



EFFICIENT DATA STORAGE SYSTEMS FOR MONITORING AND OPTIMIZING THE PERFORMANCE OF PHOTOVOLTAIC PANELS

ЕФЕКТИВНІ СИСТЕМИ ЗБЕРІГАННЯ ДАНИХ ДЛЯ МОНІТОРИНГУ ТА ОПТИМІЗАЦІЇ ЕФЕКТИВНОСТІ ФОТОЕЛЕКТРИЧНИХ ПАНЕЛЕЙ

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Abstract The advancement of photovoltaic (PV) systems has led to the generation of a massive volume of data related to electricity production, which continues to grow at an exponential rate. This data encompasses information on output power, voltage, frequency, and other electrical parameters, as well as environmental conditions, all of which are recorded in real time. Effective management of this data is essential for optimizing energy production and maintaining both the performance and functionality of the system.

However, traditional centralized data storage methods often prove to be insufficiently flexible and secure for the effective management and protection of data, especially as photovoltaic power plants grow in size and generate increasingly larger volumes of information.

Blockchain technology presents a promising alternative for storing data related to the generation and operational status of photovoltaic installations. Through decentralized storage, it enhances the reliability, transparency, and security of the data. Unlike traditional databases, blockchain is immutable and distributed, allowing for secure storage of information across multiple nodes while preserving its integrity and traceability—even in the event of cyber threats or system failures.

Анотація. Розвиток фотоелектричних (PV) систем призвів до утворення великого обсягу даних, пов'язаних із виробництвом електроенергії, обсяг яких продовжує експоненційно зростати. Ці дані включають інформацію про вихідну потужність, напругу, частоту та інші електричні параметри, а також умови навколишнього середовища, які реєструються в режимі реального часу. Ефективне управління цими даними є ключовим для оптимізації виробництва енергії та підтримки продуктивності й функціональності системи.

Однак традиційні централізовані методи зберігання даних часто виявляються недостатньо гнучкими та безпечними для ефективного управління й захисту інформації, особливо в умовах розширення фотоелектричних електростанцій і зростання обсягів генерованих даних.

Технологія блокчейн є перспективною альтернативою для зберігання даних, пов'язаних із генерацією та операційним станом фотоелектричних установок. Завдяки децентралізованому зберіганню блокчейн підвищує надійність, прозорість і безпеку даних. На відміну від традиційних баз даних, блокчейн є незмінним і розподіленим, що дозволяє безпечно зберігати інформацію на декількох вузлах, зберігаючи її цілісність і відстежуваність – навіть у разі кіберзагроз чи збоїв системи.

Ключові слова: зберігання даних, блокчейн, фотоелектричні панелі, оптимізація продуктивності, декларативне зберігання, системи моніторингу, захист даних, енергетична ефективність.

Keywords: data storage, blockchain, photovoltaic panels, performance optimization, decentralized storage, monitoring systems, data protection, energy efficiency

INTRODUCTION

In the present study, our objective is to explore the possibilities for recording data related to the power generation parameters of photovoltaic installations under various conditions. As a case study, we examine scenarios involving panel shading and contamination, with data being registered within a system utilizing blockchain technology for information management.



Fig. 1. Example of shading of photovoltaic panels affecting system performance.

Рис. 1. Приклад затінення фотоелектричних панелей, що впливає на продуктивність системи

Shading from external objects such as trees or buildings, as well as surface contamination—such as the accumulation of dust, dirt, or debris—can significantly reduce the performance of photovoltaic panels, thereby decreasing their energy efficiency. Monitoring and analyzing data related to shading and contamination events assist operators in identifying periods of reduced performance and taking preventive actions, such as adjusting the orientation of the panels or removing obstructions.

INFLUENCE OF SHADING AND POLLUTION ON PHOTOCONVERSION SYSTEMS..

Shading and fouling of photovoltaic panels, as noted in [1], are key factors that significantly affect the performance and efficiency of solar energy systems. These phenomena lead to a decrease in the efficiency of solar energy conversion, which negatively affects the energy return, return on investment and durability of photovoltaic modules.

Shading, caused by external objects such as buildings, trees or temporary barriers (Fig. 1.), leads to partial or complete overlap of the solar radiation reaching the photovoltaic panels. The electrical characteristics of solar cells are such that even slight shading of a small part of the module surface can cause a disproportionate reduction in its total output power. This phenomenon is due to the nonlinear dependence of photovoltaic conversion on illumination, which makes shading a particularly critical factor for the efficiency of the system.



Fig. 2. Example of dust contamination of photovoltaic panels affecting system performance.

Рис. 2. Приклад забруднення фотоелектричних панелей пилом, що впливає на продуктивність системи.

