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Overview of the Development Status of Distributed Wind-Solar-Storage Energy Systems and the Path to Green and Low-Carbon Transformation

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ABSTRACT
As one of the key paths for promoting green and low-carbon development, distributed wind and photovoltaic power generation and energy storage systems (referred to as wind-solar-storage systems) are indispensable for the new power system by leveraging their cleanliness, renewability, and flexible dispatch capabilities. This review elucidates integration mechanism, key technologies, and application value in green development of distributed wind-solar-storage energy systems. It systematically reviews and analyses the current research progress and application practices in system architecture, optimization dispatch, intelligent control, and energy storage management both domestically and internationally. Then, it points out the main challenges currently faced include high system integration complexity, high energy storage costs, and difficulties in control coordination. It also proposes future development directions from multiple dimensions, such as adaptive dispatch mechanisms based on artificial intelligence, novel and efficient energy storage technologies, and coordinated optimization of source-grid-load-storage. This paper can provide theoretical references and methodological insights for the integration and optimization research of distributed renewable energy systems.

KEYWORDS
Distributed wind-solar-storage system; Green and low-carbon development; Intelligent dispatching; energy storage technology

1 Introduction

Global carbon emission controlling is now playing an important role for stabilizing the climate in the past years, by rapidly and sustainably reducing greenhouse gas emissions [1]. To achieve overarching goal of the Paris Agreement, countries have put forward strategies for carbon peaking and neutrality, promoting deep adjustments in the energy structure and green, low-carbon transformation [2]. Compared with high carbon emissions energy, wind and solar energy, with their abundant resource base and clean energy attributes, has become core elements in building a new energy system. However, the large-scale integration and sustained efficient utilization of this low-carbon energy system could be restricted on unstable output and mismatch between supply and demand. Fortunately, the energy storage technology provides effective support for addressing the volatility and intermittency issues of wind and photovoltaic power generation, thus giving rise to distributed wind-solar-energy storage systems characterized by the synergy of "wind energy-photovoltaics-energy storage" [2-4].

The wind-solar-storage system refers to the organic integration of wind power generation, photovoltaic power generation, and energy storage devices within a local area. The purpose is to achieve stable energy output and dynamic scheduling through intelligent control and energy management [5]. The advantages of distributed wind-solar-storage systems, such as low-carbon cleanliness, on-site energy supply, and flexible scheduling, allow this energy systems could be appropriate for various scenarios, in especially for the urban and rural edges, industrial parks, and remote load centers, and have become an important technical path to support the consumption of distributed power sources, the construction of new power systems, and the achievement of green development goals [6-7].

The current trends of research on wind-solar-storage systems have gradually evolved from focusing on a single technology to studying complex systems involving multi-energy synergy, encompassing multiple aspects such as system structure design, operation mechanism modeling, load forecasting, optimization scheduling, and control strategy design [8]. The academic community has proposed a wealth of theoretical models and algorithmic solutions centered around system modeling, energy management, multi-source synergy, and intelligent optimization. Meanwhile, the engineering community has also successively carried out multiple demonstration projects and commercialization explorations. However, due to the complex coupling of systems, multiple energy conversion links, and variable operating environments, wind-solar-storage systems still face a series of technical bottlenecks and practical challenges in terms of regulation stability, energy efficiency and economy, as well as large-scale promotion [9].

Against this backdrop, this paper takes the distributed wind-solar-storage energy system as the research object. By reviewing its current research status and latest achievements in multi-energy coordination mechanisms, modeling methods, optimization control, and contributions to green development, it analyzes the main existing problems and

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research gaps, then looks forward to the future directions of technological evolution and development trends. This paper aims to provide systematic literature references and research perspectives for relevant researchers, while also providing theoretical support and methodological references for promoting the deep integration of distributed renewable energy systems with green and low-carbon development.

2 Overview of Distributed Wind-Solar-Storage Energy System

Distributed wind-solar-storage system would be deployed near the load center or user end, enabling a flexible and efficient energy supply-demand balance between the source side and the energy consumption side. [9]. This system usually comprises renewable energy generation modules, energy storage modules, Energy Management System (EMS), power conversion devices, load ends, and grid-connected interfaces [10]. In the term of system operation, the EMS coordinates the power distribution among wind power, photovoltaic power, and energy storage based on meteorological forecasts, load forecasts, and real-time monitoring data, achieving supply-demand balance and operational optimization [11]. Under normal operating conditions, wind and photovoltaic energy provide the main power, and the energy storage system adjusts its charging and discharging according to the predicted and real-time power differences; when there is insufficient power generation, the energy storage discharges to compensate and maintain stable power supply to the load; when there is excess power generation, the energy storage absorbs the surplus power or feeds the excess power into the grid [12].

