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A Study on the Current Status of Green Energy Development in the Context of Dual-Carbon Goals

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***Abstract*—*Whether the green energy transition can be successfully implemented directly determines the realization of the dual-carbon goals. This paper reviews relevant domestic research from 2010 to 2025, employing a framework of "timeline + technology classification + problem dimension." The study period is divided into two phases: the scale-expansion phase from 2010 to 2020, and the system-integration phase from 2020 to 2025. Within each phase, the analysis is further organized from three perspectives: power generation technology, energy storage, and market mechanisms. The review reveals that before 2020, research primarily focused on reducing the costs of new energy and expanding its scale, with development largely driven by policy subsidies. Following the introduction of the dual-carbon goals, scholarly attention shifted toward system-level issues, including the integration of grid-connected renewable power, the underutilization of installed energy storage capacity, and the coupling between electricity markets and carbon markets. Several controversies persist in the academic community, such as whether the phenomenon of "storage built but not used" is temporary or structural, what role nuclear power should play in the new energy system, and what standards should be adopted to measure energy system costs. In addition, existing research has several notable limitations: slow data updating, an overemphasis on the power sector while neglecting industrial heat supply, the nascent stage of research on the impacts of extreme weather events, and the masking of inter-provincial differences by aggregated average data. Future research should place greater emphasis on empirical analysis of high-penetration renewable power systems, quantification of supply-demand matching for long-duration energy storage, the coupling mechanisms among multiple markets, and the enhancement of energy system resilience under extreme weather conditions.*

I. INTRODUCTION

In September 2020, China announced its goals of peaking carbon emissions and achieving carbon neutrality, fundamentally reshaping the energy sector's development trajectory. Before the dual-carbon strategy, green energy played a supporting role to coal-fired power, with a relatively low position in the energy system. Following the introduction of top-level policy designs, green energy has become a main driver of energy transition and emission reduction. According to targets, non-fossil fuel power generation is expected to reach about 39% by 2025, and non-fossil energy consumption will exceed 25% by 2030, signaling an accelerating green and low-carbon transition.

Energy transition is also a global issue. The European Union introduced the Fit for 55 package, and the United States, through the Inflation Reduction Act, strongly supports its domestic new energy sector. Global competition in new energy has shifted from a focus on scale to a contest of technology and institutional design. Against this backdrop, scholars worldwide have conducted extensive research on green energy, covering technological optimization, policy design, power system dispatch, and ecological impacts.

A review of the literature clearly identifies 2020 as a critical dividing line. From 2010 to 2020, the scale-expansion phase, research focused on facilitating new energy deployment and reducing costs, addressing early-stage difficulties. From 2020 to 2025, the system-optimization and integration phase, with the rapid expansion of new energy installed capacity, core challenges such as large-scale renewable integration into the grid, grid adaptability, and market mechanism design have become increasingly prominent research hotspots.

Based on these stage-specific characteristics, this paper adopts a chronological framework—2010–2020 as the scale-expansion phase and 2020–2025 as the system-optimization and integration phase—and reviews research findings from three dimensions: generation technology, energy storage support, and market mechanisms. It summarizes core controversies in the academic community, identifies gaps in existing research, and points out possible future directions, aiming to provide references for subsequent studies and industrial practice.

II. LITERATURE REVIEW

The period from 2010 to 2020 was critical for laying the foundation and expanding the scale of China's green energy industry. The core task was to rely on policy support to increase installed capacity, continuously reduce generation costs, and facilitate the transition of new energy from demonstration projects to large-scale deployment. During this phase, academic research focused in parallel on individual technology optimization and economic viability, thereby establishing the industrial foundation for the dual-carbon transition.

In the area of power generation technology, photovoltaic (PV) research centered on technological iteration and domestic substitution. Between 2010 and 2020, laboratory conversion efficiencies of PV cells increased from 20% to 24%. In the early stage, China's PV industry faced the problem of "three dependencies abroad"—core technology, production equipment, and end markets. The "531 New Policy" in 2018 accelerated subsidy phase-down, forcing enterprises to pursue independent innovation and cost reduction, thereby shifting the industry toward market-driven competition [1][2]. In the wind power sector, research focused on fine-scale assessment of national wind energy resources, identifying a total exploitable potential of approximately 3.5 billion kW at a height of 100 meters. Between 2010 and 2019, the global levelized cost of electricity (LCOE) for PV decreased by 82% and for onshore wind by 39%. However, offshore wind power faced commercial viability challenges due to high costs associated with construction, equipment, and operation and maintenance [3][4][5]. During this period, LCOE was commonly used in academia to evaluate the economic viability of energy sources, suggesting that solar and wind power had cost advantages. However, Joskow pointed out that the traditional LCOE metric does not account for system costs such as grid integration reserves, energy storage, and grid upgrading, leading to an overestimation of the economic viability of solar and wind power—an insight that provided a new direction for system optimization research [6].

