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OPTIMIZING POWER SECTOR TRANSITION PATHWAYS IN RENEWABLE ENERGY-SCARCE REGIONS: AN OPERATIONAL RESEARCH APPROACH TO HUNAN PROVINCE UNDER CARBON PEAK GOALS

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Research Paper

Abstract: *This research investigates the electricity transformation pathways in Hunan province, China, which focuses on the issues of limited renewable energy resources and the carbon peak target. An analysis was performed on the impacts between 2022 and 2035 by applying the Low Emission Analysis Platform (LEAP) model, which developed three scenarios (BAS, EPS, and APS). This analysis was intended for gaining insights into analyse electricity demand trends, power generation structure adjustments, emission reduction potential, and policy frameworks from 2022 to 2035. The findings reveal that under the APS scenario, the share of coal-fired power would decrease by about 20%, translating to an estimated reduction of 50 million tons of CO2 emissions. The study highlights that through strategies such as industrial restructuring, widespread deployment of energy storage technologies, and the application of smart grid systems could help Hunan achieve its carbon peak target 3 to 5 years earlier compared to the BAS scenario. Key policy recommendations include: a) accelerating the transition from coal-fired power; b) supporting the moderate development of natural gas power; c) promoting energy storage technologies and distributed energy systems and d) enhancing carbon market mechanisms. These strategies aim to optimize the electricity generation mix, strengthen renewable energy integration, and improve system flexibility. In general, this interdisciplinary study offers valuable insights into operational research, technological innovation, and sustainable energy transitions. These efforts might make meaningful contributions to the practical implementation of carbon reduction goals in renewable energy-scarce regions.*

Keywords: *Renewable Energy, Power System Optimize, Scenario Analyse, Low emission analysis platform, Carbon Reduction*

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1. Introduction

The transition to green energy has become a globally recognized strategy for combatting climate change. This recognition was solidified in 2015 when 194 countries and the European Union signed the Paris Agreement. Specifically, many nations have since set clear goals to reduce emissions and achieve carbon neutrality. Importantly, carbon peaking goals have become an increasingly critical focus for several major economies (Tian et al., 2023). China, as the world's largest carbon emitter, pledged at the 75th United Nations General Assembly to reach carbon peaking by 2030 (Chai, 2022). In this country, power sector accounts for a significant share of China's carbon emissions, with 4.624 billion tons recorded in 2020-representing 45.1% of the country's total emissions of 10.252 billion tons (Zhang et al., 2024). Therefore, the green transformation of this sector is central to meeting China's carbon peaking target.

To achieve the carbon peaking goal, China has prioritized the development of renewable energy. In December 2020, the government announced plans to achieve over 1.2 billion KW of installed wind and solar power capacity by 2030, with non-fossil fuels accounting for about 25% of total energy consumption (Zhan et al., 2024). Nonetheless, Hunan province is located in inland south-central China, and this location brings it geographical limitations, which means that accessing to renewable energy resources is not that easy (Gao & Pan, 2022). Given these constraints, Hunan province's successful low-carbon transition is of national importance. Exploring feasible strategies to integrate renewable energy into its power system would not only guide regional energy policy but could also offer replicable solutions for other resource-constrained regions.

Although the LEAP model has been extensively used for energy and environmental forecasting and for designing sustainable energy pathways, several limitations remain in existing studies. First and foremost, most research has primarily focused on developed cities with well-established energy balances, while insights into how resource-constrained regions can achieve carbon peaking under carbon emission limitations are still scarce. Second, there exists a lack of systematic, integrated optimization research that integrates demand-side reforms, energy storage solutions, and renewable energy strategies into a cohesive framework.