The advantages of distributed wind-solar-storage systems are not only reflected in the flexibility and renewability of energy supply, but also in the improvement of power quality and power supply reliability. Some advanced systems have introduced demand-side response, smart metering, and artificial intelligence prediction algorithms, achieving adaptive scheduling, multi-objective optimization, and minimization of total lifecycle operating costs [13-14]. Through reasonable architectural design and control strategies, distributed wind-solar-storage systems can achieve efficient energy utilization and significant reduction in carbon emissions at the regional level, providing solid support for building a new power system and a green and low-carbon society.

3 Literature Review and Active Research on Distributed Wind-Solar-Storage Energy Systems

In the past years, distributed wind-solar-storage energy systems has been developed in various countries. Europe has accumulated rich experience in the integration of renewable energy into the grid and the construction of microgrids. Germany's "Energy Transition (Energiewende)" strategy, for example, has been achieved high-proportion renewable energy penetration in regional power grids through the large-scale deployment of distributed photovoltaic and wind power, combined with energy storage and demand-side response [15]. In Denmark, it is relying on flexible wind power dispatch and interconnection with transnational power grids, has established a wind-dominated multi-energy complementary system, and significantly reduced the impact of wind power fluctuations on system stability through an integrated forecasting-dispatching platform [16].

In North America, the research on distributed energy integration promoted by the U.S. Department of Energy (DOE) focuses on intelligent dispatch and economic evaluation of energy storage [17]. Several states have established wind-solar-storage microgrid demonstration projects, applying advanced energy management systems (EMS) to achieve real-time power optimization and distribution, and introducing load forecasting models based on machine learning, which have improved dispatch accuracy and system reliability. Japan and Republic of Korea have developed rapidly in the integration of distributed photovoltaic and energy storage, with a particular emphasis on promoting distributed microgrid technology in densely populated urban areas and carrying out resilience design for extreme events such as typhoons and earthquakes [18].

In terms of system model research, Chinese scholars generally adopt System Dynamics, Multi-Agent Modeling, and multi-objective optimization frameworks to construct the operational mechanism of the wind-solar-storage coupled system [19]. In terms of scheduling optimization research, prediction and control strategies based on machine learning have become one of the research hotspots in China. Researchers often combine short-term load forecasting and wind and solar output forecasting results, using intelligent algorithms such as genetic algorithms, Particle Swarm Optimization (PSO), and Grey Wolf Optimization (GWO) to implement multi-objective energy scheduling strategies [20]. In addition, research on the economics and policy adaptability of energy storage is also continuously deepening. Due to issues such as long investment return cycles and high operation and maintenance costs of energy storage equipment, many studies in China focus on the revenue mechanisms of energy storage participation in peak-valley electricity price arbitrage, demand response, and auxiliary services. Some regions have also conducted policy simulation research based on regional demonstration projects, such as the simulation platform for the wind-solar-storage + electric vehicle charging and discharging system in the North China Grid, which explores the economic boundaries of various types of energy storage resources [21].

Overall, scholars from various countries are gradually converging in terms of research methods, research objects, and evaluation indicators, reflecting the evolution trend of global research on distributed wind-solar-storage energy systems from "single-point optimization" to "system collaboration" [22]. Current research on wind-solar-storage systems focuses on the following technical hotspots: multi-energy collaborative modeling and dynamic optimization methods; AI-based load and output prediction technology; distributed dispatch and hierarchical control mechanisms; integration of new energy storage technologies and system energy efficiency improvement; and coupled modeling research with carbon emissions and carbon trading mechanisms. In addition, the integration of green energy systems with emerging technologies such as smart cities, smart grids, and blockchain provides vast development space for research on wind-solar-storage systems [23-24].

4 Key Technologies and Modeling Methods

4.1 System Modeling Methods and Mechanism Analysis

As a typical complex energy subsystem, the modeling objectives of a distributed wind-solar-storage system mainly include describing the system structure, characterizing energy flow, expressing the coupling relationships between key variables, and providing a mathematical foundation for scheduling and optimization. Currently, mainstream system modeling methods could be divided into three categories: physical modeling, data-driven modeling, and hybrid modeling.

