
Innovative Solutions for the Future Development of the Energy Sector

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Abstract:

Purpose: The purpose is to showcase the most important innovative initiatives undertaken by energy enterprises to meet the demands of the modern economy. The research focused on identifying and analyzing key technologies and strategies that energy enterprises are implementing in response to the growing challenges related to energy efficiency, sustainable development, and regulatory compliance.

Design/Methodology/Approach: The research utilized the desk research method and the observation method to obtain a comprehensive view of the innovative initiatives undertaken by energy enterprises. The desk research method enabled an in-depth analysis of the relevant literature, industry reports, and scientific publications, providing insights into the latest trends and solutions in the energy sector. The observation method allowed for the direct verification of the obtained results by analyzing the practices employed by specific enterprises in real-world conditions.

Findings: The research findings identified eight key areas currently being developed in the energy sector: Advanced Photovoltaics, AI and Big Data, Distributed Energy Storage Systems, Hydropower, Wind Energy, Bioenergy, Grid Integration, Green Hydrogen, Advanced Robotics, and Blockchain technology.

Practical Implications: The research findings highlight the development directions of the energy sector, enabling decision-makers to make informed decisions regarding the implementation of innovative solutions. The results also provide valuable information on current trends and strategies in energy, indicating significant technologies and practices that can contribute to increased efficiency, sustainable development, and competitiveness of energy enterprises. This allows decision-makers to better plan and execute innovative projects that address the contemporary challenges and needs of the energy market.

Originality value:

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1. Introduction

In the energy sector, innovative solutions are being implemented to ensure the development of energy enterprises in line with the latest trends and technical and environmental requirements. This includes the integration of advanced technologies such as renewable energy sources, smart grids, blockchain, digitization, and energy storage systems, all of which together support sustainable development and energy efficiency (Popp, Vona, Gregoire-Zawilski, and Marin, 2024).

The most important development directions for the energy sector in the coming years include advanced innovations in photovoltaics, which enable more efficient use of solar energy, and artificial intelligence and big data, which support the optimization of processes and energy resource management.

Also crucial are distributed energy storage systems, which ensure the stability of energy supply, and hydropower and wind energy, which are key elements in the renewable energy mix (Thalassinos *et al.*, 2022).

Furthermore, bioenergy is a significant complement to other renewable sources. By utilizing biomass, biogas, and biofuels, bioenergy can be produced independently of weather conditions, allowing for balancing fluctuations in energy generation from unstable renewable sources (Babaniyi, Ogundele, Abe, Olowoyeye, Jayeola, Oyegoke, ..., and Daramola, 2024). Grid integration allows for better coordination and distribution of energy.

In addition, hydrogen plays a key role in the energy sector as an energy carrier, with its production and use symbolized by different colors that reflect the methods of production and associated carbon dioxide emissions. Green hydrogen, produced using renewable energy sources through water electrolysis, is entirely clean as it generates no CO₂ emissions, making it a crucial element in the decarbonization of industry, transport, and energy sectors. As a clean fuel, green hydrogen has the potential to significantly reduce emissions across various economic sectors.

Advanced robotics enhance the efficiency and safety of energy operations, and blockchain technology introduces new possibilities for transaction transparency and security, as well as data management. The conducted research analyzed the latest trends and solutions that energy companies will implement in the coming decade.

This research focuses on identifying key technologies and strategies aimed at increasing energy efficiency, reducing greenhouse gas emissions, and integrating renewable energy sources. The studies showed that energy companies will need to adapt flexibly to the dynamically changing technological and regulatory environment to meet the challenges of sustainable development and ensure reliable energy supply.

2. Research Results and Discussion

The conducted literature research, based on a broad analysis of the relevant literature and systematic observations within a group of energy enterprises, allowed for the formulation of key conclusions and an in-depth discussion. The analysis of available scientific publications and industry reports provided solid theoretical foundations, which were then confronted with the real practices and experiences of companies operating in the energy sector.

This approach enabled the identification of major trends and challenges facing the industry, as well as the assessment of the effectiveness of various strategies and technologies used by energy companies.

