

Research on Low-Carbon Development Path for Key Energy-Consuming Hospitals Under the "Dual Carbon" Background

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1. Introduction

1.1 Background and Significance of the "Dual Carbon" Goals [1-5]

Before delving into the background and significance of the "dual carbon" goals, it is essential to briefly elaborate on their connotations. The "dual carbon" goals typically refer to two objectives: "carbon peaking" and "carbon neutrality," which correspond to the highest point of carbon dioxide emissions and the ultimate state of net-zero emissions, respectively. Carbon peaking denotes the point in time when carbon dioxide emissions reach their peak within a certain period and then gradually decline. Carbon neutrality, on the other hand, refers to the point in time when, through measures such as emission reduction and increasing carbon sinks, carbon dioxide emissions and absorptions reach a balanced state, achieving net-zero emissions.

Background:

With the acceleration of industrialization and the deepening of globalization, the issue of global climate change has become increasingly prominent, particularly the frequent occurrence of extreme climate events due to global warming, which has severely impacted the human living environment [1]. In response to the challenge of climate change, the international community has begun to seek ways to reduce greenhouse gas emissions to slow down the pace of global warming. Against this backdrop, China, as the largest developing country in the world, has actively participated in international climate governance and committed to achieving the goals of carbon peaking and carbon neutrality. This reflects China's international responsibility as a responsible major country and its determination to promote the construction of global ecological civilization [1].

Significance:

- **Global Responsibility and Commitment:** China's "dual carbon" goals represent a proactive response to the international community's efforts to

combat climate change, reflecting China's image as a responsible major country and enhancing its soft power [1].

- **Promoting Green and Low-Carbon Development:** The implementation of the "dual carbon" goals can drive the optimization and upgrading of energy and industrial structures, promote the development and application of green and low-carbon technologies, and provide impetus for sustainable development [4].
- **Improving the Ecological Environment:** Reducing greenhouse gas emissions helps improve air quality, mitigate climate change-related natural disasters, and enhance the quality of life for the public.
- **Catalyst for Economic Transformation:** Achieving the "dual carbon" goals requires the development of new energy technologies and industries, which will drive the development of related sectors, promote the transformation and upgrading of the economic structure, and create new economic growth points.
- **Enhancing International Competitiveness:** Actively responding to climate change and achieving the "dual carbon" goals can enhance a country's competitiveness on the international stage and provide new momentum for participating in international competition.

In summary, the introduction of the "dual carbon" goals is driven by the severe challenges of global climate change, the joint efforts of the international community, the need to promote economic transformation, and the enhancement of international competitiveness [1].

1.2 Characteristics and Challenges of Hospital Energy Consumption [6,7]

As a vital provider of public health services, hospitals face the challenge of balancing high standards of medical services with the need for energy conservation and emission reduction. The energy consumption of hospitals not only affects the quality and efficiency of medical services but also directly relates to the sustainable use of energy and the sustainable development of medical institutions.

Firstly, the energy consumption in hospitals exhibits diversity and specificity. During the provision of medical services, hospitals maintain the operation of their infrastructure, among other things. These energy consumptions are primarily manifested in the following aspects:

- **Energy Consumption of Medical Equipment:** Modern medical equipment such as MRI, CT, and linear accelerators requires substantial power support for operation. The continuous operation of these high-energy-consuming devices imposes high demands on the hospital's energy supply.
- **Energy Consumption for Medical Environment Control:** To provide patients with a comfortable medical environment, adjustments are made to lighting and other factors, which requires a significant amount of electric power resources.
- **Energy Consumption of Office Automation and Information Systems:** Activities such as patient services rely on information systems, which also consume a certain amount of electric power resources.
- **Other Auxiliary Energy Consumption:** Food and beverage services are also an important component of hospital energy consumption.

The challenges of hospital energy consumption are primarily manifested in:

- **Optimization and Management of Energy Consumption:** Hospitals need to implement refined management of energy consumption to improve energy utilization efficiency.
- **Upgrading of Technical Equipment:** With the continuous advancement of medical technology, hospitals need to upgrade their equipment while ensuring the quality of medical services, as equipment with lower energy consumption is being replaced.
- **Systematic Energy Conservation and Emission Reduction Measures:** Hospitals need to formulate strategies for energy conservation and emission reduction at the system level, utilizing energy management platforms and other means to achieve effective control of energy consumption.
- **Comprehensive Energy Demand Forecasting and Planning:** Hospitals need to scientifically predict their future energy demand and formulate long-term energy planning in alignment with national and local "dual carbon" policy requirements.

In summary, the characteristics and challenges of hospital energy consumption necessitate that hospitals, while providing high-quality medical services, must adopt effective measures to optimize energy management and enhance energy

utilization efficiency, in order to achieve the goal of energy conservation and emission reduction, and promote the sustainable development of hospitals.

1.3 Research Purpose and Significance [8–10]

In the context of current global climate change and ongoing environmental challenges, the "dual carbon" goals proposed by the Chinese government—namely, carbon peaking and carbon neutrality—have become an important component of national strategy. The achievement of these goals requires not only extensive policy support and industrial transformation but also the search for innovative solutions in specific practices. Especially in the special energy consumption field of hospitals, the research on its low-carbon development path holds significant theoretical value and practical significance.

Firstly, hospitals, as important providers of public health services, are characterized by high carbon emissions, which determines their significance in achieving the "dual carbon" goals [8]. Hospitals not only need to provide high-quality medical services for patients but also contribute to low-carbon development and environmental protection [8]. Therefore, studying the low-carbon development path of hospitals not only helps promote the sustainable development of hospitals themselves but also serves as a demonstration for promoting the low-carbon transformation of the entire society.

Secondly, as part of society, hospitals' practices and successful experiences in low-carbon development can provide references for other industries [8]. The promotion of green building design, among others, is an important approach to achieving low-carbon development in hospitals [8]. Through these approaches, it is possible to effectively reduce energy consumption and carbon emissions in hospitals while simultaneously improving the energy efficiency and quality of medical services [8].

In addition, research on the low-carbon development path of hospitals also holds significant policy-oriented implications. Through in-depth analysis and research, it can provide decision-making support for relevant government departments and a scientific basis for formulating relevant policies and standards. This not only helps accelerate the achievement of the "dual carbon" goals but also promotes low-carbon development.

In summary, researching the low-carbon development path of key energy-consuming hospitals under the "dual carbon" background is of great significance for promoting the sustainable development of hospitals, serving as an important

demonstration for achieving sustainable development goals, and holding significant policy guidance value [8]. Therefore, this study holds significant theoretical and practical importance and plays a crucial role in promoting the achievement of China's "dual carbon" goals.

