

Innovative AI tools in Renewable Energy Sources

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Abstract:

The article analyzes the role of artificial intelligence (AI) in the renewable energy sources (RES) sector, highlighting its importance in optimizing energy production, distribution, and storage processes. AI enables precise forecasting of energy production, minimizing the effects of weather instability and increasing the operational efficiency of renewable energy systems by up to 25%. AI-based tools also allow for dynamic adjustment of wind turbines and photovoltaic panels, which reduces energy losses and operating costs. An important application of AI is predictive maintenance, which reduces failures through early detection of faults. Smart grid management enables the optimal use of renewable energy sources by analyzing demand and supply and integrating different energy storage technologies. AI also supports the planning of renewable energy investments, helping to select optimal locations for wind and solar farms. However, the implementation of AI in the energy sector faces challenges, such as the need for access to large data sets, the cost of integration with existing systems, and cybersecurity issues. Despite these barriers, the future of AI in RES looks promising, especially in the context of its integration with IoT, big data and quantum technologies. With the right technological and regulatory support, AI can become a key element of the global energy transition, increasing the stability and profitability of renewables and supporting the fight against climate change.

Keywords: artificial intelligence (AI), renewable energy sources (RES), internet of things (IoT), big data, energy optimization



1. Introduction

The energy transition is one of the main challenges of the modern world. Renewable energy sources such as solar, wind and hydro energy provide an opportunity to move towards a sustainable model of energy production. However, their development faces a number of challenges, such as supply instability, unpredictable weather conditions and the need to effectively manage power grids. In addition, the increase in global energy demand requires solutions that are not only efficient but also scalable. Innovative AI tools can help solve these problems by using advanced algorithms to analyse data, predict change and optimise processes.

AI in RES is particularly important in the context of the instability of natural resources, such as wind or solar, which are dependent on weather conditions. The use of AI enables precise forecasting of these variables and adaptation of the operation of energy systems in real time. For example, research by the European Renewable Energy Laboratory showed that the introduction of AI tools in photovoltaic installations improved system efficiency by 22 %, while reducing losses associated with predicting weather changes. According to the report "Present and Future of AI in Renewable Energy Domain: A Comprehensive Survey", AI integration in energy systems, it can increase operational efficiency by up to 25%. The introduction of this technology not only improves efficiency, but also reduces operating costs, which is crucial for the wide implementation of RES [1].

2. Forecasting energy production from RES with AI

One of the biggest challenges facing the renewable energy sources (RES) sector is the variability of energy production resulting from the natural dependence on weather conditions. Solar energy production is strictly dependent on sunlight, while wind energy is dependent on wind speed and direction. These factors are variable and often difficult to predict, which introduces significant complications in the management of RES systems. In response to these challenges, artificial intelligence (AI) plays a key role in forecasting energy production, enabling more accurate prediction and management of energy supply.

The role of AI in forecasting energy production

Forecasting energy production is one of the most important key challenges related to the effective use of RES. Machine learning (ML) models analyze historical data, current weather conditions, and other variables to accurately predict the amount of energy that will be produced over a specific period of time. The introduction of AI in this field not only increases the accuracy of forecasts, but also enables operators to better manage their assets. Among the promising technical areas for the use of AI in energy production forecasting, solar energy can be distinguished in which AI models integrate variables such as radiation intensity, cloud cover, temperature and season, which enables dynamic prediction of energy production. Research conducted in the paper "Solar energy forecasting with deep learning technique" shows that AI can increase the accuracy of forecasts by 18% compared to traditional methods. Moreover, the use of predictions based on computer vision allows for better adjustment of the settings of photovoltaic panels in real time. These algorithms are also able to predict the wear and tear of components, making them easier to maintain. In wind energy, AI models predict wind speed and direction, taking into account complex atmospheric conditions such as turbulence and local weather changes. According to a study published in "New developments in wind energy forecasting with artificial intelligence and big data: a scientometric insight", AI systems have reduced the operating losses of wind turbines by 15%, while increasing their efficiency by optimizing the timing of turbine operation. In the regions [2, 3] with unstable winds, such as Patagonia, AI supports operators in efficiently scheduling turbine operation. AI for forecasting complex hybrid systems that combine different energy sources such as solar, wind and biomass. AI algorithms analyze which



energy source will be most efficient under certain conditions, which enables dynamic optimization of the entire system.

