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An in-depth study of the principles and technologies of wind-solar complementary systems: Optimization strategies and future development trends

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Abstract. In the face of the global energy crisis and the challenges of climate change in the 21st century, there is an urgent need to shift to sustainable energy solutions. Wind-solar hybrid systems, renewable energy technologies that combine wind and solar energy, are particularly important because they improve the stability and efficiency of energy supply. Through the analysis of technological innovation and system optimization strategies, this study explores ways to enhance system performance and economy by relying on the latest research on wind and solar energy technology development as well as empirical studies of wind-solar complementary systems in different application scenarios. The results of the study show that wind-solar hybrid systems can effectively reduce the dependence on fossil fuels and reduce environmental pollution, and they play an increasingly important role in the transformation of the global energy structure. Continued technological innovation and policy support are key to advancing the widespread deployment of the system.

Keywords: sustainable energy, wind and solar hybrid systems, technological innovation, system optimization, energy transition

1. Introduction

The wind-solar hybrid system combines two renewable energy sources, wind and solar, and utilizes their complementary nature in time and space in order to improve the stability and efficiency of the overall system's energy supply. For example, in some areas where solar power is higher during the day and wind power is higher at night, a smoother and more continuous energy supply can be achieved by combining the use of these two sources of energy. In addition, wind and solar hybrid systems can reduce dependence on the power grid, especially in remote areas or areas with unstable power grids, providing a more reliable energy solution for the local area.

Wind-solar hybrid systems are not only important for mitigating the energy crisis and climate change, but also play a key role in promoting the transformation of the global energy structure and facilitating green and low-carbon development. With technological advances and cost reductions, the application of wind and solar hybrid systems is promising and is considered an important part of future sustainable energy solutions. Therefore, in-depth research and promotion of wind-solar complementary systems are of great practical significance and long-term impact for realizing global sustainable development goals.

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2. Principles and technologies of wind-powered complementary systems

2.1. Wind energy technology

The journey of wind energy technology is full of challenges and opportunities. As the global demand for sustainable energy grows, wind power has become one of the most cutting-edge technologies. In the field of wind power generation, innovations in direct-drive and doubly-fed induction generator (DFIG) technologies, especially in the application of hybrid control models, have significantly improved the smoothness and reliability of power output [1-2]. These advances have not only increased the attractiveness of wind power, but have also paved the way for the development of wind and solar hybrid systems.

Recent studies that comprehensively evaluate the conversion, control and application of wind energy have shown that the optimization of existing technologies and the development of new ones are necessary in order to achieve a sustainable technological transition [3]. Advances in wind energy conversion technology, including improved conversion efficiency and reduced system costs, are critical to improving the overall performance of wind and solar hybrid systems [4].

Recent reviews of technologies and challenges have highlighted innovations in wind turbine design and the need for optimization strategies for wind farms. These studies point out that power generation efficiency and system reliability can be substantially improved by improving wind energy capture equipment and optimizing wind farm layout [5]. This means higher energy yield and lower operating costs for wind and solar hybrid systems, providing a strong case for sustainable energy solutions.

2.2. Solar technology

Solar technologies, especially photovoltaic (PV) and solar thermal systems, have become a key part of the global energy transition. Innovative design and thermal analysis methods, such as the new solar CBS-PVT system, have significantly improved the efficiency of solar energy utilization through the use of thin-film beam splitting technology [6]. These technological advances have not only facilitated the economics of solar power generation, but also enhanced its potential for application in diversified energy systems.

Exploring the potential of concentrating solar energy technologies for specific applications, such as vertical farming in arid regions, reveals the important role of solar technologies in solving specific social and environmental problems [7]. Meanwhile, an overview of the development and application of solar thermal technologies, especially the use of hot water systems in West Africa, shows the wide applicability of solar energy in different parts of the globe [8].

In addition, the synergistic effect of combining solar technology with other sustainable technologies, such as photovoltaic-thermal desalination, provides an innovative solution to address the global shortage of freshwater resources [9]. This convergence of technologies not only improves the efficiency of energy conversion, but also provides new perspectives on the socio-economic impacts of solar technologies [10].

2.3. Principle of Complementarity

The complementary nature of wind and solar energy provides a theoretical basis for designing efficient and reliable hybrid renewable energy systems. By optimizing the combination of wind and solar energy, the energy supply can be maximized in different geographical locations and climatic conditions [11]. Empirical studies have shown that wind-solar hybrid systems can effectively reduce the instability of energy output due to weather changes and seasonal fluctuations [12]. The design of such systems typically involves a detailed analysis of wind speed and solar radiation to ensure that the maximum energy output is obtained from at least one source at any given time.

Simulation studies have further confirmed the potential of wind and solar hybrid systems to improve energy efficiency and reduce dependence on fossil fuels. By optimizing the configuration of solar and wind power generators, these systems are able to meet the power needs of different regions while reducing the environmental impact [13]. For example, studies combining floating offshore wind and

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solar photovoltaic (PV) systems have shown the possibility of maximizing energy use under specific conditions [14].

Applications in the transportation sector, such as hybrid energy storage systems based on rooftop solar and wind power in railroad traction systems, demonstrate the practical value of wind and solar complementary technologies in providing a reliable and continuous energy supply [15]. This not only reduces the dependence on the traditional grid, but also demonstrates the versatility and adaptability of wind and solar hybrid systems.

The performance of wind-solar complementary systems can be significantly improved by intelligent algorithms and accurate system design [16-17]. This optimization involves not only hardware improvements, but also innovations in energy scheduling strategies and demand response mechanisms, thus ensuring a balance between optimal economic and environmental benefits.