Physical modeling methods rely on tools such as System Dynamics, state space modeling, and multi-objective optimization to establish mathematical models that reflect the operating laws of the system, starting from energy conservation and electrical characteristics [25]. These models can better reflect energy interaction and operating mechanisms, but the high dependency of parameters may bring highly uncertain adaptability to complicated external environments.

Data-driven modeling methods leverage historical operational data to establish the mapping relationship between system inputs and outputs through techniques such as machine learning and deep learning, without explicitly modeling the physical laws of the system, thus exhibiting strong adaptability. For instance, methods based on BP neural networks and LSTM time series models have been widely applied in wind speed prediction, solar radiation prediction, energy storage state estimation, and other fields. However, their "black box" nature limits interpretability and generality.

The hybrid modeling approach combines the advantages of the aforementioned two methods by introducing a data-driven submodule to dynamically correct the results of physical modeling, thereby enhancing the model's prediction accuracy and robustness [26]. For instance, some studies employ physical models to describe energy balance processes while simultaneously correcting nonlinear disturbance terms through neural networks, achieving a balance between modeling accuracy and computational efficiency.

4.2 Optimized Scheduling and Energy Management Strategies

Optimization scheduling is the key to achieving economical and efficient operation of wind-solar-storage systems. Its goal is to rationally arrange power generation, energy storage charging and discharging, load management, and other aspects in the time dimension based on information such as load demand, meteorological forecasts, and energy storage status, in order to achieve optimal energy allocation and system economy optimization. Scheduling optimization strategies are generally divided into two categories: deterministic optimization and uncertainty optimization.

Deterministic optimization methods assume accurate and error-free predictive data and often employ mathematical optimization tools such as linear programming (LP), nonlinear programming (NLP), and mixed-integer linear programming (MILP), which are suitable for systems with clear structures and high computational accuracy [27]. Such methods are widely used in microgrid dispatch, energy storage strategy formulation, and operation cost minimization problems.

Uncertainty optimization methods consider uncertainties such as meteorological disturbances and load forecasting errors, and enhance the system's adaptability to external disturbances through methods such as robust optimization, fuzzy optimization, and scenario generation [28]. In addition, stochastic optimization (such as stochastic MILP) can optimize scheduling strategies under multiple scenarios, improving the expected performance of the system.

4.3 Multi-Energy Coordinated Control Technology

The core characteristic of the wind-solar-storage system lies in multi-source complementarity. Wind and solar power output are significantly affected by weather, energy storage is constrained by capacity and efficiency on the other hand. Therefore, it is necessary to construct a highly reliable collaborative control system to maintain power quality and system operation balance.

Currently, mainstream control strategies have be divided into centralized control mode and distributed control mode. The centralized control mode obtains global information through a central controller and performs unified scheduling and control over various subsystems. Its advantages include strong optimization performance and unified decision-making, but it faces issues such as high communication load and system stability dependence on centralized nodes on the other hand [29]. The distributed control mode emphasizes local autonomy and information sharing. Each submodule makes dynamic decisions based on local state and information from neighboring nodes, offering higher system resilience and scalability [30]. In recent years, researchers have proposed a collaborative control architecture based on multi-agent systems and blockchain technology, aiming to address the "single point of failure" issue in traditional centralized control systems.

In addition, some studies have introduced feedforward control strategies such as rolling optimization and model predictive control (MPC) to update system state predictions and decision paths in real-time, thereby enhancing system response speed and stability.

4.4 Application of Artificial Intelligence in Wind-Solar-Storage System

As the complexity of energy systems continues to increase, traditional models struggle to cope with issues such as multi-source inputs, strong nonlinear coupling, and dynamic disturbances. Artificial intelligence (AI) technology, with its advantages of self-learning, non-parametric, and real-time adaptation, has become an important supporting tool for the research of wind-solar-storage systems.

Typical applications of AI technology mainly include:

(1) Data prediction: For short-term prediction of key variables such as wind speed, solar irradiance, electricity price, and load, commonly used methods include support vector machine (SVM), long short-term memory network (LSTM), and convolutional neural network (CNN);

(2) Operation status identification: Determine the operation status of equipment and predict the probability of fault occurrence through real-time data;

(3) Adaptive scheduling and control: Implementing online learning and strategy updating for the system using techniques such as reinforcement learning and fuzzy control;

(4) Anomaly detection and security management: AI models can be utilized to identify abnormal fluctuations and potential risks in system operations, thereby enhancing system security.