The discussion conducted allowed for a critical evaluation of the collected data, drawing conclusions, and identifying directions for further research and actions that could contribute to process optimization and efficiency improvement in the energy sector. The conducted literature reviews and observations allowed for the identification of key issues that will be implemented in energy companies in the coming years. The studies also enabled the formulation of guidelines for decision-makers responsible for making strategic decisions in these companies.

3. Top Innovations in the Energy Sector

Photovoltaics:

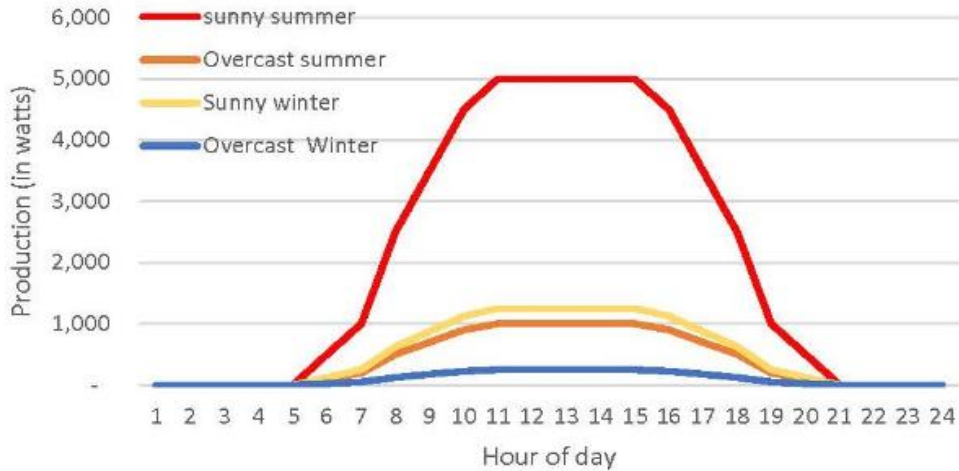
Advanced innovations in photovoltaics enhance high-efficiency technologies, allowing for more effective use of solar energy. Modern high-tech photovoltaic systems integrate cutting-edge technologies, significantly boosting their efficiency and versatility.

A key component is the use of high-performance photovoltaic panels, often made from materials with increased efficiency in converting sunlight into electricity. These systems are equipped with intelligent inverters, which not only convert direct current to alternating current but also monitor and optimize the operation of the entire installation in real-time (Czepło and Borowski, 2024).

Artificial intelligence (AI) and big data play a crucial role in managing and maintaining photovoltaic systems. AI aids in predicting and preventing failures through predictive maintenance and optimizes performance by analyzing weather conditions and adjusting the operational parameters of the panels.

Distributed Energy Storage Systems (DESS) allow for the storage of excess energy produced during periods of high sunlight, making it available during times of increased demand or low production. An example of the diversity of energy production depending on the season, time of day and climatic conditions is presented in Figure 1.

Figure 1. Hypothetical energy production for a 5kW solar panel



Source: <https://www.vpuc.com/conservation/solar-energy/>.

Advanced photovoltaic systems are also integrated with smart grids, which manage energy distribution and ensure stability. This integration makes it possible to efficiently incorporate solar energy into national and local energy systems, minimizing transmission losses and increasing supply reliability.

Modern advanced photovoltaic systems are not only a source of renewable energy but also a part of the modern energy infrastructure that supports sustainable development and technological innovation.

Big Data and Artificial Intelligence:

Big data and artificial intelligence (AI) improve the utilization of renewable energy, facilitating applications such as predictive maintenance and intelligent management, which enhance the reliability and efficiency of energy systems (Hamdan, Ibekwe, Ilojiyanya, Sonko, and Etukudoh, 2024). By analyzing big data, massive amounts of information from various sources, such as photovoltaic panels, wind turbines, and energy storage systems, can be monitored and analyzed (Borowski, 2021).

AI uses this data to create advanced predictive models that help forecast and prevent failures through predictive maintenance. These models, powered by sensor and monitoring data, use AI algorithms to identify patterns and anomalies indicating potential issues. This enables the detection of early signs of failure before they become critical, allowing for proactive maintenance actions.