2. Research Methods and Data Sources

2.1 Explanation of Research Methods [11,12]

When conducting research on the low-carbon development path of key energy-consuming hospitals under the "dual carbon" goals, it is crucial to ensure both scientific rigor and practical applicability. The following research methods are employed in this study to achieve these objectives:

- **Literature Review:** A systematic review and analysis of existing literature are conducted to outline the current status and development trends of research related to "dual carbon" low-carbon technologies. This involves examining both domestic and international studies to identify gaps and opportunities for further investigation.
- **Case Analysis:** Representative energy-consuming hospitals are selected as research subjects, with a focus on the application status of low-carbon technologies and management systems. In-depth case studies are used to explore practical paths and successful experiences in hospital low-carbon development.
- **Data Collection and Analysis:** Information on the application status of green technology is gathered through expert interviews. Statistical and data analysis techniques are then applied to process and analyze the data scientifically, yielding objective research results.
- **Comparative Policy Analysis:** The implementation strategies and effectiveness of "dual carbon" goals across various hospital types are examined. This involves summarizing successful experiences and identifying existing issues to provide a basis for targeted policy recommendations.
- **Model Construction and Prediction:** Comprehensive evaluation models for indicators such as economic benefits are utilized, along with life cycle assessment methods, to simulate and predict potential influencing factors and development trends in hospital low-carbon development.

- **Policy Suggestions and Strategy Optimization:** Based on in-depth analysis and comprehensive evaluation, low-carbon development strategies and policy suggestions for hospitals are proposed. These recommendations aim to align with the requirements of the "dual carbon" goals and promote management system innovations.
- **Sustainable Development Strategy:** A sustainable low-carbon development strategy is proposed, tailored to the actual situation of hospitals and industry characteristics. This strategy ensures the harmonious development of environmental and social benefits while achieving the "dual carbon" goals.

By integrating these research methods, a systematic analysis and evaluation of the low-carbon development path for key energy-consuming hospitals under the "dual carbon" background can be conducted, providing valuable decision-making references.

2.2 Specific Methods of Data Collection [13–17]

Data collection is a critical aspect of this study, aiming to obtain sufficient information to ensure the reliability and comprehensiveness of the research. The data collection methods employed in this study include:

- **Literature Retrieval and Screening:** To ensure the scientific quality of the materials, literature retrieval is conducted using databases such as CNKI and Web of Science Core Collection. Keywords like "green," "low-carbon," "sustainable," "competitiveness," "enterprise," "company," and "organization" are used to search for relevant domestic and foreign literature.
- **Screening and Bibliometric Analysis:** The retrieved literature is manually screened with the assistance of database relevance rankings and professional literature management software (e.g., Zotero). The focus is on literature that primarily discusses corporate green competitiveness, excluding irrelevant studies.
- **Content Analysis:** After screening, content analysis is performed to deeply analyze the current research status and future trends. This involves carefully reading the literature to extract key information and case studies.
- **Other Auxiliary Means:** On-site research is also utilized to obtain first-hand data and information regarding the energy consumption characteristics and low-carbon development pathways of medical

institutions. This helps identify potential low-carbon development opportunities and propose practical improvement measures.

In summary, the data collection process in this study is systematic and complex, requiring multiple channels and methods to ensure the comprehensiveness and accuracy of information. Through scientific methodology and rigorous screening processes, solid data support is provided for the research on low-carbon development paths for key energy-consuming hospitals under the "dual carbon" goals.

2.3 Detailed Description of Data Sources [18,17,19,20]

The selection of reliable and accurate data sources is crucial for the research on the low-carbon development path of key energy-consuming hospitals under the "dual carbon" goals. The data sources for this study include:

- **Official Statistical Data and Databases:** Extensive official data are collected from sources such as the China Statistical Yearbook and the China Energy Statistical Yearbook, released by the National Bureau of Statistics of China. The CSMAR database is also utilized, providing data on listed companies, including annual reports of manufacturing listed companies.
- **Industry Standards and Guidelines:** Professional indicators such as carbon content per unit of calorific value and carbon oxidation rate are primarily referenced from standards and guidelines like "General Principles for Calculating Comprehensive Energy Consumption (GBT2589-2020)," "Guidelines for Compiling Provincial Greenhouse Gas Inventories (Trial)," and the "2006 IPCC Guidelines for National Greenhouse Gas Inventories."
- **Academic Databases and Journals:** Relevant literature is collected from domestic and international academic databases, including the SSCI and CSSCI databases. These documents provide insights into the current research status and future trends in the field of green investment.
- **Professional Software and Models:** Analysis tools such as the SBM-ML model and fsQCA are used to comprehensively analyze potential paths and strategies for low-carbon development in hospitals. Accurate and detailed data input is essential to ensure the validity of the analysis results.
- **Other Auxiliary Materials:** Management manuals, best practice guides, academic papers, and industry reports related to hospital logistics and energy management are referenced to ensure that the proposed low-

carbon development path is both theoretically sound and practically applicable.

In summary, this study conducts rigorous screening and strict data quality control in the selection of data sources, accurately reflecting the current status and needs of hospitals' low-carbon development under the "dual carbon" background. Through comprehensive analysis of these data, practical and feasible low-carbon development paths can be proposed to promote the sustainable development of hospitals and environmental protection.

3. Analysis of Current Energy Consumption and Carbon Emissions

3.1 Analysis of Energy Consumption Data of Key Energy-Using Hospitals [11,21]

In the context of the "dual carbon" goals, analyzing the energy consumption data of key energy-consuming hospitals is a significant research direction. As crucial providers of public health services, hospitals' energy consumption levels directly impact overall energy consumption and carbon emissions, thereby influencing the achievement of carbon peak and carbon neutrality goals. This study aims to explore feasible low-carbon development paths by analyzing the energy consumption data of key energy-consuming hospitals.

Firstly, it is essential to collect and organize energy consumption data from key energy-consuming hospitals, including heat usage, as well as the temporal changes and energy consumption structure of these data. By integrating this data with national or local energy consumption statistics, the rationality of hospital energy use and the potential for energy conservation and emission reduction can be evaluated.

Secondly, a detailed statistical analysis of the collected energy consumption data is conducted, covering energy consumption intensity (energy consumption per unit of service), energy consumption structure (proportion of various types of energy consumption), and energy consumption trends (both historical and forecasted). Establishing an energy consumption database provides data support for subsequent analysis and management.

Furthermore, in alignment with the "dual carbon" goals, the carbon emissions from hospital energy use should be quantitatively calculated to assess the potential for low-carbon development in terms of energy structure and efficiency. For instance, by comparing the costs and energy consumption of traditional fossil

fuels with those of renewable energy, and considering the potential economic benefits of the carbon trading market, the economic and environmental benefits of hospital energy transition can be evaluated.

Additionally, through energy consumption data analysis, problems and deficiencies in hospital energy management, such as outdated equipment, can be identified, providing a scientific basis for hospital energy management decisions and promoting the rationalization and scientification of hospital energy consumption behavior.

Finally, based on the analysis results of energy consumption data, a low-carbon development path for the hospital is formulated. Strategies such as dual control of total energy consumption and intensity are implemented. At the same time, measures in terms of management improvement are taken to achieve continuous optimization of energy use and the achievement of low-carbon development goals. In summary, through comprehensive analysis of energy consumption data from key energy-consuming hospitals, not only can it provide decision support for energy management and low-carbon development in hospitals, but it also holds significant importance for promoting the optimization of the energy structure and achieving carbon emission reduction goals in the entire society.

