

Insights and Policy Directions for China's Power Sector Amid Carbon Neutrality Goals

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Abstract: China's carbon neutrality largely relies on its energy and electricity sector, the biggest carbon emitter. This study tracks the sector's low-carbon transition to provide policy insights for China and other nations. Based on data mining from official statistics, government documents and reports, the research finds China has significantly expanded wind and solar capacity to peak carbon emissions by 2025, but new coal projects, inadequate grid infrastructure and flawed regulatory frameworks hinder the transition, as local governments prioritize energy security over sustainability. Policy recommendations include establishing an emission peaking framework, enhancing resource security, promoting distributed renewable energy and energy storage, and repositioning coal as a supplementary power source. Its originality lies in comprehensively analyzing the interplay between renewable expansion and coal investment, addressing China's unique energy challenges with innovative policies, and offering practical references for global decarbonization efforts. Balancing energy demand and economic pressures remains critical, requiring concerted innovative policies for a sustainable low-carbon power sector.

Keywords: Carbon Emission, Power Sector, Neutrality, Policy Suggestions

1. Introduction

It has been near one year since the conclusion of the 28th Conference of the Parties (COP28) to the United Nations Framework Convention on Climate Change, where the first global stocktake culminated in the "UAE Consensus," signaling the important need to phase out fossil fuels. The conference highlights that by mid-century, the world must achieve a just energy transition away from fossil fuels to reach net-zero emissions. Energy combustion is the primary source of carbon dioxide emissions in China, accounting for approximately 88% of total emissions, while carbon emissions from the power sector comprise over 40% of the energy sector's total emissions ^[1]. The power sector is not only a significant contributor to China's carbon emissions but also a key player in achieving the country's dual carbon goals ^[2-4].

The "14th Five-Year Plan" and the "15th Five-Year Plan" periods mark the first phase of a three-step development for building a new power system ^[5]. The key tasks during this phase are to transform the role of coal power, promote renewable energy as the main contributor to electricity generation growth, achieve leapfrog and large-scale development of renewable energy and energy storage, and establish a solid foundation for the power sector to peak carbon emissions by 2025 in support of the new power system ^[6-7]. The significance of China's power sector's low-carbon transition has been widely acknowledged in policymaking. For example, on March 15, 2021, the Central Financial and Economic Committee, during its ninth meeting, officially introduced the concept of "building a new power system with new energy as the mainstay." In May 2022, the National Development and Reform Commission, along with the National Energy Administration, released the "Implementation Plan for Promoting High-Quality Development of New Energy in the New Era," reaffirming the need to "accelerate the construction of a power system that accommodates the increasing share of new energy."

Meanwhile, the academia plays great attention to the low-carbon transition of China's power sector simply owing the fact that China is the world's largest emitter of greenhouse gases, primarily due to its reliance on coal for electricity generation ^[8-12]. As climate change intensifies, the necessity for a low-

carbon transition in China's power sector has become increasingly critical and also the possible need for an example in the world for other countries to learn and likely imitate, particularly for certain similar power supply structure and other characteristics. Scholars have dedicated into examining the low-carbon transition paths, policies and challenges associated with this transition^[13-16]. With respect to the transition path, the role of renewable energy growth has been widely highlighted in literature^[17-19]. Scholars agreed that searching for and developing substitute power is the major path for China to transform its' power sector toward a low-carbon one. In this regard, China has made great progress. According to the National Energy Administration (2022), China accounted for over 50% of the world's new solar capacity in 2021. The total installed renewable capacity reached 1,000 GW, with wind and solar contributing significantly to the energy mix. In addition, scholars highlights the technological innovations, e.g., smart grid technologies and energy storage systems, within the power sector in helping the power sector to achieve a low-carbon goal^[20]. Bai et al.^[21] highlighted breakthroughs in energy storage technologies such as lithium-ion batteries, which are crucial for balancing supply and demand within an increasingly complex and volatile energy landscape. Jiang et al.^[22] further emphasised that the proliferation of electric vehicles plays a pivotal role in advancing China's low-carbon transition within the power sector, aligning closely with the central government's developmental objectives. According to the Ministry of Industry and Information Technology's planning, electric vehicle sales are projected to account for 20% of total national automobile sales by 2025.