Example AI cases in the forecasting of energy production, you can find in India, where AI has been used in regions with variable weather conditions to optimize the operation of both wind and solar farms. The result was a 20% increase in production stability. In the Mojave Desert in the United States, AI systems predict the intensity of solar radiation, which enables precise management of energy storage [4] and network load. In Germany, the use of AI in wind farms has made it possible to identify optimal turbine locations, reducing operating costs by 18% [5].

Application of Machine Learning in Forecasting

Machine learning, a key technology used by AI, plays a central role in forecasting energy production. Algorithms such as neural networks, random forests and support vector machines are able to analyse huge data sets, identifying patterns and relationships that may not be visible to traditional forecasting methods.

Neural networks, for example, are particularly effective at forecasting variables with complex relationships, such as weather conditions. With the ability to learn from past data and adapt to new information, neural networks can continuously improve their predictions. In the context of RES, this approach allows for more accurate prediction of energy production in different weather conditions, which is crucial for the stability of energy systems.

Benefits of accurate energy production forecasts

Accurate forecasts of energy production bring a number of benefits for RES system operators and for the entire energy system:

- a) Improved asset management: Accurate forecasts allow operators to better plan asset utilization, minimizing the risk of energy shortages or overproduction. In the event of overproduction, operators can schedule the transfer of excess energy to storage facilities or to other parts of the grid, preventing wasted resources.
- b) Optimizing Grid Integration: The variability of renewable energy production poses a challenge to the stability of power grids. Accurate forecasts help to better integrate RES into the grid, allowing supply to be adjusted to current demand and minimizing the need to deploy backup energy sources, which are typically more polluting.
- c) Reduction of Operating Costs: With accurate forecasts, operators can better manage their maintenance and operational processes. For example, if forecasts indicate an upcoming period of low wind power production, operators can schedule maintenance work for this time, minimizing the impact on energy supply.
- d) Support for Investment Planning: Accurate forecasts are also invaluable in planning new investments in renewables. Potential investors can better assess the viability of projects by predicting future profits based on accurate forecasts of energy production at a given location.

Examples of the use of AI in energy production forecasting

In practice, AI is already being used in forecasting energy production in many renewable energy projects around the world. For example, solar farm operators are using AI to analyze solar data and predict energy production throughout the day, allowing for more efficient energy management.



In a similar way, wind farms use AI to forecast wind speeds, allowing them to optimize turbine operation and maximize energy production.

One of the most famous examples is Google's use of AI in its wind farms, where AI algorithms predict energy production 36 hours in advance. This allows Google to more accurately plan energy distribution and optimize energy usage in its data centers, which contributes to increased operational efficiency and cost reduction.

Challenges and the future of AI-powered energy production forecasting

Despite its numerous benefits, forecasting energy production using AI also faces some challenges. One of them is the need to have access to large and diverse data sets, which are crucial for accurate forecasts. In addition, the complexity of AI models and the need for continuous improvement require high technical skills and investment in infrastructure.

However, as AI technology continues to evolve, we can expect to see a further increase in the accuracy of energy production forecasts. The introduction of more advanced machine learning models, integration with data from new sources (such as satellite data or advanced weather monitoring systems) and the development of computing infrastructure will contribute to even better RES management.

Energy production forecasting with the use of artificial intelligence is becoming an indispensable element of the management of renewable energy sources. AI allows for precise prediction of changing weather conditions, which translates into more effective management of energy production and distribution. As AI technologies continue to evolve, their role in the renewable energy sector will grow, contributing to the stability and profitability of these energy sources, as well as to global climate protection goals [6].

