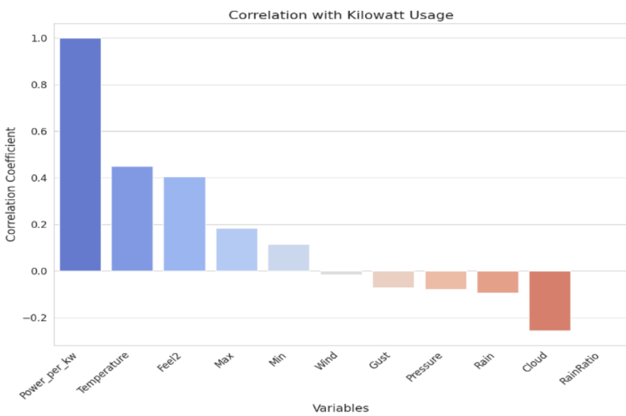


Fig. 2. Correlation coefficient between meteorological factors 'Min', 'Max', 'Temperature', 'Feel2', 'Rain', 'RainRatio', 'Cloud', 'Pressure', 'Wind', 'Gust' and solar power generation 'Power_per_kw'.

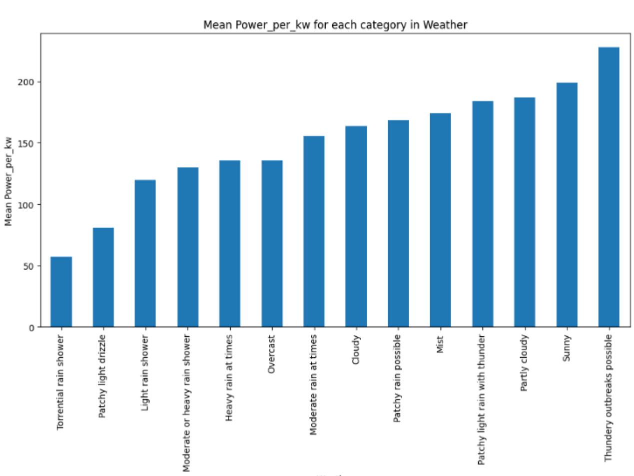
In general, the above results show that meteorological factors such as temperature, pressure, rain, and clouds have a significant impact on solar power generation. This is important in planning of solar power projects.

Figures 3 to 7 show the diversity in how each weather condition and feeling temperature affects solar power output at the PV sites S1 to S5, respectively. It can be seen that certain weather conditions have a strong relationship with solar power output. This helps identify conditions that need attention to optimize solar energy output.

Weather conditions such as "sunny" or "partly cloudy" have a positive correlation with solar power output, reflecting the amount of direct sunlight reaching the PV panels.

Rain and clouds have a negative relationship with solar power output, reducing the efficiency of PV panels in harvesting energy from sunlight.

Comparison between the PV sites also shows a clear similarity in the influence of "Weather" and "Feel1" on solar power output.



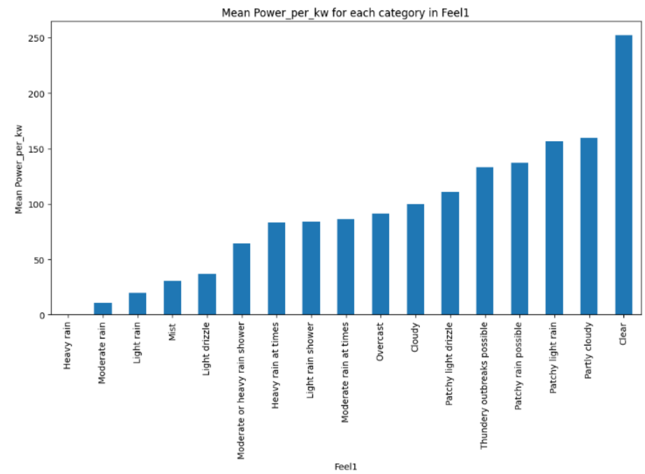
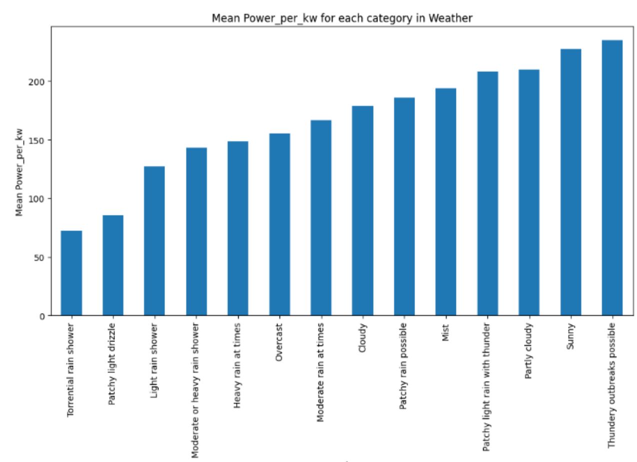


