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Assessing the Carbon Reduction Contribution of Renewable Energy Integration in Smart Grids: A Qinghai Pilot Case Study

Jinghao Shang

Department of Electrical Engineering, Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
Jinghao.Shang@student.lut.fi

Abstract. To address the contradiction between large-scale grid integration of renewable energy and safe grid operation under the goal of carbon neutrality, this paper examines the adaptability and quantifiable contribution of multi-type renewable energy to smart grids. Through a literature review, this paper systematically examines the core attributes of smart grids, renewable energy grid integration technologies, and relevant research on carbon neutrality pathways. It finds that current research lacks analysis of regionalized multi-energy synergy and adaptation and a quantitative model for carbon reduction contributions. Using the Qinghai Province smart grid pilot project as a case study, this paper analyzes its intelligent dispatching system configuration, wind power/photovoltaic power integration scale (12 GW of wind power installed capacity and 8 GW of photovoltaic power installed capacity, with renewable energy accounting for 42%), and carbon reduction results (a 6% increase in renewable energy consumption will reduce carbon emissions by 1.8 million tons in 2023). The paper identifies issues such as delayed dispatching response (12% peak error), low output forecast accuracy (16% error), and gaps in carbon contribution assessment. The method of combining case analysis and data modeling is adopted to propose adaptive optimization strategies and construct a carbon emission reduction quantitative model. The research results can provide a practical basis for regional power grid planning and improve the theoretical system of the integration of carbon neutrality and smart grid.

Keywords: Smart Grid, Carbon Neutrality, New Energy

1. Introduction

As global pressure to address climate change continues to grow, achieving carbon neutrality has become a core driver of energy system transformation. Academia and industry are increasingly focusing on collaborative research on renewable energy grid integration and smart grids. The relationship between grid dispatch and carbon reduction efficiency has become a key issue, particularly with high renewable energy penetration. Existing research shows that renewable energy sources such as wind and photovoltaics exhibit significant intermittency and volatility. This volatility, when integrated on a large scale, can cause frequency and voltage fluctuations in the

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power system, as well as pressure on the dispatch of energy storage facilities [1,2]. Therefore, how to improve renewable energy absorption capacity and dispatch efficiency through smart grid technologies, and quantify their contribution to carbon reduction, has become a current research hotspot.

In terms of the core technologies of smart grids, Satymov et al. [1] proposed that the key characteristics of smart grids are "elasticity" and "flexibility", which can effectively cope with the uncertainty brought about by the large-scale grid connection of renewable energy. Through case analysis of the Nordic energy system, they emphasized the important role of edge computing and high-speed communication technology in real-time data collection and intelligent scheduling, which provides technical support for the efficient access of renewable energy. Keiner et al. [2] studied the application of distributed energy management combined with 5G communication technology, pointing out that through high-speed, low-latency data transmission and sharding management, the response speed of renewable energy access can be significantly improved, the output forecast error can be reduced, and the adaptability of regional power grids can be enhanced. These studies provide basic theoretical and practical references for the coordinated access of multiple energy sources.

In terms of specific scheduling algorithms and data analysis methods, Bustos-Bríñez et al. [3] conducted a detailed analysis of the data characteristics of power substations and proposed a method based on data feature matrix, which can accurately identify load fluctuation patterns and provide support for intelligent scheduling. Lin et al. [4] used the CBAM-BiLSTM algorithm to non-invasively identify residential loads, achieve high-precision short-term load forecasting, and provide a data basis for multi-energy coordinated scheduling. On this basis, Karim et al. [5] proposed an optimized LSTM model, which achieved high-precision prediction of smart grid stability by integrating historical output data and environmental variables, providing high reliability guarantee for scheduling decisions. The above studies all show that deep learning and data-driven methods have significant application potential in smart grid scheduling and can effectively alleviate the system pressure caused by the volatility of new energy.

In terms of carbon emission reduction quantification, López et al. [6] emphasized the role of photovoltaic power generation in the transformation of energy structure, and proposed that there is a direct relationship between photovoltaic absorption rate and carbon emission reduction benefits, and reasonable scheduling strategy can improve carbon emission reduction efficiency. Al Khaffaf et al. [7] systematically sorted out the technical paths and strategies for achieving carbon neutrality in different industries, including optimization methods for the entire process of energy production, transmission and use, and provided a macro framework for carbon emission reduction research. Guo et al. [8] evaluated the role of various catalytic and energy conversion technologies in carbon emission reduction through bibliometric analysis, and pointed out that a more sophisticated carbon emission reduction model needs to be constructed under high-penetration new energy systems to accurately quantify the contribution of various energy sources and scheduling strategies. Dong et al. [9] studied the impact of green technology innovation on carbon emission efficiency and found that technology upgrading and regional energy structure optimization can significantly improve carbon emission reduction benefits, indicating that new energy scheduling and technological innovation have a synergistic effect. Galimova et al. [10] pointed out that the combination of energy system transformation and new energy export potential can achieve the coordinated development of regional carbon neutrality strategy and energy economy, and provide an important reference for energy planning in high-new energy penetration areas.

