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CORRELATION ANALYSIS OF PARAMETERS OF CLIMATE GEOINFORMATION SYSTEMS FOR RENEWABLE ENERGY

Abstract. *The paper examines the technical aspects of the integration of distributed renewable generation, in particular solar energy, into the energy system of Ukraine, which is undergoing a large-scale transformation with the aim of increasing reliability, sustainability and efficiency. The relevance of the transition to renewable energy sources in the context of global environmental challenges and Ukraine's obligations to reduce greenhouse gas emissions is considered. Special attention is paid to the analysis of meteorological data as a key factor for accurate forecasting of electricity generation by solar power plants. The main part of the research is focused on the correlation analysis of data from NASA POWER and Open Meteo open climate geoinformation systems. These resources provide access to a wide range of data, including parameters of insolation, air temperature and wind speed, which are critical for modelling and forecasting the operation of solar and wind farms. A comparison of these data with data obtained from weather stations installed at an operating solar power plant was carried out, which made it possible to assess the accuracy and reliability of data from each source. Combining data from NASA POWER, known for its high overall accuracy, and Open Meteo, characterised by higher spatial and temporal resolution, has been found to significantly improve forecast accuracy. This is especially important in the context of operational power system management and load planning. A conclusion was made about the need for a systematic and interdisciplinary approach to solving the tasks. The implementation of modern forecasting methods using machine learning and artificial intelligence algorithms for processing large volumes of meteorological data is recommended. The importance of the development of the national data collection and analysis infrastructure is emphasised, which will increase the reliability and efficiency of the energy system in the face of a growing share of renewable generation.*
Keywords: distributed generation, renewable energy sources, geographic information system, GIS, solar power plant, wind power plant, meteorological data, forecasting, integration, energy system.

1. Introduction

Ukraine, like many other countries around the world, is actively moving towards increasing the share of renewable energy sources, including solar energy, in the energy balance. However, one of the main challenges for the successful integration of solar power plants into the grid is their dependence on weather conditions, which can vary significantly throughout the year [1]. Given that Ukraine is located in a temperate climate zone with a diverse weather pattern, ensuring reliable forecasting of electricity generation becomes critical for the stable operation of the power system [2].

Meteorological data is a key factor in forecasting solar energy production. The use of accurate and reliable data on insolation, air temperature, wind speed and other meteorological parameters allows optimising the operation of solar power plants, predicting their efficiency, and preventing possible energy shortages. As Ukraine faces the need to improve its energy security, this study is of particular relevance [3].

The purpose of this article is to analyse the available open sources of meteorological data in terms of their accuracy and suitability for forecasting electricity generation by solar power plants in Ukraine. This study is aimed at identifying the most effective data sources for use in power grid management systems, as well as assessing possible problems associated with differences in forecasts from different sources.

There is a significant amount of literature on the impact of meteorological conditions on the efficiency of solar power plants [4–7]. Previous studies have highlighted the importance of accurate meteorological data for forecasting electricity production, analysing seasonal variations in insolation, and assessing long-term trends. In particular, studies in different regions of the world have shown that the accuracy of forecasts significantly depends on the quality of meteorological data [8]. In light of this, analysing open data sources available for Ukraine is an important step in ensuring the reliability of forecasts.

The main question of this study is which open sources of meteorological data are most suitable for forecasting electricity generation by solar power plants in Ukraine. It is also important to investigate whether there are significant discrepancies between the forecasts obtained from different sources and what factors may influence these discrepancies.

2. Methodology

This study used meteorological data from several open sources, including such geographic information systems (GIS) as NASA POWER and Open Meteo. In addition, other available sources providing meteorological information were considered, but unfortunately, these services either do not provide information in the public domain at all or provide a very limited number and quality of parameters, which is insufficient for full-fledged research [9, 10]. To better understand further data analysis and the differences in their readings, let's look at how the above-mentioned services collect and analyse data.

2.1. NASA POWER

NASA POWER (Prediction Of Worldwide Energy Resources) builds a database from a variety of sources, including satellite observations, meteorological models and ground stations. The main meteorological data used by NASA POWER comes from satellites that provide global observations of the atmosphere, oceans and land. In addition, NASA uses climate models to analyse the data and make forecasts [11].