Another factor that significantly affects the performance of photovoltaic systems is surface contamination, including the accumulation of dust (Fig. 2), dirt, bird droppings and other foreign materials, which also significantly affect their performance. Contaminants not only block sunlight, but also increase the reflectivity of the surface, which leads to a



lower coefficient of efficiency (efficiency) of solar energy conversion. Over time, the accumulation of contaminants can lead to the formation of microcracks and degradation of photovoltaic materials, exacerbating the negative impact on the efficiency of the system.

The combination of shading and pollution poses a synergistic threat to photovoltaic systems, causing cumulative energy losses and accelerated equipment degradation. These factors significantly impact the payback period and overall economic feasibility of using solar technology.

To minimize the negative impact of shading and contamination on photovoltaic systems, it is necessary to implement integrated strategies for monitoring, analyzing and managing these phenomena. The use of automated monitoring and surface cleaning systems allows for rapid response to changes in operating conditions, ensuring stable and high performance of photovoltaic modules throughout their service life.

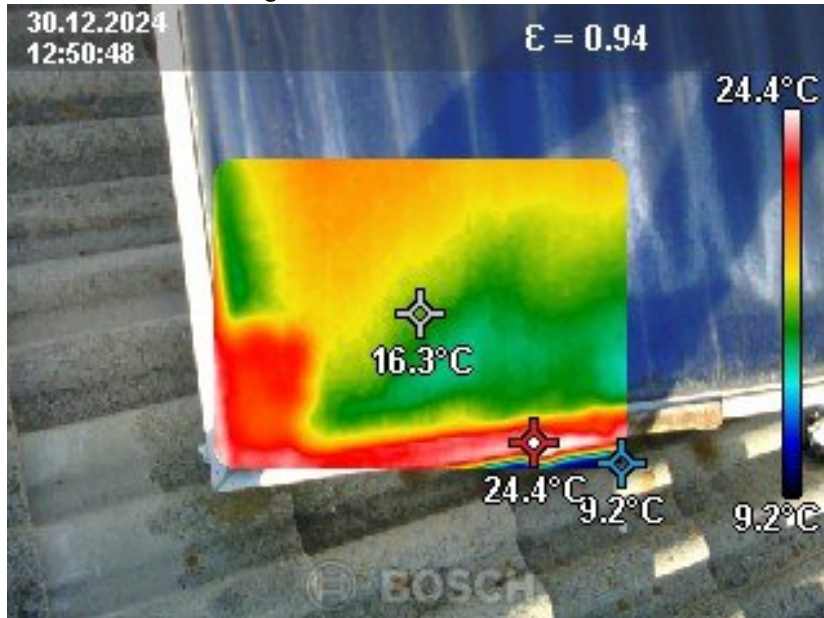


Fig. 3. Example of recording the impact of a combination of shading and contamination of photoconversion panels affecting system performance.

Рис. 3. Приклад запису впливу комбінації затінення та забруднення фотоперетворювальних панелей на продуктивність системи.

DATA REGISTRATION

Data Collection

In photovoltaic systems, data registration is carried out using various sensors integrated into smart inverters and Internet of Things (IoT) class devices. These sensors enable real-time monitoring of critical system parameters, including light intensity, degree of shading, and solar irradiance.

By recording characteristics related to shading, surface contamination, and environmental conditions, the sensors provide essential information for optimizing panel placement, thereby enhancing overall energy efficiency.

To ensure data integrity, each collected data packet is assigned a unique digital signature and timestamp, after which the information is securely recorded onto the blockchain. This process guarantees data reliability and establishes a trustworthy foundation for subsequent analysis.

Data Transmission

During the transmission of data concerning shading and surface contamination, along with overall system performance, to the control unit, blockchain technology functions as a reliable safeguard against unauthorized alterations. Encryption and decentralization ensure the security of this process.

IoT-based recording units capture and transmit the data to blockchain nodes, where it is authenticated and validated. This approach prevents unauthorized access. Even if one of the nodes becomes compromised, the distributed blockchain architecture ensures data integrity, as each node independently stores an identical copy of the recorded information.

The key components that ensure the reliability of such a decentralized system include:

Distributed Ledger Technology (DLT)

Each node in the blockchain network stores its own independent copy of the entire ledger, ensuring redundancy of the information. In the event of tampering or hacking of one of the nodes, the remaining nodes compare their copies to identify discrepancies, if any exist. This mechanism enables the detection and prevention of isolated incidents of unauthorized intervention in the data.

Such a decentralized approach ensures that any attempt at unauthorized access will be detected, and potential unauthorized modifications to the original data can be effectively mitigated.

Consensus Mechanisms

Blockchain is an innovative technology based on consensus algorithms such as Proof of Work (PoW) and Proof of



Stake (PoS). These are algorithms used for verifying existing and adding new records from data packets.

For a record to be accepted into the system, the consensus of the majority of participants in the network is required. This effectively eliminates the possibility of data manipulation by malicious actors. This consensus requirement provides an additional layer of security and data reliability.