Predictive maintenance minimizes the risk of unplanned downtime and extends the lifespan of equipment, contributing to the overall reliability of the system. Additionally, precise predictions allow for optimal planning of maintenance activities, leading to more efficient use of resources and reduced operational costs.

As a result, advanced predictive models support more sustainable and economical management of energy infrastructure, contributing to its long-term stability and efficiency.

Intelligent energy management, supported by AI, optimizes the operation of energy systems by dynamically adjusting operational parameters to changing weather conditions and energy demand. These systems can, for instance, predict periods of high solar energy production and adjust storage accordingly to ensure energy availability during periods of low production. AI can also analyze energy consumption patterns, enabling more efficient planning and distribution of energy resources ((Franki, Majnarić, and Višković, 2023).

These technologies collectively contribute to creating a more sustainable and reliable energy system. Increased reliability and efficiency result from the ability to quickly respond to issues, minimize downtime, and optimize the use of available renewable resources, leading to reduced operational costs and increased overall efficiency of energy systems.

Distributed Energy Storage Systems:

Distributed Energy Storage Systems (DESS) significantly enhance the flexibility and stability of renewable energy generation, enabling better management of production variability from renewable sources.

DESS allow for the storage of excess energy during periods of high production, such as sunny days for photovoltaic panels or windy days for wind turbines. The stored energy can then be used during periods of lower renewable energy production, ensuring continuous supply and minimizing the risk of power outages (Kandil, Farag, Shaaban, and El-Sharafy, 2018).

With DESS, energy systems can better respond to changing energy demands, which is crucial for unstable renewable sources. The flexibility of these systems allows for quick adaptation to short-term fluctuations in production and consumption, increasing the overall stability of the energy grid. Additionally, distributed energy storage reduces dependence on large, central energy storage facilities, improving the energy system's resilience to failures and increasing energy security.

Integrating DESS with smart grids enables dynamic management of energy flows, optimizing resource use and reducing transmission losses. Consequently, distributed energy storage systems not only support grid stability and flexibility but also contribute to more sustainable and efficient use of renewable energy sources (Tsao and Vu, 2023).

Grid integration technologies, such as advanced transmission and distribution systems, reduce transmission losses and effectively stabilize the grid. They also optimize the use of off-grid sources like biofuels, wind energy, and hydropower,

even when located far from demand centers, allowing for more sustainable energy management on a large scale.

Hydrogen Solutions:

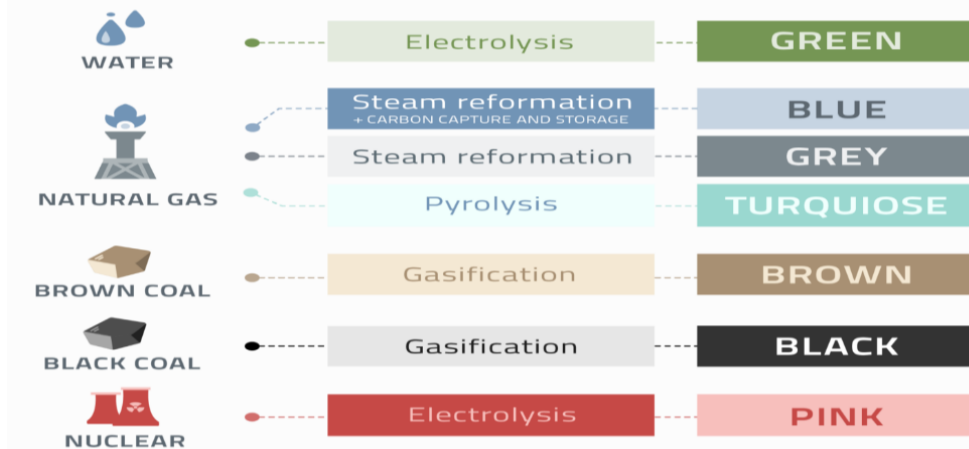
Hydrogen solutions in the energy sector encompass various hydrogen production technologies, identified by colours that symbolize their production methods and environmental impact. Green hydrogen, produced from renewable energy sources through water electrolysis, is entirely clean, emitting no CO₂, and plays a crucial role in the decarbonization of industry, transport, and energy.