Although significant progress has been made in existing research, there are still many shortcomings. First, most studies focus on the scheduling or carbon emission reduction analysis of a

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single type of renewable energy, and do not fully consider the synergistic effects of wind power, photovoltaics, and energy storage in regional scenarios. For example, a single-sequence scheduling strategy may ignore the peak-shifting characteristics of renewable energy, resulting in a decrease in overall energy utilization efficiency. Second, carbon emission reduction quantification methods often use extensive calculation methods, such as "new energy power generation × thermal power carbon emission coefficient", which lacks the decomposition and refined evaluation of the contribution of multi-energy collaborative access. In addition, existing research still has technical bottlenecks in scheduling response, prediction accuracy, and energy storage utilization efficiency, which directly limits the adaptability of smart grids to large-scale renewable energy and the realization of carbon emission reduction potential.

To address the shortcomings of existing research, scholars have proposed a variety of improvement schemes in recent years. First, in terms of smart grid adaptability, the introduction of edge computing, the Internet of Things, and high-speed communication technologies can achieve second-level acquisition and preprocessing of renewable energy output, improving dispatch response speed. Second, in terms of dispatch logic, a coordinated dispatch strategy based on multi-energy complementarity can fully utilize the staggered characteristics of wind power's nighttime output peak and photovoltaic power's daytime peak, optimize the energy storage system's charging and discharging strategy, and achieve load matching and output balance. In terms of carbon emission reduction quantification, a full life cycle model is constructed, incorporating implicit carbon emission factors such as energy storage, transmission losses, and equipment operation and maintenance. The baseline-increment method is used to decompose the carbon emission reduction contributions of wind power, photovoltaic power, energy storage, and dispatch optimization, achieving a refined assessment of the carbon emission reduction effects of multiple entities.

Existing research has made some progress in smart grid dispatching technology, data analysis methods, and carbon emission reduction quantification models. However, systematic research on regionalized, multi-energy collaborative access and refined carbon emission reduction remains insufficient. This paper focuses on the collaborative access of multiple types of renewable energy to smart grids. Through a combination of literature review, case analysis, and data modeling, it aims to deeply analyze the technical bottlenecks of multi-energy collaborative access, propose optimization strategies, and construct a quantifiable carbon emission reduction model. This will provide a scientific basis and practical guidance for grid planning and carbon neutrality goals in regions with high penetration of renewable energy.

2. Overview and operational characteristics of Qinghai Province Smart Grid pilot project

This study focused on the Qinghai Smart Grid provincial pilot project. This project, a key implementation project of my country's "West-to-East Power Transmission" strategy and Qinghai Province's plan for high renewable energy penetration, commenced construction in 2021 and is expected to be fully operational in 2023. The project, covering two major new energy bases in Haixi and Hainan prefectures in Qinghai Province, integrates wind and photovoltaic power stations, along with supporting intelligent dispatching centers and energy storage facilities. With 42% of installed renewable energy capacity, it represents a typical scenario for a high proportion of renewable energy integrated into the smart grid. This provides a robust data foundation and practical support for studying the adaptability of multi-energy collaborative integration and its quantified contribution to carbon emission reduction.

The pilot project uses a two-level intelligent dispatching system at the provincial and regional levels, forming a full-process data collection, analysis, and control chain from the power station to

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the dispatching center. On the provincial dispatching platform, the system can centrally monitor and optimize the dispatching of wind power, photovoltaic power generation data, and regional load data from power stations in Haixi and Hainan Prefectures; the regional dispatching platform is responsible for fine-grained data processing of distributed new energy power stations, enabling rapid response to local power grids. Edge computing nodes are deployed at the new energy power station end and are responsible for collecting and initially processing data such as wind speed, light intensity, and power generation power in seconds, ensuring that the data obtained by the dispatching center is highly real-time and accurate. At the same time, the processed data is transmitted to the dispatching center via a high-speed communication network, enabling 1- to 5-minute updates of power generation and load data. The system has initially achieved coordinated monitoring of multiple energy sources and data-driven dispatching support, but still has shortcomings in responding to peak fluctuations and full-process intelligent control.