This study addresses these gaps by exploring practical green and low-carbon energy transition pathways within the resource-constrained context of Hunan province. By establishing carbon peaking constraints, this research systematically analyses power demand and incorporates an energy storage model. On the other hand, it attempts to identify optimal low-carbon strategies and technological pathways. All these efforts seek to meet the carbon peaking timeline. The findings can serve as a reference for energy transitions in other resource-limited regions. The primary objective of this study is to design real-time carbon reduction policies while maintaining stable electricity supply, ensuring the feasibility of achieving the carbon peaking target in Hunan's power sector. Three scenarios were developed: the Baseline Policy Scenario (BAS), the Enhanced Policy Scenario (EPS), and the Accelerated Peaking Scenario (APS). With these scenarios, the LEAP-Hunan power optimization model was established to quantitatively assess variables such as power demand, generation structure, installed capacity, and carbon emissions under different constraints. This research holds theoretical and policy significance for resource-constrained provinces and developing nations, aiding scholars and policymakers in understanding energy conservation, emissions reduction, and the carbon peaking transition. Its key contributions include:

(1) Proposing and outlining alternative pathways for low-carbon transitions in regions reliant on coal and with limited renewable energy resources.
(2) Creating a multidimensional optimisation model that incorporates demand-side reform, energy storage, and renewable energy expansion to provide low-carbon solutions. This model provides actionable advice for policy implementation issues and assures a reliable low-carbon energy transition.

2. Literature Review

The majority of the literature on low-carbon transition pathways in China's power sector focuses on economically developed regions with abundant renewable energy resources, which leaves inland areas with limited resources relatively understudied (Froemelt et al., 2021; Hu et al., 2022; Wang et al., 2023). In terms of research methodologies, medium- and long-term energy and carbon emission prediction models are generally divided into top-down and bottom-up approaches. Top-down models predominantly rely on economic frameworks to analyse energy prices and economic elasticity (Unnewehr et al., 2022).

Bottom-up models, such as TIMES and MARKAL, are technical in detail and are useful for analysing specific technologies and optimizing long-term energy systems (Du Hanbei et al., 2022; Fragkos et al., 2023; Shi et al., 2023) However, conventional models are often resource-intensive and rigid in terms of their optimization frameworks, which restrict their applicability in areas like Hunan Province, which are relatively resource-constrained. This study addresses these issues by using the flexible Low Emissions Analysis Platform (LEAP) model to forecast Hunan's energy trends. LEAP simulates energy, economic, and environmental policy scenarios, supporting energy policy analysis and climate change mitigation (Hu et al., 2022).

LEAP has been widely used to explore energy and environmental issues at national and regional levels. For instance, it has been used to predict energy trends in China (Huang et al., 2023), Thailand (Tippichai et al., 2023), and Pakistan (Raza et al., 2023). Sahabuddin and Khan (2023) analysed the power generation scenarios of Bangladesh, while (Cai et al., 2023) simulated electricity demand in Beijing. Other studies involved renewable energy planning (Sahabuddin & Khan, 2023; Sisma et al., 2024), optimization of energy storage (Cai et al., 2023; Ren et al., 2024), and carbon emission forecasting (Gong et al., 2024). These results indicate the capabilities of LEAP in formulating emission reduction plans, thus providing scientific basis for energy transitions and carbon reduction targets.

3. Methodology

3.1 Regional and Policy Analysis

Hunan Province has experienced steady economic growth, with electricity consumption increasing at an average annual rate of 5.9% during the 13th Five-Year

Plan (2015–2020), aligning with a GDP growth rate of 7% (HNSY, 2015–2022). However, the province remains heavily dependent on coal-based power, with 2022 energy generation comprising thermal power (61.39%), hydro-power (27.28%), wind power (9.8%), and solar power (1.54%) (Development and Reform Commission of Hunan Province, 2022). This reliance on thermal power has driven higher fossil fuel consumption, exacerbating carbon emissions and air pollution. During the 13th Five-Year Plan period (2015–2020), the average annual growth rate of carbon emissions from the energy sector in Hunan stood at approximately 1.53%.

