

A Study on the Development Pathway of Electric Energy Substitution in Guangdong Province Based on Dual Carbon Goals and Regional Policies

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Abstract. With the global energy transition and rising environmental awareness, electric energy substitution (EES) has emerged as a clean and efficient energy consumption model, crucial for promoting sustainable energy development. As a major economic powerhouse in China, Guangdong Province's implementation of its EES strategy serves as a demonstration model for regional green and low-carbon development. This paper conducts an in-depth study of the future development models for Guangdong's EES strategy. By analyzing the current implementation status, achievements, and existing challenges, key issues such as inadequate EES potential forecasting technology, limited policy support, and lagging technological development are identified. Consequently, strategies including optimizing the energy structure, improving supporting policies, and promoting technological progress are proposed to advance the in-depth implementation of Guangdong's EES strategy. This research aims to provide theoretical references and practical guidance for the formulation and optimization of EES strategies in Guangdong and other regions across China, contributing to the construction of a clean, low-carbon, safe, and efficient energy system.

Keywords: Electric Energy Substitution; Energy Structure; Policy Support; Technological Advancement; Sustainable Development.

1. Introduction

The world is currently undergoing a profound energy transition, driven by the urgent need to address escalating climate change and ensure energy security. The goals established by the Paris Agreement to limit global average temperature rise to well below 2°C above pre-industrial levels, and to pursue efforts to limit it to 1.5°C, alongside China's ambitious "carbon peak" and "carbon neutrality" targets, have set a clear direction and urgency for optimizing the global energy structure and transforming development models. In this overarching context, the development of a clean, efficient, and sustainable energy system has become an imperative choice. Electricity, as a carrier of clean energy, has its share in final energy consumption increased through "electric energy substitution" (EES). This is recognized as a vital strategic pathway for optimizing the energy structure, reducing greenhouse gas emissions, improving air quality, and promoting sustainable economic development. The Chinese government has placed significant emphasis on EES, issuing policies such as the "13th Five-Year Plan for Energy Development" and the "Energy Production and Consumption Revolution Strategy (2016-2030)" to explicitly promote the construction of a clean, low-carbon, safe, and efficient energy system. The introduction of "dual carbon" goals further underscores the pivotal role of EES in this energy revolution.

In recent years, scholars have delved deeper into research on EES, focusing primarily on several key areas: First, the economic and environmental benefits of EES, analyzing its role in reducing energy consumption, mitigating pollutant emissions, and enhancing energy efficiency [1,2]. Second, the study of EES technologies, models, and pathways in various sectors, such as industrial, transportation, residential, and agricultural applications, with the proliferation of electric vehicles (EVs) and charging infrastructure being a focal point in the transportation sector [3]. Third, the impact of EES



on energy structure, grid operations, and electricity markets. Fourth, the exploration of the roles played by policy support, technological innovation, and market mechanisms in driving EES adoption. However, for specific regions, particularly economically robust provinces with complex energy consumption structures like Guangdong, the pathways for in-depth EES development under the "dual carbon" goals, the region-specific challenges encountered, and precise policy optimization strategies still require more thorough and targeted research. Current studies exhibit certain deficiencies in forecasting EES potential, evaluating policy effectiveness, and integrating multifaceted resources for synergistic development.

This study focuses on Guangdong Province, a highly economically developed and energy-intensive region in China, examining its EES strategy under the dual constraints and guidance of "dual carbon" goals and regional policies. It provides an in-depth analysis of the current status, achievements, and challenges of EES implementation. The marginal contributions of this paper are as follows: Firstly, based on the latest data, it comprehensively reviews the implementation status and development level of EES in Guangdong, clearly illustrating the evolutionary trends of its power generation structure through tables, thereby laying a foundation for understanding regional energy transition. Secondly, after a thorough analysis of key challenges faced by Guangdong's EES, including "inadequate EES potential forecasting technology," "limited policy support," and "lagging technological development," this paper proposes a series of targeted and actionable development strategies. These include optimizing the energy structure with electricity as the core, vigorously developing distributed photovoltaic microgrids, accelerating smart grid construction, and promoting EES technological innovation and standardized governance. Finally, the research findings not only offer theoretical references and practical guidance for Guangdong to optimize and deepen its EES strategy but also provide valuable insights for other regions in China to advance EES and construct a clean, low-carbon, safe, and efficient energy system, thereby contributing regional practical experience to the global trend of green and low-carbon energy transition.

2. Current Status of EES Implementation in Guangdong

2.1. Overview of Electric Energy Substitution

Guangdong Province has made significant progress in EES implementation. According to data from the Huajing Industry Research Institute [4], Guangdong's cumulative power generation reached 671.86 billion kWh in 2023, a year-on-year increase of 9.5%. Specifically, thermal, hydro, nuclear, wind, and solar power accounted for 73.57%, 2.99%, 17.57%, 4.54%, and 1.33% of the total generation, respectively. The total electricity consumption reached 850.2 billion kWh, an 8.0% increase, making Guangdong the first province in China to exceed 800 billion kWh in annual electricity consumption [5].