Terra and Aqua satellites are equipped with spectroradiometers that measure the amount of solar radiation reaching the Earth's surface. Insolation data are essential for estimating solar energy production [12]. MODIS (Moderate Resolution Imaging Spectroradiometer) is an instrument on board Terra and Aqua that provides information on cloud cover, surface temperature and other meteorological parameters.

Global Circulation Models (GCMs) are used to predict large-scale climate change and atmospheric behaviour on a global scale. These models analyse satellite data to create weather and climate forecasts. MERRA-2 (Modern-Era Retrospective analysis for Research and Applications) is a NASA model that provides a retrospective analysis of the atmosphere and provides data for assessing past climate conditions. Data from MERRA-2 allows tracking long-term trends in insolation, temperature, humidity and other parameters [13].

Access to the processed data is provided through an API, which allows you to obtain information on insolation, temperature, wind speed and other parameters for any point on Earth with a resolution of 0.5.

2.2. Open Meteo

This is a modern platform that specialises in providing data on current weather conditions, short-term forecasts and historical data. Their system is based on weather information models that combine information from various sources, such as global and regional climate models, as well as data from ground-based weather stations.

The Global Forecast System (GFS) is a model developed by the US National Weather Prediction Centre that provides global forecasts of weather factors based on the analysis of atmospheric conditions. The GFS generates forecasts every 6 hours, taking into account various parameters such as temperature, humidity, wind speed and atmospheric pressure [14].

The ICON model (ICOsahedral Nonhydrostatic Model) is used for highly accurate regional forecasts in Europe. This model was developed by the German Weather Service (DWD) and provides high-resolution forecasts for local conditions [15].

Ground-based weather stations in this GIS collect information about actual weather conditions. These stations are located all over the world and provide local data on temperature, humidity, precipitation and other parameters that are important for short-term forecasts.

Data from different climate models are compared and combined to improve forecast accuracy. The Open Meteo API provides accurate forecasts for different geographical regions with a resolution of up to 0.1° and covers all major meteorological parameters such as temperature, humidity, wind speed, precipitation and insolation [16].

3. Methods

Statistical methods of data processing were used to analyse the meteorological data. The data were compared with each other to determine the degree of their discrepancy. Elements of regression analysis were used to determine the correlation between various meteorological parameters and electricity generation.

All calculations were performed using R and Python software packages that provide a wide range of tools for data processing and analysis [17].

The correlation coefficient between two samples X and Y with a normal distribution law was determined by the formula [18]:

$$r = \frac{\mathrm{cov}(x, y)}{\sigma(x)\cdot\sigma(y)} = \frac{\mathbf{M}\left\{(x-\mathbf{M}\{y\})\cdot(y-\mathbf{M}\{y\})\right\}}{\sqrt{\mathbf{D}(x)\cdot\mathbf{D}(y)}},$$

where **cov**(*x*,*y*) is the operator of covariance of random variables *x* and *t*; $\sigma(x)$ and $\sigma(y)$ are the variances of *x* and *y*, respectively.

This indicator allowed us to assess the degree of data consistency and identify possible problems with data reliability. Additionally, a sensitivity analysis was conducted to determine the impact of individual meteorological parameters on the overall electricity generation forecast.

4. Results

4.1. Insolation data analysis

It should be noted that measuring solar insolation is not a simple task. There are dozens of different methods and instruments designed to make such measurements [19]. However, even when using the same instruments and methodologies, the results may differ due to the influence of various factors, such as the variability of atmospheric phenomena (humidity, wind speed, air purity) and the angle of inclination relative to the sun, etc.8].

NASA Power generates about 10 different parameters that allow to estimate solar activity, while Open Meteo, in turn, also has several parameters describing solar activity. For the comparative analysis, we chose the "global horizontal insolation" parameter, since it is present in both services and is most often used in research to predict solar energy generation. The angle of inclination is 0 degrees, i.e. parallel to the ground, which is rarely used in practice, but in order to avoid possible additional errors, this option was chosen [20]. Figure 1 shows 3 curved lines corresponding to the average hourly solar insolation values for April 2021. This time of year was chosen to investigate the difference between data sources in the most variable season - spring. Data for other periods of the year will not be considered in this article. The results of the correlation analysis are presented in Table 1.