Hunan province, located in south-central China, is an inland province with limited energy resources (Zhou et al., 2022). Due to its geographical conditions, Hunan faces a scarcity of renewable energy resources. The province's annual average utilization hours for photovoltaic power generation are about 900 hours, classifying it as a Category III solar energy region (by national standards) with relatively low solar potential. Similarly, wind energy resources are categorized as Category IV, with an average wind speed of approximately 5–6 m/s at a height of 70 meters. The annual average utilization hours for wind power generation are approximately 2,100, a figure that reflects limited wind energy potential (Tian et al., 2023). While the province is rich in water resources, hydro-power development has largely reached its limit, making further development challenging and costly (Wang et al., 2021). Additionally, more than 80% of the province's total installed hydro-power capacity comes from non-regulating small- and medium-sized run-of-river power plants. Even worse, fewer than 10 hydro-power stations offer significant regulation capacity. Although Hunan has potential resources for nuclear power, it is unlikely to become operational in the near future.

To accelerate industrial transformation and achieve energy conservation and emission reduction, the Hunan provincial government has implemented a series of strategic measures. These initiatives include promoting low-carbon development, reducing coal consumption, advancing pumped storage, and accelerating the development of clean energy. The application of energy storage technologies has also been suggested. By expanding solar, wind, biomass energy, and storage projects, Hunan aims to permanently increase the share of non-fossil fuels in its energy consumption structure, in an effort to optimize the efficiency of its energy system. The Hunan Province 13th Five-Year Plan Central Compilation & Translation Press (2016) and 14th Five-Year Plan for Renewable Energy Development (NEEC, 2022), clearly outline the overarching principles, frameworks, and mandatory targets. These policy documents not only guide the province's energy development but also lay the foundation for constructing a new low-carbon energy system. Based on these strategies, this study designs multiple low-carbon transition scenarios for the power sector, while exploring pathways to achieve carbon peaking. This research finding provides a scientific basis for Hunan's energy transition efforts.

3.2 Scenario Development

Based on factors such as provincial energy activity levels, resource and environmental conditions, electricity consumption, installed capacity structure, and carbon emission constraints, three main scenarios were developed: the baseline scenario, the enhanced policy scenario, and the accelerated peak scenario. The strategies for each scenario are summarized in Table 1. All scenarios use 2022 as the base year. The year of 2035 is set as the target year. The period from 2022 to 2035 is divided into five-year intervals to align with the national five-year planning cycles.

(1) Baseline Scenario: This scenario considers only the basic requirements of China's dual carbon goals for Hunan's power sector development. From 2025 to 2030, the development model largely follows the trajectory outlined in the 14th Five-Year Plan. Under this scenario, the share of renewable energy increases moderately, but at a slow pace, while total electricity consumption maintains stable growth.

(2) Enhanced Policy Scenario: This scenario further increases the proportion of renewable energy installations while optimizing the electricity consumption structure. It takes into account Hunan's socio-economic development status and environmental needs. Meanwhile, it emphasizes changes in economic development and consumption patterns to achieve low emissions. This scenario represents a natural optimization pathway for the province's development.

(3) Accelerated Peak Scenario: This scenario attaches great importance to carbon peaking constraints are given priority, with green and low-carbon development placed at the forefront. The optimization of the power generation mix progresses more rapidly. This process is supported by active development of energy storage technologies. Economic transformation is also witnessing progress, which triggers an increase in the proportion of green electricity consumption sees a significant rise.