With the terms of policies, scholars highlighted the financial mechanisms, such as feed-in tariffs and subsidies for renewable energy projects. For instance, research by Sun et al.^[23] indicates that these incentives have significantly lowered the cost of renewable energy deployment, making it more competitive with traditional energy sources. Wu et al.^[24] and Zhang and Xie^[25] studied the role of subsidies and tax incentives in help China to achieve the low-carbon transition of power sector. Besides these great achievements that China has achieved in the decarbonization of power sector and scholars' seminal insights into this issue, the academic work also expressed their concerns related to the challenges that might confront China's successful transition. These challenges can be outlined by three aspects. First, the infrastructure limitations. China's existing power grid was primarily designed for centralized fossil fuel generation, making it difficult to accommodate the decentralized nature of renewable energy. Studies by Ding et al.^[26] show that regional disparities in infrastructure investment lead to imbalances in energy distribution and grid stability. Second, the economic and financial barriers. The high upfront costs of renewable energy technologies pose a substantial barrier to widespread adoption. Coal remains a major energy source due to its affordability and established infrastructure. Research by Wang et al.^[27] highlights the economic challenges associated with phasing out coal while maintaining energy security. Third, the policy and regulatory hurdles. Inconsistent enforcement of environmental regulations at the local level complicates the implementation of national policies. The complexity of the regulatory framework can create uncertainty for investors and hinder the transition to cleaner energy sources Zhang et al.^[28].

To help policymakers and scholars better track and understand China's continuous transition of power sector to a low-carbon one, this study intends to clarify the progress of the power sector's low-carbon transition with the efforts to sustain its' great work in this regard, and pointing out some cautious points that we might care about, particularly in the point view of policymaking. To achieve this goal, we collected the latest data from China's power sector in various resources, and highlight six major trends. In the end, we recommend policies for policymakers.

2. New Trends of Low-Carbon Transition in China's Power Sector

Trend 1: Renewable Energy Emerges as the Primary Source of New Installed Capacity and Generation in China

In 2023, renewable energy sources, particularly wind and solar power, have overtaken coal power, establishing themselves as the primary contributors to new installed capacity and generation within China's energy landscape. Specifically, while coal power capacity saw an increase from 1,010 million kilowatts in 2018 to 1,160 million kilowatts in 2023—a net gain of 150 million kilowatts—this growth has led to a significant decline in coal's share of total installed capacity, dropping from 53% at the end of 2018 to 39.9%. This shift underscores a pivotal transition in China's energy strategy, highlighting a growing commitment to cleaner energy sources.

In contrast, the installed capacity of wind and solar energy has seen a significant increase, jumping from 358 million kilowatts in 2018 to an impressive 1,050 million kilowatts by 2023. This expansion

boosts the proportion of renewables in the overall generation capacity to 35.96%. By the end of 2023, the newly added capacity for wind and solar power totaled an extraordinary 295 million kilowatts. If this upward trend continues, with an average annual growth rate of 23.97% observed from 2018 to 2023, China is well-positioned to achieve an astounding installed capacity of 2.4 billion kilowatts (2400 gigawatts) or more in wind and solar power by 2030. This target aligns with the overarching goal of tripling global renewable energy capacity by the same year, further cementing China's leadership role in global renewable energy development.

When examining generation capacity, the increase in renewable energy generation has been equally impressive. The share of new renewable energy generation in the total new generation mix has skyrocketed from 21.11% in 2018 to an extraordinary 66.33% in 2022. This remarkable shift is complemented by an average annual growth rate of total renewable energy generation, which reached 21.69% during the same period. Given this trajectory, the continuous expansion of wind and solar installations positions China to not only meet the rising electricity demand but also to achieve significant milestones in carbon reduction. By the conclusion of the "14th Five-Year Plan," the anticipated growth in non-fossil energy generation could facilitate the peaking of emissions before 2025, thereby supporting China's attainment of its carbon emissions peak target by 2030. This will make a substantial contribution to global climate objectives and sustainable development.

Trend 2: Coal Power Approvals Hit 106 Million Kilowatts in 2023, Marking a Record High for the "14th Five-Year Plan"

The latest statistics from China's low-carbon development programme reveal that newly approved coal-fired power generation projects nationwide reached a staggering 106 gigawatts in installed capacity during 2023 – a figure that is deeply concerning. Notably, this capacity accounts for 73.5 per cent of the total approved during the 13th Five-Year Plan period, reflecting a significant rebound in coal investment. This number not only exceeds the approved capacities of 18.55 million kilowatts in 2021 and 90.716 million kilowatts in 2022, but it also underscores a worrisome shift back towards coal power, even as efforts for low-carbon transitions continue.