In terms of energy storage, the project includes two pumped-storage power stations and 15 electrochemical energy storage stations, with a total storage capacity of 1,800MWh. These are used to regulate fluctuations in renewable energy output and support grid stability. Pumped-storage power stations are primarily used for long-term energy balancing, storing water at night and releasing electricity during the day; electrochemical energy storage stations are responsible for smoothing short-term fluctuations, achieving minute-by-minute power regulation. However, due to limitations in scheduling logic and forecasting accuracy, approximately 25% of the energy storage capacity remains idle during periods of renewable energy output fluctuations, failing to fully utilize its fluctuating power.

The project's renewable energy integration capacity includes 12 GW of wind power, primarily concentrated in the wind-rich Haixi Prefecture, generating approximately 22 billion kWh of electricity annually. It also includes 8 GW of photovoltaic capacity, primarily located in the Hainan Prefecture photovoltaic park, generating approximately 12 billion kWh of electricity annually. This total renewable energy generation accounts for 42% of Qinghai Province's annual power supply, demonstrating a high penetration rate of renewable energy. Wind power output exhibits significant diurnal fluctuations: power generation can rise rapidly during high wind speeds at night, but output can plummet by up to 35% during calm periods. Solar power output is concentrated between 9:00 AM and 5:00 PM during the day, with the midday peak potentially coinciding with grid load troughs. This can prevent some power from being absorbed in a timely manner, leading to a high curtailment rate of 8%. This volatility and imbalance pose significant challenges to intelligent scheduling and energy storage matching, directly impacting the safe operation of the grid and the efficiency of renewable energy absorption.

In terms of dispatch response, when wind and photovoltaic power output fluctuate simultaneously—for example, a sudden sandstorm causing a 30% drop in photovoltaic output—the existing dispatch platform takes approximately 30 minutes to complete load redistribution and energy storage dispatch. This delayed response results in peak dispatch errors of up to 12%, causing grid frequency fluctuations exceeding the ±0.2Hz safety range. Inadequate dispatch matching for energy storage facilities further exacerbates this problem, with some storage devices failing to perform their regulatory role during critical periods, limiting the ability to quickly respond to fluctuations in renewable energy output. Short-term wind power forecasts (within 24 hours) have an error of 16%, while photovoltaic forecasts have an error of 14%, resulting in significant discrepancies between dispatch plans and actual output. In the summer of 2023, cumulative forecast errors led to 12 wind and solar power curtailment events, resulting in a cumulative loss of approximately 500 million

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kWh of power generation. This not only reduces the efficiency of renewable energy utilization but also causes direct economic losses.

In terms of multi-energy coordinated dispatch logic, the current system still adheres to a sequential strategy of "wind power first, photovoltaics supplementary," failing to fully consider the staggered peak-load characteristics of the two renewable energy sources at different times. For example, wind power in Haixi Prefecture peaks at night, while photovoltaic power in Hainan Prefecture peaks during the day. While dispatch strategies should have achieved this complementarity, the current strategy fails to effectively utilize this characteristic, resulting in an approximately 8% loss in overall energy efficiency. Furthermore, the dispatch system still faces bottlenecks in the linkage between load forecasting and energy storage dispatch, lacking a dynamic adjustment mechanism, making it difficult to achieve a rapid response to emergencies or extreme weather.

3. Analysis of adaptability and operational issues of multi-energy collaborative access

While the Qinghai Province Smart Grid pilot project has achieved initial operation with the coordinated integration of multiple renewable energy sources, numerous compatibility bottlenecks remain, directly impacting grid dispatch efficiency, energy absorption capacity, and carbon emission reduction benefits. This section systematically analyzes dispatch response, output forecasting, energy storage matching, dispatch logic, and cross-regional coordination to uncover key issues hindering smart grid optimization.

First, the lag in dispatch response is the main factor restricting the coordinated adaptability of multiple energy sources. The output of wind power and photovoltaic power in the project fluctuates frequently. When sudden weather events or load fluctuations occur, the existing dispatch system takes about 30 minutes to complete load redistribution and energy storage dispatch, resulting in peak dispatch errors of up to 12%, frequently causing the grid frequency to deviate from the acceptable range. Response lag not only reduces grid stability but also limits the effective use of energy storage facilities. For example, although the total energy storage capacity is 1,800MWh, approximately 25% of the energy storage is idle during critical output fluctuation periods, failing to play a role in smoothing fluctuations. This problem shows that the existing dispatch platform still has bottlenecks in multi-energy data processing and rapid decision-making capabilities. Technology upgrades and algorithm optimization are needed to achieve response times in seconds or minutes to meet the dynamic control needs of a high proportion of new energy access.