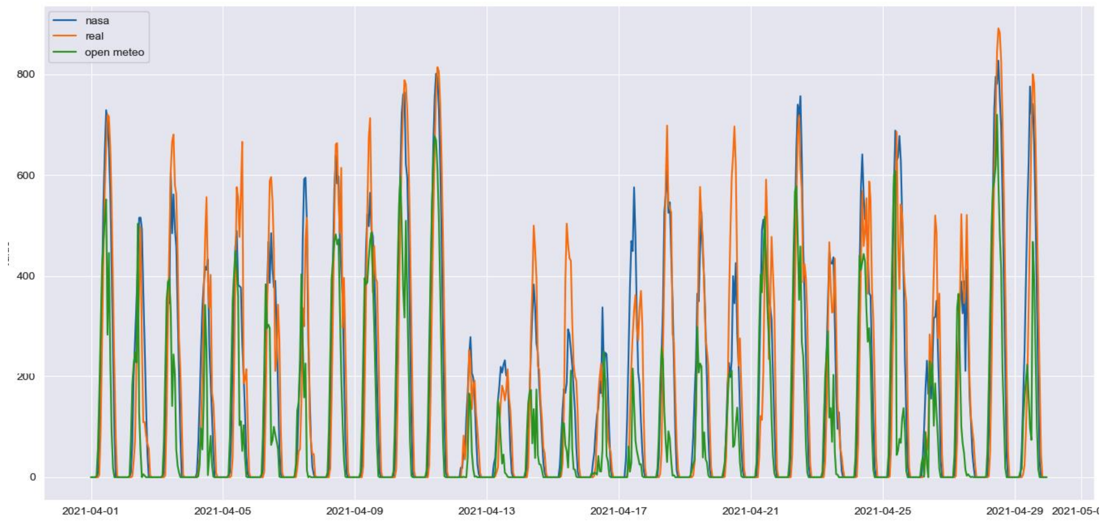

Fig. 1. Comparison of NASA Power and Open Meteo data with actual insolation values for April 2021

Table 1. Correlation matrix of solar insolation data

	NASA	*Real*	*Open-Meteo*
NASA	1	0.90	0.79
Real	0.90	1	0.64
Open-Meteo	0.79	0.64	1

The correlation analysis of the insolation data revealed significant relationships between NASA POWER data, real on-site measurements, and Open Meteo data. The highest *r* value (0.90) between NASA data and real measurements emphasises the high accuracy and reliability of NASA data for forecasting solar energy generation in Ukraine [21]. This is especially important in a changing climate, where accurate insolation forecasts can ensure stable operation of solar power plants and minimise the risk of energy shortages.

The discrepancy between NASA and Open Meteo data (r = 0.79) may be due to different model resolutions and approaches to data processing. For example, NASA uses more detailed climate models that take into account global climate processes, while Open Meteo can use simplified algorithms for more immediate forecasting. Nevertheless, Open Meteo data remains useful, especially for short-term forecasts when data processing speed is a critical factor.

The *r-value* between real measurements and Open Meteo (0.64) indicates that this data can also be used, but with some caveats. For example, in conditions of high weather variability, the use of Open Meteo data may require additional calibration based on local measurements. This will improve the accuracy of forecasts and ensure more efficient management of energy resources.

Insolation analysis that takes into account data for a full day may not fully reflect the actual operating conditions of solar power plants. Including nighttime hours or periods with low insolation, when there is little or no power generation, can distort the results and reduce the accuracy of forecasts due to additional noise.

To achieve more accurate and practically meaningful results, it is important to consider only those periods when insolation really affects generation. This will improve the quality of the analysis and allow for more accurate forecasts. Therefore, considering filtered data that includes only active insolation hours is a necessary step.

The filtered data covers the periods of active solar insolation between 10 am and 6 pm, when the sun is at its highest position in the season selected for analysis.

After filtering the data, the r-value between NASA data and real measurements dropped to 0.87, as can be seen in Table 2. This still indicates a high positive correlation, but slightly lower than the unfiltered data. This may be due to the fact that the filtering reduced the impact of periods with lower solar radiation intensity.