Immutability and Traceability

One of the key features of blockchain is its immutability, which is ensured through the use of cryptographic hash functions within the distributed network. When data is added to the blockchain, it is assigned a unique hash that depends on both the content of the current data block and the hash of the previous block. If an attempt is made to alter the data within a given block, the hash changes, invalidating all subsequent blocks, as their hashes will no longer match the preceding ones.

Altering all blocks would require an enormous amount of computational resources to recreate all subsequent blocks, making such data tampering virtually impossible for potential attackers. In this way, all transactions and performance records – such as data from photovoltaic installations – are secured and can be verified by any authorized user. This fosters trust among network participants and ensures data integrity.

Furthermore, this architecture enables transparent accounting systems, which is particularly beneficial in industries where efficiency and performance must be closely monitored, as well as in contexts where protection against data manipulation is essential.

Transparency and Auditability

Blockchain technology is an innovative tool that opens new perspectives for the monitoring and management systems of photovoltaic installations (PV systems).

One of the key advantages of using blockchain in this field is its ability to provide transparency and immutability of data. All transactions and changes to information are recorded on the blockchain, making them accessible to all network participants. This enables operators, investors, and regulators to easily monitor and verify data regarding energy conversion performance.

Moreover, as previously noted, blockchain ensures the protection of data against unauthorized access and manipulation. The cryptographic methods employed within blockchain technology minimize the risks of falsification and fraud, thereby making the system more reliable.

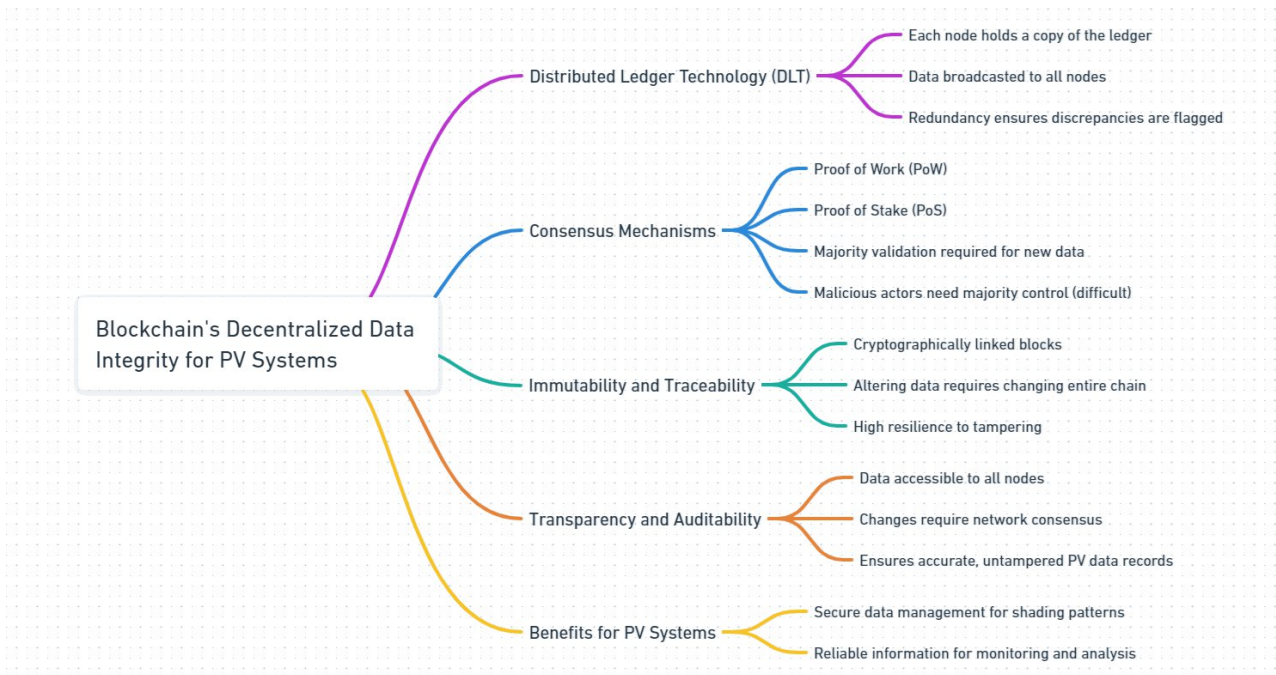


Fig. 4. Illustrates a linear algorithm highlighting the key aspects ensuring the reliability of blockchain technology as applied to photovoltaic systems.¹

Рис. 4. Ілюструє лінійний алгоритм, що виділяє ключові аспекти забезпечення надійності технології блокчейн, що застосовується до фотоелектричних систем.

