Pathway Analysis of Low-Carbon Energy System Transition

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Abstract. This study examines the transition pathways of low-carbon energy systems in the provinces of Guangdong, Jiangsu, and Shanxi. By analyzing factors such as economic foundation, population and urbanization level, natural conditions, and policies, it reveals how these factors influence the energy structure and transition process. The study finds that economically developed Guangdong and Jiangsu, supported by strong investment capacity and policy support, can significantly promote the development of clean energy and gradually reduce dependence on fossil fuels. In contrast, Shanxi, heavily reliant on coal resources, faces a longer transition period and technical challenges. This paper summarizes the differences among the provinces in wind power, photovoltaic, nuclear power, and natural gas, and proposes general transition patterns suitable for different regions, providing a theoretical basis for formulating energy transition strategies tailored to local characteristics.

Keywords: Low-carbon energy, energy transition, energy structure, clean energy, policy

1 Introduction

In recent years, the challenges posed by global climate change and the pursuit of sustainable development goals have made the necessity of energy transition increasingly urgent. The Paris Agreement calls for countries worldwide to limit temperature rise by reducing carbon emissions, and China has set dual targets of achieving peak carbon emissions by 2030 and carbon neutrality by 2060 [1]. This is not only a collective commitment to global climate governance but also crucial for national energy security and high-quality economic development. Overreliance on fossil fuels has led to a sharp increase in greenhouse gas emissions, exacerbating climate change, frequent extreme weather events, and ecosystem degradation. Therefore, accelerating the transition to renewable energy sources, such as wind and solar energy, is a key measure to address the climate crisis and an effective means to enhance energy security, reduce fossil fuel dependence, and promote green development [2]. Against this backdrop, promoting low-carbon energy transition has become a global consensus.

The low-carbon energy transition is influenced by a combination of factors, including economic foundation, technological level, policy guidance, natural conditions,

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social culture, and external environment [3]. Economic foundation determines the ability of regions to invest in clean energy and build related infrastructure, while technological progress affects the efficiency and cost of clean energy applications. Policy guidance, through tools such as carbon taxes, subsidies, and international cooperation, supports the adjustment of the energy structure, while natural conditions determine the development potential of renewable energy. Social culture, public awareness of environmental protection, as well as energy demand and industrial structures, also influence the acceptance and effectiveness of the transition. Furthermore, external factors such as global energy market fluctuations, international political dynamics, and supply chain stability impact regional pathways to low-carbon transition [4]. This study selected four key factors—economic foundation, population and urbanization level, natural conditions, and policy orientation—that directly affect energy transition outcomes and determine the pathways of different regions.

This study focuses on Guangdong, Jiangsu, and Shanxi, mainly due to their significant differences in economic development, energy structure, and natural resource endowments. Guangdong and Jiangsu represent economically developed provinces in China, with strong capabilities for clean energy investment and technological innovation, while Shanxi, as a traditional energy province, faces more challenges in its transition [5]. Analyzing these three representative provinces provides a comprehensive understanding of the low-carbon energy transition pathways under different economic and resource conditions, offering valuable references for other regions.

2 Methods

This study employs a mixed-methods approach, combining quantitative and qualitative analysis, to systematically examine the low-carbon energy transition pathways of Guangdong, Jiangsu, and Shanxi. The research involves collecting economic data, energy structure information, and policy documents from each province to quantitatively assess the impact of economic foundation, population and urbanization level, natural conditions, and policy orientation on energy transition. In conjunction with relevant domestic and international literature, the study explores the theoretical framework and current research status of low-carbon energy transition to ensure a solid theoretical and scientific basis. Using a case study approach, the specific challenges and opportunities faced by each province during the transition process are examined, along with an analysis of their policy effectiveness and technology choices. To forecast the energy structure of each province in 2030, a time series analysis was conducted, employing regression analysis of trends in various energy data from 2019 to 2023 to predict future developments. Additionally, a comparative analysis was applied to examine differences in clean energy investment, technological progress, and policy responses among the three provinces, deriving general patterns and policy recommendations applicable to various regional contexts.