Table 2. Correlation matrix of filtered solar insolation data

	NASA	*Real*	*Open-Meteo*
NASA	1	0.87	0.76
Real	0.87	1	0.74
Open-Meteo	0.76	0.74	1

The correlation between NASA and Open Meteo data also dropped after filtering, to 0.76. Although this still indicates a strong connection.

The correlation between the real measurements and Open Meteo is 0.74, which also indicates a moderately high agreement, which is clearly visible in the graphical visualisation in Figure 2. This may indicate that after filtering, the Open Meteo data reflects the real conditions a little better than it did before filtering.

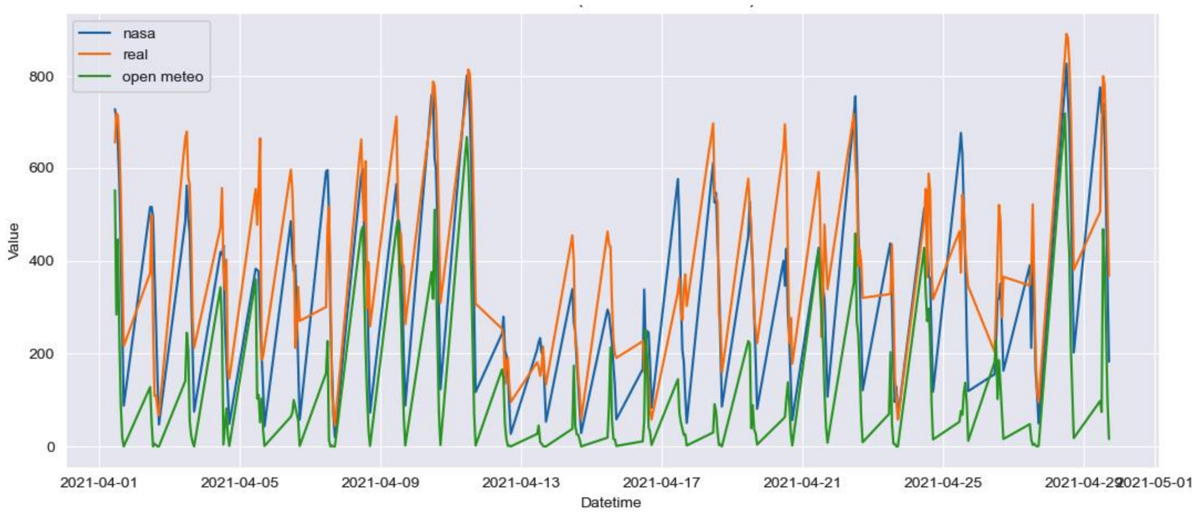

Fig. 2. Comparison of NASA Power, Open Meteo data with actual insolation values for April 2021 from 10 am to 6 pm

The analysis of the filtered data showed that all three data sources continue to demonstrate a high level of consistency, but with a slightly reduced correlation compared to the unfiltered data. This highlights the importance of taking into account periods of active insolation for accurate solar power generation forecasting.

4.2. Analysing temperature data at a height of 2 metres

This review discusses the main meteorological parameters that have the greatest impact on the efficiency of solar panels. The relationship between thermal effects and solar cell performance has been studied many times and indicates a significant degradation of generation levels when the temperature goes beyond normal conditions [22]. Therefore, ambient temperature plays a critical role in the overall efficiency of photovoltaic systems [23].

Consider Fig. 3, which illustrates temperature changes at a height of 2 metres above the ground.