Table 1: Key Strategies under Three Scenarios

Scenarios	Key Scenario Descriptions
Baseline Scenario (BAS)	(1) The future GDP growth rate, population, and industrial structure parameters are set based on historical trends. (2) The industrial structure is assumed to follow historical development trends. (3) No carbon emission targets are set. (4) Renewable energy installation targets are based on the 14th Five-Year Plan's short-term policies and relevant literature. (5) No additional energy storage technologies are applied.
Enhanced Policy Scenario (EPS)	(1) GDP growth rate, population, and industrial structure are further optimized based on medium- and long-term policies and literature. (2) The pace of industrial structure transformation is accelerated, with an increased proportion of the third industry. (3) No carbon emission targets are set. (4) Renewable energy installation targets are based on medium- and long-term policies and literature, with the proportion of renewable energy installations increased to 70%. (5) Pump storage energy storage is increased.
Accelerated Peak Scenario (APS)	(1) GDP growth rate, population, and industrial structure are further optimized based on medium- and long-term policies and EPS. (2) The proportion of the third industry increased based on EPS. (3) Achieve the carbon peaking target before 2030. (4) The proportion of renewable energy installations increased to 75% by 2035. (5) Increase the deployment of pumped storage, electrochemical energy storage, cascade hydropower station energy storage, flywheel energy storage, compressed air energy storage, and thermal energy storage technologies are being applied on a large scale (HNDI&T, 2024).

3.3 LEAP-Hunan Model

3.3.1 Key Assumptions and Data

(1) GDP and Growth Rate: The GDP of Hunan Province increased from 2.9 trillion yuan in 2015 to 4.15 trillion yuan in 2019, achieving an average annual growth rate of over 7% during the 13th Five-Year Plan period (2015-2020) (Central Compilation & Translation Press, 2016). According to the Hunan Provincial Government Work Report (People's Government of Hunan Province, 2024), the province set a target of maintaining an average annual GDP growth rate of over 6% during the 14th Five-Year Plan period (2020-2025). Under the BAS scenario, the GDP growth rate for 2023-2035 is uniformly set at 6.5%, aligning with the growth target outlined in the 14th Five-Year Plan and assuming stable economic growth over the period. However, considering China's ongoing transition from "high-speed growth" to "high-quality development," the GDP growth rate under the EPS scenario is adjusted to reflect Hunan Province's ongoing industrial upgrading and structural adjustments. Specifically, the growth rates are assumed to be 6.5% for 2023-2030 and 6.0% for 2030-2035. This adjustment is based on growth structure projections provided by the National Bureau of Statistics and the Hunan Provincial Development and Reform Commission (Central Compilation & Translation Press, 2016). Under the APS scenario, the GDP growth rates are further adjusted to prioritize green, low-carbon development and accelerated industrial transformation. The rates are set at 6.5% for 2023-2030 and 5.5% for 2030-2035. These adjustments account for the potential short-term impacts of resource reallocation and industrial restructuring on economic growth while ensuring long-term stability. The assumptions are aligned with the goals and specific implementation pathways outlined in Hunan Province's energy and industrial development plans, reflecting the coordinated advancement of low-carbon development and sustainable economic growth.

(2) Population and Growth Rate: From 1995 to 2020, the population of Hunan increased from 63.92 million to 66.453 million, an increase of 2.533 million, with a growth rate of 3.96%. This growth is attributed to the rapid economic development in Hunan. Since 2023, with a global decrease in population and a gradual slowdown in economic growth, Hunan Province has shown a trend of negative population growth. To alleviate the population crisis, Hunan Province has implemented a three-child policy (HNHC, 2024), accompanied by a series of supportive measures, including fertility subsidies, quality reproductive health services, and inclusive childcare services. Considering these comprehensive factors, the population of Hunan Province is likely to maintain a relatively low growth rate in the future. Based on historical population data and using the exponential smoothing method Rathnayaka and Seneviratna (2024) , population projections for Hunan Province from 2023 to 2035 will be made.

(3) Electricity Demand Forecasting: Historical electricity data was obtained from the China Electric Power Statistical Yearbook (CEC, 2023). By combining the historical consumption data from 2015 to 2022, the total electricity consumption for the entire society in Hunan Province from 2023 to 2035 was estimated using the elasticity coefficient method (Csereklyei, 2020) , regression analysis (Tawari., 2024), and the energy consumption per unit of output method (Zhong et al., 2021). Subsequently, a weighted average method was applied to adjust the growth rates, with weight ratios set at 0.4:0.2:0.4. The calculations indicate that the total electricity consumption in

Hunan Province is expected to maintain a medium to high growth rate, reaching approximately 335 billion kilowatt-hours by 2030 and around 400 billion kilowatt-hours by 2035.