3 Results and Discussions

This study conducted a systematic analysis of the low-carbon energy transition in Guangdong, Jiangsu, and Shanxi, revealing that differences in economic foundation, natural conditions, population and urbanization levels, and policy orientation significantly impact the adjustment pathways of their energy structures. Guangdong and Jiangsu, leveraging their economic advantages and policy support, have gradually optimized their energy structures by reducing the proportion of fossil fuels and expanding the use of clean energy sources such as nuclear, wind, and solar power. In contrast, Shanxi, due to its heavy reliance on coal and relatively underdeveloped economy, faces a longer transition period and technical challenges, though it is gradually promoting coal clean-up and the introduction of renewable energy through policy support. Based on the analysis of energy data from 2019 to 2023, the study predicts that by 2030, Guangdong and Jiangsu will continue to increase the share of clean energy, while Shanxi's coal-fired power share will gradually decrease but still remain substantial. The changes in energy structures and future projections of the provinces reflect the coordinated effects of economic capacity, natural resource endowments, and policy implementation in their energy transition processes.

3.1 Objective Factors

Economic Foundation: Guangdong is the most developed, followed by Jiangsu, with Shanxi being the least developed. In 2023, Guangdong's GDP reached 13.6 trillion yuan, with a per capita GDP of 106,986 yuan, making it the economic leader of China. In contrast, Jiangsu's GDP was slightly lower at 12.7 trillion yuan, with a per capita GDP of 150,487 yuan. Shanxi's GDP was only 2.57 trillion yuan, with a per capita GDP of 73,984 yuan. As shown in "Figure 1", due to these economic differences, the investment in clean energy by Guangdong and Jiangsu is significantly higher than that of Shanxi.

Population and Urbanization Level: Guangdong has the largest population, at 127 million, with an urbanization rate of 75.4%. Jiangsu has a population of 84.75 million and also a high urbanization rate. Shanxi has a relatively small population of 34.92 million, with lower population density and urbanization rate.

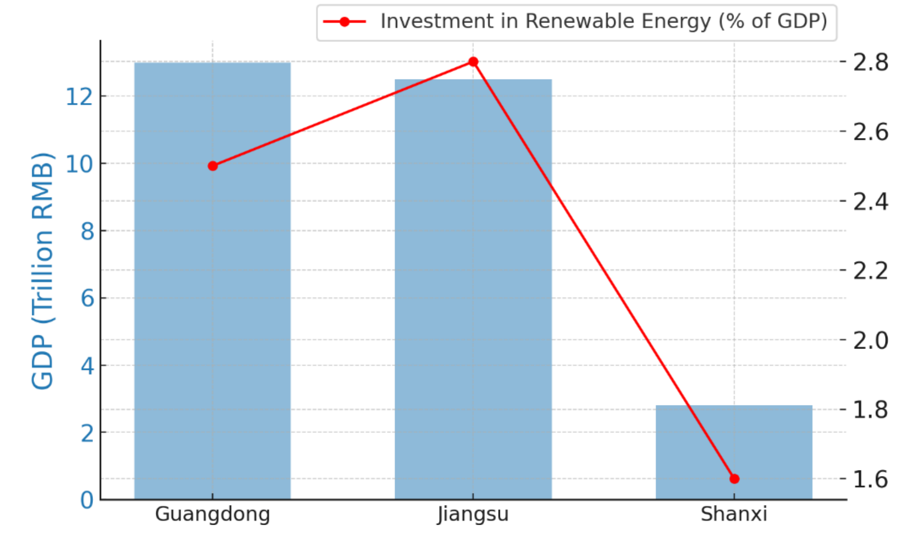

Fig. 1. Economic Base and Renewable Energy Investment

Natural Conditions: As shown in "Figure 2", both Guangdong and Jiangsu are coastal provinces with abundant wind energy resources. Guangdong, located at a low latitude, has ample sunlight, while

Jiangsu's flat terrain offers favorable solar conditions. In contrast, Shanxi is an inland province with complex terrain, mainly consisting of plateaus and mountains, and possesses abundant coal resources.