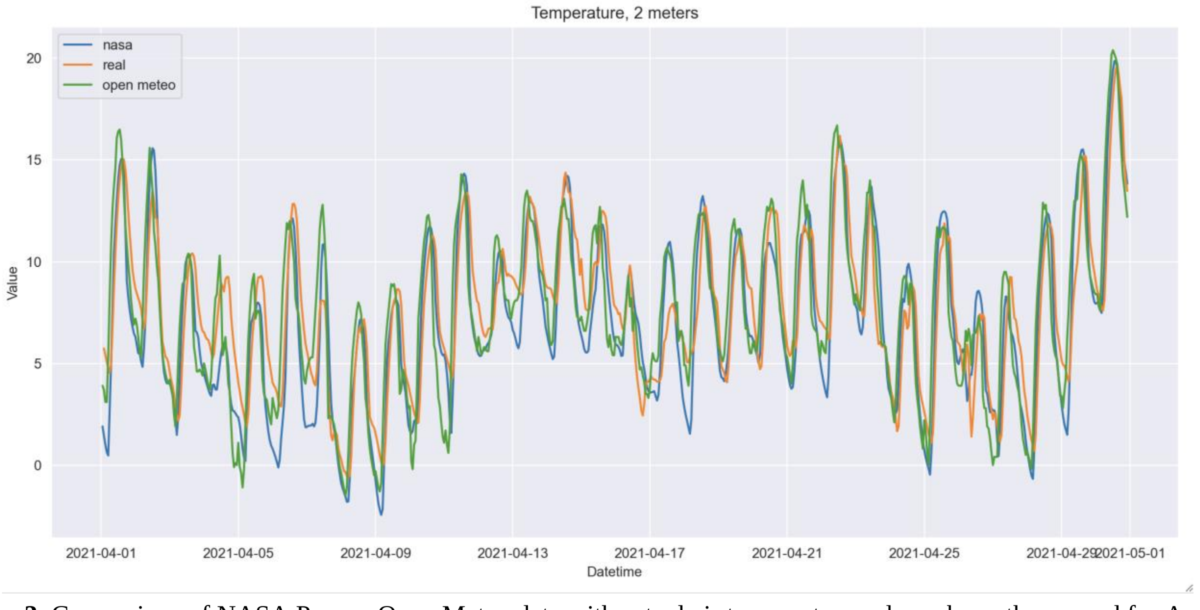

Fig. 3. Comparison of NASA Power, Open Meteo data with actual air temperature values above the ground for April 2021

The blue and green lines (NASA and Open Meteo data, respectively) show high agreement throughout the period. This confirms the high correlation found in the correlation matrix (0.89), making these sources reliable for temperature forecasting.

The orange line, representing the real measurements, also has a high level of agreement with NASA POWER (0.89) and Open Meteo (0.78). Despite some differences, the real data basically follows the same trends as the NASA and Open Meteo data.

While all three sources show similar overall trends, there are differences in short-term temperature fluctuations at some locations. This may be the result of different temporal resolution of the data or different methods of data processing. The correlation matrix is presented in Table 3.

Table 3. Correlation matrix of temperature data at a height of 2 metres

	NASA	*Real*	*Open-Meteo*
NASA	1	0.89	0.89
Real	0.89	1	0.78
Open-Meteo	0.89	0.78	1

The analysis of NASA POWER data revealed a high correlation with both actual measurements and Open Meteo data (0.89), which indicates a close correspondence between these sources in terms of temperature at a height of 2 metres. This consistency makes both datasets reliable for temperature forecasting in the context of solar power plant operations.

Although the correlation between real measurements and Open Meteo is slightly lower (0.78), it is still high enough to be used effectively in forecasts. This confirms that both sources can be used to analyse temperature conditions that affect electricity production. Despite the slight difference in correlation scores, Open Meteo data is also a valuable tool for short-term temperature forecasts, especially in the context of solar power plant management.

4.3. Analysing wind speed data at a height of 10 metres

Wind speed is a critical parameter for the efficient operation of solar power plants, as it affects the cooling of the panels and, consequently, their efficiency. Wind can help to cool the panels, which increases their performance, especially in high temperature conditions. It is also important to consider wind speed when designing solar panel structures, as strong winds can lead to mechanical damage [4, 24].

Therefore, accurate forecasting of wind speeds at different heights is necessary to ensure stable operation of solar power plants and to plan their operation [25]. Figure 4 shows a comparison of wind speed data at a height of 10 metres from three different sources.