The surge in coal-fired power project approvals reflects the escalating energy demands driven by accelerated industrialisation and urbanisation. As China's economy continues to expand, local governments face mounting pressure to ensure stable electricity supply for both residential and industrial sectors. Against this backdrop, despite coal-fired power's long-term environmental risks stemming from fossil fuel dependency, such projects remain viewed as a quick-fix solution to alleviate energy shortages. This policy shift has prompted external scrutiny of China's carbon neutrality objectives. At a critical juncture in the transition towards clean energy, coal's continued prominence in the energy mix – reinforced by this surge in approvals – risks perpetuating high carbon emissions for decades. This not only hampers renewable energy development but also creates a tension between short-term energy security and long-term sustainability. More significantly, the resurgence of the coal industry may divert resources that could otherwise be channelled into renewable energy. Local governments may prioritise coal-fired projects over clean energy sources like solar and wind power, which are crucial for achieving carbon reduction targets. Striking a balance between urgent energy security needs and national climate commitments has become an urgent challenge, demanding a reassessment of current energy policies that remain heavily skewed towards coal development.

To address these issues, policymakers must evaluate the long-term implications of expanding coal-fired power generation. A gradual reduction in coal dependence, alongside policies that encourage renewable energy growth, is essential. Enhanced regulations and financial incentives can support this transition, ensuring energy investments align with national sustainability goals. Ultimately, how China navigates this complex energy landscape will determine its success in achieving carbon neutrality and reinforcing its global leadership in climate action.

Trend 3: Guangdong, Jiangsu, Zhejiang, and Hebei Provinces Approve Over 5 Million Kilowatts of New Coal Power for Two Consecutive Years

In recent years, widespread power restrictions across various regions have prompted government authorities to prioritize energy security. The increasing frequency of energy shortages and blackouts has raised concerns about the stability and reliability of electricity supplies, leading to closer scrutiny of available energy sources. In response, local governments, responsible for approving coal power projects, have ramped up their support for such initiatives, viewing coal as a critical safeguard for ensuring stable energy supplies. This shift was particularly evident in 2023, when 22 provinces collectively approved an astounding 106 million kilowatts of new coal power projects. Among these, ten provinces approved over 5 million kilowatts each, with Jiangsu at the forefront with 11.42 million kilowatts, followed by

Shandong at 11.20 million kilowatts and Shaanxi at 10.66 million kilowatts. Zhejiang (7.776 million kilowatts), Hebei (7.71 million kilowatts), and Inner Mongolia (6.71 million kilowatts) also contributed significantly to the surge. Additionally, Hubei and Anhui each approved more than 6.6 million kilowatts, while Guangdong and Ningxia rounded out the approvals with 6 million and 5.186 million kilowatts, respectively.

It is noteworthy that eastern provinces such as Hebei, Jiangsu, Guangdong and Zhejiang have approved over 5 million kilowatts of new coal-fired power generation projects for two consecutive years. This reflects that even against the backdrop of an ongoing energy transition, dependence on coal remains deeply entrenched. This trend is not confined to eastern regions; coal-rich provinces including Shandong, Inner Mongolia and Shaanxi are also accelerating approvals for coal-fired power projects.

The ongoing reliance on coal-fired power generation raises the fundamental question of balancing short-term energy security with long-term sustainable development. As China advances its low-carbon transition, continued expansion of coal infrastructure investment risks hindering emissions reduction efforts and undermining progress towards achieving carbon neutrality by 2060. This situation highlights the dual challenge of reconciling energy demands with environmental commitments, underscoring the urgent need for a more scientifically grounded energy planning framework. Such a system must simultaneously address current energy supply requirements while safeguarding long-term sustainable development.