3.2 Analysis of Carbon Emission Data from Key Energy-Using Hospitals [22-25]

Under the "dual carbon" policy, medical institutions, as significant energy-consuming entities, play a crucial role in reducing carbon emissions to achieve the overall carbon reduction goal. This section aims to explore potential pathways for low-carbon development by analyzing the carbon emission data of key energy-consuming hospitals.

Firstly, according to the information in "Industrial Green Transformation under the 'Dual Carbon' Goals," it is evident that the key to achieving carbon emission reduction lies in optimizing the energy structure and improving energy efficiency. Therefore, for key energy-consuming hospitals, enhancing the efficiency of medical energy use is of utmost importance.

Secondly, as indicated in the study titled "Research on Medium and Long-term Energy Demand Forecasting and Transformation Paths in China under the 'Dual Carbon' Context," the future energy transformation will lead to a decrease in the proportion of traditional fossil fuels, while the usage of renewable and clean energy will increase. This provides direction for optimizing the energy structure

of hospitals, which means gradually reducing dependence on fossil fuels and increasing the proportion of green energy usage.

Next, according to the content of "Development Trends of New Energy Industries under the 'Dual Carbon' Goals," wind energy and other sectors will have significant room for development. Therefore, hospitals can consider installing solar photovoltaic systems to reduce carbon emissions through renewable energy, while also reducing energy costs.

In addition, the information provided in "Carbon Price Trends and Banking Service Strategies" indicates that the carbon market will become more mature in the future, and the rationalization of carbon prices will prompt energy-consuming entities such as hospitals to pay more attention to their own carbon management and energy conservation and emission reduction measures.

Finally, combining the content of "Research on Medium and Long-term Energy Demand Forecast and Transformation Path in China under the 'Dual Carbon' Background" and "Strategic Conception of Building a New Power System in Three Steps," it can be foreseen that the low-carbon development of hospitals in the future will be a gradual process, driven by both industrial policy support and the improvement of market mechanisms.

In summary, the low-carbon development path for key energy-consuming hospitals should include:

- Updating medical equipment and adopting more energy-efficient technologies and devices to reduce energy consumption.
- Optimizing the energy structure, reducing dependence on fossil fuels, and increasing the proportion of green energy use.
- Leveraging the development of the carbon market to incentivize emission reduction through carbon trading.
- Following the national energy transformation plan and formulating a low-carbon strategy that aligns with long-term development.
- Strengthening carbon emission management and establishing a comprehensive monitoring and management system for carbon emissions.

Through the aforementioned measures, key energy-consuming hospitals can not only effectively reduce carbon emissions but also enhance their economic benefits and social image while achieving the "dual carbon" goals.

3.3 Comparison between Key Energy-Using Hospitals and Non-Key Energy-Using Hospitals [26–29]

Based on relevant research in the context of "dual carbon" goals, an in-depth analysis and comparison of the low-carbon development paths taken by key energy-consuming hospitals and non-key energy-consuming hospitals can be conducted. As an important component of the public health system, the significance of low-carbon development for key energy-consuming hospitals has become increasingly prominent under the guidance of the "dual carbon" goals.

Firstly, from the perspective of energy consumption structure, key energy-consuming hospitals often exhibit high energy consumption characteristics, maintaining comfortable medical environments such as constant temperature. Non-key energy-consuming hospitals, on the other hand, tend to have relatively lower energy consumption, which is related to their service content and technical equipment level. Therefore, key energy-consuming hospitals have greater optimization space on the low-carbon development path, such as using renewable energy and improving energy management levels.

Secondly, from the perspective of low-carbon technology application, key energy-consuming hospitals should actively explore and adopt the use of clean energy, such as wind energy, to reduce their dependence on traditional fossil fuels. At the same time, through intelligent energy management systems, real-time monitoring and optimized scheduling of energy consumption can be achieved to reduce energy consumption levels. Although non-key energy-consuming hospitals should also pay attention to energy consumption and carbon emissions, due to their scale and functional limitations, the breadth and depth of their low-carbon technology application may be relatively limited.

Furthermore, in terms of the promotion and application of low-carbon technologies, key energy-consuming hospitals, due to their social attention and demonstration effect, tend to accept and promote new low-carbon technologies more rapidly. For instance, applying efficient air conditioning and heating technologies in building energy systems, as well as installing photovoltaic systems to meet part of the electricity demand, are all low-carbon development measures that they can adopt. Although non-key energy-consuming hospitals can also adopt similar measures, they may face more challenges in terms of economic investment and technological updates.

Finally, from the perspective of regulatory and incentive mechanisms for low-carbon development, key energy-consuming hospitals, due to their high energy

consumption levels, often become the focus of government regulation and incentives. This provides them with opportunities for policy support and financial subsidies for their low-carbon development, helping them make progress in the research, development, and application of low-carbon technologies. In contrast, non-key energy-consuming hospitals may not be as likely to receive similar policy support, and their external incentives for low-carbon development are relatively weaker.

In summary, under the "dual carbon" background, key energy-consuming hospitals possess unique advantages and face unique challenges on the path of low-carbon development. Leveraging government regulatory and incentive mechanisms, these hospitals are expected to achieve significant results on this path and serve as a positive demonstration for other non-key energy-consuming hospitals.

4. Discussion on Low-Carbon Development Path

4.1 Types of Energy Consumption and Their Impacts on the Environment [2,30,31,29]

In the current discourse on environmental protection and sustainable development, the "dual carbon" goals (carbon peaking and carbon neutrality) have emerged as pivotal policy directives and societal development objectives. For key energy-consuming hospitals, the pressing issue is how to achieve low-carbon development while maintaining the quality of medical services. This section aims to explore the types of energy consumption and their environmental impacts, as well as the low-carbon development pathways for hospitals in pursuit of the "dual carbon" goals.

The types of energy consumption mainly include fossil fuels (such as natural gas) and renewable energy sources (such as hydropower). The use of fossil fuels has led to the emission of greenhouse gases like carbon dioxide, which is one of the primary causes of global climate change. Furthermore, environmental issues such as water pollution and soil contamination have emerged. In contrast, renewable energy is a clean source of energy, and its development and utilization do not produce greenhouse gas emissions, thus having a lesser negative impact on the environment.

As an important provider of public health services, the impact of hospitals' energy consumption behavior on the environment cannot be ignored. Hospitals' energy consumption is mainly concentrated in the following aspects:

- **Operation of Medical Equipment and Facilities:** Power consumption of air conditioning, etc.
- **Refrigeration and Lighting:** Energy consumption of the building itself and energy consumption for maintaining a comfortable indoor environment.
- **Production of Medical Services:** Energy use in medical service processes such as pharmacy.