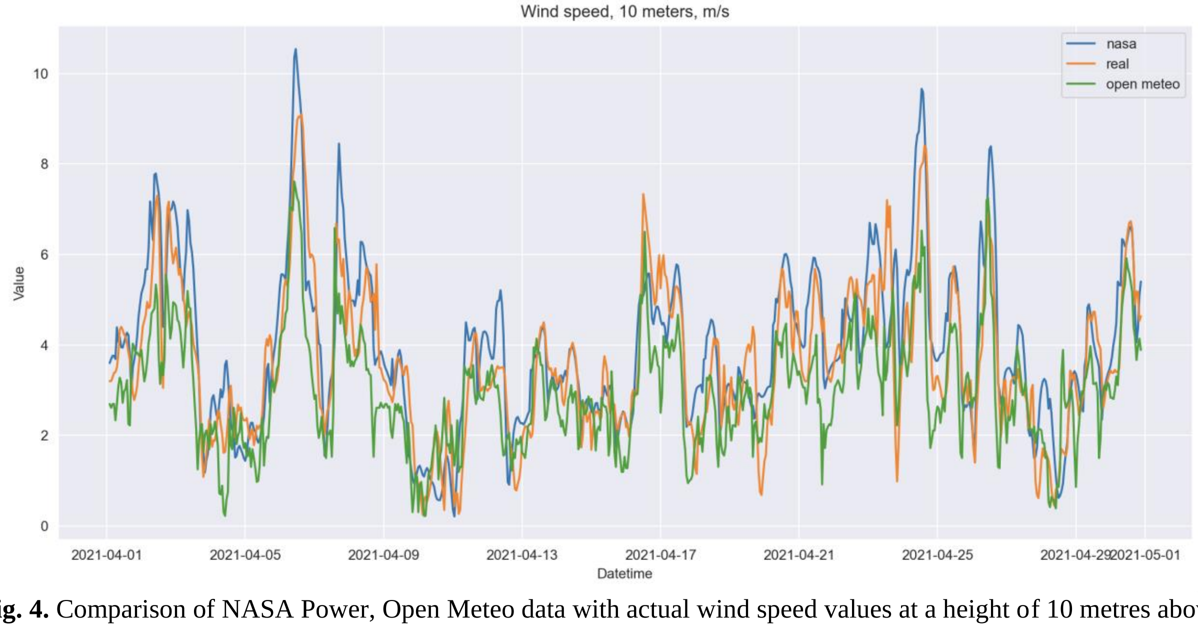

Fig. 4. Comparison of NASA Power, Open Meteo data with actual wind speed values at a height of 10 metres above the ground for April 2021

Table 4. Correlation matrix of wind speed data at a height of 10 metres above the ground

	NASA	*Real*	*Open-Meteo*
NASA	1	0.85	0.83
Real	0.85	1	0.79
Open-Meteo	0.83	0.79	1

The graph and results of the correlation analysis in Table 4 show that the data from NASA POWER and Open Meteo have a high degree of consistency both with each other and with real wind speed measurements. Since wind speed is a very variable quantity, it is necessary to use averages over time, but each source has different methods and periods of data collection, which can explain the lowest correlation among the 3 parameters considered. This is because wind speed, although it affects the efficiency of the panels, has a more cumulative effect and does not affect generation rates instantly. This allows us to consider these sources as reliable for forecasting wind conditions.

5. Discussion

The study shows that the correlation of meteorological parameters between different data sources differs. This can be explained by several reasons:

1. Methods of data collection and processing. Different sources use different approaches to collecting and analysing information. For example, NASA POWER is based on satellite observations and global climate models, which provides high accuracy on a global scale, but may be less accurate in regions with pronounced local climate features.
2. Influence of local conditions. Topography, water bodies, forests, and other geographical features can significantly affect parameters such as temperature and wind speed. Local factors can change even over short distances, making global models less accurate for specific locations.
3. Time scales of forecasts. The accuracy of forecasts depends on their duration. Short-term forecasts may be more accurate for parameters such as temperature and insolation, while long-term forecasts take into account general climate trends that may affect accuracy at a particular point in time.
4. The different levels of correlation between the parameters underline the importance of using a combination of different data sources to forecast electricity generation. Combining information from several resources allows to compensate for the shortcomings of each of them and provide more accurate and reliable forecasts.

Taking into account various meteorological parameters such as insolation, temperature and wind speed allows us to more accurately predict the amount of electricity that will be generated by a solar power plant at a particular time. This, in turn, helps to optimise the operation of the power system, reduce the risks of electricity shortages or surpluses, and increase the overall efficiency of solar resources [26].