Fig.3. Correlation between "Weather" and "Feel1" on "Power" of the PV site S1.



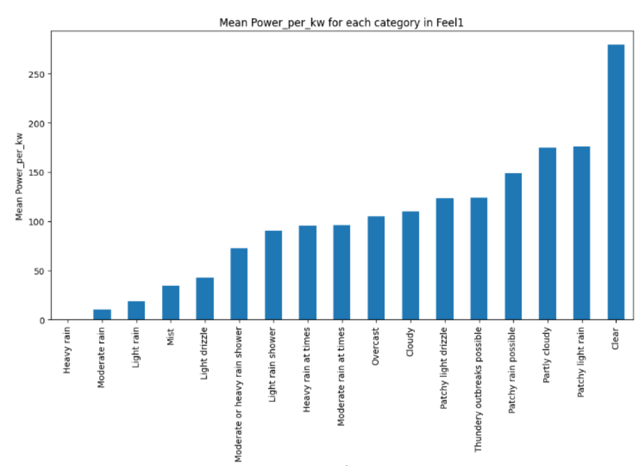
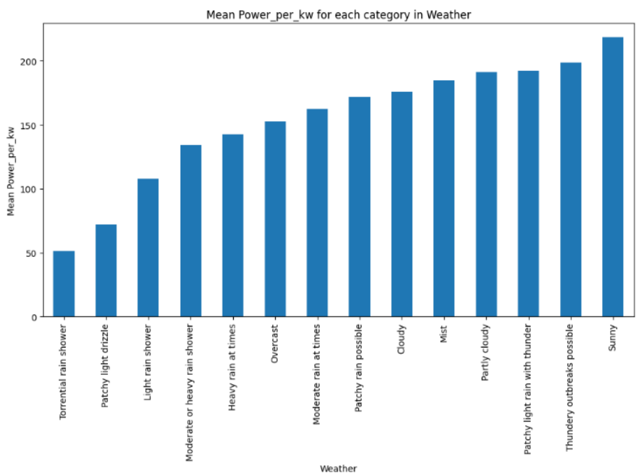


Fig. 4. Correlation between "Weather" and "Feel1" on "Power" of the PV site S2.