For hydropower and nuclear power as mature low-carbon energy sources, research focused on technological optimization, safety, and ecological balance. In hydropower, mature optimal dispatch theories were developed, and the concept of ecological hydraulic engineering guided green hydropower development. Nuclear power research prioritized safety, focusing on safety technology upgrades and new reactor designs, although the high initial investment and insufficient economic viability of new nuclear plants remained challenges [7][8][9][10].

In the area of energy storage and system flexibility, the energy storage industry was in a phase of technological reserve and small-scale demonstration. Pumped hydro storage was the only commercially viable large-scale storage technology, with an operational installed capacity of 31.8 GW by the end of 2020, serving grid peak shaving and valley filling functions. Electrochemical energy storage remained at the pilot application stage, with capital and operating costs far exceeding those of pumped hydro, making it unsuitable for market-oriented deployment. Academic research on energy storage was limited to the optimization of technical parameters, lacking practical studies on business models, market fit, and application scenarios, leaving a theoretical gap in the market-oriented development of energy storage [11][12][13].

In market and policy research, green energy development was highly dependent on renewable energy electricity price subsidies. While subsidies drove rapid capacity expansion, they also resulted in a cumulative subsidy shortfall of over RMB 300 billion, imposing a heavy fiscal burden. Related research focused on administrative policies such as subsidy standards, phase-down pathways, and benchmark electricity price adjustments, adopting a narrow perspective. There was insufficient research on long-term mechanisms such as electricity market reform, cross-provincial new energy trading, and market fit, and a research mindset oriented toward market-driven energy transition had not yet been established [14]. Although this phase achieved the goals of technological iteration, cost reduction, and scale expansion, the research suffered from fragmentation, excessive reliance on subsidies, and a lack of empirical support for integration analyses, laying the groundwork for subsequent systemic contradictions.

Following the implementation of the dual-carbon goals, global renewable energy installed capacity increased by 48% between 2020 and 2024, while China experienced a 55% increase. The expansion of new energy capacity shifted the core challenge of the industry from large-scale deployment to high-quality operation, efficient integration, and system compatibility. In parallel, academic research increasingly focused on system optimization, grid integration, multi-energy complementarity, and market mechanism design [15].

Research on power generation technologies exhibited new characteristics. In the PV sector, distributed photovoltaics experienced substantial growth, with an average annual growth rate of 68% from 2021 to 2024. By 2024, newly installed distributed PV capacity exceeded that of centralized PV. Technologically, PERC cells were replaced by N-type cells such as TOPCon and HJT, achieving mass production conversion efficiencies of 25.4%, while laboratory efficiencies of perovskite tandem cells exceeded 33.9%. However, the long-term stability of perovskite cells remains a concern [16][17][18]. The growth of PV capacity has led to regional disparities in integration performance, with a national average utilization rate of 96.5%, while in some areas of northwest China, the utilization rate has fallen below 90%. Academic debate persists regarding whether the resurgence of integration pressure is attributable to phase-specific issues or short-term fluctuations [19][20].

In the wind power sector, offshore wind achieved grid parity. In 2024, China led the world in newly installed offshore wind capacity, and turbine upscaling improved generation efficiency. However, the anti-peaking characteristics of wind power exacerbated grid peaking pressures, with the national curtailment rate rebounding to 3.2% in 2024. Academia remains divided on the causes, with two main perspectives: insufficient flexibility retrofitting of coal-fired power plants and low utilization rates of cross-regional transmission channels [21][22][23][24][25].

Hydropower development has approached saturation, with an exploitation rate exceeding 65%. Its role has shifted from a primary power source to a regulating source. Pumped hydro storage has become a key source of flexibility, but there is a temporal mismatch between its construction cycle and the growth rate of new energy. Extreme droughts have led to significant reductions in hydropower output in southwest China, making integrated hydro-wind-solar-storage systems and cascade hydropower station coordinated dispatch active research topics [26][27][28][29].

Nuclear power capacity has steadily increased, with 56 reactors in operation by the end of 2024, totaling 57.2 GW, yet nuclear power accounts for only 4.5% of total generation. While domestic nuclear technology systems are mature, there is intense academic debate over the role of nuclear power between baseload support and insufficient cost-effectiveness [30][31][32].