Additionally, a linear regression analysis was employed to fit the average growth rates of electricity consumption across various industries. Considering that Hunan Province will focus on transitioning towards the tertiary industry in its future economic development (SZISD, 2022), by 2035, the proportion of consumption in the tertiary sector in the EPS and APS scenarios is expected to increase from 19.8% in the BAS scenario to 35%.

(4) Forecast of Power Generation Installed Capacity Structure: Under the three scenarios, the energy installation structure is progressively optimized each year, with a continuous increase in the proportion of renewable energy. The share of photovoltaic and wind power installations grows rapidly, while the proportion of coal-fired power is moderately restricted, and the scale of electrochemical energy storage steadily expands. The baseline data for renewable energy in 2022 is sourced from the "Hunan Provincial Energy Development Report."

In the BAS scenario, the growth of renewable energy is based on the historical development trend of Hunan Province from 2015 to 2022. Under this scenario, the power sector installation structure in Hunan undergoes some degree of optimization but essentially continues the development model of the 13th Five-Year Plan. A comparative analysis with the growth patterns of Hubei and Jiangxi Provinces reveals that Hunan's growth rate is slightly lower than Jiangxi's but higher than Hubei's, aligning with the characteristics of regional energy development. According to the targets outlined in the "Hunan Province 14th Five-Year Plan for Renewable Energy Development" (2022) and the "Hunan Province Carbon Peak Implementation Plan," by 2025, the installed capacity of renewable energy in Hunan Province is expected to reach approximately 44.5 GW, including 12 GW of wind power and 13 GW of photovoltaic power. By 2030, the installed capacity of wind and photovoltaic power is planned to reach 40 GW, with the total installed capacity of non-fossil energy exceeding 73.9 GW.

In terms of new energy storage development, the "Hunan Province New Power System Development Plan Outline" proposes that the installed capacity of new energy storage should reach 3 GW by 2025 and 4.5 GW by 2030. These targets provide a clear basis for the EPS scenario, which considers the medium-term planning objectives of the 14th Five-Year Plan. The APS scenario, however, represents a projection of the long-term energy development pathway in Hunan Province, taking into account the goals of the 15th Five-Year Plan, trends in technological advancement, and potential adjustments in energy structure. This scenario particularly emphasizes the demonstration and application of new technological routes, such as electrochemical energy storage, compressed air energy storage, flywheel energy storage, thermal (cold) energy storage, and hydrogen (ammonia) energy storage. The advancement of these technologies is expected to drive the upgrading of the energy storage industry. Key data for the three scenarios are presented in Table 2.

(5) Other Key Data: Detailed data on the electricity load curve for Hunan Province is sourced from the China Electricity Council (CEC, 2023). The emission factors for CO2 generated by the consumption of various energy types in the electricity sector are

primarily derived from Dong et al. (2023) and the Asia and China-specific data in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report Scenario Database (Lee et al., 2024). Additionally, localized factors specific to Hunan Province, such as the regional energy mix, grid efficiency, and industrial energy usage patterns, have been incorporated to ensure the model reflects the unique characteristics of the province. This detailed approach enhances the technical credibility and applicability of the LEAP model in capturing region-specific energy and emission dynamics.