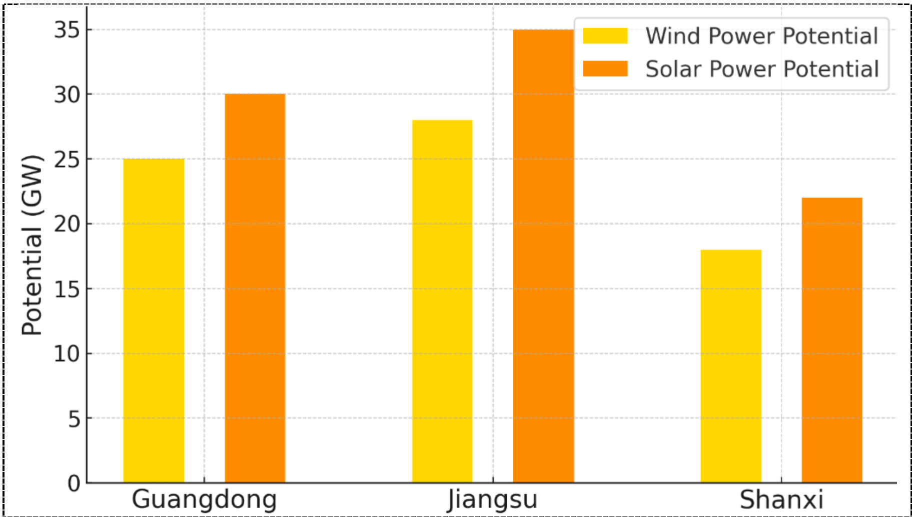

Fig. 2. Wind and Solar Potential in Provinces

3.2 Policy Response

Policies are formulated in response to objective conditions, reflecting the strategic choices and adjustments of local governments in energy transitions [6]. Guangdong, leveraging its economic strength, focuses on diversifying and stabilizing the energy structure, with significant investments in nuclear, wind, and solar power, supplemented by natural gas generation to ensure a stable and large-scale energy supply. Jiangsu's policy emphasizes technological innovation, aiming to improve energy efficiency and promote the use of clean energy through the development of smart grids, photovoltaic, and wind power projects, thereby reducing dependence on traditional energy sources. In contrast, Shanxi, constrained by its economic and natural conditions, adopts a more conservative approach, primarily focusing on promoting clean coal technologies and gradually introducing renewable energy, balancing energy transition with economic stability.

3.3 Energy Structure

This section provides an overview of the energy structure characteristics of Guangdong, Jiangsu, and Shanxi, analyzing the share and trends of various energy sources in each region. "Figure 3" presents the current energy composition of the three provinces. The study focuses on the differences in the application of coal-fired power, nuclear power, natural gas, wind power, and photovoltaic energy across these provinces, and examines the economic, resource, and policy factors underlying these differences. This analysis reveals the distinct pathways and challenges faced by each province in the transition to low-carbon energy.