Overall, artificial intelligence provides a new modeling paradigm and optimization method for wind-solar-storage systems, particularly demonstrating strong advantages when dealing with uncertainty and complex nonlinear system behaviors. However, its engineering application still requires comprehensive design, the specific system characteristics, data resource quality, and interpretability requirements should be fully taken into account.

5 Conclusion

Through literature review and systematic analysis, this article draws the following conclusions:

Firstly, the distributed wind-solar-storage system is composed of wind energy, photovoltaic, and energy storage modules, integrated into the regional energy network. It achieves resource optimization and multi-energy coordination through an energy management system. It is a typical distributed, multi-source coupled, and intelligent energy system, with good scalability and autonomous operation capabilities.

Secondly, significant progress has been made in research in this field both domestically and internationally, covering multiple aspects such as high-precision resource prediction, multi-energy complementary optimization scheduling, energy management system development, control algorithm evolution, and system integration. Especially with the support of technologies such as artificial intelligence and edge computing, the system is promoted to upgrade from functional integration to intelligent collaboration.

Thirdly, the wind-solar-storage system plays multiple roles in green and low-carbon development: it can directly replace fossil fuels to achieve carbon emission reduction, optimize the operational efficiency of the power system, enhance energy self-sufficiency, and construct a new energy architecture with greater resilience and risk resistance. It serves as a crucial pillar in building a new power system and an Internet plus.

However, current development still faces multiple challenges, including complex system modeling, limited operational control accuracy, high energy storage costs, the lack of a standard system, and the need to improve policy mechanisms. In the future, research should focus on the following directions: system modeling technology for multi-energy coupling, adaptive scheduling optimization strategies, safety design oriented towards resilience, the construction of standards and policy systems, and integration with new mechanisms such as the carbon market and green finance.

In summary, the distributed wind-solar-storage system is currently at a pivotal stage of technological breakthroughs and institutional innovation. Its efficient development will have a profound impact on the green transformation of the energy system, the improvement of the ecological environment, and sustainable economic development. Continuing to advance theoretical deepening, technological integration, and institutional innovation will provide a solid foundation and strong support for building a new energy system that is clean, low-carbon, safe, efficient, and intelligently interactive.

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References

[1] Boubaker S, Liu Z, Mu Y, et al. Carbon dioxide emissions and environmental risks: Long term and short term[J]. Risk Analysis, 2025, 45(3): 523-543.

[2] Wang Y, Wang R, Tanaka K, et al. Global spatiotemporal optimization of photovoltaic and wind power to achieve the Paris Agreement targets [J]. Nature Communications, 2025, 16(1): 2127.

[3] Tong D, Farnham D J, Duan L, et al. Geophysical constraints on the reliability of solar and wind power worldwide[J]. Nature communications, 2021, 12(1): 1-12.

[4] Jahangir A, Mishra S. Autonomous battery storage energy system control of PV-wind based DC microgrid[C]//2018 2nd International Conference on Power, Energy and Environment: Towards Smart Technology (ICEPE). IEEE, 2018: 1-6.

[5] McCabe K, Prasanna A, Lockshin J, et al. Distributed wind energy futures study[R]. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022.

[6] Jahangir A, Mishra S. Autonomous battery storage energy system control of PV-wind based DC microgrid[C]//2018 2nd International Conference on Power, Energy and Environment: Towards Smart Technology (ICEPE). IEEE, 2018: 1-6.

[7] Wang H, Bai X, Xu J. Reliability assessment considering the coordination of wind power, solar energy and energy storage[C]//Zhongguo Dianji Gongcheng Xuebao(Proceedings of the Chinese Society of Electrical Engineering). Chinese Society for Electrical Engineering, 2012, 32(13): 13-20.

[8] Li B, Zhao J, Zhang Y, et al. Optimal configuration and economic operation of Wind – Solar-storage complementary system for agricultural irrigation in mountainous areas[J]. Journal of Electrical Engineering & Technology, 2023, 18(4): 2649-2666.

[9] Chowdhury B H, Tseng C L. Distributed energy resources: Issues and challenges[J]. Journal of Energy Engineering, 2007, 133(3): 109-110.