Table 2: Key Data for the Three Scenarios

Module	Context	Year	Scenario		
			BAS	EPS	APS
Key Assumption	GDP Growth Rate	2022-2025	6.5%	Refer to BAS	Refer to BAS
		2025-2030	6.50%	6.00%	5.50%
		2030-2035	6.50%	6.00%	5.50%
Electricity Demand	The Third Industrial Proportion	2022-2025	19.8%	Refer to BAS	Refer to BAS
		2025-2030	22%	28%	28%
		2030-2035	25%	35%	35%
Renewable Target	Solar Capacity (MW	2022-2025	Increase to 13,000NMW	Refer to BAS	Refer to BAS
		2025-2030	Increase by 400 MW Annually.	Increase by 1,400 MW Annually.	Increase by 2,400 MW Annually.
		2030-2035	Increase by 2,000 MW Annually.	Increase by 2,400 MW Annually.	Increase by 3,200 MW Annually
	Wind Capacity (MW)	2022-2025	Increase to 12,000MW	Refer to BAS	Refer to BAS
		2025-2030	Increase by 250 MW Annually.	Increase by 1,200 MW Annually.	Increase by 2,000 MW Annually.
		2030-2035	Increase by 1,000 MW Annually.	Increase by 1,000 MW Annually.	Increase by 1,000 MW Annually.
Storage Target	Hydro Capacity (MW)	2035	Increase to 17,000 MW	Refer to BAS	Refer to BAS
	Pump Storage (MW)	2022-2025	Increase to 1,200 MW	Refer to BAS	Refer to BAS
		2025-2030	1,200 MW	Increase by 600 MW Annually.	Increase by 900 MW Annually
		2030-2035	1,200 MW	Increase by 600 MW Annually.	Increase by 900 MW Annually
	Storage (MW)	2022-2025	Increase to 840 MW	Refer to BAS	Refer to BAS
		2025-2030	Increase by 250 MW Annually.	Increase by 250 MW Annually.	Increase by 500 MW Annually
		2030-2035	Increase by 1,000 MW annually.	Increase by 250 MW Annually.	Increase by 500 MW Annually
Environmental Target	Carbon Emission	2030	No Limit	Refer to BAS	Reach Carbon Peak

3.3.2 Model Framework

The LEAP-Hunan model framework is designed to simulate and analyses the energy supply-demand balance, carbon emission pathways, and policy impacts of Hunan Province's power system under different scenarios. It establishes a comprehensive analytical system integrating demand, supply, energy storage, and environmental impacts. The model consists of modules including fundamental parameters, power demand analysis, power supply analysis, conversion and dispatch, and environmental impacts. The structure and main components of the model are illustrated in Figure 1.