Trend 4: Large Coal-Fired Power Units Exceeding One Million Kilowatts Dominate Approvals by Local Authorities

Since the beginning of the 14th Five-Year Plan, a noticeable disconnect has emerged between the characteristics of newly approved coal power projects at the local level and the central government's evolving position on coal power. The government has increasingly framed coal not as a primary energy source, but as a supportive component within the broader energy landscape. Despite this shift in strategy, local governments continue to approve the construction of large coal-fired power units exceeding one million kilowatts. This trend is concerning, as these large units are inherently less adaptable to the flexible operational adjustments required in a modern energy grid, especially given the rising integration of renewable energy sources. Statistics shows that the technical costs associated with retrofitting flexibility in larger units—specifically those with capacities of one million kilowatts and 600,000 kilowatts—are significantly higher. Additionally, these larger units experience a more pronounced decline in overall system energy efficiency compared to smaller units, such as those with a capacity of 300,000 kilowatts. This inefficiency undermines efforts to create a responsive and sustainable energy system that can accommodate variable renewable energy sources.

According to the latest statistics from China's Energy Low-Carbon Development Project Team, 2023 saw the approval of 82 new coal power projects, with a striking 70.73% of these being large coal-fired units of one million kilowatts or more. This trend is particularly pronounced in eastern provinces like Guangdong, Zhejiang, and Jiangsu, where newly approved projects predominantly consist of these large units. The prevalent "first build, then retrofit" approach adopted in these regions raises further concerns about the long-term viability and sustainability of the energy infrastructure being developed. This strategy not only complicates the ability to meet future energy demands flexibly but also hinders the nation's transition towards a more balanced and low-carbon energy system. As local and central government policies continue to diverge, the implications for China's energy landscape and its broader environmental goals remain significant.

Trend 5: Nearly Sixty Percent of Newly Approved Coal Power Projects from 2021 to Mid-2023 Have Commenced Construction

At a routine press conference in the third quarter of 2023, the National Energy Administration underscored the urgency of accelerating power grid project constructions while adhering to established timelines for coal power projects. This directive reflects a growing recognition of the importance of timely energy infrastructure development in supporting both current and future energy demands. To gain a clearer picture of the actual progress made in newly approved coal power projects since the initiation of the 14th Five-Year Plan, Greenpeace undertook a comprehensive analysis utilizing publicly available information.

From 2021 to mid-2023, a notable 58.96% of the approved coal power projects have clearly commenced construction. This substantial figure indicates that a majority of these projects are moving forward in alignment with national energy policy objectives. Among the remaining unbuilt projects, 47.89% have already entered the bidding phase for engineering construction services, signaling proactive

steps towards realization. This development is encouraging, as it suggests a robust commitment at both local and national levels to advance coal power initiatives despite ongoing transitions toward renewable energy sources.

Given the typical construction cycle of approximately 20 months for coal power units, the projects currently underway are projected to reach completion by the end of the 14th Five-Year Plan. This timeline suggests the potential addition of around 105 million kilowatts of coal power capacity during this period, significantly contributing to the country's energy portfolio. While this expansion of coal power capacity may help address immediate energy needs, it also raises questions about the long-term implications for China's transition to a more sustainable energy system. Balancing the development of coal power infrastructure with investments in renewable energy and grid modernization will be crucial in ensuring that China's energy landscape evolves to meet both current and future challenges effectively.

Trend 6: The Capacity Pricing Mechanism for Coal Power Could Prompt Local Governments to Expedite Project Construction

In November 2023, a capacity pricing mechanism was timely established to address ongoing challenges in the coal power sector. The National Development and Reform Commission, in collaboration with the National Energy Administration, has issued a notice regarding a new pricing mechanism for coal power capacity, set to take effect on January 1, 2024. This two-part pricing system aims to stabilize financial returns for coal power plants but poses significant risks that could inadvertently accelerate the construction of coal power projects.

One primary concern is the mechanism's reliance on fixed financial cost compensation, which may incentivize local governments to increase investments in coal power. This could lead to capacity redundancy and over-investment in the sector. The rigidity of the coal power capacity pricing system limits its responsiveness to the existing overcapacity in coal generation. As a result, local governments, particularly in electricity-receiving regions, might feel compelled to pursue additional coal power projects to mitigate economic concerns related to "stranded assets" from existing coal facilities.

While the pursuit of energy security and autonomy is understandable for ensuring a stable power supply, it significantly raises the risk of over-investment in coal power. The current framework fails to consider the long-term implications of expanding coal capacity, especially as the country strives for a more sustainable energy mix. Additionally, the lack of effective competition within the capacity market compounds the issue. Participants have not yet established a coherent method for assessing effective load capacity, resulting in a market that lacks the dynamism necessary to foster innovation and adaptability.