[10] Nadeem T B, Siddiqui M, Khalid M, et al. Distributed energy systems: A review of classification, technologies, applications, and policies[J]. Energy strategy reviews, 2023, 48: 101096.

[11] Bakare M S, Abdulkarim A, Shuaibu A N, et al. Energy management controllers: strategies, coordination, and applications[J]. Energy Informatics, 2024, 7(1): 57.

[12] Meng Q, He Y, Hussain S, et al. Day-ahead economic dispatch of wind-integrated microgrids using coordinated energy storage and hybrid demand response strategies[J]. Scientific Reports, 2025, 15(1): 26579.

[13] Deshpande V. Smart grids integration with AI-powered demand response[J]. Research Journal of Computer Systems and Engineering, 2024, 5 (1): 45-58.

[14] Babayomi O, Zhang Z, Dragicevic T, et al. Smart grid evolution: Predictive control of distributed energy resources—A review[J]. International Journal of Electrical Power & Energy Systems, 2023, 147: 108812.

[15] Buchan D. The Energiewende–Germany's gamble[M]. Oxford Institute for Energy Studies, 2012.

[16] Acaroğlu H, García Márquez F P. Comprehensive review on electricity market price and load forecasting based on wind energy[J]. Energies, 2021, 14(22): 7473.

[17] Eyer J M, Corey G P. Energy storage for the electricity grid: benefits and market potential assessment guide: a study for the DOE Energy Storage Systems Program[R]. Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA (United States), 2010.

[18] Li Y, Gao W, Ruan Y, et al. The performance investigation of increasing share of photovoltaic generation in the public grid with pump hydro storage dispatch system, a case study in Japan[J]. Energy, 2018, 164: 811-821.

[19] Zhang F, Luo J, Gui Y, et al. A Study on Energy Management Research for Ubiquitous Power Internet of Things[C]//2019 IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2). IEEE, 2019: 1036-1041.

[20] Guo J. Research on optimal scheduling and energy management strategy of wind-solar storage complementary microgrid [J]. Journal of Electrical Engineering, 2020, 8: 36.

[21] Zhang M, Huang Y, Zhou M, Ma L. Research on Battery Allocation and Economy of Battery Swapping Station Under the Battery Swapping Ecosystem. Journal of Industrial Technological Economics. 2022, 41(9): 18-25

[22] Xia Y, Wu H, Xin J, et al. Evaluation of economic operation for microgrid with complementary DGs and energy storage[J]. Electric Power Automation Equipment,2017,37(7): 63-69.

[23] Mei S, Li R, Huang S, et al. Modeling and dynamic evolution mechanism of multi-energy complementary network [J]. Journal of Global Energy Interconnection, 2018, 1(1).

[24] Sun H, Guo Q, Pan Z, et al. Energy internet: driving force, review and outlook [J]. Power System Technology, 2015, 39(11): 3005-3013.

[25] Wang Y, Wang R, Tanaka K, et al. Global spatiotemporal optimization of photovoltaic and wind power to achieve the Paris Agreement targets [J]. Nature Communications, 2025, 16(1): 2127.

[26] Gijón A, Eiraudo S, Manjavacas A, et al. Integrating Physics and Data-Driven Approaches: An Explainable and Uncertainty-Aware Hybrid Model for Wind Turbine Power Prediction[J]. arXiv preprint arXiv:2502.07344, 2025.

[27] Alhumaid Y, Khan K, Alismail F, et al. Multi-input nonlinear programming based deterministic optimization framework for evaluating microgrids with optimal renewable-storage energy mix[J]. Sustainability, 2021, 13(11): 5878.

[28] Bade S O, Tomomewo O S, Maan M, et al. Optimal Sizing and Techno-Economic Evaluation of a Utility-Scale Wind–Solar–Battery Hybrid Plant Considering Weather Uncertainties, as Well as Policy and Economic Incentives, Using Multi-Objective Optimization[J]. Energies, 2025, 18(13): 3528.

[29] Olivares D E, Cañizares C A, Kazerani M. A centralized energy management system for isolated microgrids[J]. IEEE Transactions on smart grid, 2014, 5(4): 1864-1875.

[30] Mishra J, Behera P K, Pattnaik M, et al. A multi-agent petri net model power management strategy for wind – solar-battery driven DC microgrid[J]. Sustainable Energy Technologies and Assessments, 2023, 55: 102859.