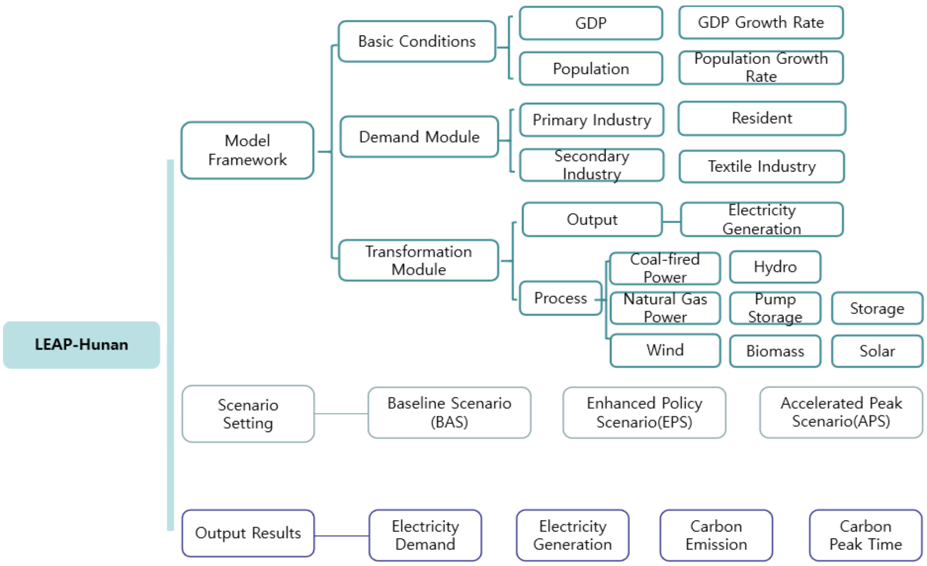


Figure 1: LEAP-Hunan Model

4. Results and Discussion

4.1 Energy Demand

The energy demand projection data is shown in Figure 2, indicating a continuous growth trend for Hunan Province between 2022 and 2035. Under the BAS Scenario, energy demand would increase from approximately 223.5 TWh in 2022 to about 400 TWh in 2035, representing a growth rate of 78.9%. In the EPS and the APS Scenario, the overall growth rate of demand would slow but still remain upward, reaching 387.2 TWh and 375 TWh in 2035, respectively, which are reductions of about 3.2% and 6.3% compared to the BAS. From a temporal perspective, energy demand would accelerate between 2025 and 2030, but EPS and APS scenarios would begin to demonstrate control effects, reducing demand by approximately 5.3 TWh and 10.4 TWh, respectively. From 2030 to 2035, the impact of policy interventions would become more pronounced, particularly under the APS, where the growth rate of energy demand would decelerate significantly. Based on current projections, even in the most proactive scenario, energy demand in 2035 would still grow substantially compared to 2022. Strengthening the implementation of energy-saving technologies and policies would be essential to achieve sustainable control of energy demand.

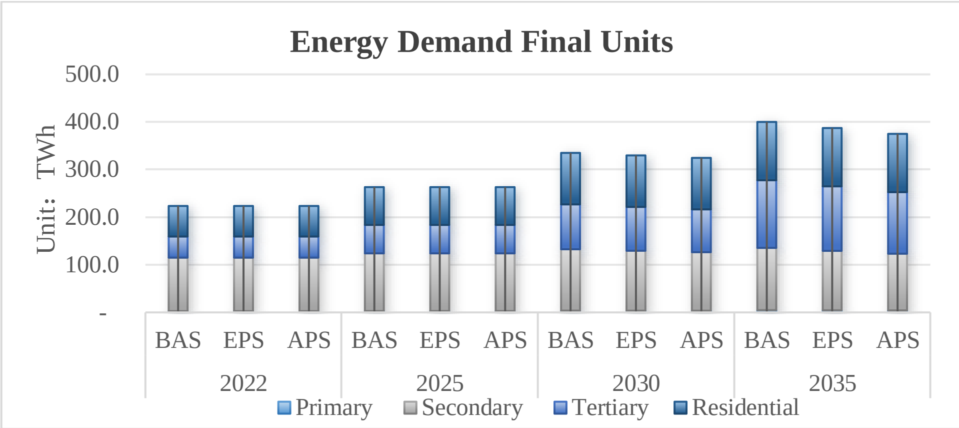


Figure 2: Electricity Demand Projections under Different Scenarios (2022–2035)

From the perspective of energy demand by sector, significant differences in growth patterns among various sectors can be observed between 2022 and 2035, as shown in Figure 3.