In view of the aforementioned energy consumption types and their environmental impacts, hospitals can embark on a low-carbon development path towards achieving the "dual carbon" goals from the following aspects:

- **Energy Structure Optimization:** Hospitals should reduce their dependence on fossil fuels, utilize renewable energy sources such as wind energy, optimize their energy structure, and reduce carbon emissions.
- **Equipment and Technology Renewal:** Renew and upgrade medical and office equipment in hospitals, adopting energy-saving equipment such as LED-efficient air conditioning systems, to improve energy utilization efficiency.
- **Digital Management:** By establishing a digital management platform, real-time monitoring and management of energy consumption can be achieved, improving management efficiency and reducing unnecessary energy consumption.
- **Energy Conservation Management and Training:** Establish a dedicated energy conservation management department to train hospital staff on energy conservation awareness and techniques, fostering a society-wide awareness of energy conservation and emission reduction.
- **Carbon Footprint Assessment and Carbon Neutrality:** Regularly assess the carbon footprint of the hospital, and implement carbon capture and other methods to achieve carbon neutrality, in order to ensure carbon neutrality in hospital operations.

In summary, in the process of achieving the "dual carbon" goals, hospitals should pay attention to the type selection and use efficiency of energy consumption, and reduce carbon emissions through various measures to achieve sustainable

development. This is not only a contribution to environmental protection but also an inherent requirement for the sustainable development of hospitals.

4.2 Comparison of Energy Consumption and Carbon Emissions among Different Types of Hospitals [32–35]

In the context of the "dual carbon" policy, comparing energy consumption and carbon emissions across different types of hospitals has become an important aspect of assessing their low-carbon development paths. As vital providers of public health services, hospitals' energy consumption and carbon emission levels not only affect the sustainability of medical services but are also a key component in achieving national carbon emission reduction targets.

Firstly, hospital energy consumption primarily consists of the following aspects: energy consumption of other auxiliary facilities. Among them, building energy consumption accounts for the largest proportion, followed by medical equipment, while energy consumption for other services and maintenance is relatively low. Different types of hospitals exhibit variations in their energy consumption structures, and hospitals such as traditional Chinese medicine hospitals also differ in their energy consumption levels and carbon emissions.

There are various types of equipment, and their energy consumption levels are generally higher than those of other types of hospitals. In addition, the types of energy consumption involved in the service process of general hospitals are also more complex, such as gas. Due to the specificity of services, oncology hospitals may adopt some special medical equipment and treatment technologies, and the energy consumption levels and carbon emissions of these equipment and technologies also need to be evaluated in detail. In the process of traditional Chinese medicine preparation, the characteristics of energy consumption and carbon emissions are also unique.

In the comparison of actual energy consumption and carbon emissions, it is necessary to conduct energy audits and carbon emission assessments for each type of hospital. Energy audits involve conducting detailed investigations and recording of the hospital's energy usage, including the usage amount and efficiency of gas and other energy sources. Carbon emission assessments require the calculation of direct and indirect carbon dioxide emissions generated during hospital operations, which involves the calculation of energy consumption and emission factors of combustion products.

By comparing energy consumption and carbon emissions across different types of hospitals, a scientific basis can be provided for the low-carbon development path of hospitals. For instance, through comparative analysis, links with high energy consumption and large carbon emissions can be identified, and corresponding energy-saving and emission-reduction measures can be proposed. Additionally, measures to improve energy utilization efficiency can also be suggested.

In summary, the comparison of energy consumption and carbon emissions among different types of hospitals is an important component of research on hospital low-carbon development paths in the context of "dual carbon" goals. Through scientific and reasonable comparative analysis, it can provide guidance for hospital energy management and low-carbon development, helping to achieve sustainable development of hospitals and national carbon emission reduction targets.

4.3 Comparison of Energy Consumption and Carbon Emissions between Hospitals with Different Bed Capacities [36,32,11,37]

This section aims to explore the energy consumption and carbon emission characteristics of hospitals with different bed capacities, and propose corresponding low-carbon development paths under the "dual carbon" policy background. The analysis will be based on existing energy consumption data and carbon emission calculation models, conduct a quantitative comparison of energy consumption and carbon emissions across hospitals of different sizes, and propose targeted low-carbon development strategies.

Firstly, analyze the energy consumption of hospitals with different bed capacities, focusing on aspects such as canteens and administrative offices. According to the direct sources of energy consumption, it can be divided into three major categories: equipment energy consumption and operational energy consumption. Among them, material and building operation management play a decisive role; equipment energy consumption is mainly determined by the energy consumption and maintenance of medical equipment; operational energy consumption is closely related to the operational management efficiency of the hospital.

Secondly, analyze the carbon emissions of hospitals with different bed capacities. Greenhouse gas emissions generated during transmission and consumption processes. The carbon emissions of hospitals mainly come from their energy consumption, including the process of direct combustion of fossil fuels (cooking, etc.) and indirect emissions (such as emissions generated by the power

consumption of medical equipment). The calculation of carbon emissions can adopt the Life Cycle Assessment (LCA) method, which calculates carbon emissions throughout the entire process from use to disposal.

Under the "dual carbon" policy, the low-carbon development path for hospitals should start from the following aspects:

- **Optimization of Energy Structure:** Promote the use of clean energy , renewable energy such as wind energy, reduce dependence on traditional fossil fuels, and reduce carbon emissions.
- **Energy Efficiency Improvement:** Enhance the energy efficiency of medical processes, reduce energy consumption and carbon emissions per unit of service.
- **Application of Carbon Capture and Storage (CCS) Technology:** For unavoidable carbon emissions, CCS technology can be considered to safely store carbon emissions underground, thereby reducing the carbon content in the atmosphere.
- **Energy Consumption Monitoring and Management:** Establish a sound energy consumption monitoring system, monitor energy consumption in real time, continuously optimize operational management through data analysis, and achieve energy conservation and emission reduction.
- **Carbon Footprint Management:** Establish a carbon footprint management system for the hospital, regularly assess the hospital's carbon emissions, and formulate corresponding emission reduction targets and measures based on the assessment results.

In summary, through a comprehensive quantitative analysis of energy consumption and carbon emissions, and in alignment with the requirements of the "dual carbon" policy, this article proposes a low-carbon development path for hospitals. In the future, hospitals will face new challenges and development opportunities as they strive to enhance the quality of medical services while promoting sustainable development.

4.4 Trend Analysis of Energy Consumption and Carbon Emissions [27,6,29,7]

In the context of "dual carbon" goals, the research on the low-carbon development path of key energy-consuming hospitals involves an in-depth analysis of energy consumption and carbon emission trends. The objective of this study is to identify and evaluate the key links in the process of hospitals achieving low-carbon

transformation, and propose corresponding strategies to optimize energy consumption and reduce carbon emissions.