Overall, wind and solar hybrid systems represent a critical step in the transition to cleaner, more sustainable energy. By utilizing the complementary nature of wind and solar energy in an integrated manner, these systems not only provide a more stable and efficient energy supply, but also mitigate environmental impacts and contribute to the transformation of the global energy mix. As technology advances and costs decrease, it is expected that wind and solar hybrid systems will play an increasingly important role in future energy solutions.

3. Design and optimization of wind-solar complementary systems

3.1. System Design Principles

The key design principle of wind-solar hybrid systems is to efficiently integrate wind and solar resources to suit different application environments and needs. While designing the wind and solar complementary energy air conditioning system, BLDC motors were used to improve the efficiency and adaptability of the system considering the characteristics of the Indian home environment [18]. In addition, designs for desalination systems have demonstrated the potential of wind and solar complementary technologies to improve desalination efficiency and reduce energy consumption [19]. In urban infrastructures, such as street light management systems, automated management and optimized energy utilization of wind and solar hybrid systems are achieved through ZigBee-based intelligent control [20].

3.2. Optimization Strategies

For the optimization strategy of wind-solar hybrid systems, research on capacity allocation has shown that the performance and efficiency of wind-solar hybrid systems in heat supply can be effectively improved through accurate energy demand analysis and system design [21]. In a case study in China, capacity optimization and feasibility assessment of solar and wind energy systems revealed ways to achieve optimal energy use under different geographical conditions [22]. Applied research in extreme environments such as Antarctic research stations has emphasized the importance of wind and solar hybrid system design and optimization in ensuring the stability of energy supply and system reliability [23].

Through these studies, it can be seen that the design and optimization of wind-solar complementary systems need to take into account various factors such as technological innovation, environmental adaptability and energy efficiency. Accurate system design and optimization strategies can significantly improve the performance of wind-solar hybrid systems in a variety of application scenarios, providing an effective way to achieve more sustainable and efficient energy use.

4. Challenges and future directions

While wind-solar hybrid systems have significant potential to improve energy efficiency and promote sustainable development, high initial investment, O&M costs, and the wide range of technology applications remain major challenges. For example, the wind-solar complementary urban power supply demonstration project in Erlianhot reveals that despite facing a high initial investment, the long-term economic and social benefits are significant by reducing fossil fuel dependence and reducing

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environmental pollution [24]. In addition, through technological innovation and system design optimization, as shown in the case of a wind-solar complementary LED street light lighting system, a significant increase in cost-effectiveness can be achieved while ensuring the quality of lighting [25].

A comprehensive technical and economic analysis highlights the importance of optimized system design in improving energy efficiency and the economy. Combining wind and solar energy with hydrogen, geothermal energy, and energy storage technologies not only maintains the economy of the system but also effectively reduces energy consumption [26]. Facing the challenges of technological advancement, system stability, and environmental adaptability, the cost of wind-solar complementary systems is expected to be further reduced with the maturity of the technology and the expansion of the economic scale, and the system performance will improve [27, 28]. Future directions show that wind-water multi-energy systems can further improve the stability and economics of energy supply through the wider integration of renewable energy sources, such as hydropower. Technological innovation and system optimization will be the key to promote the increasingly important role of wind-solar hybrid systems in areas far from the grid and energy-poor regions [29]. Therefore, despite the challenges, continuous technological advances and innovations augur well for wind and solar hybrid systems to play a greater role in the future transformation of the energy mix towards a sustainable and economical energy supply.

5. Conclusion

As a renewable energy solution that integrates wind and solar energy, wind-solar hybrid systems have proven their important role and value in the global sustainable energy transition. By effectively integrating these two complementary forms of energy, wind-solar hybrid systems not only provide a more stable and reliable energy supply, but also significantly reduce dependence on fossil fuels, thereby reducing greenhouse gas emissions and environmental pollution. The development and application of such systems provide strong support for realizing the green and low-carbon transitions in the energy mix.

Economic analyses reveal the potential for cost-effectiveness of wind-solar complementary systems, especially as the payback period for such systems is diminishing, driven by technological advances and economies of scale effects. With continuous improvements in system design and optimization strategies, as well as effective responses to system operational stability and environmental adaptability issues, the prospects for commercialization and large-scale application of wind-powered complementary systems are becoming increasingly clear.

Nevertheless, the development and application of wind and solar hybrid systems still face technical, economic and policy challenges. While technological innovation is key to driving system performance improvements and cost reductions, economic analysis is an important tool for assessing and optimizing project feasibility. In addition, policy support and the creation of incentives are equally critical to promoting the widespread deployment of wind-powered complementary systems.

Therefore, it is particularly important to continue research and development of wind-solar complementary systems. Future research should further explore new approaches to system design and optimization to improve energy efficiency and system economics. At the same time, more field trials and case studies on the application of wind-solar hybrid systems under different geographic and climatic conditions will help to gain a deeper understanding of the actual performance and application potential of the systems. In addition, enhanced interdisciplinary and cross-disciplinary collaboration, integrating knowledge and technologies from energy sciences with those from economics, environmental sciences, and policy research, is equally critical to drive innovation and practicalization of wind and solar hybrid systems.

In conclusion, wind and solar hybrid systems play a crucial role in advancing global energy sustainability and addressing the challenges of climate change. Through continuous technological innovation and system optimization, as well as corresponding policy support and market promotion, wind-solar complementary systems are expected to occupy a more important position in the future energy supply and contribute significantly to the realization of sustainable global energy development.

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