Moreover, the construction of large coal-fired power generation units may crowd out opportunities for developing flexible solutions within the electricity system. This could impede the integration of renewable energy and innovative technologies, which are crucial for delivering the flexibility and resilience required in a rapidly evolving energy landscape. As the nation advances its energy strategy, balancing current capacity demands with long-term sustainability objectives is paramount. It is essential to ensure that investments in coal-fired power do not compromise a more diversified and resilient energy future. While the pursuit of energy security and autonomy is understandable within the context of ensuring stable electricity supply, it significantly heightens the risk of overinvestment in coal-fired generation. The current framework fails to adequately consider the long-term implications of expanding coal capacity, particularly as the nation commits to transitioning towards a more sustainable energy structure. Furthermore, the lack of effective competition within the capacity market exacerbates this issue. Participants have yet to develop a coherent assessment of effective load capacity, resulting in a market lacking the dynamism required to drive innovation and adaptability.

3. Policy Recommendations

Suggestion 1: Optimizing Decarbonization in the Electricity Sector through Policy and Renewable Energy Expansion

Under the stringent requirements of carbon neutrality goals, the technological trajectory in the electricity sector has become increasingly defined, showcasing both substantial decarbonization potential and technical feasibility. The sector has already seen substantial advancements in renewable energy technologies, such as wind, solar, and hydropower, and further developments in grid infrastructure and energy storage systems provide a solid foundation for decarbonization. In light of this, it is imperative to issue a comprehensive top-level design policy document dedicated to achieving carbon peaking in the electricity sector. Such a document should outline clear and enforceable guidelines, including the

establishment of stringent restrictions on new coal power projects and the progressive phasing out of existing coal-based generation capacity. This will encourage the electricity sector to accelerate its transition towards low-carbon alternatives. Managing coal power generation effectively is essential, particularly through the adoption of more efficient technologies, retrofitting older plants, and implementing carbon capture and storage (CCS) solutions. However, the long-term strategy should prioritize guiding critical areas within the electricity sector—especially coal power—towards deeper low-carbon transformations. This may involve incentivizing investments in clean technologies and fostering public-private partnerships to fund research into next-generation renewable energy solutions.

Moreover, by increasing the renewable energy generation capacity target for 2030, we can create favorable conditions for the gradual replacement of coal power with renewable energy increments, fostering a cleaner energy mix. Such a target could not only drive innovation in renewable technologies but also contribute to lowering costs and improving the scalability of these solutions. Achieving this transition will be a key step toward meeting both the carbon peaking and net-zero emission goals, potentially allowing the electricity sector to reach carbon peaking by 2025—years ahead of schedule. Through consistent policy support, technological innovation, and a robust regulatory framework, the electricity sector can play a pivotal role in the broader national and global efforts to combat climate change and realize a sustainable low-carbon future.

Suggestion 2: Building a Flexible and Economical Peak Load Resource Assurance System

The establishment of a resource assurance system for peak load management is crucial to enhancing the reliability of the electricity supply and improving climate resilience in a more economically efficient manner. In many regions, the power supply-demand dynamics are marked by a situation of "year-round surplus power but short-term shortages," especially during peak load periods such as extreme weather events or seasonal demand spikes. This imbalance between supply and demand frequently leads to power shortages during critical periods. However, the existence of a power deficit does not necessarily necessitate the construction of new generating units. On the contrary, it underscores the importance of optimising existing resources and systems to achieve peak-load management.

Considering that the construction cycle for coal power projects typically spans nearly 20 months—from the commencement of construction to final commissioning—investments in new coal-based power sources to address peak loads are unlikely to alleviate short-term power supply-demand imbalances. Furthermore, such investments could lead to greater long-term challenges by adding transition costs as the energy sector moves toward low-carbon systems. New coal projects would create a heavy financial and operational burden in the future, especially as the need to decommission or retrofit these plants would arise due to stringent decarbonization goals and the shift toward cleaner energy.