The energy storage industry has entered a phase of large-scale development. By the end of 2024, new energy storage capacity reached 58 GW / 140 GWh, and the cost of lithium iron phosphate (LFP) storage fell below RMB 0.8/Wh. However, the problems of "storage built but not used" and low utilization rates are pronounced. The average equivalent utilization factor of electrochemical energy storage is only 12%. Some researchers attribute this to a lack of dispatch incentives and immature revenue models, while others argue that the implementation of electricity spot markets will improve utilization rates. There is also a structural mismatch characterized by an oversupply of short-duration storage and a shortage of long-duration storage [33][34][35].

Market policies and mechanisms have undergone a transition from administrative support to market-based regulation. Green electricity, green certificates, and the national carbon market have become core instruments. In 2024, green electricity trading reached 150 TWh, and 820 million green certificates were issued. However, the environmental premium was only RMB 0.03/kWh, providing limited incentives. The national carbon market currently covers only the power sector, with carbon prices ranging from RMB 80 to 110/tCO_2, leading to insufficient price signal transmission. The EU's Carbon Border Adjustment Mechanism (CBAM) has introduced new challenges related to international trade barriers [36][37][38].

A comparison of the two phases reveals that the development goal has shifted from scale expansion to high-quality system development; technological iteration has led to advances in solar and wind power and made energy storage a necessity; the integration situation has exhibited a U-shaped trend; policy instruments have transitioned from subsidies to market-based regulation; and the research paradigm has shifted from single-point technological analysis to system-level coordination. At present, China's green energy sector has reached a critical juncture in its transition from incremental expansion to the optimization of existing capacity.

III. RESEARCH CONTROVERSIES, CURRENT LIMITATIONS, AND RESEARCH GAPS

A consensus has yet to be reached in the academic community regarding the key issues surrounding the high-quality development of green energy. Core controversies are concentrated in three areas. First, there is disagreement over the nature of the "storage built but not used" phenomenon, specifically whether it represents a phase-specific market problem or a long-term structural contradiction. An optimistic view holds that market improvements will enhance utilization rates, while another view argues that the oversupply of short-duration storage and the shortage of long-duration storage constitute an irreversible mismatch requiring policy intervention. Second, the role of nuclear power in the green energy system remains debated, with the discussion centering on cost, safety, and social acceptance. Proponents argue that nuclear power can serve as baseload support, while opponents contend that its cost-effectiveness is low and that it is unsuitable for large-scale deployment. Third, there is no unified standard for calculating energy system costs. The traditional LCOE fails to capture system-level costs, and although the concept of system LCOE has been proposed, the accounting framework remains unstandardized, leading to considerable deviations in conclusions [34,35,31,32,39,40].

Current research exhibits significant lags and limitations. First, data updates are slow. Most studies still rely on data from 2022–2023 and have not yet captured recent developments such as the rebound in wind and solar curtailment, low energy storage utilization rates, and the impacts of extreme weather events after 2024. Second, there is a pronounced bias toward the power sector while neglecting heat. Industrial heat accounts for 40% of final energy consumption, yet research on non-power sectors such as green hydrogen and biomass heating remains scarce. Third, research on adaptation to extreme weather events started late. Studies on the climate resilience of energy systems and risk assessment have only gradually emerged after 2024. Fourth, regional differentiation is insufficiently addressed. Reliance on national average data obscures inter-provincial differences in energy structures, undermining the practical applicability of research conclusions.

In addition, four major research gaps can be identified in the field: insufficient empirical research on the operational characteristics of high-penetration renewable energy power systems; a lack of quantitative assessment of structural mismatches in energy storage; unclear logical coupling mechanisms among multiple markets; and a research void in energy planning and operational optimization under extreme weather scenarios. These represent important directions for future academic research.

IV. CONCLUSION

The 2020 dual-carbon goals marked a critical turning point for green energy development and research in China. From 2010 to 2020, supported by policy subsidies, China established the world's largest green energy industrial system, achieving foundational progress in technology, cost, and scale. However, research during this period remained fragmented and lacked systematic thinking, laying the groundwork for subsequent structural contradictions. From 2020 to 2025, guided by the dual-carbon targets, green energy has become central to the energy system, with rapid advancements in distributed photovoltaics, offshore wind power, new energy storage, and market-based trading systems. At the same time, challenges have emerged, including renewed pressure on renewable integration, low utilization rates of energy storage, disputes over the role of nuclear power, and disruptions from extreme weather events. Academic research has shifted toward system optimization but still lags behind industrial practice. China's green energy sector has moved beyond extensive capacity expansion into a refined development phase that prioritizes quality and system-level optimization. Future research should rely on empirical data from 2024–2025 to conduct systematic analyses of high-penetration renewable power systems, quantify the scale of structural energy storage mismatches and the long-duration energy storage gap, clarify the coupling mechanisms among the carbon market, green certificate market, and electricity spot market, and develop resilience optimization strategies for energy systems under extreme weather conditions—thereby promoting a high-quality green energy transition.

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