Table 1 shows the province's power generation from 2016 to 2023, indicating a 65.3% growth over the period and reflecting the rapid development of its power industry.

Table 1. Guangdong Province Power Generation Statistics (2016-2023)

Year	Power Generation (billion kWh)	Year-on-Year Growth Rate (%)
2016	408.2	21.2%
2017	400.0	15.0%
2018	451.59	10.6%
2019	472.63	10.0%
2020	500.99	20.0%

2021	500.0	4.3%
2022	610.22	4.1%
2023	671.86	9.5%

Table 2 details the generation breakdown by type in 2023, with solar power leading in growth at 26.6%, highlighting the rapid expansion of renewable energy.

Table 2. Guangdong Province Power Generation by Type (2023)

Generation Type	2023 Year Generation	Year-on-Year Increase	Year-on-Year Growth Rate	Share
Hydropower	20.06	2.59	12.1%	2.99
Nuclear Power	118.05	3.19	2.8%	17.57
Wind Power	30.52	3.14	13.8%	4.54
Solar Power	8.915	2.47	26.6%	1.33
Thermal Power	494.31	47.16	10.7%	73.57

Guangdong is actively promoting "New Electrification." In 2023, approximately 8.7 million kW of backbone power sources were put into operation, alongside the grid connection of 5.84 million kW of centralized wind and solar power. Green electricity trading volume reached 3.97 billion kWh, a 160% increase, equivalent to a CO₂ emission reduction of 2.53 million tons. The cumulative installed capacity of new energy storage power stations exceeded 1.6 million kW, a 125% increase.

2.2. Relevant Policies for EES

Guangdong's EES policies aim to increase the share of electricity in final energy consumption. The Guangdong Provincial 13th Five-Year Plan for Energy Development (2018) proposed measures to adjust the energy consumption structure and promote EES to reduce pollutant emissions. As of 2023, the province continues to deepen these policies by accelerating project implementation, planning grid infrastructure, offering investment incentives, supporting R&D, and strengthening project supervision.

2.3. Classification of EES Projects

Coal-to-Electricity: In the industrial sector, electrification retrofits of coal-fired boilers and kilns have reduced emissions of sulfur and nitrogen oxides. In residential life, the promotion of electric heaters and induction cooktops has improved energy efficiency and air quality.

Oil-to-Electricity: The province is promoting electric vehicles (EVs) and shore power technology in ports. EV adoption is encouraged through subsidies and charging infrastructure construction. In agriculture, electric equipment is replacing diesel generators.

Gas-to-Electricity: In households and the catering industry, electric appliances like rice cookers, water heaters, and electric hot pots are replacing gas-burning equipment, enhancing energy efficiency and safety.

3. Key EES Projects and Development Level

3.1. Key EES Projects in Guangdong

Three Gorges Yangjiang Shapa Offshore Wind Power Project: As China's first gigawatt-scale offshore wind project, it has produced over one billion kWh of electricity as of March 2022. The project's success signifies major breakthroughs in marine engineering and new energy technology.

China Southern Power Grid's First "Shore Power" Project: Implemented at Zhuhai's Gaolan Port, this project allows docked ships to connect to the land-based grid, replacing their diesel auxiliary engines. It is estimated to save shipping companies about 1 million RMB annually and reduce CO₂ emissions by 5,620 tons.

Zhuhai Haihong Road Bus Charging Infrastructure Project: This project, led by the Zhuhai Power Supply Bureau, supports the city's transition to an electric public bus fleet. The fast-charging station significantly reduces reliance on fossil fuels and demonstrates clear economic, environmental, and social benefits.

3.2. Development Level of EES in Guangdong

In the first half of 2023, Guangdong achieved an EES volume of 14.3 billion kWh, a 4.6% increase. EES has expanded into transportation, construction, and agriculture. For every 1% increase in electricity's share of final energy consumption, energy consumption per unit of GDP decreases by about 4%.

The Guangdong Provincial 14th Five-Year Plan for Energy Development sets ambitious targets for 2025, as shown in Table 3.

Table 3. Main Targets of Guangdong's 14th Five-Year Plan for Energy Development

Development Target Category	2025 Target	Cumulative Increase/(Decrease)
Comprehensive Energy Production Capacity (million tce)	100	8
Power Installed Capacity (billion kW)	2.6	0.9
Flexible Regulation Power Source Share (%)	12.5	0.2 percentage points
Non-fossil Energy Consumption Share (%)	29	2 percentage points
Electricity Share of Final Energy Consumption (%)	40	2 percentage points

These targets reflect Guangdong's commitment to optimizing its energy structure and promoting a clean energy transition.