Therefore, instead of defaulting to new power generation projects, it is critical to focus on improving the efficiency and flexibility of existing infrastructure. By ensuring electricity supply security through better utilization of current resources—such as optimizing grid operation, enhancing energy storage systems, and demand-side management—it is possible to meet peak load needs without incurring excessive costs. A method that rigorously compares the technical and economic aspects of available power resources should be adopted at the planning level to optimize the electricity supply structure. For instance, enhancing energy storage systems, load-shifting strategies, and flexible demand response programs can help meet the same power service demands during peak periods.

This approach would allow for the design of a peak load resource assurance system that meets electricity demand in a more economical and efficient manner. By leveraging advanced forecasting techniques, energy storage solutions, and grid management strategies, such a system would ensure that power supply remains reliable and resilient, even during peak loads, without overburdening the economy with unnecessary investments in new capacity. Ultimately, this would minimize overall social and capital investment while avoiding further declines in the efficiency of the power system. It would also contribute to long-term sustainability by aligning energy infrastructure development with broader decarbonization and modernization goals for the electricity sector.

Suggestion 3: Maximizing Flexibility in High-Load Provinces through Renewable Energy and Storage Solutions

Major eastern provinces with high electricity loads should fully leverage the flexibility potential of the "source-network-load-storage" model to better align with the evolving development needs of new power systems, which are increasingly integrating higher shares of renewable energy. These provinces, as critical hubs of economic activity and energy consumption, must adopt forward-thinking strategies to accommodate the fluctuating nature of renewable energy sources, such as solar and wind. This

necessitates a proactive shift in perspective, moving away from viewing new coal power projects as the "optimal solution" for addressing energy demands. Continued dependence on coal could impede the sector's capacity to adapt to future energy challenges.

The large-scale construction of coal-fired power plants in certain provinces may obscure opportunities for developing more flexible solutions within the electricity system. Overreliance on coal-fired generation could stifle innovation in areas such as distributed energy, advanced energy storage technologies, and smart grids. Ultimately, these provinces risk becoming entrenched in rigid energy systems ill-equipped to adapt to the dynamic shifts in energy demand demanded by a low-carbon future. To create a more resilient and adaptable energy ecosystem, local governments should fully leverage the flexibility potential of the "source-network-load-storage" model. This model emphasizes energy production from diverse sources, efficient transmission through the grid, load-adjusted energy delivery, and robust energy storage systems.

To achieve this objective, local governments must break free from the entrenched mindset of over-reliance on coal to safeguard energy security and economic stability. Priority should be given to developing distributed renewable energy systems, such as rooftop solar installations, small-scale wind farms, and community energy projects. Investment in novel energy storage technologies—including battery systems and pumped storage—is vital for balancing the intermittent nature of renewables and ensuring a stable, reliable electricity supply. Furthermore, enhanced demand-side response measures can encourage consumers to adjust their usage patterns during peak periods. This not only helps maintain grid stability but also reduces dependence on large, inflexible power plants.

By adopting these flexible and innovative solutions, provinces can create more favourable policy conditions for the widespread adoption of low-carbon, efficient and economically viable energy technologies. Such actions will not only contribute to achieving carbon neutrality goals but also stimulate economic growth by generating new industries and job opportunities associated with green energy development. Furthermore, fostering green growth will position these regions as leaders in sustainable development, attracting investment and driving long-term economic resilience. Through concerted efforts to promote renewable energy, new energy storage systems, and demand-side resources, eastern provinces can lead the way toward a cleaner, more efficient, and flexible energy future.

Suggestion 4: Transforming Coal Power into a Supportive Role within a Renewable Energy Grid

It is essential to actively promote the transition of coal power from its traditional role as a primary energy source to one that supports and regulates the broader power system, especially as the grid becomes increasingly dominated by renewable energy. In this new paradigm, coal power must adopt a flexible, supplementary role to enhance grid stability, serving as a backup or peaking resource to complement the variability of renewable sources. To facilitate this transition, it is recommended to develop and refine a research framework for evaluating the functional transformation of coal power. This framework would provide a comprehensive system for assessing how well coal plants are adapting to their new role in supporting renewable energy integration. Establishing an evaluation system for the degree of functional transformation in coal power is crucial to ensure alignment with broader energy transition goals. This system should track key performance indicators such as the flexibility to ramp power generation up or down, responsiveness to grid demand, and efficiency in balancing intermittent renewable sources.