3. Optimize wind turbine operation with AI tools

Artificial intelligence (AI) plays a key role in optimizing the operation of wind turbines, which are one of the most important elements in renewable energy production. Wind turbines need to be precisely managed to achieve maximum efficiency, especially in the face of changing wind conditions. AI provides tools that allow for dynamic adjustment of turbine operation, optimization of efficiency and minimization of the risk of failure, which translates into greater efficiency and reliability of entire wind farms.

Dynamic real-time turbine tuning

Wind conditions, such as wind speed and direction, are constantly changing, which affects the performance of wind turbines. For optimal performance, turbines must be continuously adapted to these variables. AI enables dynamic monitoring and analysis of atmospheric conditions in real time, allowing you to adjust turbine settings instantly.

AI algorithms analyze data from sensors mounted on turbines that measure wind speed, direction, pressure, temperature, and other key parameters. Based on this data, AI systems can automatically adjust the pitch angle of the blades and the rotation speed of the rotor to maximize energy efficiency. For example, if the wind changes direction or speed, AI can quickly adjust the turbine blades to make the best use of the available wind energy resource.

This type of dynamic adjustment is critical to maximizing energy production, especially in conditions where wind is erratic or variable. Optimizing turbine operation also contributes to extending turbine life, as the blades are positioned in a way that minimizes mechanical stress and component wear.



Predictive Maintenance

One of the most important applications of AI in wind turbine optimization is predictive maintenance. Traditional maintenance methods often rely on fixed maintenance schedules or responses to failures that have already occurred, which can lead to unplanned downtime and costly repairs. AI brings a new quality to these activities, enabling proactive management of turbine maintenance.

AI systems use advanced algorithms to analyze data from sensors mounted on turbines that monitor the health of various components, such as bearings, transmissions, generators, and hydraulic systems. These algorithms are able to detect subtle changes in the operation of these components that may indicate impending failures.

For example, AI can detect an increase in vibration in turbine bearings, which can be an early sign of wear or damage. With this information, operators can plan maintenance or replacement of components before a major failure occurs that could lead to long-term downtime. Predictive maintenance not only minimizes the risk of failure, but also optimizes operating costs, as maintenance is only performed when it is really needed.

Optimize performance across the entire wind farm

AI not only optimizes the operation of individual turbines, but also manages their cooperation on the scale of the entire wind farm. In large farms, where turbines are spread over a large area, there is a phenomenon called 'wake effect', where turbines further down the farm may experience reduced wind speed due to turbulence generated by turbines upstream.

AI can analyze the interactions between turbines and optimize their operation to minimize the impact of wake effect. For example, algorithms can adjust the rotational speed or angle of the blades of the front turbines to reduce turbulence and allow more wind flow to the turbines located at the rear of the farm. In this way, the entire wind farm can operate more efficiently, which translates into more total energy production.

Applications of AI in Environmental and Safety Monitoring

AI is also used to monitor the environmental impact of wind turbines and to ensure the safety of their operation. Wind turbines can affect local ecosystems, such as bird populations. AI systems can analyze data from cameras and other sensors to monitor bird migrations and temporarily halt turbines if necessary, minimizing the risk of collisions.

Additionally, AI can monitor weather conditions and predict extreme weather events such as storms, strong winds, or ice fall, which could pose a threat to turbines. This allows operators to take appropriate countermeasures, such as stopping turbines or adjusting turbine settings to avoid damage.

The future of wind turbine optimisation with AI

As AI technology continues to evolve, we can expect even more advanced tools to optimize the operation of wind turbines. The integration of AI with technologies such as the Internet of Things (IoT), big data and satellite technologies will allow for even more precise management of wind farms. In the future, AI could also support the development of autonomous wind farms that can self-manage energy production and maintenance without the need for constant supervision from operators.

In conclusion, AI plays a key role in optimizing the operation of wind turbines, ensuring more efficient, reliable and economic operation of wind farms. By dynamically adapting turbines to changing wind conditions, predictive maintenance, and optimizing turbine collaboration, AI



contributes to maximizing renewable energy production, supporting global efforts for sustainability and greenhouse gas reduction [7].