Secondly, low forecast accuracy for renewable energy output is a major factor leading to scheduling errors and curtailment of wind and solar power. Short-term forecasts for wind power (within 24 hours) have an error of 16%, while those for photovoltaic power generation are 14%, resulting in significant discrepancies between scheduling plans and actual output. In actual operation, these cumulative forecast errors resulted in 12 wind and solar power curtailment events during the summer, with a total loss of approximately 500 million kWh of power generation. The fundamental reasons for this lack of forecast accuracy lie in the limited granularity of meteorological data collection, the inadequate integration of historical output and multi-dimensional load characteristics in AI forecasting models, and the dispatch system's lack of a dynamic response mechanism to extreme weather and emergencies. Therefore, improving forecast accuracy can not only reduce wind and solar power curtailment but also provide more accurate reference data for energy storage scheduling and load balancing, thereby enhancing renewable energy absorption capacity and system operational efficiency.

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Third, insufficient energy storage matching is also a core issue affecting adaptability. Pumped-storage power stations and electrochemical energy storage power stations have different responsibilities in long- and short-cycle energy regulation. However, due to the single scheduling logic, prediction errors, and delayed energy storage response, energy storage facilities have failed to achieve efficient coordination. During nighttime peak wind power or sudden drop in photovoltaic output, energy storage facilities fail to release or absorb electricity in a timely manner, resulting in the inability to fully absorb some new energy sources and increasing grid operation risks. Energy storage matching issues also include unreasonable scheduling priority settings. For example, the system defaults to wind power priority and photovoltaic supplementation, without dynamically adjusting the energy storage discharge or charging strategy according to actual output characteristics and load curves, thus failing to fully utilize the stabilization effect of energy storage.

Fourth, the multi-energy coordinated dispatch logic has limitations. The current system follows a single order of "wind power first, photovoltaic supplementary", failing to take advantage of the complementary output characteristics of the two types of renewable energy in different time periods. For example, there is a natural peak-shifting effect between the nighttime wind power output peak in Haixi Prefecture and the daytime photovoltaic peak in Hainan Prefecture. If the dispatch logic can fully utilize the peak-shifting characteristics, it can significantly improve energy consumption efficiency and grid stability. However, the existing strategy does not achieve this optimization, resulting in an overall energy utilization efficiency loss of approximately 8%. In addition, the dispatch system lacks an emergency response mechanism for extreme events. When extreme weather conditions such as sandstorms or long periods of no wind occur, the system cannot quickly adjust the energy storage discharge or load transfer strategy, further increasing the uncertainty of grid operation.

Fifth, insufficient cross-regional dispatch coordination also hinders adaptive optimization. In areas with high penetration of new energy, local power grids alone struggle to maximize power consumption and smooth fluctuations. Although Qinghai Province's smart grid has achieved power interconnection with some neighboring provinces, cross-regional load coordination and energy optimization still suffer from information delays, fragmented dispatch authority, and insufficient real-time data sharing, failing to fully leverage the external grid's regulatory capabilities. If cross-provincial dispatch coordination mechanisms are optimized, load sharing and power exchange could reduce wind and solar curtailment rates, improving overall new energy efficiency and reducing carbon emissions.

Overall, while the Qinghai Province Smart Grid pilot project has established a preliminary operational system for the coordinated access of multiple energy sources, it still faces numerous challenges, including delayed dispatch response, insufficient forecasting accuracy, inadequate energy storage matching, a single dispatch logic, and a lack of cross-regional coordination. These issues not only impact the efficiency of new energy consumption but also limit the stable operation of smart grids under conditions with a high proportion of renewable energy and their ability to quantify carbon emissions reductions. Therefore, improving the real-time response capabilities of the dispatch system, optimizing forecasting models, improving energy storage management logic, establishing dynamic dispatch strategies, and strengthening cross-regional coordination are key pathways to optimizing the adaptability of coordinated access to multiple energy sources and maximizing carbon emission reduction benefits..