Firstly, as one of the public buildings, hospitals exhibit energy consumption characteristics that include, but are not limited to, diversified energy sources. Driven by the "dual carbon" goals, the analysis of hospital energy consumption and carbon emission trends should primarily focus on the following aspects:

- **Optimization of Energy Consumption Structure:** Hospitals should promote the optimization of their energy consumption structure, reduce the proportion of high-carbon energy use, and increase the application of renewable and clean energy. For example, using technologies such as ground source heat pumps can reduce dependence on traditional fossil fuels.
- **Energy Efficiency Improvement:** Improving the energy efficiency of hospitals is the key to reducing energy consumption and carbon emissions. Measures such as promoting efficient energy management platforms can achieve effective control of energy consumption and comprehensive improvement of energy efficiency.
- **Energy Use Management and Energy Conservation:** Establish a scientific energy use management system, implement refined management of hospital energy consumption, utilize water-saving appliances and other energy-saving products, as well as conduct reasonable energy consumption monitoring and energy efficiency management, to further reduce energy consumption and carbon emissions.
- **Carbon Footprint Monitoring and Reporting:** Establish a hospital carbon footprint monitoring system to conduct real-time monitoring and scientific analysis of the hospital's energy consumption and carbon emissions. Report the trends of energy consumption and carbon emissions to the management in a timely manner, providing data support for the formulation of low-carbon development strategies.
- **Green Building Design:** Hospitals should follow green building standards in new construction or renovation, using energy-saving materials and optimizing building design to reduce energy consumption and carbon emissions [29].
- **Carbon Sink Construction and Ecological Compensation:** Activities such as restoring ecosystems, increasing the area of carbon sinks, and

achieving negative carbon emissions to compensate for carbon emissions during their operation.

In summary, measures such as green building design, carbon sink construction, and ecological compensation can effectively reduce energy consumption and carbon emissions in key energy-consuming hospitals, achieving their goal of low-carbon development. In the future, with technological advancements and policy support, the low-carbon development of hospitals will become an important factor driving their high-quality development.

5. Existing Problems and Challenges

5.1 Identification of Major Issues Related to Energy Consumption and Carbon Emissions [31,29,7]

In the current context of the "dual carbon" goals, hospitals, as one of the public service institutions, face energy consumption and carbon emission issues that not only affect their own sustainable development but also relate to the green transformation of society and the achievement of carbon neutrality goals. This section aims to identify the main problems of hospital energy consumption and carbon emissions and propose corresponding low-carbon development paths.

Firstly, hospital energy consumption is primarily concentrated in the following areas: energy consumption for medical operations and waste disposal; energy consumption for heating and cooling systems; equipment energy consumption mainly stems from the daily use of medical equipment, inspection and testing equipment, etc.; medical operation energy consumption mainly includes electricity consumption during medical services, operation of treatment room equipment, etc.; and energy consumption during processing and disposal.

Secondly, the carbon emissions from hospitals primarily stem from direct emissions generated during energy consumption and indirect emissions. Direct emissions primarily arise from the direct combustion of fossil fuels (natural gas) and the operation of medical equipment. Indirect emissions encompass carbon emissions during energy production and supply chain, as well as those generated during the disposal of hospital waste.

After identifying the main issues, the hospital's low-carbon development path should start from the following aspects:

- **Energy Efficiency Improvement:** Improve energy utilization efficiency by upgrading and renovating the hospital's energy system. For example, using efficient medical equipment, etc.
- **Utilization of Clean Energy:** Actively introduce renewable energy sources such as wind energy to reduce dependence on traditional fossil fuels.
- **Green Building Design:** When constructing or renovating hospital buildings, adopt green building design concepts to improve the energy efficiency and emission reduction capabilities of the buildings themselves.
- **Optimization of Medical Equipment and Services:** Optimize the utilization efficiency of medical equipment, promote the use of electronic medical record systems to reduce the use of paper documents, and optimize service processes to reduce unnecessary energy consumption.
- **Waste Management:** Implementing recycling and reuse systems to reduce energy consumption and carbon emissions during waste disposal.
- **Carbon Footprint Monitoring and Management:** Establish a hospital carbon footprint monitoring system, conduct regular assessments of energy consumption and carbon emissions, and formulate emission reduction targets and measures.
- **Employee Training and Awareness Enhancement:** Strengthen energy conservation and emission reduction training for hospital employees, and enhance the awareness of low-carbon development among all employees.

Through the aforementioned measures, hospitals can not only effectively reduce energy consumption and carbon emissions but also make positive contributions to promoting the green transformation of society and achieving the "dual carbon" goals.

5.2 Analysis of Technical and Management Challenges Faced [38,24,39,40]

In the current "dual carbon" context, an analysis of the technical and management challenges faced by key energy-consuming hospitals indicates that the low-carbon development path in this field requires overcoming various challenges to achieve its sustainable development goals.

Firstly, the technical challenges primarily revolve around the optimization and upgrading of energy management systems. Hospitals, as significant energy consumers, face challenges in various aspects such as heating and ventilation. To reduce energy consumption and enhance energy utilization efficiency, hospitals need to introduce advanced energy management systems, such as intelligent

energy monitoring and control systems, energy efficiency analysis, and optimized scheduling. Furthermore, there is a need to upgrade and retrofit existing outdated equipment, such as adopting energy-efficient LED-based heating and ventilation systems. These efforts necessitate significant technological investment and equipment renewal costs.

Secondly, management challenges involve changes in organizational structure and management systems. To better optimize energy management, hospitals need to establish a scientific internal management system for energy management and energy conservation and emission reduction. This includes, but is not limited to, establishing a dedicated energy management department, formulating detailed energy management norms and operational procedures, and establishing incentive mechanisms for energy consumption monitoring and energy efficiency improvement. At the same time, it is also necessary to train employees in energy conservation awareness and operational skills to improve the energy management level of the entire organization.

In addition, hospitals face challenges posed by policies and regulations in the process of low-carbon development. As the "dual carbon" goals progress, government supervision of energy consumption and carbon emissions will become stricter. Hospitals need to strictly adhere to relevant laws and regulations, and actively seek policy support, financial subsidies, etc., to reduce transformation costs.

In summary, in the low-carbon development path of key energy-consuming hospitals under the "dual carbon" background, there are technical and management challenges in various aspects such as organizational structure and management system transformation, as well as adaptation to policies and regulations. Only through comprehensive and systematic strategies and measures can these challenges be effectively addressed and the hospital's low-carbon development goals be achieved.

6. Suggested Low-Carbon Development Paths

6.1 Application of Energy-Saving Technology [41,6]

In the pursuit of achieving the "dual carbon" goals, hospitals, as significant energy-consuming entities, hold great importance in exploring their low-carbon development pathways. The application of energy-saving technologies stands as one of the pivotal avenues towards attaining these objectives. Not only does it aid

in reducing energy consumption within hospitals, but it also provides continuous and sustainable support for medical services.

Firstly, the application of energy-saving technologies in hospitals is primarily manifested in optimizing the energy structure. By adopting clean and renewable energy sources such as wind energy, hospitals can effectively reduce their reliance on fossil fuels, thereby decreasing carbon emissions. Furthermore, hospitals can utilize distributed energy supply methods like Combined Cooling, Heat, and Power (CCHP) to achieve efficient and circular utilization of energy. This not only aids in energy conservation and emission reduction but also lowers operational costs.

Secondly, in terms of equipment performance optimization, hospitals need to upgrade and retrofit their existing energy-consuming equipment. For example, replacing old and inefficient equipment with energy-saving ones can significantly reduce the hospital's energy consumption. In addition, optimizing lighting systems and hot water supply systems are also important aspects of energy-saving technology application. Measures such as replacing high-efficiency LEDs and optimizing energy-saving control of hot water systems can further promote energy conservation and emission reduction.