Aligning the coal power capacity pricing mechanism with these transformative goals is vital. Financial incentives for coal power plants should shift from rewarding mere energy production to encouraging operational flexibility and support services. In this context, regional coal power pricing standards must be adapted to reflect local realities regarding the green transition, ensuring that prices incentivize cleaner and more efficient coal operations that complement renewable energy.

As the energy landscape evolves, it is crucial to incorporate new technologies such as energy storage systems and virtual power plants into capacity pricing compensation mechanisms. This integration process should adhere to the principles of technology neutrality and equal pay for equal work, ensuring that energy storage solutions contribute equally to grid stability. By providing fair compensation, energy storage facilities and flexible resources will be incentivised to participate in delivering "effective capacity" during peak demand periods, rather than relying solely on traditional energy sources such as coal-fired power generation. Modern technologies—ranging from large-scale battery storage systems to virtual power plants that aggregate distributed energy resources—can respond quickly to fluctuations in demand and supply, making them ideal for supporting renewable energy-dominated grids. Integrating these technologies into the capacity compensation system would not only incentivize their development but also enhance overall grid resilience.

Furthermore, including energy storage in the compensation mechanism will ensure that regions with high renewable energy penetration have reliable backup resources during peak demand or low renewable production periods. This will result in a more balanced and efficient grid that leverages both traditional and modern technologies to provide reliable electricity while advancing carbon reduction goals. By fostering competition between traditional coal power and new energy storage systems, governments can accelerate the transition to a cleaner, more sustainable energy system where coal serves as a supportive, rather than primary, power source. This approach will ultimately encourage broader participation from flexible resources, driving innovation in grid management and renewable energy integration.

4. Conclusions & Discussions

This study systematically reviews the current trends and challenges in the low-carbon transition of China's power sector, offering insights and policy recommendations essential for achieving carbon neutrality by 2060. As highlighted, China's power sector is at a pivotal juncture, shifting from heavy reliance on coal to a more diversified and renewable energy-based system. The findings indicate several key trends.

Firstly, the significant expansion of wind and solar power capacity underscores the strategic resolve to position renewable energy as the cornerstone of new power generation. This trend aligns with the national objective of achieving peak carbon emissions by 2025, while also indicating further growth potential should the policy framework be strengthened. Secondly, despite progress in the renewable energy sector, the approval of numerous new coal-fired power plant projects poses a significant risk to the low-carbon transition. Data indicates that local governments prioritise energy security and supply stability over long-term sustainable development, a tendency that may impede the achievement of carbon neutrality objectives. Thirdly, existing grid infrastructure and inconsistent regulatory frameworks remain the primary obstacles hindering the effective integration of renewable energy. These challenges necessitate a comprehensive reassessment of energy policies and infrastructure investment to build a more flexible and resilient electricity system.

In light of these trends, the proposed policy recommendations aim to guide the transition towards a sustainable electricity sector while addressing inherent challenges. Consequently, this study recommends that establishing a strategic framework for peaking carbon emissions in the electricity sector is of paramount importance. This involves tightening controls on new coal projects and incentivizing the growth of renewable energy capacities, fostering a more balanced energy mix. Then, it recommends that developing a resource assurance system will enhance the reliability of energy supply without resorting to new coal-fired generation. This approach can optimize resource utilization and promote economic efficiency while ensuring energy security. Next, it is suggested to encourage the development of distributed renewable energy and innovative storage solutions can alleviate over-reliance on coal power. Local governments should actively seek alternative energy strategies that enhance flexibility and resilience within the grid. Finally, it suggests that shifting the function of coal power from primary generation to supportive and regulatory roles will help align with renewable energy goals. Establishing an evaluation system for coal power's functional transformation will facilitate this transition and ensure equitable competition among energy sources.

Notably, the implications of this study extend beyond China, offering valuable lessons for other nations navigating similar energy transitions. As countries worldwide confront the urgent need for decarbonization, the experiences and strategies developed within China's power sector could serve as a critical reference point. The path to carbon neutrality is complex and requires coordinated efforts among policymakers, industry stakeholders, and academic researchers to address the multifaceted challenges inherent in this transition.

In conclusion, while the identified trends indicate significant progress, the dual pressures of energy demand and economic considerations must be carefully managed. A commitment to innovative policies and collaborative approaches will be essential in steering China's power sector toward a sustainable and low-carbon future.

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