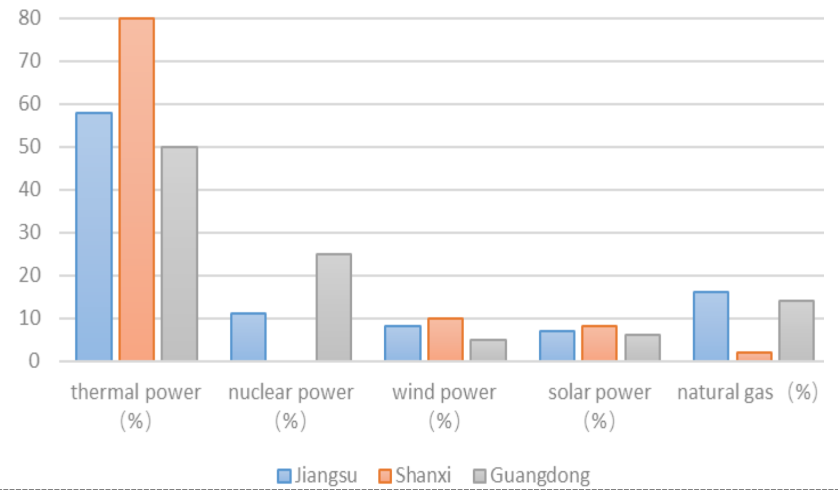

Fig. 3. Energy Structure of the Three Provinces

Shanxi's coal-fired power generation is 334 TWh, accounting for 75% of the province's total electricity generation, highlighting its heavy reliance on coal. Jiangsu and Guangdong generate 384 TWh (60%) and 350 TWh (47%) from coal-fired power, respectively. Shanxi's vast coal reserves and low extraction costs have led to its dependence on coal-fired power, which poses a significant challenge for the energy transition, requiring substantial investment and technology to gradually reduce this dependency [7]. In contrast, Guangdong and Jiangsu have limited coal resources and more proactive energy policies aimed at reducing the share of coal and promoting clean energy. Their strong economic capacity enables them to invest in clean energy technologies and infrastructure to decrease reliance on coal. Shanxi, being economically less developed, finds coal the most economical choice and cannot rapidly adjust its energy structure.

Guangdong is the fastest in developing nuclear power, generating 155 TWh, which accounts for 21% of its total electricity generation. Jiangsu generates 45 TWh (7%), while Shanxi has almost no nuclear power development. The high development and maintenance costs of nuclear power mean that only regions with strong economic foundations can develop it at scale. Guangdong's strong economy supports its large-scale nuclear development, providing stability and sustainability to meet its substantial power demand [8]. While economically advanced, Jiangsu's nuclear development is slower, which relates to its policy and industrial structure. Shanxi's weaker economic base and technological limitations prevent it from developing nuclear power. The high population and urbanization rate in Guangdong require stable large-scale power supply, which nuclear power provides, while in Jiangsu, nuclear power serves more industrial needs. In Shanxi, with its smaller population and lower urbanization, nuclear power demand is low, reducing the motivation for its development.

Guangdong generates 130 TWh from natural gas, accounting for 18% of its electricity generation, while Jiangsu generates 96 TWh (15%) and Shanxi only 18 TWh (4%). Guangdong and Jiangsu, being coastal provinces, have convenient access to natural gas import channels, making it an important energy source to balance the intermittency of wind and solar power and stabilize the grid. Shanxi, being inland, has underdeveloped natural gas pipelines and higher access costs. Additionally, natural gas power is costly and requires strong economic support. Guangdong and Jiangsu's developed economies can bear these costs, whereas Shanxi's weaker economic base makes large-scale adoption challenging.

Jiangsu generates 64 TWh (10%), Guangdong 58 TWh (8%), and Shanxi 54 TWh (12%) from wind power. Jiangsu and Guangdong have favorable coastal conditions for wind energy, making them suitable for large-scale offshore wind development [9]. Shanxi's inland location and complex terrain limit wind power development efficiency compared to coastal provinces. The initial costs of wind power construction are high, and Guangdong and Jiangsu's strong economies support large-scale investments, whereas Shanxi's limited economic capacity restricts wind power development.

Jiangsu generates 51 TWh (8%), Guangdong 40 TWh (6%), and Shanxi 28 TWh (6%) from photovoltaic energy. Jiangsu's flat terrain and good solar conditions have enabled significant photovoltaic development. Although Guangdong's terrain is varied, its low latitude provides ample sunlight. Shanxi's complex terrain restricts photovoltaic project development, keeping it at a relatively low level. The economic strength of

Jiangsu and Guangdong supports research and infrastructure in the photovoltaic industry, promoting widespread adoption, while Shanxi's financial and technological limitations slow the construction pace and scale of photovoltaic projects.