The decentralized nature of blockchain also contributes to enhancing collaboration among various participants in the renewable energy market. All stakeholders have equal access to the data, which promotes partnerships and the exchange of information. The automation of processes through smart contracts simplifies and accelerates various operations related to the production, sale, and payment for electricity.

Data Verification

Due to its decentralized nature, blockchain eliminates the need for centralized control and minimizes the risks of fraud

¹ The image was generated using ChatGPT according to the description of the authors.



and human error.

In the energy sector, the application of blockchain can lead to significant changes in accounting and energy management practices. For example, blockchain can assist in tracking the origin of energy, enabling consumers to verify that the energy they consume is "clean."

Data regarding shading, surface contamination, and other indicators recorded on the blockchain can contribute to more efficient management of the electrical grid load. The use of smart contracts can automate transactions between energy producers and consumers, minimizing the likelihood of disputes and simplifying the settlement process.

Cross-Referencing with Historical Data

The process of comparing newly incoming data with previously registered and stored data enables the analysis of changes in energy generation due to shading and surface contamination of the panels, and it is a key element in ensuring the reliability and accuracy of photovoltaic panel performance assessment. Regular registration over extended periods helps identify anomalies caused by various factors, such as changes in weather conditions, surface contamination of the panels, or mechanical damage.

The use of blockchain technology to store historical shading and contamination data ensures security and prevents possible manipulation of information, which is a crucial aspect for maintaining transparency and trust in the system. If significant deviations from expected patterns are detected, they can be flagged for further investigation, allowing specialists to make informed and well-founded maintenance decisions. This, in turn, contributes to improving efficiency and extending the operational life of the equipment.

The integration of advanced data analysis technologies and blockchain into photovoltaic systems can significantly enhance the quality of decision-making and improve the efficiency of resource management.

Consensus Mechanisms in Verification

Blockchain employs consensus algorithms, like Proof of Work (PoW) or Proof of Stake (PoS), to validate each new shading data entry. For the data to be permanently recorded, the network requires a majority of nodes to reach consensus on its validity. This requirement of majority agreement prevents unauthorized changes or false data entries, as an attacker would need to control most nodes to manipulate records. Consensus mechanisms ensure that data verification is both secure and transparent, further reinforcing the trustworthiness of the data.

Automated Verification and Smart Contracts

Smart contracts are a powerful tool for automating data verification and management processes. They can significantly simplify various business operations and enhance their efficiency.

In our example, involving thresholds of shading intensity and surface contamination, a smart contract can be configured to manage different aspects of electricity generation as follows:

Automated Data Registration: The system will utilize digitized shading and contamination data obtained from sensors or other information sources.

Parameter Control: The collected data will be compared against predefined criteria and thresholds.

Conditional Execution of Actions: If the data meet the specified conditions, the smart contract can automatically execute certain actions, such as confirming the fulfillment of contractual conditions, initiating payments, or notifying relevant stakeholders.

Ensuring Transparency: All operations performed by the smart contract will be recorded on the blockchain, ensuring transparency and data accessibility for all participants.

Such an approach significantly reduces the risk of human error, accelerates processes, and enhances their reliability and efficiency. Furthermore, automation allows for a reduction in management and verification costs, which is a crucial advantage for businesses.

Data Storage

After a thorough audit, data regarding emerging issues—such as shading and surface contamination in our case—are securely stored on the blockchain or in a database integrated with the blockchain. By storing incident information on the blockchain, photovoltaic system operators can be assured that the data remains immutable and cannot be manipulated or deleted once recorded.

The inherent security and redundancy of blockchain technology provide protection against unauthorized access to the data. This ensures that changes, such as those caused by shading over time, can be tracked without compromising the integrity of the information. Moreover, stakeholders can access previously stored data with full confidence in its authenticity.

Data Replication and Redundancy

In the world of blockchain technologies, each node in the network stores a complete copy of the system register, which guarantees the system's stability against failures and attacks. In the context of photovoltaic systems, this is particularly important, as data on panel performance, shading, and surface contamination can significantly impact operational efficiency and influence decision-making processes.

The redundancy of data within the blockchain ensures the reliable preservation of information related to shading and contamination. This enables users and system operators to always have access to up-to-date data for optimizing performance and identifying potential issues. Additionally, it simplifies analysis and reporting processes, as all information is stored in an immutable and secure form.

The use of blockchain can significantly enhance trust among market participants. Information about shading, contamination, and system performance will be accessible to all relevant stakeholders, ensuring its immutability and



security. As a result, such systems can become more transparent and efficient, which is particularly important amid the growing competition in the renewable energy market.

Scalability and Storage Efficiency

Managing data related to emerging issues in photovoltaic systems presents a challenge that requires flexible solutions, particularly given the continuously increasing volume of information. In this regard, blockchain technology offers many advantages, such as decentralization, security, and data immutability. However, using blockchain to store large volumes of information may not always be the most efficient approach.