Blue hydrogen is derived from natural gas through steam methane reforming with carbon capture and storage (CCS), minimizing emissions compared to grey hydrogen, which is produced from natural gas without CCS and generates significant CO₂ emissions.

Brown (black) hydrogen, produced from coal, is the most environmentally harmful due to high carbon dioxide emissions. Pink hydrogen, produced using nuclear energy for water electrolysis, generates no CO₂ emissions, and the stability of nuclear energy ensures continuous production.

Turquoise hydrogen, produced from methane via pyrolysis, generates less CO₂ provided effective management of solid carbon (Dawood, Anda, and Shafiullah, 2020). The colour combination of hydrogen is shown in Figure 2.

Figure 2. The hydrogen colour spectrum



Sources: <https://whatswatt.com.au/true-colours-what-do-the-different-colours-of-hydrogen-mean/>.

The number of announced low-emission hydrogen production projects worldwide is rapidly increasing. Annual production of low-emission hydrogen could reach 37 Mt by 2030. It is forecasted that 27 Mt will be based on electrolysis and low-emission

electricity, while 10 Mt will come from fossil fuels with carbon capture, utilization, and storage (CCUS) (Global Hydrogen Review, 2023).

Hydrogen can be used as a fuel for electricity generation in gas turbines, fuel cells, and as an energy carrier to store excess energy from renewable sources. Furthermore, hydrogen supports the decarbonization of industrial sectors such as metallurgy and chemicals, as well as transportation, especially in heavy-duty vehicles, ships, and airplanes (Borowski, 2024).

The introduction and development of hydrogen technologies, particularly green hydrogen, are crucial for achieving global sustainable development goals and reducing greenhouse gas emissions, making the energy sector cleaner and more reliable.

The conducted studies have shown that environmentally friendly hydrogen will be an element of innovative strategies implemented by energy companies. An overview of hydrogen production technologies was presented, demonstrating that hydrogen, as a low-emission energy carrier, can significantly contribute to reducing greenhouse gas emissions, improving energy security, and supporting innovation in the energy sector.

Bioenergy:

Bioenergy, due to its decentralized nature, remains a preferred choice in many locations, enabling local energy production and use, further supporting sustainable energy development. Its advantage lies in the ability to produce energy at the point of consumption, reducing the need for long-distance transmission and associated energy losses. Local bioenergy production uses resources available in the immediate vicinity, such as agricultural, forestry, or urban waste, contributing to waste reduction and promoting a circular economy (Borowski and Barwicki, 2022).

Additionally, bioenergy can be easily scaled according to local energy needs, making it a flexible and efficient solution for various communities, from small villages to larger cities. This allows local communities to achieve greater energy independence, increasing their resilience to energy market fluctuations and external threats.

Bioenergy also supports job creation at the local level, both in the production sector and in biomass processing, positively impacting regional development. The use of bioenergy in local energy systems helps reduce greenhouse gas emissions, supporting global efforts to combat climate change. Thus, bioenergy not only meets local energy needs but also contributes to achieving sustainable development goals on a broader scale.

Grid Integration:

Grid integration technologies primarily involve the transmission, distribution, and stabilization of renewable energy, which is crucial given the increasing scale of

variable renewable energy production. This energy is often generated far from demand centers, leading to transmission and distribution losses. To address this, energy-efficient electronic technologies are used to minimize these losses and increase transmission efficiency.

Frequency and voltage fluctuations, resulting from variable renewable energy production, are stabilized using microcontroller-based solutions that monitor and regulate these parameters in real-time. Despite the use of advanced technologies, grid stabilization remains a significant challenge due to unstable energy consumption, requiring continuous system adjustments to dynamically changing conditions.

Integrating these technologies is essential to ensure the reliability and stability of energy networks in the era of increasing renewable energy participation. The demand for smart grids is growing exponentially as more variable renewable energy sources are integrated into the power system. As a result, the power grid and electricity market are gradually transitioning from a centralized to a more decentralized structure (Khalid, 2024).