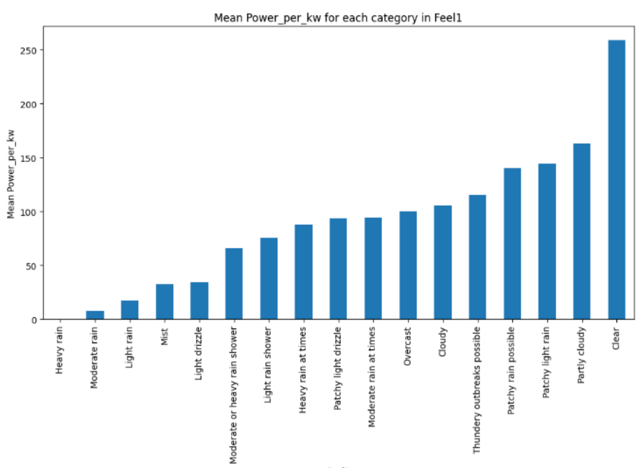
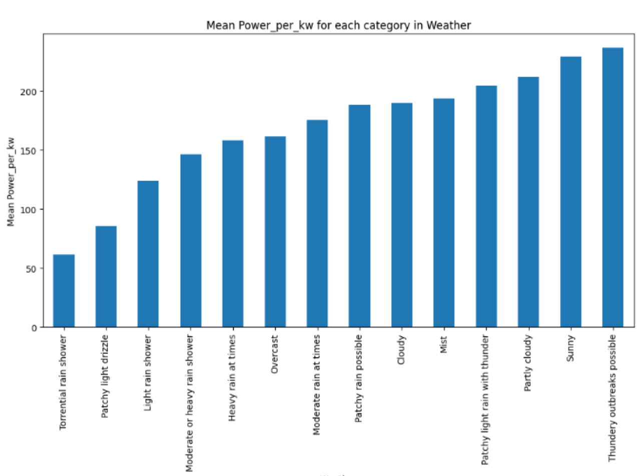


Fig.5. Correlation between "Weather" and "Feel1" on "Power" of the PV site S3.



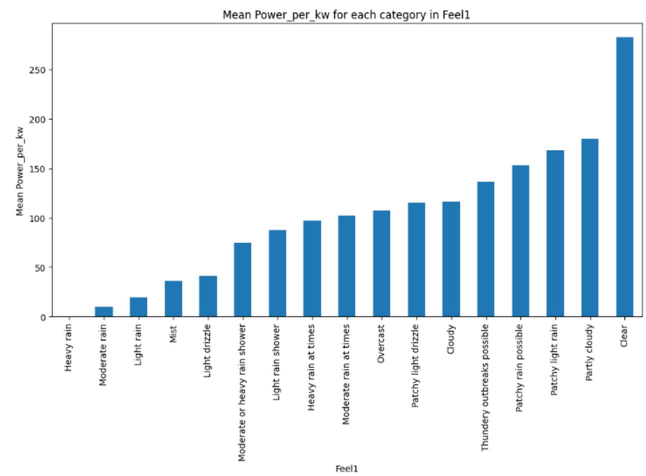
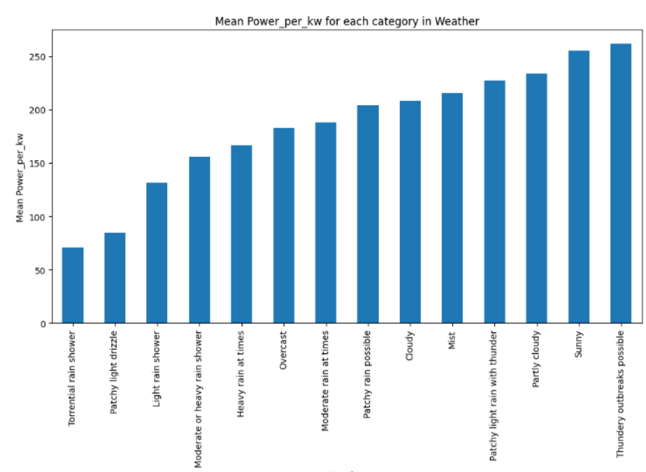


Fig. 6. Correlation between "Weather" and "Feel1" on "Power" of the PV site S4.

■ Generally, from the above results, correlation analysis provides detailed information about the relationship between weather variables and solar power generation, helping to identify conditions that can positively or negatively impact solar power generation.