The construction of digital platforms is another crucial aspect of energy-saving technology applications. By establishing a digital management platform, hospitals can achieve precise monitoring and management of energy consumption, enhancing energy management levels. The application of digital platforms also facilitates the quantification of carbon emissions, enabling data analysis to optimize energy consumption assessment and energy operations.

Fourthly, energy-saving management serves as the foundation for the application of energy-saving technologies in hospitals. Hospitals need to establish specialized energy-saving management positions and personnel, formulate comprehensive energy-saving management regulations, and implement the PDCA (Plan-Do-Check-Act) cycle management concept to inspect and continuously improve.

Finally, hospitals should establish a dual control system for carbon asset inventory and energy consumption. By investigating and managing the carbon assets of hospitals, effective control over energy consumption and carbon emissions can be achieved, providing support for the implementation of energy conservation and emission reduction measures.

In summary, the application of energy-saving technologies plays a pivotal role in the hospital's low-carbon development path. Through measures such as energy-

saving management and carbon asset inventory, hospitals can not only effectively reduce energy consumption and provide a comfortable medical and working environment, but also contribute to fulfilling social responsibilities and achieving the "dual carbon" goals.

6.2 Establishment and Optimization of Energy Management System [41,42,6,29]

In the current context of "dual carbon" goals, hospitals, as crucial public service institutions, play a pivotal role in reducing carbon emissions. This serves as a key approach to promoting sustainable development within hospitals. This section aims to explore strategies and methods for establishing and optimizing hospital energy management systems.

Firstly, the establishment of a hospital energy management system should be based on comprehensive energy consumption data and energy efficiency evaluation. By adopting scientific methods such as the formula $E = \sum_{i=1}^n (e_i \times p_i)$ to calculate the comprehensive energy consumption of medical institutions, data support can be provided for subsequent energy management optimization. The application of this formula helps to quantify energy consumption, providing a basis for formulating energy conservation and emission reduction measures.

Secondly, hospitals should conduct overall design and planning during the top-level design phase to ensure the scientific and systematic management of energy. This includes implementing energy-saving management measures and conducting an inventory of carbon assets. For instance, hospitals can reduce the use of fossil fuels by adopting clean and renewable energy sources such as solar and wind power, thereby reducing direct and indirect carbon emissions. Simultaneously, optimizing the hospital's energy consumption structure, such as adopting distributed energy supply methods like Combined Cooling, Heat, and Power (CCHP), can enhance energy utilization efficiency and reduce operational costs.

In terms of equipment performance optimization, hospitals should replace outdated and inefficient equipment with energy-saving new technologies and equipment, such as LED lighting systems and efficient hot water supply systems. Additionally, by conducting real-time monitoring and management of medical equipment, hospitals can ensure safe and reliable operation of the equipment while reducing energy consumption.

The construction of a digital platform is a crucial means to enhance energy management efficiency. By establishing a digital management platform, real-time monitoring and analysis of energy consumption can be achieved, enabling effective analysis of energy consumption data and optimization of energy operation management.

Energy-saving management is an important component of hospital energy management, requiring the establishment of specialized energy-saving management positions and personnel, and the formulation of a comprehensive energy-saving management system to ensure the effective implementation of energy-saving measures [6]. Meanwhile, the PDCA (Plan-Do-Check-Act) cycle management concept is applied to continuously improve energy-saving measures and enhance energy management levels.

Finally, hospitals should conduct an inventory of carbon assets, establish a dual control system for energy consumption, and manage energy consumption and carbon emissions. Through quota management and full-process carbon emission management, hospitals can provide a clear basis for energy conservation and emission reduction measures.

In summary, establishing and optimizing an energy management system in hospitals under the "dual carbon" background is a systematic project that requires consideration and implementation from multiple dimensions. By establishing an energy-saving management system and implementing carbon asset management, hospitals can effectively improve energy utilization efficiency, reduce energy consumption, and decrease carbon emissions, thereby contributing to the achievement of the "dual carbon" goals.

6.3 Exploration of Renewable Energy Utilization [43,44,29]

In the current "dual carbon" context, that is, the broader context of carbon peaking and carbon neutrality, the rapid development of the new energy industry has become a global consensus. Especially in hospitals, which are key energy-consuming places, low-carbon development has become a key path to promote their sustainable development. This section delves into the application of renewable energy in hospitals, exploring implementation pathways and potential benefits.

Firstly, the utilization of renewable energy plays a crucial role in the low-carbon development of hospitals. As public service institutions, hospitals have high carbon emissions and are one of the key areas for achieving the "dual carbon"

goals. By promoting the application of renewable energy, such as wind energy, it is possible to effectively reduce the consumption of fossil fuels in hospitals, lower greenhouse gas emissions, and promote green and low-carbon development.

Secondly, the utilization of renewable energy requires hospitals to make a series of improvements and innovations in their construction and operation. For example, technologies such as solar water heating can achieve energy self-sufficiency and reduce dependence on traditional energy sources. Furthermore, by utilizing solar water heating systems and other methods, hospitals can improve energy utilization efficiency and reduce carbon emissions.

Furthermore, hospitals should establish an energy management system to scientifically manage and optimize energy consumption. By adopting an energy management system, hospitals can monitor energy consumption in real-time, analyze energy use efficiency, and provide data support for the optimized use of energy. At the same time, hospitals should also strengthen the training of energy management personnel to improve their understanding and operational capabilities of renewable energy technologies, ensuring the effective utilization of renewable energy.

Lastly, the cooperation model between energy suppliers and other stakeholders jointly promotes the implementation of renewable energy projects. Measures such as financial subsidies reduce the investment and operational costs of renewable energy projects, increase the return on investment, and thereby enhance the enthusiasm of hospitals to adopt renewable energy.

In summary, the utilization of renewable energy provides an effective path for hospitals to pursue low-carbon development. Through management optimization and multi-party cooperation, hospitals can effectively reduce carbon emissions, achieve sustainable development, and contribute to the realization of the "dual carbon" goals.

6.4 Carbon Footprint Management and Emission Reduction Strategies [45,29,28,46]

In the current context of "dual carbon" goals, hospitals, as significant providers of public health services, face important practical implications in exploring their low-carbon development pathways. As major energy consumers, optimizing their energy consumption structure and enhancing energy efficiency have a direct impact on achieving carbon emission reduction targets. Therefore, this section

aims to explore how hospitals can promote low-carbon development through carbon footprint management and emission reduction strategies.

Firstly, hospitals should clarify the goals and paths of energy management through top-level design and planning. Based on the actual situation of the hospital, scientific energy consumption reduction plans and specific measures should be formulated to ensure the effectiveness and sustainability of energy management. Secondly, hospitals need to optimize their energy structure, reduce the use of high-carbon energy, and actively introduce clean and renewable energy. For example, by using ground source heat pumps and other methods, they can reduce their dependence on fossil fuels, thereby effectively reducing carbon emissions. Furthermore, hospitals should enhance equipment performance optimization by upgrading outdated medical and office equipment and adopting more energy-efficient new equipment, thereby improving the energy efficiency ratio and effectively reducing energy consumption.