4. Other selected innovative AI tools in RES

Power Network Management

Energy grids are becoming more complex as the integration of renewables increases. AI enables smart grid management, providing tools for monitoring, optimizing energy flows, and responding quickly to failures. Managing power grids in RES-based systems is a challenge due to the decentralization and variability of energy sources. AI plays a key role in managing energy flows in such networks, ensuring stability and reliability of supply.

AI algorithms analyze data on energy demand, supply, and grid conditions to optimize energy transmission and minimize losses. For example, in the event of excess energy production from a solar farm, AI can divert the excess energy to energy storage or redirect it to where there is greater demand. AI can also manage the integration of various renewable energy sources with traditional power plants, which is crucial for grid stability.

Energy Storage

Energy storage is a key element in the integration of RES into power grids, especially in the context of production variability. AI supports the optimization of the management of energy storage, such as lithium-ion batteries, helping to efficiently collect and release energy.

AI systems can predict when energy storage should be charged or unloaded, depending on forecasts of energy production and demand. This makes it possible to make the most of the stored energy during periods of peak demand, which reduces the need to run additional energy sources from traditional power plants.

Optimizing the placement of solar panels

In the solar energy sector, AI is used to optimize the placement and positioning of photovoltaic panels. AI algorithms analyze data on sunlight, tilt angles, and shading to design solar systems that maximize energy absorption.

Thanks to AI, it is also possible to dynamically adjust the angle of the solar panels during the day to track the movement of the sun and ensure that the available solar energy is used to the maximum. Such intelligent systems allow for a significant increase in the efficiency of photovoltaic installations.

The use of AI in RES Planning and Development

AI is also a tool that supports the planning and development of new renewable energy projects. Analysis of spatial, environmental and economic data allows to identify the most profitable locations for new wind, solar or water farms. AI can also simulate different investment scenarios, taking into account volatile market conditions, technology costs, and energy demand forecasts.

Such analyses allow for better planning and optimisation of investments in renewable energy sources, which is crucial for the sustainable development of this sector.

Examples of AI applications in RES

Innovative AI tools are already being used in various renewable energy projects around the world. An example is DeepMind, which, in cooperation with Google, uses AI to optimize the operation



of wind farms, increasing their efficiency by over 20%. By analyzing weather data and optimizing turbine settings, AI systems enable better use of available wind energy.

Another example is Tesla, which uses AI to manage its energy storage, such as Powerwall and Powerpack. Thanks to advanced algorithms, these systems can optimize energy storage and distribution depending on current conditions and demand [8].

5. Challenges and the future of AI in RES

Artificial intelligence (AI) brings significant benefits to the renewable energy (RES) sector by offering tools that improve the efficiency, stability and sustainability of energy systems. However, the implementation of AI in renewable energy also faces a number of challenges that must be overcome in order to fully exploit the potential of these technologies.

The need for access to big data

One of the main challenges related to the implementation of AI in the renewable energy sector is the need for access to huge amounts of data. AI algorithms require large and diverse data sets to be able to effectively analyze patterns and make accurate decisions. This data must include various aspects such as meteorological conditions, operational data from energy installations, information on energy demand and many other factors. For smaller companies that do not have the resources to collect and process such data, this challenge can be particularly difficult to overcome. The lack of standardization of data and the limitations in its sharing are also an obstacle [9].

Complexity of AI systems and integration with existing energy systems

Integrating advanced AI systems into existing energy systems can be complex and requires advanced technical expertise. The implementation of AI in RES often involves the need to modernize the infrastructure, which is expensive and time-consuming. Additionally, the complexity of AI systems requires highly skilled professionals who are able to manage both the integration process and subsequent operations. The shortage of specialists in the field of AI and renewable energy may be a significant barrier to the development of these technologies, especially in regions where access to technical education is limited.