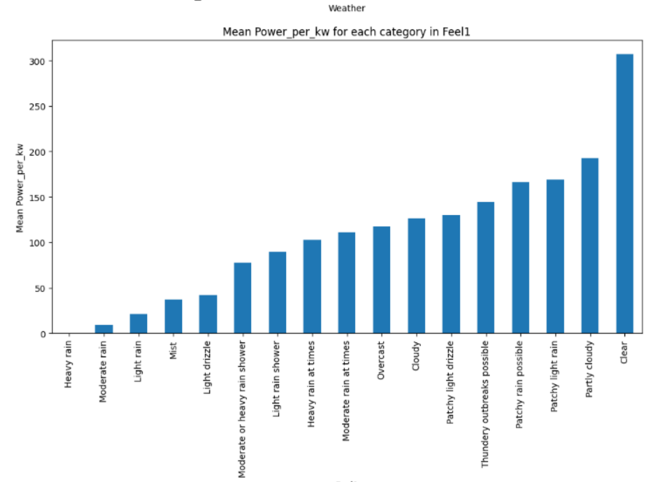


Fig. 7. Correlation between "Weather" and "Feel1" on "Power" of the PV site S5.

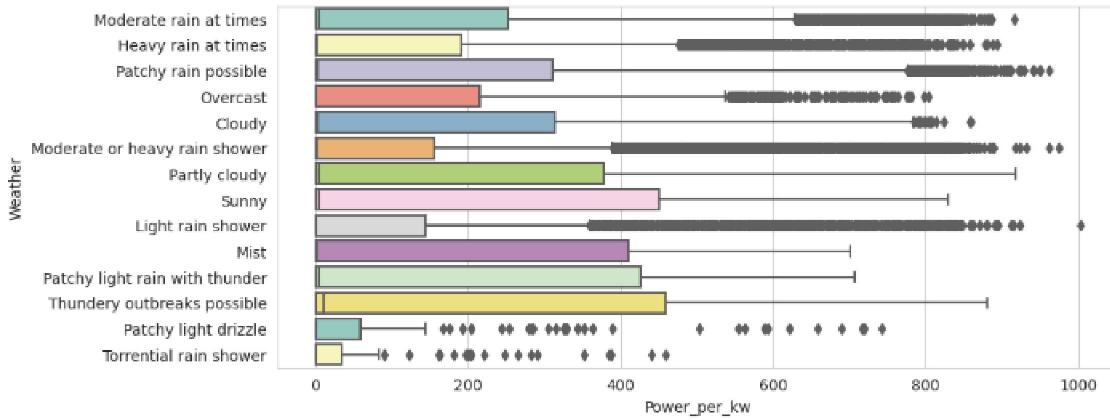


Fig. 8. Solar power generation (Power_per_kW) S1 according to weather factors.

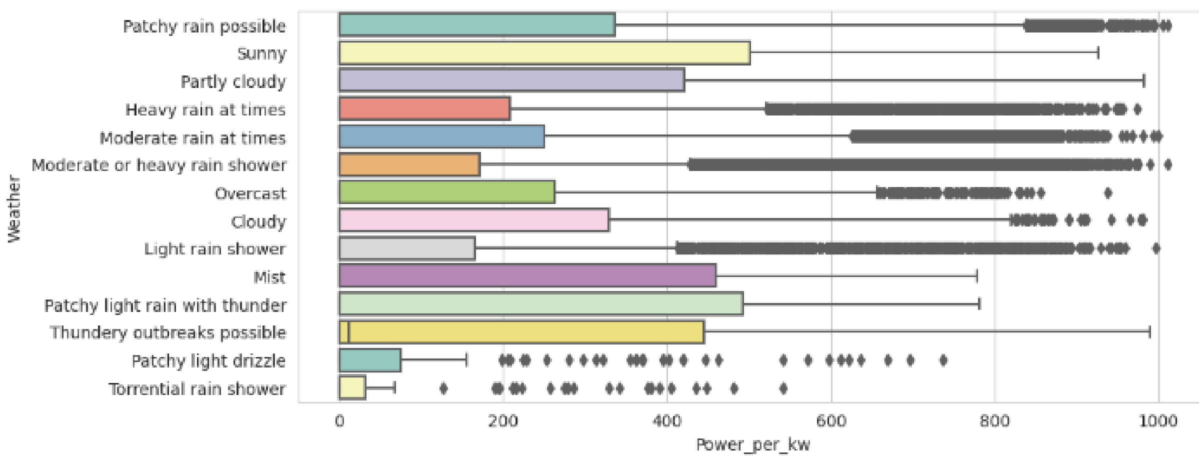


Fig. 9. Solar power generation (Power_per_kw) S2 according to weather factors.