Eliminating less significant data would help reduce network load and optimize system performance, while also facilitating easier access to truly critical information. Hybrid models, as previously discussed, combine the advantages of blockchain and traditional data storage methods. This approach is logical, as blockchain ensures the integrity and security of key information, while larger volumes of data can be stored in specialized systems that are more efficient for handling big data.

Additionally, the use of external data links within the blockchain would allow for a maintained degree of transparency and accessibility of information, which is crucial for systems requiring auditing or tracking. In such cases, the combination of blockchain technologies with traditional storage systems opens new horizons for data management and the development of photovoltaic systems.

Data Analysis

Blockchain technology provides a reliable foundation for storing data related to various incidents, serving as the basis for detailed analysis of their impact on energy production. The decentralized nature of blockchain ensures the security of all data, including the duration, intensity, and frequency of shading and surface contamination. This eliminates the possibility of unauthorized alterations to the information, which is a critical factor for conducting accurate analysis within photovoltaic systems.

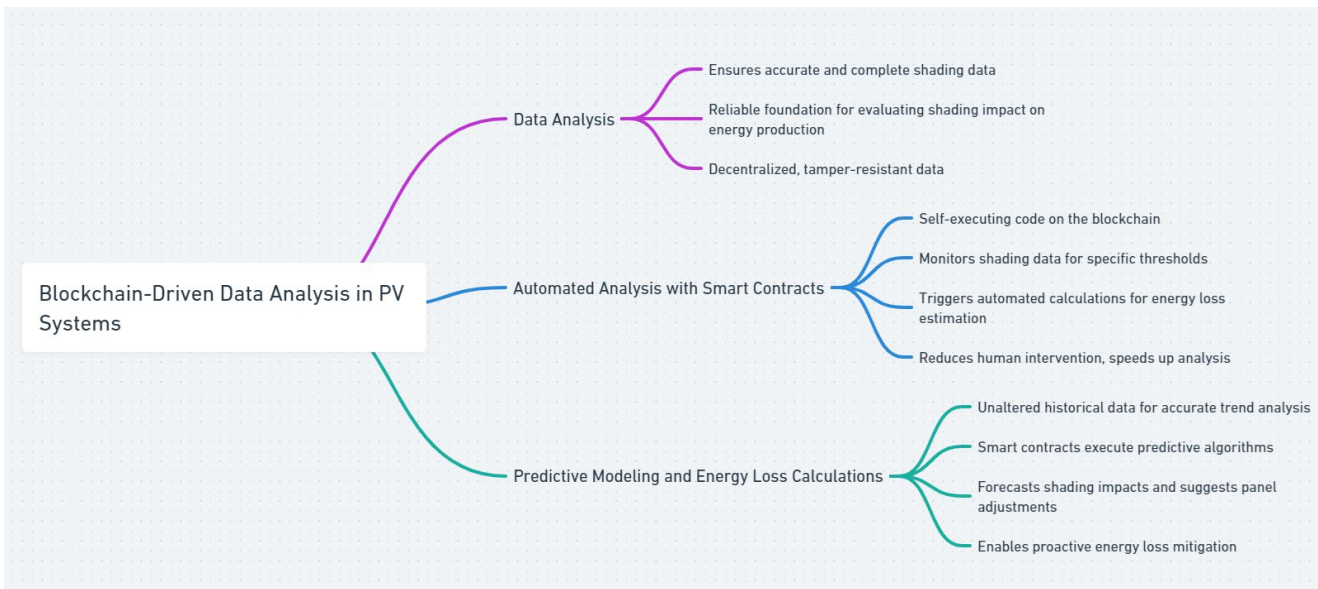


Fig. 5. The interpretation of the technology of data analysis of the effectiveness of phototransformation systems registered in the blockchain network is linear and algorithmic².

Рис. 5. Інтерпретація технології аналізу даних ефективності систем фототрансформації, зареєстрованих у мережі блокчейн, є лінійною та алгоритмічною.

Automated Analysis with Smart Contracts

Smart contracts are self-executing programs stored on the blockchain. They play a key role in automating data analysis processes.

For example, a smart contract can be configured to monitor changes in shading and surface contamination levels, including daily or seasonal fluctuations. When the shading level reaches a critical threshold or exceeds predefined parameters, the smart contract automatically triggers a computational process to assess the potential energy losses caused by shading.

This automation significantly reduces the need for human intervention and greatly accelerates the analysis process. Operators can quickly adjust the parameters of photovoltaic systems based on real-time data obtained through this mechanism.

Predictive Modeling and Energy Loss Calculations

The integration of blockchain and machine learning technologies into photovoltaic systems offers new opportunities for optimizing and effectively managing energy resources.