"Figure 4" shows the energy structure data of the three provinces from 2019 to 2023, along with predictions for the future based on the average annual decline rate. By 2030, Guangdong's coal-fired power proportion will be around 38%, nuclear power 25%, natural gas 22%, wind power 10%, and photovoltaic 8%. By 2030, Jiangsu's coal-fired power proportion will be about 55%, nuclear power 10%, natural gas 18%, wind power 12%, and photovoltaic 10%. By 2030, Shanxi's coal-fired power will account for approximately 70%, with nuclear power at 0%, natural gas 5%, wind power 14%, and photovoltaic 8%.

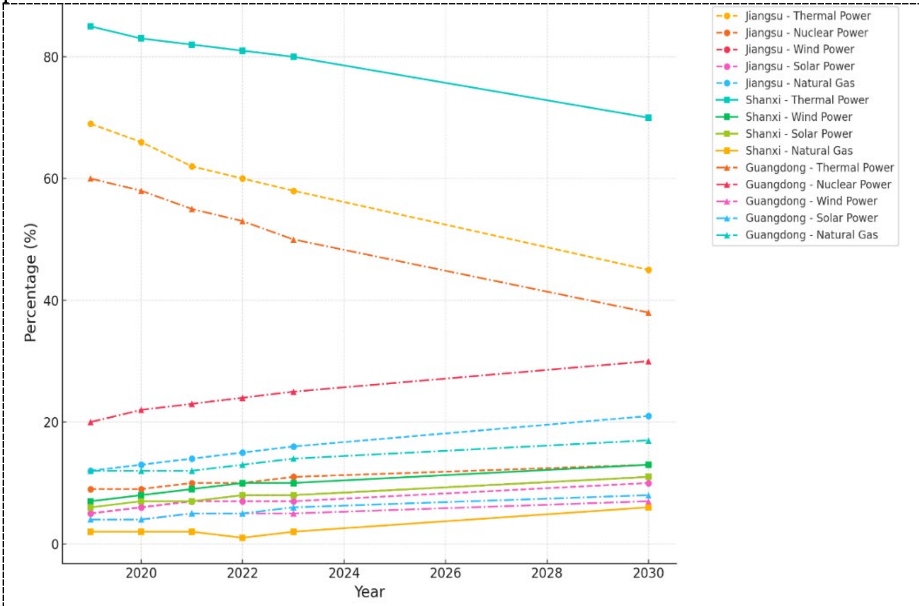

Fig. 4. Energy Structure Trends in Jiangsu, Shanxi and Guangdong

4 Conclusions

Through an in-depth comparative analysis of the three provinces, it can be clearly concluded that the economic foundation determines the speed of the transition and the technological pathway, population and urbanization levels influence energy demand patterns, natural conditions determine energy composition and development potential, and policy serves as a key mechanism for adjusting and optimizing these objective factors. This study distills general principles applicable to broader regions, providing a reference for understanding the low-carbon energy system transition in different areas and assisting other regions in formulating energy transition strategies based on their own characteristics.

The economic foundation dictates the choice of technological pathways and the speed of adjustments. Developed regions can leverage strong economic support to rapidly implement complex and high-cost technologies, while less developed regions must first improve existing technological conditions and achieve their goals through a gradual transition. Population size and urbanization levels determine the diversity and stability of energy supply [10]. In regions with dense populations and high urbanization levels, the stability and diversity of energy demand are crucial. High urbanization areas need diverse and distributed energy strategies to meet their complex energy needs, while less urbanized areas can gradually optimize existing centralized energy supplies. Natural conditions affect the initial energy structure and the difficulty of the transition pathway. Natural conditions directly determine the potential for developing fossil and renewable energy and their spatial distribution [11]. For regions with poor resource endowments, the focus of energy transition is on promoting clean energy development through technological innovation and policy guidance, utilizing external resources and market mechanisms. For regions rich in fossil resources, the transition will involve a longer adjustment period and technical challenges, requiring adaptive modifications to the existing energy structure and a gradual advancement of renewable energy projects [12]. The flexibility and specificity of policies determine the effectiveness of the transition. Under the constraints of economic, demographic, and resource factors, policy flexibility becomes key to driving low-carbon transition. Policies need to align with the regional economic and resource realities while also being flexible and forward-looking to effectively respond to the evolving external environment during the transition process.

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