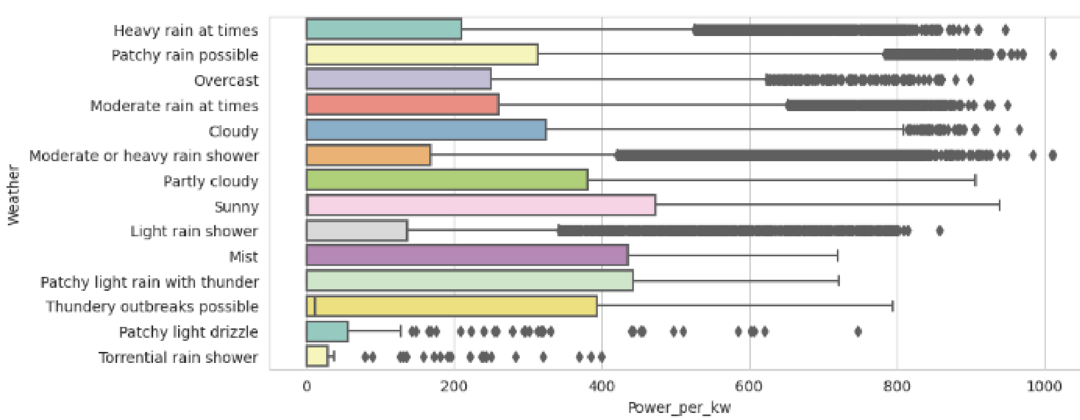


Fig. 10. Solar power generation (Power_per_kw) S3 according to weather factors.

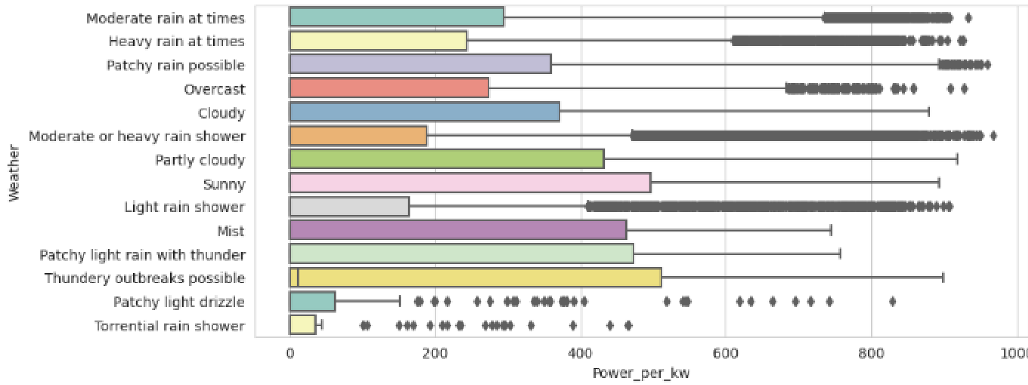


Fig. 11. Solar power generation (Power_per_kw) S4 according to weather factors.