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4. Suggestions

4.1. Optimization scheme of smart grid adaptability

To address the issues of delayed dispatch response and low output forecast accuracy, we must address both technological upgrades and restructuring dispatch logic. Technically, we recommend building upon the existing provincial-regional dispatch platform and introducing a three-tiered monitoring architecture: edge computing + 5G + IoT. Edge computing nodes should be deployed at renewable energy power plants to enable sub-second data collection and pre-processing of power generation data. 5G slicing technology should be used to establish dedicated communication channels, reducing data transmission latency from the current five minutes to under one minute. IoT devices should collect real-time meteorological data (such as wind speed and light intensity) and load data (such as industrial and residential electricity consumption) to provide multi-dimensional data support for output forecasts. Furthermore, we should optimize AI forecasting algorithms by introducing an LSTM (Long Short-Term Memory) model incorporating an attention mechanism. This model, which uses meteorological data, historical output data, and load data as input features, will improve short-term forecast accuracy. The goal is to reduce wind power forecast errors from 16% to below 10%, and photovoltaic forecast errors from 14% to below 8%. Regarding dispatch logic, we need to break away from the single priority of "wind power first, photovoltaic power second," and establish a "multi-energy complementary and coordinated dispatch" mechanism. Based on the staggered characteristics of Haixi Prefecture, Qinghai Province, with its nighttime peak wind power output (8:00 PM - 6:00 AM) and Hainan Prefecture's daytime peak photovoltaic output (9:00 AM - 5:00 PM), a coordinated model combining output forecasting, load matching, and energy storage dispatch has been established. During peak daytime photovoltaic output, photovoltaic power is prioritized, with excess power stored in pumped-storage power stations. During peak nighttime wind power output, wind power is the primary power source, supplemented by electrochemical energy storage stations to smooth short-term fluctuations. In the event of a sudden output drop (e.g., a 30% drop in photovoltaic output due to sandstorms), emergency discharge from the energy storage stations is triggered, reducing dispatch response time from 30 minutes to within 5 minutes and ensuring grid frequency stability within the acceptable range of ±0.2 Hz. Furthermore, a "regional dispatch coordination mechanism" is recommended, connecting the Qinghai power grid with neighboring provinces such as Gansu and Sichuan. This cross-provincial load sharing will further enhance renewable energy absorption capacity, with the goal of reducing wind and solar curtailment from 8% to below 5%.

4.2. Carbon emission reduction model improvement plan

To achieve a refined assessment of carbon emission reduction contributions, a "full life cycle carbon emission reduction quantification model" is needed to address the gaps in existing models. First, the carbon emission accounting dimensions should be expanded. In addition to the existing "emission reduction from renewable energy replacing thermal power," new implicit carbon emission factors should be added: First, carbon emissions from energy storage facilities, calculated based on the water consumption of pumped-storage power stations and the energy consumption of electrochemical storage cell production; second, carbon emissions from transmission lines, calculated based on transmission distance and line loss rate (the average transmission loss rate in Qinghai is approximately 6%); and third, carbon emissions from equipment operation and maintenance, which includes the power consumption of intelligent dispatching systems and

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monitoring equipment. Through full life cycle accounting, carbon emission reduction calculations are more realistic.

Secondly, a "multi-agent carbon contribution decomposition model" will be established to clarify the respective carbon emission reduction contributions of wind power, photovoltaic power, scheduling optimization, and energy storage facilities. Specifically, the "baseline-increment method" will be adopted: using "thermal power supply without new energy access" as the baseline, the total carbon emission reduction will be calculated; then, through sensitivity analysis, the incremental carbon emission reduction brought about by separately increasing wind power and photovoltaic power generation, separately optimizing scheduling logic, and separately expanding energy storage facilities will be calculated, and the contribution proportion of each entity will be finally determined. For example, if the total carbon emission reduction is 1.8 million tons, the model can be used to calculate that wind power contributes 60%, photovoltaic power contributes 25%, scheduling optimization contributes 10%, and energy storage facilities contribute 5%, providing data support for "precise carbon control." At the same time, it is recommended that the model be connected to the Qinghai Province carbon emission reduction statistical system to achieve real-time data updates and dynamic calibration, thereby improving the practicality and authority of the model.

4.3. Research and promote economic security programs

To address regional limitations and economic inefficiencies, efforts must be made to expand scenarios and balance costs. Regarding scenario expansion, it is recommended to conduct "regional adaptability verification": selecting one or two grid pilot sites in eastern load centers (such as Jiangsu) and in central regions with medium-resource resources (such as Henan), and adapting the Qinghai Province optimization plan to local conditions (e.g., adding a distributed photovoltaic and distribution network coordinated dispatching module in the Jiangsu pilot, and strengthening the integrated configuration of wind, solar, and storage in the Henan pilot). Through multi-scenario verification, model parameters will be refined to form a "regionally differentiated adaptation guide" to enhance the national applicability of research findings.