In addition, hospitals should strengthen the construction of digital platforms, utilize modern information technology, big data analysis, etc., to achieve precise monitoring and intelligent management of energy consumption, and improve energy management efficiency.

At the same time, hospitals need to establish a sound energy-saving management system, by formulating detailed energy-saving management regulations and operational procedures, and setting up dedicated energy consumption management positions, to ensure the effective implementation of energy-saving measures.

In terms of carbon asset management, hospitals should develop a carbon emission inventory, accurately measure and monitor carbon emissions, and provide data support for achieving carbon emission reduction targets.

Lastly, hospitals should strengthen communication and collaboration with other stakeholders, such as equipment suppliers, to jointly promote the application of low-carbon technologies and the continuous optimization of energy consumption.

In summary, the low-carbon development path of hospitals under the "dual carbon" background involves multiple aspects, requiring systematic planning and implementation. By comprehensively utilizing various management and technical means, hospitals can not only effectively reduce energy consumption but also contribute to building a low-carbon society.

7. Case Analysis

7.1 Experience and Lessons from Successful Cases [8,47,48]

In exploring the low-carbon development path for key energy-consuming hospitals under the "dual carbon" background, we can draw valuable experience and lessons from successful cases to provide practical references for other medical institutions. By analyzing the low-carbon development practices of different hospitals, we can summarize some key success factors and extract valuable lessons to guide future practical activities.

Firstly, successful low-carbon development cases typically feature comprehensive top-level design and systematic planning. These cases emphasize the importance of integrating "dual carbon" goals into various aspects of hospital logistics management, equipment operation, and other key links, forming a comprehensive low-carbon development plan [8]. Significant improvements have been made in equipment usage and energy consumption [8].

Secondly, successful cases highlight the importance of technological innovation and technology introduction

. For example, hospitals have significantly reduced energy consumption and carbon emissions by adopting energy-saving LED lighting, efficient air conditioning systems, and optimized medical equipment. Meanwhile, through the application of intelligent management systems, such as intelligent energy management systems, precise monitoring and effective management of energy consumption have been achieved.

Thirdly, successful cases usually have well-established energy-saving management and continuous improvement mechanisms. These cases demonstrate that by applying the PDCA (Plan-Do-Check-Act) cycle management concept, hospitals can continuously optimize energy-saving measures and achieve sustained energy management improvements and carbon emission reductions [8]. Moreover, successful cases indicate that hospitals need to monitor and manage carbon emissions at all operational levels [8]. By establishing a dual energy consumption control system and conducting carbon asset inventories, hospitals can more accurately grasp the situation of energy consumption and carbon emissions, providing data support for the implementation of energy conservation and emission reduction measures [8].

From the aforementioned successful cases, we can draw the following lessons:

- Top-level design and systematic planning are the foundation for achieving low-carbon development in hospitals.

- Technological innovation and introduction are key drivers for reducing energy consumption and carbon emissions.
- Continuous energy-saving management and improvement mechanisms are the guarantees for ensuring long-term effectiveness.
- Carbon emission monitoring and management are crucial to achieving the "dual carbon" goals.

In summary, through the analysis of successful cases, we can provide references and guidance for other hospitals to pursue low-carbon development, facilitating substantial progress towards achieving the "dual carbon" goals.

7.2 Reason Analysis and Lessons Learned from Failure Cases [40,3]

In the context of implementing the "dual carbon" goals, researching the low-carbon development path for key energy-consuming hospitals is a complex and challenging task. A successful low-carbon development path requires not only comprehensive planning and scientific management but also effective technical support and policy guidance. In the process of exploring the low-carbon development path, some hospitals may encounter various challenges and difficulties, leading to project implementation failures. This section aims to analyze the reasons for these failure cases and propose corresponding lessons to facilitate the successful implementation of the low-carbon development path in the future.

Firstly, the failure of projects is often related to inadequate planning and preparation in the early stages. When promoting low-carbon development projects, some hospitals fail to conduct thorough feasibility studies and fully consider the actual operational needs and energy consumption characteristics of the hospital. For instance, in the process of optimizing energy management and improving energy utilization, the actual energy consumption data and operational characteristics of the hospital are not taken into account, making it difficult to implement optimization measures and achieve the expected energy-saving effect. Secondly, the selection and application of technology are also significant factors leading to project failure. In the process of low-carbon development, some hospitals may not have chosen appropriate technologies to achieve efficient energy utilization. For instance, in the process of adopting clean and renewable energy, due to insufficient understanding of costs and maintenance requirements, they may select technologies that are not suitable for their own conditions,

resulting in low return on investment and making it difficult for the project to continue.

Inadequate policy and regulatory support is also a reason for project failure. In the process of advancing the "dual carbon" goals, some regions lack sufficient policy support and face policy risks and market uncertainties during investment and operation. Furthermore, relevant regulations and standards may also be inadequate, bringing additional uncertainties to low-carbon development.

Fourthly, the absence of a continuous monitoring and evaluation mechanism is also a common issue leading to project failure. During the implementation of low-carbon development projects, some hospitals fail to continuously track and evaluate project progress, resulting in issues not being identified and resolved in a timely manner. Additionally, the lack of effective incentive and restraint mechanisms has also affected the enthusiasm and sense of responsibility of project participants.

Lastly, organizational management and personnel training are also crucial factors for project success. In the process of promoting low-carbon development, some hospitals may have neglected the adjustment of their internal organizational structure and management mechanisms, leading to inefficiencies in project management. Furthermore, inadequate training on low-carbon technology and management knowledge for relevant personnel can also hinder the smooth implementation of the project.

In summary, to successfully achieve the low-carbon development path for key energy-consuming hospitals under the "dual carbon" goals, it is necessary to conduct sufficient preliminary planning and preparation, select appropriate technical solutions, obtain adequate policy support, establish a sound supervision and evaluation mechanism, and strengthen organizational management and personnel training. Only through comprehensive measures can we ensure the smooth implementation and long-term stable operation of low-carbon development projects, providing a solid foundation for achieving the "dual carbon" goals.