The application of immutable and transparent trusted data enables analysts to build more accurate predictive models,

² The image was generated using a custom GPT according to the description of the authors.



which is particularly important given the variability of solar energy.

Smart contracts operating within the blockchain framework are capable of automating the processes of data collection and shading analysis. They can be configured for specific conditions, such as triggering forecasting algorithms based on the time of year, weather conditions, or other factors that influence shading levels. This allows not only for the identification of trends but also for the assessment of potential risks and impacts.

Machine learning models assist in building adaptive systems that can self-train on new data. For example, the system could adjust its forecasts, thereby reducing potential energy losses. If the system predicts an upcoming period of increased shading, it can recommend optimizing the tilt angle of the solar panels or schedule operational intervals based on anticipated changes.

The synergy of blockchain, predictive modeling, and machine learning will significantly enhance the management of photovoltaic systems, improve their resilience and efficiency, and promote the better utilization of renewable energy sources.

Documentation and Reporting

Blockchain is a modern technology that ensures transparency and reliability in the field of documentation and reporting. It creates an immutable and constantly accessible database for shading and performance analysis results, guaranteeing their accuracy and immutability.

Each record on the blockchain—including events related to changes in energy generation conditions, performance indicators, and maintenance data—is securely stored. This enables effective reporting for photovoltaic systems, as all data is accessible and can be easily traced.

Timestamped Records and Audit Trails

Blockchain automatically records the timestamp of each transaction, significantly simplifying the reporting process. These reports provide accurate information about the timing of shading and surface contamination events, reflect historical trends, and document measures taken to mitigate their effects.

Thanks to such timestamping, operators can identify patterns in the variation of shading intensity over time. For example, seasonal changes can be tracked, or the dynamics of shading intensity can be analyzed, creating a complete and chronologically verified history of shading events.

For auditors, these records become an indispensable tool for regulatory compliance. They can easily trace all activities related to shading and be assured of the validity of the data.

THE ROLE OF MACHINE LEARNING

Machine learning is a powerful tool that can significantly enhance the efficiency, reliability, and forecasting capabilities of photovoltaic systems (PVS). By applying machine learning algorithms to analyze large volumes of data related to solar plant operation, shading conditions, and environmental parameters, we can identify complex patterns and relationships that often remain undetected by traditional analysis methods.

This ability to quickly and accurately uncover hidden structures in the data opens up many opportunities for substantial improvements:

- Optimization of solar plant operation in real time.
- Forecasting of energy output based on weather conditions and panel contamination levels.
- Early detection of component failures and degradation, reducing maintenance costs.
- Development of more resilient energy management strategies.

Thus, integrating machine learning methods into the infrastructure of solar power plants contributes to more rational use of solar energy and enhances the overall efficiency of power generation facilities.

In the practice of analyzing and managing photovoltaic systems, a wide range of machine learning algorithms is employed, each designed to solve specific problems:

- **Neural Networks (ANN, CNN, RNN)** are particularly effective for tasks such as output power forecasting, anomaly detection, and time-series data processing. For example, Convolutional Neural Networks (CNN) can be used to analyze drone images to detect contamination or mechanical damage to panels.
- **Support Vector Machines (SVM)** are used to classify system states (normal/faulty) and to identify causes of performance degradation.
- **Decision Trees and Ensemble Methods** (Random Forest, Gradient Boosting) are commonly applied for fault diagnosis and for evaluating the impact of various factors (e.g., temperature, angle of incidence, shading) on system performance.
- **Clustering Algorithms** (e.g., K-means clustering) assist in data segmentation and detection of abnormal behavior, which may indicate potential failures.

Real-world applications of machine learning in photovoltaic systems include:

- **Google DeepMind's Power Forecasting Project:** ML was used to accurately predict solar energy output based on weather data. This improved forecasting accuracy by 20% compared to traditional models.
- **SunPower**, one of the largest solar panel manufacturers, uses machine learning algorithms to detect module degradation and automatically allocate service resources, thus reducing maintenance costs and extending the lifespan of installations.
- **PVInsight Research Project:** Neural network-based models were developed to determine the degree of panel contamination, allowing for the optimization of cleaning schedules and avoiding unnecessary maintenance expenses.

Integrating these algorithms into the management systems of photovoltaic installations not only improves system



performance but also ensures resilience against external influences, reducing the impact of factors such as dust, shading, weather conditions, and equipment degradation.

Table 1. Comparative Table of Machine Learning Algorithms Applied in Photovoltaic (PV) Systems, Indicating Their Tasks, Advantages, and Real-World Application Examples.