6. Conclusions

The study found that NASA POWER data is the most reliable for long-term forecasts due to its high correlation with real measurements. This makes them indispensable for strategic planning of solar power plants, especially when the accuracy of forecasts is crucial, for example, when estimating annual electricity generation or planning large-scale projects.

Open Meteo, although showing a slightly lower correlation, has its advantages. Its higher resolution allows it to be effectively used for short-term forecasts or situations where a quick assessment of meteorological conditions at a particular time is required. This is especially useful for operational management of stations when it is necessary to respond immediately to weather changes.

It is important to note that temperature parameters show the highest stability between both sources, which allows you to expect high accuracy regardless of the service you choose. However, for other parameters, such as wind speed, where there is more variability, differences in accuracy between NASA POWER and Open

Meteo should be taken into account. In particular, it is recommended to use NASA POWER data for forecasting wind risks at solar power plants.

Based on the results obtained, it is advisable to combine data from both sources, adapting them to specific tasks, to achieve maximum forecast accuracy. This approach will compensate for the shortcomings of each resource and increase the overall reliability of forecasts. In situations where the priority is the speed of response, you can rely on Open Meteo, while for strategic planning, NASA POWER is better suited.

Further research should focus on developing forecasting models that integrate data from different sources to improve forecast accuracy, even when data availability or accuracy is limited. Regular validation and comparison of these resources will help to identify discrepancies in a timely manner and adjust models for long-term planning.

In addition, the development of adaptive algorithms that can automatically select the most accurate data for each parameter will help to take into account regional and seasonal characteristics, increasing the reliability of forecasts. Further research should also focus on the impact of additional meteorological parameters, such as cloud cover and humidity, which can significantly improve power generation forecasting.

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КОРЕЛЯЦІЙНИЙ АНАЛІЗ ПАРАМЕТРІВ КЛІМАТИЧНИХ ГЕОІНФОРМАЦІЙНИХ СИСТЕМ ДЛЯ ВІДНОВЛЮВАНОЇ ЕНЕРГЕТИКИ

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Анотація. *У статті досліджено технічні аспекти інтеграції розподіленої відновлюваної генерації, зокрема сонячної енергії, в енергетичну систему України, яка перебуває на етапі масштабної трансформації, з метою підвищення надійності, стійкості та ефективності. Розглянуто актуальність переходу до відновлюваних джерел енергії в контексті глобальних екологічних викликів та зобов'язань України щодо зменшення викидів парникових газів. Особливу увагу приділено аналізу метеорологічних даних як ключового фактора для точного прогнозування генерації електроенергії сонячними електростанціями. Основну частину дослідження зосереджено на кореляційному аналізі даних відкритих кліматичних геоінформаційних систем NASA POWER та Open Meteo. Ці ресурси надають доступ до широкого спектру даних, включаючи параметри інсоляції, температури повітря та швидкості вітру, які є критично важливими для моделювання та прогнозування роботи сонячних та вітрових електростанцій. Проведено порівняння цих даних з даними метеостанцій, встановлених на діючій сонячній електростанції, що дозволило оцінити точність та надійність даних з кожного джерела. Виявлено, що комбінування даних із NASA POWER, відомого своєю високою загальною точністю, та Open Meteo, яке характеризується більшою просторовою та часовою роздільною здатністю, призводить до значного покращення точності прогнозів. Це особливо важливо в контексті оперативного управління енергосистемою та планування навантажень. Зроблено висновок про необхідність системного та міждисциплінарного підходу до вирішення поставлених завдань. Рекомендовано впровадження сучасних методів прогнозування, що використовують алгоритми машинного навчання та штучного інтелекту для обробки великих обсягів метеорологічних даних. Наголошено на важливості розвитку національної інфраструктури збору та аналізу даних, що дозволить підвищити надійність та ефективність роботи енергетичної системи в умовах зростаючої частки відновлюваної генерації.*

Ключові слова: розподілена генерація, відновлювані джерела енергії, геоінформаційна система, ГІС, сонячна електростанція, вітрова електростанція, метеорологічні дані, прогнозування, інтеграція, енергетична система.

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