To ensure economic viability, a cost-benefit linkage evaluation system needs to be established. First, detailed cost calculations should be implemented, breaking down technical solutions into three categories: hardware upgrades (such as edge computing equipment and 5G base stations), software development (such as AI prediction algorithms and scheduling models), and operations and maintenance services. Initial investment and average annual operations and maintenance costs should be calculated for each. Second, quantified benefits should be considered, encompassing not only carbon reduction benefits (calculated at the carbon price), but also electricity revenue from increased renewable energy consumption and reduced losses from faults due to enhanced grid stability. Through cost-benefit analysis, grid companies can be provided with a payback period (e.g., an upgrade to an intelligent dispatching system has a payback period of approximately 3-5 years). Furthermore, supporting government policies (such as carbon reduction subsidies and special funds for technological transformation) should be introduced to reduce implementation costs for companies and facilitate the transition of research findings from theoretical proposals to practical projects.

5. Conclusion

This study, using the Qinghai Province smart grid pilot project as a case study, examined the adaptability and quantified contribution of coordinated integration of multiple renewable energy

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sources to carbon emissions reduction. The study's key findings include three key areas. First, it identified the core bottlenecks of regionalized, multi-energy coordinated integration. Case analysis revealed that delayed dispatch response (peak error of 12%), low output forecast accuracy (16% for wind power and 14% for photovoltaics), and insufficient energy storage dispatch matching (25% idle energy storage) are key issues hindering smart grid adaptability. Furthermore, the existing dispatch logic fails to leverage the complementary nature of wind and solar output, resulting in an approximately 8% loss in energy efficiency. Second, it proposed a targeted adaptability optimization strategy: through a technological upgrade combining "edge computing + 5G + AI prediction," data response time can be reduced from 5 minutes to under 1 minute, and prediction error can be reduced by 30%-40%. By reconfiguring the "multi-energy coordinated dispatch" logic and integrating cross-provincial load sharing, the wind and solar curtailment rate can be reduced from 8% to below 5%, significantly improving the capacity to absorb renewable energy. Third, a full-lifecycle carbon reduction quantitative model was constructed. This model incorporates implicit carbon emission factors such as energy storage consumption and transmission losses, and establishes a multi-agent carbon contribution decomposition mechanism. This addresses the inability of traditional extensive calculations to distinguish between individual contributions, providing a practical assessment tool for "precise carbon control." The research results validate the technical feasibility of integrating smart grids with diverse renewable energy sources and offer a practical paradigm for regional power grid planning under the goal of "carbon neutrality."

This study effectively fills two key gaps in existing research. First, by using the Qinghai Province case study, it deeply explores the complementary output characteristics of regionalized multi-energy sources (wind power + photovoltaics) and proposes differentiated adaptation strategies, addressing the shortcomings of traditional research that focuses on a single energy source and ignores regional differences. Second, it constructs a full-lifecycle carbon emission reduction quantitative model, achieving a refined decomposition of carbon contributions. This addresses the existing research challenges of extensive carbon emission reduction assessments and a lack of multi-agent decomposition, and further improves the theoretical framework for the integration of smart grids and carbon neutrality. This research suffers from regional limitations, insufficient data dimensionality, and a lack of economic analysis. Future advancements could be made in three areas: first, expanding the case study coverage by validating different power grid scenarios in eastern and central China to develop a nationally differentiated solution. Second, extending the data observation period (e.g., over five years) to incorporate scenarios such as extreme weather and policy adjustments to enhance model robustness. Third, supplementing the economic analysis with a cost-benefit-carbon price linkage model based on carbon market price fluctuations will further enhance the practical application of research findings and provide a Chinese solution for global renewable energy grid integration and carbon neutrality. The importance of this research lies in both theoretical and practical dimensions: theoretically, it improves the correlation system between multi-energy coordinated adaptation and carbon emission reduction quantification, filling the gap in regional research; in practice, it provides provincial power grids with feasible adaptation solutions and carbon assessment tools, which can directly guide the power grid upgrades in Qinghai and similar regions, help promote the "dual carbon" goals efficiently, and provide a reference for the safe operation of power grids in high-energy new energy penetration regions around the world.

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