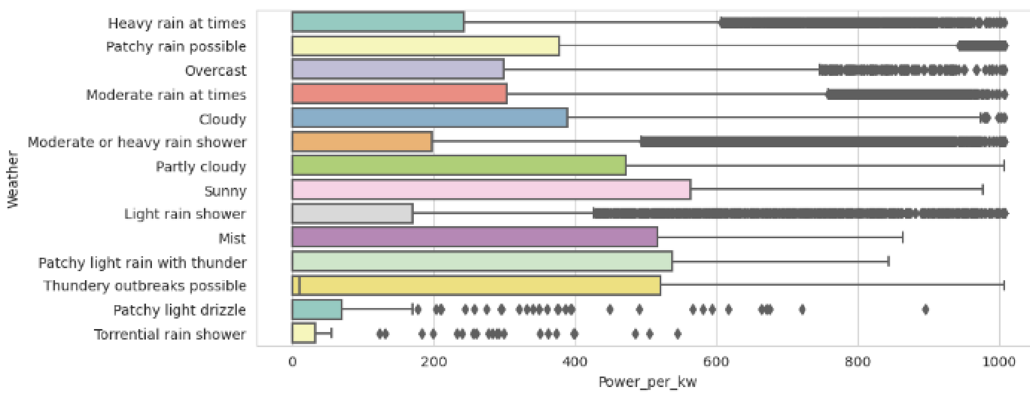


Fig. 12. Solar power generation (Power_per_kw) S5 according to weather factors.

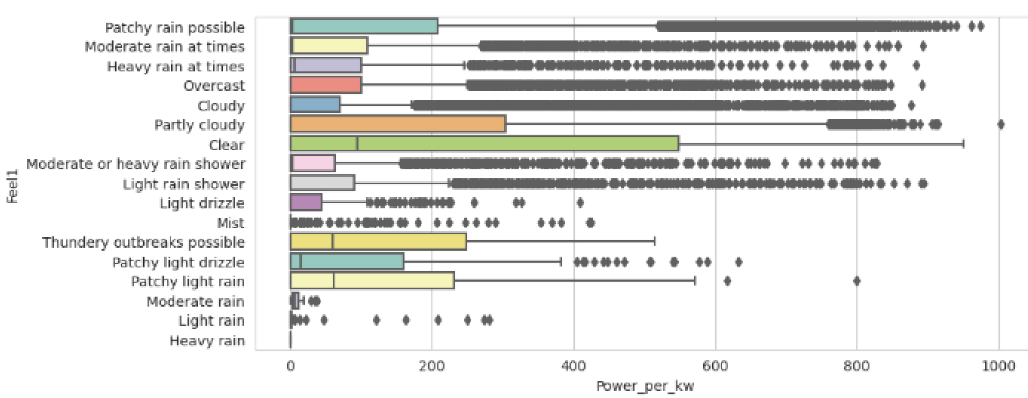


Fig. 13. Solar power generation (Power_per_kw) S1 according to Feel1.

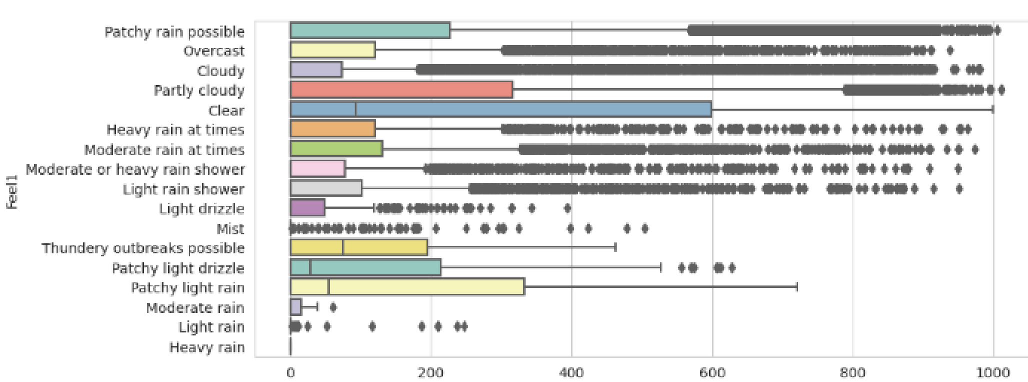


Fig. 14. Solar power generation (Power_per_kw) S2 according to Feel1.