Implementation and maintenance costs

The costs associated with the implementation of advanced AI technologies in RES can be significant, especially for smaller companies or developing markets. These investments include not only the purchase of appropriate hardware and software, but also the costs of staff training, infrastructure maintenance, and continuous improvement of AI systems. In addition, the return on such investments may not be immediate, which discourages some companies from implementing them. In this context, the development of business models and financing strategies that support the implementation of AI in RES will be crucial for the further development of this sector.

Data security

As energy systems become more integrated with AI technologies, the issue of data security and privacy becomes increasingly relevant. Securing the vast amounts of data that are necessary for AI to operate from cyberattacks and unauthorized access is essential to ensure the reliability and stability of energy systems. Companies need to invest in advanced data protection measures and develop risk management procedures to minimize potential cybersecurity risks.



6. The future of AI in RES

Further development of AI in the RES sector will focus on the integration of various technologies, such as blockchain, IoT or edge computing, to create more autonomous and intelligent energy systems. There are several potential scenarios for the development of AI in RES:

Breakthrough development scenario: In this scenario, extensive investment in AI research and development allows for the implementation of advanced deep learning algorithms in micro-grid management and resource forecasting. The capabilities of AI are further enhanced by the development of quantum technologies, which significantly speeds up data processing. As a result, AI enables almost 100% optimization of the use of energy from RES, which translates into a reduction in CO₂ emissions by more than 50% on a global scale by 2040. These systems are particularly suitable for rural and remote areas, where micro-grids allow for energy independence [8].

Stable progress scenario: The development of AI in RES is proceeding at a moderate pace, with a limited number of pilot implementations in developed markets. The introduction of technology standardization and international cooperation makes it possible to gradually increase the efficiency of RES systems by about 25% on a global scale by 2035. In this scenario, AI effectively supports power grid management and energy demand prediction, although it has not yet reached its full potential in reducing operating costs.

Limited development scenario: Financial constraints, lack of regulatory support, and gaps in education are slowing down the development of AI in renewables. AI-based solutions are only being deployed in select regions, and many of the potential benefits of the technology remain untapped. As a result, energy efficiency gains are marginal (around 10% by 2040) and global climate targets are becoming more difficult to achieve.

Increased efficiency and sustainability

AI will continue to support the optimization of processes in renewable energy sources, which will allow for even more efficient use of natural resources. Better forecasting of energy production, optimization of installation operation and dynamic management of power grids will contribute to reducing energy losses and increasing supply stability. As a result, RES will become more competitive with traditional energy sources, contributing to the reduction of global CO₂ emissions and supporting sustainable development goals [10].

Development of New Technologies and Innovations

The future of AI in RES also means the development of new technologies and innovative solutions that can change the way we manage energy. The integration of AI with the Internet of Things (IoT) and big data will allow for even more accurate monitoring and management of energy installations. In addition, the development of autonomous energy systems that can independently optimize their work and respond to changing conditions will open up new opportunities for decentralization and flexibility of energy systems.

New business models

AI in RES will open the door to new business models that will support the development of distributed energy and the circular economy. An example is the development of local energy grids (so-called microgrids), which will be managed by AI systems and integrate a variety of energy sources, both renewable and traditional. These types of business models will promote more sustainable and self-sufficient communities, reducing dependence on central energy systems.



Increased availability of technology

As the cost of implementing AI technology decreases and access to the right infrastructure increases, more and more businesses – including small and medium-sized businesses – will be able to take advantage of advanced AI tools. This, in turn, will accelerate the adoption of renewables around the world, even in regions that have so far had limited access to modern technologies.

7. Global Cooperation and Policy

In the context of the future of AI in RES, global cooperation and appropriate policies supporting the development of these technologies will play a key role. Governments and international organisations should invest in research and development, promote knowledge sharing and create a regulatory framework that fosters innovation in the renewable energy sector. International cooperation will be essential to address the challenges of the global transition to sustainable energy sources.

Although the implementation of artificial intelligence in the renewables sector, it faces a number of challenges, such as the need for access to big data, the complexity of systems, and costs, the future of AI in renewables is extremely promising. As technology advances, AI will play an increasingly central role in optimizing energy production, distribution and management, contributing to more sustainable and efficient energy systems. Supporting the development of AI in renewables through policy, technological innovation, and global collaboration will be key to accelerating the transition to renewable energy sources and meeting global climate goals [11].