8. Conclusion and Outlook

8.1 Main Findings of the Study [20,29,6]

In the current context of the "dual carbon" goals, the study of low-carbon development paths for key energy-consuming hospitals is an important topic. The main findings of this study include:

- **Significant Achievements in Energy Conservation and Emission Reduction:** Through the implementation of energy-saving and low-carbon projects and measures, such as the renovation of the water supply system and the optimization of air conditioning system management, the total CO₂ emissions of the hospital have been effectively controlled. In particular, the year-on-year decrease in CO₂ emission intensity per unit area indicates that the implementation of energy conservation and emission reduction measures has achieved remarkable results, effectively enhancing the hospital's CO₂ emission management level.
- **Specific Achievements in Gas Boiler Retrofitting and Air Conditioning System Management:** Compared to 2022, the gas boiler retrofitting project achieved a significant reduction of 2% in CO₂ emissions from natural gas in 2023. Through the correction of the regression coefficient of relative humidity, the carbon emission reduction effect of the project was further accurately evaluated. Meanwhile, management measures for the air conditioning system also significantly reduced CO₂ emissions from outsourced electricity by 9%, further confirming the effectiveness of energy conservation and emission reduction measures.
- **Importance of Energy Management Optimization:** To achieve low-carbon development in hospitals, it is essential to optimize energy management and improve energy utilization efficiency, thereby effectively reducing energy consumption [29]. Hospitals should support the achievement of the "dual carbon" goals through various means such as logistics control and strengthen energy conservation management and conduct carbon asset inventories.
- **Application and Development Trends of Renewable Energy:** In the context of the "dual carbon" goals, the development trends of the renewable energy industry offer significant insights into the low-carbon development of hospitals. The enhancement of the development and utilization of renewable energy is expected to boost the proportion of non-fossil energy consumption, presenting new opportunities for the low-carbon development of hospitals.

- **Application of Ultra-Low Energy Consumption Building Technology:** The development of ultra-low energy consumption building technology provides technical support for the low-carbon development of hospitals. By optimizing spatial layout and energy supply schemes, the design of ultra-low energy consumption buildings should aim to minimize energy consumption to the greatest extent possible.
- **Enlightenment from the Path of Multi-Energy Integration Development:** Realizing the complementary integration of various energy sources through technological innovation provides new ideas for the low-carbon development of hospitals. The technical framework of multi-energy integration helps to achieve multi-objective optimization of energy resource utilization, providing important theoretical support for hospital energy management and low-carbon development.

In summary, by implementing energy-saving and low-carbon projects and measures, optimizing energy management, and drawing on the trends of new energy industry development and the application of ultra-low energy consumption building technology, key energy-consuming hospitals can effectively advance their low-carbon development path and meet the requirements of the "dual carbon" goals.

8.2 Summary of Countermeasures and Suggestions [24,49,50]

Under the "dual carbon" background, achieving low-carbon development in key energy-consuming hospitals is a systematic project involving multiple aspects such as management optimization. The following is a summary of the countermeasures and suggestions comprehensively proposed based on the provided materials and titles: "Challenges and Countermeasures Faced by China in Achieving the 'Dual Carbon' Goals," "Thoughts on the Path for Hospital Logistics to Assist in Achieving the 'Dual Carbon' Goals in Hospitals," "Research on China's Medium and Long-term Energy Demand Forecast and Transformation Path under the 'Dual Carbon' Background," "China Will Build 100 Carbon Peaking Pilot Projects," and "Research on China's Medium and Long-term Energy Demand Forecast and Transformation Path under the 'Dual Carbon' Background."

- **Policy Guidance and Top-Level Design:** Specific action plans under the "dual carbon" goals should be further clarified and incorporated into the central environmental protection supervision system to ensure policy implementation. At the same time, top-level design should be strengthened,

resource allocation should be optimized, and key sectors such as construction should adopt a "national unified" mindset to achieve overall coordination of regional development and industrial layout, breaking through regional barriers.

- **Technological Innovation and Energy Efficiency Improvement:** Efforts should be increased in research and development of low-carbon technologies, promoting energy-saving technologies and new processes in industries such as transportation, and enhancing energy efficiency. For key energy-consuming units such as hospitals, the application of clean energy, such as wind energy, should be promoted to optimize the energy structure and achieve effective control of energy consumption through technological progress and management improvement.
- **Market Mechanism Improvement:** The carbon pricing mechanism should be perfected, and market-based means such as carbon taxes and carbon trading mechanisms should be utilized to incentivize enterprises to reduce emissions and promote technological innovation [24]. Meanwhile, the development of distributed energy and natural gas distributed energy should be encouraged to enhance the efficiency of the energy system and promote

low-carbon development.

- **Systematic Layout and Comprehensive Management:** A systematic layout for the "dual carbon" goals should be strengthened, considering various factors such as social livelihood, to achieve the carbon neutrality goal [24]. At the same time, a sound economic means and policy system for emission reduction should be established, new energy infrastructure should be planned ahead, the energy structure should be optimized, and energy consumption and carbon emissions should be reduced.

In summary, implementing comprehensive measures such as "dual carbon" management, through systematic planning and integrated management, can enhance energy efficiency and effectively control carbon emissions, thereby promoting low-carbon development in key energy-consuming hospitals as well as the entire society.

8.3 Limitations of the Study and Future Research Directions [24,5,51,52,29]

In exploring the low-carbon development path for key energy-consuming hospitals under the "dual carbon" goals, it is essential to acknowledge the

limitations of the research and anticipate future research directions based on these limitations. The current research faces several limitations, including:

- **Limitations of Data and Cases:** Current research may rely on specific regions or case analyses, which may limit the universality of research results. Factors such as policy environment and social acceptance can affect the choice and implementation of low-carbon pathways.
- **Limitations of Policies and Regulations:** Imperfections in policies and regulations may hinder the pace of low-carbon development in hospitals. For example, the lack of specific requirements for new energy and energy efficiency standards, or insufficient rigor in policy implementation, may affect the effectiveness of low-carbon development.
- **Uncertainty in Technological Development:** Technological progress is one of the key factors in achieving low-carbon transformation. The promotion and application of technology are uncertain, which may lead to deviations between the actual development path and expectations.
- **Economic and Cost Constraints:** Economic costs are a significant constraint in promoting low-carbon transformation. For hospitals, achieving a win-win situation between economic benefits and environmental benefits while ensuring service quality and patient safety is an issue that requires in-depth research.
- **Lack of Long-term Tracking and Evaluation:** Existing research may lack systematic tracking studies and comprehensive evaluations regarding the long-term impact and effectiveness assessment of hospitals' low-carbon development, which limits a deep understanding of the effectiveness of strategies.

Future research directions should include:

- **Multiple Case Studies:** Conduct case studies on low-carbon development in hospitals of various types and at different stages of development to enhance the universality and depth of the research.
- **Policy and Regulation Improvement:** Research, formulate, and improve the policy framework supporting the low-carbon development of hospitals, as well as the formulation and enforcement of regulations.
- **Technological Innovation and Application:** Explore the development trends and application cases of intelligent management systems to provide technical support for hospitals' low-carbon transformation.

- **Economic Benefit Analysis:** Conduct an in-depth analysis of the economic benefits of low-carbon transformation, including return on investment, to support decision-making.
- **Long-term Tracking and Evaluation:** Establish a long-term tracking and evaluation mechanism for low-carbon development to assess the long-term impact of low-carbon strategies and provide a basis for continuous improvement.
- **Stakeholder Collaboration:** Strengthen communication and cooperation among stakeholders, including suppliers and patients, to foster a positive atmosphere of joint promotion.

Through the understanding of the limitations of the aforementioned research and the outlook on future research directions, we can deeply understand and promote the low-carbon development path of key energy-consuming hospitals under the "dual carbon" background.

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