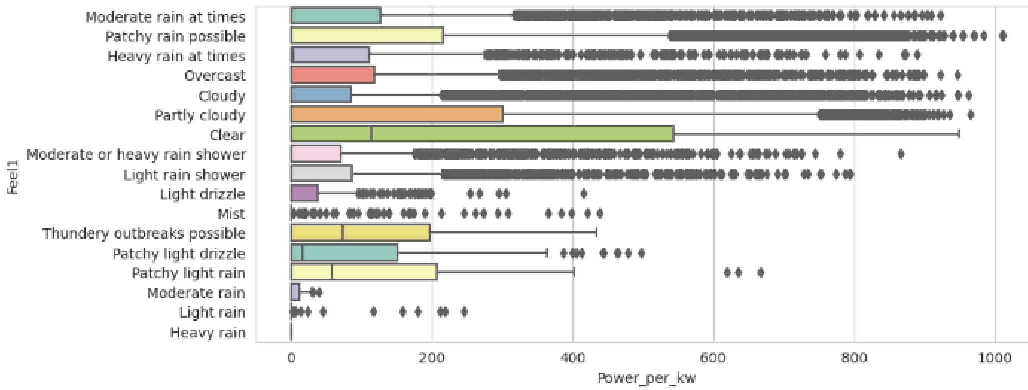


Fig. 15. Solar power generation (Power_per_kw) S3 according to Feel1.

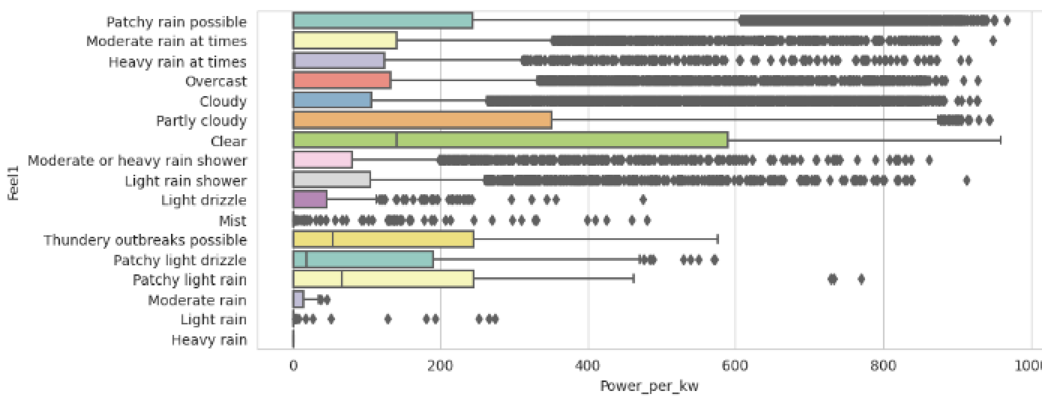


Fig. 16. Solar power generation (Power_per_kw) S4 according to Feel1.

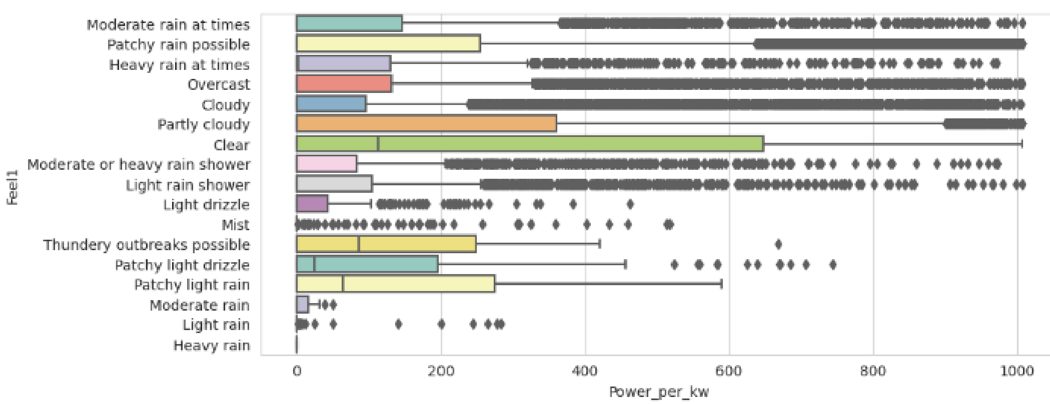


Fig. 17. Solar power generation (Power_per_kw) S5 according to Feel1.