4. Challenges in The Implementation of Guangdong's EES Strategy

4.1. Need for Improvement in EES Potential Forecasting Technology

Current methods for forecasting EES potential in Guangdong lack scientific rigor and accuracy. This deficiency hinders data-driven project planning, increases investment risks, and prevents optimal resource allocation, thereby affecting the long-term sustainability of EES initiatives.

4.2. Requirement for Enhanced Policy Support

While EES policies exist, their coverage is limited and lacks comprehensive support across all sectors. Subsidies are often insufficient to cover the entire project lifecycle, from investment to operation. High upfront costs for users and additional expenses for grid capacity upgrades remain significant barriers. Furthermore, electricity pricing policies, such as time-of-use rates and cross-subsidies for EES, have not yet achieved breakthroughs, with high commercial and industrial tariffs impeding adoption.

4.3. Need for Advancement in EES Technology

Guangdong lags behind developed regions in EES technology research and application. A lack of uniform standards for EES products leads to inconsistent quality, affecting user confidence. Many existing technologies suffer from performance issues related to energy efficiency, stability, and intelligence, increasing operational costs. The slow pace of innovation and a shortage of professional talent further constrain the industry's development.

5. Strategies for Optimizing The EES Strategy and Future Development Models

5.1. Optimizing Energy Structure With Electricity as The Core and Developing Distributed Photovoltaic Microgrids

Guangdong should build an energy system centered on electricity by conducting in-depth research on energy consumption across all sectors to identify conservation potential. A key strategy is to vigorously develop distributed energy resources, particularly solar PV microgrids, leveraging the region's abundant sunlight. As of February 2024, Guangdong's distributed PV capacity reached 16.95 million kW. To address grid absorption challenges, power grid companies must enhance technical R&D, formulate reasonable grid connection plans, and collaborate with the government to secure policy support and financial incentives.

5.2. Improving Supporting Policies and Accelerating Smart Grid Construction

Guangdong should continue to lead in distribution network upgrades by promoting a "clean energy + energy storage" model to enhance system reliability. This involves simplifying approval processes for EES projects, providing financial support for grid infrastructure, and promoting efficient electrical equipment in industrial and residential sectors [6]. The construction of a smart grid is paramount. A smart grid integrates advanced sensing, communication, and control technologies to create a reliable, secure, and efficient power network. The Guangdong Power Grid Company must increase investment in smart grid technologies, focusing on R&D and pilot projects to build a unified and powerful smart grid system.

5.3. Promoting Technological Advancement in EES and Standardizing Distribution Network Governance

To accelerate technological progress, Guangdong should formulate EES implementation strategies that align with national plans, encourage private capital participation, and establish benchmark projects. The government must play a leading role by setting stricter emissions standards for vehicles and offering greater incentives for EVs [7]. Differentiated electricity pricing policies, such as seasonal and tiered rates, should be implemented to improve the economic viability of EES [8]. Investment in R&D must be increased to enhance equipment performance and intelligence. Furthermore, standardizing the governance of the distribution network is crucial for improving power supply reliability and customer satisfaction, which forms the foundation for a successful EES rollout [9-11].

6. Conclusions

This paper proposes systematic optimization strategies and future development models. The core innovation lies not only in summarizing Guangdong's existing achievements in EES (such as the significant growth in total power generation and consumption, and the rapid expansion of renewable energy generation) but also in presenting three key strategic initiatives: Firstly, optimizing the energy structure with electricity as the core and vigorously developing distributed photovoltaic microgrids. This approach can fully leverage Guangdong's solar resources while enhancing the resilience and autonomy of the energy system. Secondly, focusing on improving supporting policies and accelerating smart grid construction. By simplifying approval processes, providing financial incentives, building a "clean energy + energy storage" model, and investing in smart grid technologies, this aims to lay a solid infrastructural and institutional foundation for the in-depth development of EES. Thirdly, comprehensively promoting technological advancements in EES and standardizing distribution network governance. This involves encouraging technological innovation, attracting social capital, establishing benchmark projects, and incentivizing broader EES adoption through differentiated electricity pricing policies and stringent emission standards.

Looking towards future development directions, it is imperative to further deepen power market reforms and establish more flexible and incentive-driven electricity pricing mechanisms. Increased investment should be directed towards cutting-edge EES technologies (such as high-efficiency energy storage, intelligent charging management, and deep industrial electrification applications) and exploring their large-scale deployment across various scenarios. Furthermore, strengthening regional cooperation and knowledge exchange is essential for building a coordinated national EES development framework. Through continuous innovation and optimization, the in-depth implementation of Guangdong's EES strategy will undoubtedly contribute more significantly to building a clean, low-carbon, safe, and efficient modern energy system for China and the world, propelling sustainable economic and social development.

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