Machine Learning Algorithm	Type of Task	Advantages	Example Applications
Neural Networks (ANN, CNN, RNN)	Energy output forecasting, image analysis, anomaly detection	High accuracy, ability to detect complex dependencies	Analysis of drone images of panels, weather-based energy output forecasting (Google DeepMind)
Support Vector Machines (SVM)	System state classification, fault diagnosis	Performs well on small to medium datasets, high accuracy	Classification of fault types in panel systems
Decision Trees / Random Forest / Gradient Boosting	Analysis of influencing factors, diagnostics, state prediction	Interpretability, robustness to noise, high ensemble accuracy	Evaluation of the impact of temperature, pollution, and shading on output power
Clustering (K-means, DBSCAN, etc.)	Data segmentation, anomaly detection, operation mode grouping	Does not require labeled data, finds hidden patterns	Grouping panels by behavior, detection of unusual deviations from norms
Linear/Logistic Regression	Simple forecasting, binary classification	Simplicity, good interpretability	Degradation forecasting, basic fault diagnostics
Hybrid Models (e.g., LSTM + CNN)	Time-series and visual data processing simultaneously	High accuracy and versatility	Forecasting output based on weather and panel image analysis

Performance Forecasting and Predictive Maintenance

One of the most significant aspects of using machine learning in photovoltaic energy systems is the forecasting of their performance.

Machine learning models, based on historical data such as shading parameters, weather conditions, and generation volumes, are capable of predicting future energy production with high accuracy. These forecasts play a crucial role in efficient energy consumption planning, preventing supply interruptions, and optimizing resource distribution within the grid infrastructure.

Integrating such models into the management system makes it more flexible and adaptive to seasonal and short-term environmental changes, thereby improving the overall efficiency and reliability of operation.

Additionally, the use of machine learning as part of predictive maintenance ensures continuous real-time monitoring of system components' condition. Algorithms are capable of detecting efficiency declines in individual modules—due to factors such as contamination, degradation, or hidden defects—even before critical failures occur.

This approach minimizes transactional costs through early problem detection, reduces production losses, and extends equipment lifespan. As a result, it increases the return on investment in solar energy projects, enhances infrastructure reliability, and ensures the sustainability of the entire energy system.

Optimization of Energy Efficiency

In the context of renewable energy sources, machine learning represents an extremely important and timely topic. It has the potential to significantly enhance the efficiency of photovoltaic systems by adapting their operation to changing environmental conditions in real time. Several key aspects deserve particular attention:

- **Real-Time Data Analysis:** Machine learning algorithms are capable of analyzing massive datasets collected from photovoltaic panels, including information about solar activity, air temperature, panel tilt angles, and many other parameters. This opens opportunities for forecasting future changes in these parameters and proactively adapting system operation.
- **Optimization of Inverter Performance:** Machine learning also contributes to predicting optimal inverter settings, enabling more stable operation under varying load and external conditions. This may involve adjusting conversion factors, regulating frequency, or modifying voltage to minimize energy losses.
- **Reinforcement Learning:** One actively utilized approach in such systems is reinforcement learning. Algorithms can "learn" from mistakes and successes in real time, continuously improving the management strategy of the photovoltaic system to achieve maximum performance under any conditions.
- **Intelligent Forecasting:** In addition to real-time adaptations, algorithms can predict weather conditions or long-term changes in irradiance, helping the system to adjust proactively to new conditions. This is particularly important for large solar farms, where such information contributes to more efficient planning and management.

The implementation of such technologies not only enhances the performance of photovoltaic systems but also reduces operational costs, improves equipment longevity, and ultimately accelerates the transition to more sustainable energy



sources.

Automatic Defect Detection and Fault Diagnosis

Machine learning is a powerful tool capable of significantly improving the monitoring and maintenance processes of photovoltaic systems. Its application for anomaly detection and defect diagnostics ensures high reliability and performance of these systems.

In photovoltaic devices such as solar panels, any damage or defect can lead to a reduction in output power. Machine learning algorithms are capable of analyzing panel power data, revealing hidden patterns and anomalies. For instance, a sudden drop in power output in a specific section of the system may indicate panel damage or an inverter issue. Computer vision algorithms can process images and infrared imagery obtained from drones or other sensors to detect defects such as cracks, overheating, dirt accumulation, or shading. For example, infrared cameras can identify "hot spots"—areas of panels that overheat due to internal defects.

Upon detecting an anomaly or defect, machine learning models can classify it by type. This capability allows not only for the identification of the issue but also for recommending optimal solutions, such as cleaning the panels, replacing a damaged system component, or servicing the inverter.

One of the main advantages of using machine learning is the possibility of automatic real-time fault diagnostics. Systems based on such algorithms can automatically notify operators of identified problems and suggest solutions, significantly speeding up the fault identification and correction process. Thus, the application of machine learning in photovoltaic systems not only enhances performance and reduces the need for regular visual inspections but also improves the overall quality of maintenance and operation of these systems, reducing costs and boosting their efficiency.