Distributions of solar power generation (Power_per_kw) according to Feel1 of the 5 PV sites can be seen in Figures 13 to 17.

4.2. Results of analysis of variance ANOVA

Distributions of solar power generation data (Power_per_kw) according to Weather of the 5 PV sites are shown in Figures 8 to 12.

Table 4 represents ANOVA analysis for "Weather" and "Feel1" as compared to "Power_per_kw" at 5 PV sites.

Table 4. Relationship of "Weather" and "Feel1" with "Power_per_kw" at 5 PV sites from ANOVA analysis

PV site	Weather F-statistic	Weather P-value	Feel1 F-statistic	Feel1 P-value
S1	46.36	0.00	319.47	0.00
S2	51.28	0.00	318.52	0.00
S3	57.15	0.00	320.31	0.00
S4	53.47	0.00	325.27	0.00
S5	59.11	0.00	318.75	0.00

■ As can be seen from the Table 4, at all PV sites, the factors "Weather" and "Feel1" have a significant influence on "Power_per_kw". Both factors have high F-statistics and very low P-values, demonstrating significant differences in solar power generation under different weather conditions and feeling temperatures.

4.3. Results of Kruskal-Wallis test

Results of Kruskal-Wallis analysis for "Weather" and "Feel1" as compared to "Power_per_kw" for 5 PV sites are represented in Table 5.

■ As can be seen in Table 5, similar to ANOVA analysis, Kruskal-Wallis test method shows that "Weather" and "Feel1" significantly affect "Power_per_kw" at all PV sites. Both factors have high statistical values and very low P-values, demonstrating a significant difference in solar power generation under different "Weather" and "Feel1" weather conditions.

Table 5. Relationship of "Weather" and "Feel1" with "Power_per_kw" at 5 PV sites using Kruskal-Wallis analysis

PV site	Weather Statistic	Weather P-value	Feel1 Statistic	Feel1 P-value
S1	209.84	0.00	3122.80	0.00
S2	254.48	0.00	3140.15	0.00
S3	271.16	0.00	3236.46	0.00
S4	258.74	0.00	3230.00	0.00
S5	269.33	0.00	3188.50	0.00

4.4. Typical chart of solar power according to weather

In this work, typical charts of solar power generation according to each specific weather condition are also provided for 5 PV sites. These charts give essential information for estimating generating power of solar power sources under different weather conditions. These charts, along with load charts and charts of other power sources in the system, will provide necessary information for grid management and operation units.

5. CONCLUSIONS

This work provides clear evidence on the significant influence of meteorological factors on the performance of solar power systems. Temperature and cloud cover are identified as two main factors that negatively affect solar power generation. An increase in temperature leads to a decrease in efficiency of solar panels, while dense clouds reduce the amount of direct sunlight reaching the panels. Humidity and wind speed also have an impact but are not as significant as the above two factors. This result has important implications in the design and management of solar power systems, especially in integrating accurate weather forecasts to optimize solar system performance.

Compared with previous studies, the results found in this work are consistent with the finding of negative effects of humidity in [9] and negative effects of temperature in [20] on solar panel performance. However, this result goes further in assessing the combined impact of many different meteorological factors, instead of just focusing on a single one. This provides a more comprehensive view of how weather affects solar power systems. Although there are similarities with the above two studies on the effects of humidity, this study shows that humidity is not the most important factor.

This work has also been successful in analyzing and clarifying the effects of weather factors (especially temperature, feeling temperature (Feel2), weather type (Weather), and feeling weather (Feel1)) on solar power generation.

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