8. Summary

Artificial intelligence (AI) is a key element of the energy transition, enabling more efficient use of renewable energy sources (RES) and reducing greenhouse gas emissions. AI-based solutions allow for the optimization of energy production, distribution and storage processes, which significantly improves the reliability and flexibility of energy systems. The introduction of AI technology to the RES sector not only supports the management of current challenges, but also accelerates the development of innovations that are becoming the foundation for the future of the energy sector.

One of the most important aspects of the use of AI in renewables is its ability to support global climate goals. Predictive algorithms and machine learning models enable precise planning of energy production and distribution, which reduces resource waste and greenhouse gas emissions. AI also stimulates the development of innovative technologies, such as new materials used in energy storage. By quickly analyzing millions of possible chemical combinations, it is possible to design flow and lithium-sulfur batteries that offer higher performance and are greener. This process, supported by AI, accelerates scientific research and brings more effective solutions to the market.

Another important area is increasing economic efficiency. Automation of maintenance processes and monitoring of RES installations with the use of AI leads to significant savings. Case studies in Japan and Australia show that AI-enabled management of energy installations has reduced operating costs by 15-20% while increasing the reliability of these systems.

AI-managed smart grids enable dynamic adaptation of energy supply to changing demand, increasing flexibility. Combined with IoT and edge computing technologies, AI offers the ability to respond quickly to changes in real time, making energy systems more resilient to unstable weather conditions [12].

Despite these benefits, the development of AI in the renewable energy sector faces a number of challenges. Lack of data standardization, infrastructural limitations and the need for appropriate regulations are barriers that need to be overcome. The introduction of international standards for data



collection and analysis, investment in infrastructure, and support for developing countries are key to ensuring that the full potential of AI is realized.

To sum up, artificial intelligence has great potential in accelerating the energy transition. With the right technological, financial and regulatory support, AI can become the foundation of the global energy system, contributing to the fight against the climate crisis and building a more sustainable future.

References

- [1] Rashid P.: "Present and Future of AI in Renewable Energy Domain: A Comprehensive Survey", Cornell University, 2024.
- [2] Bassey K.: "Solar energy forecasting with deep learning technique", Engineering Science & Technology Journal, 2023.
- [3] Zhao E.: "New developments in wind energy forecasting with artificial intelligence and big data: a scientometric insight", Data Science and Management, 2022.
- [4] Hossain M.: "AI-Driven Optimization and Management of Decentralized Renewable Energy Grids", Nanotechnology Perceptions, 2024.
- [5] Yousef H.: "Artificial Intelligence for Management of Variable Renewable Energy Systems: A Review of Current Status and Future Directions", Energies, 2023.
- [6] Ahmad Hamdan K.: "AI in renewable energy: A review of predictive maintenance and energy optimization", International Journal of Science and Research Archive, 2024.
- [7] Veena S.: "Artificially intelligent models for the site-specific performance of wind turbines", International Journal of Energy and Environmental Engineering, 2020.
- [8] Dellos J. T. and Palconit C.: "Artificial Intelligence (AI) in Renewable Energy Systems: A Condensed Review of its Applications and Techniques", International Conference on Environment and Electrical Engineering (EEEIC), 2021.
- [9] Onwusinkwue S.: "Sustainable energy solutions through AI and software engineering: Optimizing resource management in renewable energy systems", Education, 2022.
- [10] Odunaiya O.: "Artificial intelligence (AI) in renewable energy: A review of predictive maintenance and energy optimization", World Journal of Advanced Research and Reviews, 2024.
- [11] Nzubechukwu Chukwudum Ohalet A.: "AI-driven solutions in renewable energy: A review of data science applications in solar and wind energy optimization", World Journal of Advanced Research and Reviews, 2023.
- [12] Lakshmi M.: "Advances in Novel Power Generation Technology and AI Software Tools", 2024.