Blockchain:

Energy sector companies increasingly use blockchain technology to support trusted transactions in the renewable energy sector. Blockchain, due to its properties, provides security, transparency, and immutability of data, making it an ideal tool for managing transactions in this sector.

For example, smart contracts on the energy market streamline peer-to-peer (P2P) electricity trading. These contracts enable market participants to exchange energy directly, fostering the development of transactional energy and decentralizing the energy market (Wang, Li, and Zhan, 2021).

Energy networks are vulnerable to various cyber threats, and blockchain plays a crucial role in enhancing their security by encrypting data related to operations and network monitoring. This encryption ensures that any information transmitted within the system is protected from unauthorized access and manipulation. Thus, blockchain facilitates secure digital transactions, which is especially important in energy trading.

Renewable energy providers also use blockchain technology to track the supply chain of network materials. Through a decentralized ledger, each transaction and material movement can be accurately monitored and recorded, providing full transparency and traceability of raw materials and their compliance with environmental standards.

Additionally, blockchain allows regulatory authorities easy access to data, which is crucial for ensuring compliance with regulations (Vionis and Kotsilieris, 2023).

These authorities can monitor operations and transactions in the energy market in real-time, enhancing their ability to oversee and enforce regulations. As a result, blockchain technology not only supports the development of trusted transactions and increases the security of energy networks but also facilitates transparency and regulatory compliance, contributing to the more efficient and secure functioning of the renewable energy sector.

Advanced Robotics:

Production and process efficiency are major hurdles in harnessing renewable energy. To minimize these obstacles, advanced robotics solutions are employed to ensure precision and optimal resource utilization (Oró, Depoorter, Garcia, and Salom, 2015).

For example, automated solar panels can orient themselves to maximize energy conversion. Precise and efficient management of solar panels increases their efficiency, leading to greater clean energy production and reduced carbon footprint. Robotics also contribute to advanced monitoring and diagnostics of photovoltaic systems.

Inspection robots equipped with high-resolution cameras and thermal sensors can conduct thorough inspections of panels, detecting early signs of damage, such as cracks or overheating. By analyzing the data collected by these robots, potential issues can be quickly addressed, significantly enhancing system reliability and extending its lifespan.

Additionally, robotics enable the optimization of natural resource use and minimize waste associated with maintenance and repairs. Automation of equipment also speeds up maintenance processes while reducing the need for human labor (Olayiwola, Elsdén, and Dhimish, 2024).

4. Conclusion

In the energy sector, companies are increasingly implementing innovative solutions to meet growing technological, legal, and environmental demands. In response to global challenges related to climate change and increasing regulatory pressure, energy companies are focusing on integrating advanced technologies that support sustainable development and energy efficiency.

This decade is poised for dynamic growth in high technologies such as smart grids, advanced energy storage systems, blockchain, and artificial intelligence, which enable the optimization of energy resource management and enhance the reliability of energy supply. Digitalization plays a key role in monitoring and data analysis, allowing for more precise and efficient management of energy infrastructure.

Simultaneously, innovations that support CO₂ emission reduction, such as green hydrogen, photovoltaic technologies, and wind energy, are priority investment areas. These efforts not only help companies meet legal requirements but also contribute to environmental protection, laying the foundations for a sustainable and eco-friendly energy future.

The results presented in the studies provide crucial insights that can significantly impact the process of strategic decision-making in business management. These analyses offer a detailed view of current trends, challenges, and market opportunities, enabling leaders and managers to effectively plan for development and adjust strategies.

This enables companies to better understand their business environment, identify potential threats, and seize emerging opportunities. The conducted studies are an effective tool in strategic business management, supporting decision-making processes and allowing for better adaptation to changing market conditions.

With the obtained data, decision-makers can better understand market dynamics, assess potential risks, and identify areas for growth and innovation. Consequently, the research findings support informed decision-making that can contribute to optimizing business operations, enhancing competitiveness, and achieving long-term development goals.

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