Data-Driven Insights for Strategic Planning

Machine learning represents a powerful tool that provides new opportunities for the efficient and intelligent operation of photovoltaic systems. It enables the acquisition of accurate and reliable information, forming the basis for strategic planning and long-term investments.

Machine learning models, analyzing data related to emerging incidents, changes in energy production indicators, and maintenance reports, are capable of identifying long-term patterns. This significantly improves the design and scheduling of maintenance for such systems. For example, machine learning can detect that certain regions experience increased shading and surface contamination during the winter months. This allows operators to proactively adjust panel settings and seek solutions to minimize the effects of shading and contamination. These data also play a critical role in decision-making regarding the modernization and expansion of systems, ensuring the effective utilization of photovoltaic installations to meet future energy demands.

By using machine learning, operators can maximize their investments and contribute significantly to achieving sustainable energy goals. Machine learning not only analyzes current and historical data but also takes into account external factors such as weather conditions, air pollution, and changes in panel tilt angles. This allows for more accurate forecasting of long-term system performance. These forecasts can be utilized to improve energy demand planning and adjust maintenance strategies.

Machine learning models can be integrated into monitoring systems, enabling real-time observation of panel condition and performance. For instance, they can analyze panel-level metrics to identify faults or reductions in efficiency before these issues impact the overall performance of the installation. By analyzing the dynamics of changes in performance, shading patterns, and maintenance history, it becomes possible to more accurately predict when systems will require upgrades. This allows for proactive equipment updates and the avoidance of costs associated with emergency repairs.

Analyzing shading and contamination data across different seasons, as well as local climatic features, enables systems to be tuned for more efficient operation under regional conditions. This may involve optimizing panel tilt angles or adapting energy storage systems to account for seasonal variations.

The use of data to achieve optimal efficiency and reduce environmental impact is an integral part of sustainable development. Machine learning models can assist operators in tracking and minimizing their carbon footprint, ensuring that systems comply with environmental standards and requirements.

Thus, the capabilities of machine learning in photovoltaic systems offer tremendous promise for enhancing system efficiency, improving maintenance strategies, and supporting long-term planning. This, in turn, contributes both to economic benefits and to achieving global sustainable energy goals.

CONCLUSION

In conclusion, modern technologies for data storage and management offer numerous opportunities to improve the performance of photovoltaic systems. The use of cloud solutions, blockchain, and machine learning significantly enhances the efficiency of data analysis and management, while also providing better security and performance optimization.

The implementation of blockchain in the management of photovoltaic systems not only opens new horizons for improving the efficiency and reliability of renewable energy sources but also lays the foundation for a more sustainable and innovative energy industry. Through the integration of cloud technologies, blockchain, and machine learning, not only is a more transparent and secure environment created for all market participants, but also exceptional opportunities for maximizing system productivity and security.

Transparency and trust in the energy sector increase significantly due to the fact that all data and changes are stored on the blockchain, ensuring immutability and security. This provides operators and investors with confidence in the accuracy of the information provided, minimizing the risk of manipulation and errors. Blockchain technologies establish the foundation for building trust in inter-company interactions while providing a high level of data protection.



Research shows that the implementation of blockchain in the management of shading, surface contamination, and performance data in photovoltaic systems can elevate the industry to a new level. Operators will be able to respond more quickly and effectively to changing conditions, optimize planning processes, and ensure the necessary transparency and trust in the rapidly evolving renewable energy sector.

New technologies such as cloud solutions, blockchain, and machine learning not only optimize data processing but also ensure a high level of security in data storage. This is crucial not only for protecting commercial information but also for complying with energy efficiency and environmental sustainability requirements.

Cloud solutions enable the storage and real-time analysis of large volumes of data, allowing operators to make informed decisions based on up-to-date information about system performance and status. These solutions offer exceptional flexibility and ease in scaling infrastructure according to operator needs, leading to greater efficiency and sustainability.

Blockchain technologies radically enhance data security and guarantee protection against unauthorized access. Each record on the blockchain is fully transparent, verifiable, and immutable, thereby building trust among all participants—from operators to investors. In this way, a system is created where all critical operations—from maintenance to repairs and performance measurements—are reliably recorded and easily accessible for verification.

Machine learning plays a key role in optimizing the operation of photovoltaic systems. It not only enables the prediction of potential failures and real-time performance analysis but also optimizes energy production through intelligent algorithms that account for changing conditions such as weather factors and seasonal variations.

Modern methods for data processing and storage provide a high level of security, which is vital not only for protecting commercial interests but also for complying with international standards and regulations in the energy sector.

In conclusion, innovations in the management of photovoltaic systems through cloud solutions, blockchain, and machine learning not only significantly increase system efficiency but also create new opportunities for sustainable and responsible management of energy resources. These technologies not only ensure improved economic efficiency but also lay the foundation for a greener and more transparent industry, which will play a key role in the future of renewable energy.

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