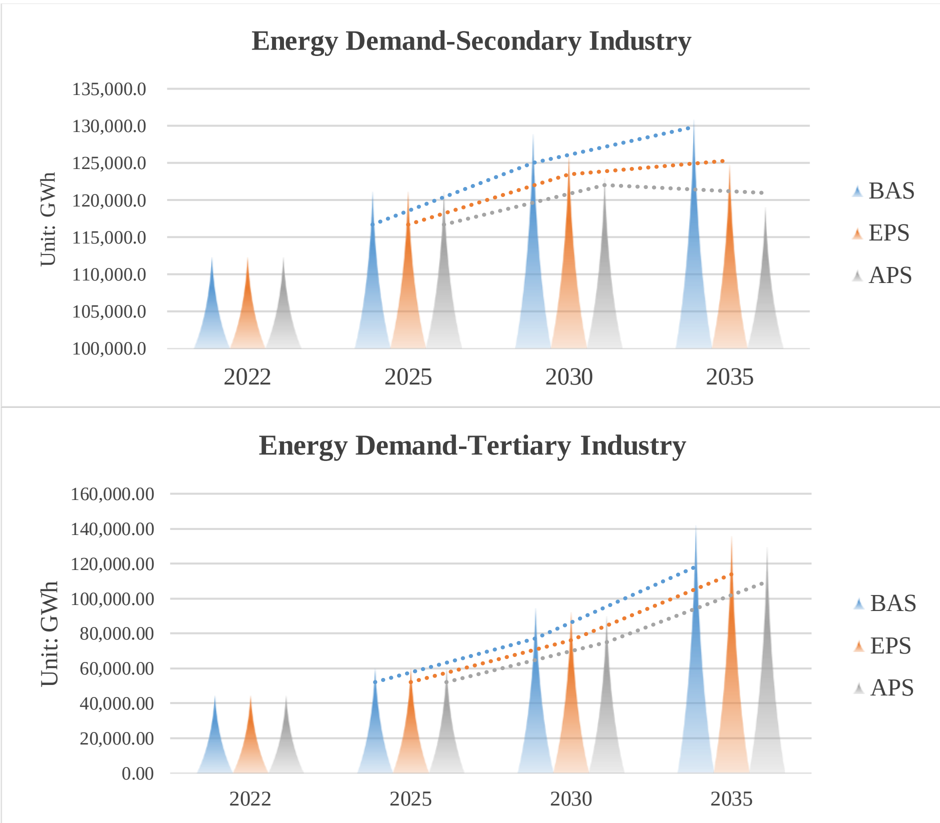


Figure 3: Trends in Electricity Demand for the Secondary and Tertiary Sectors under Different Scenarios

First, the secondary sector (industrial energy use), being the primary source of energy demand, accounted for approximately 50% of total demand in 2022. Under the baseline scenario (BAS), its demand would increase from 112,300 GWh in 2022 to 130,800 GWh in 2035, representing a growth rate of 16.5%. Enhanced Policy Scenario (EPS) and Accelerated Policy Scenario (APS) are projected to significantly reduce industrial energy demand after 2030, with reductions of approximately 4.6% and 9.0%, respectively, by 2035, indicating substantial energy-saving potential in the industrial sector. For example, implementing stricter energy efficiency standards and retrofitting programs in the industrial sector could significantly lower energy consumption.

The tertiary sector (service energy use) is projected to grow most significantly, from 44,400 GWh in 2022 to 142,100 GWh in 2035 under the BAS scenario, marking a 220% increase. This rapid growth reflects economic restructuring and industrial upgrading. Policy interventions would yield notable effects, with service sector demand in 2035 reduced by approximately 4.6% under EPS and 9.0% under APS. Policies aimed at incentivizing the adoption of energy-efficient technologies in commercial buildings and encouraging the implementation of smart energy management systems could significantly improve energy conservation in this rapidly expanding sector.

Residential energy demand is projected to grow moderately, increasing from 64,100 GWh in 2022 to 122,400 GWh across all scenarios, reflecting a growth rate of 91%. Policy measures, such as subsidies for energy-efficient appliances and the promotion of household renewable energy systems (e.g., rooftop solar panels), can effectively moderate demand growth while reducing emissions in the residential sector. The data reveal significant differences in demand growth trends and policy impacts across sectors. Future efforts should prioritize the promotion of energy-saving technologies in the industrial and service sectors, alongside strengthening policy implementation to fully realize energy conservation and emission reduction potential.

4.2 Electricity Generation and Capacity Mix

By analysing the installed capacity and electricity generation data under the three scenarios (BAS, EPS, and APS), as shown in Figures 4 and 5, it can be observed that from 2022 to 2035, total electricity generation would increase with rising power demand. Electricity generation would grow from 223.5 TWh in 2022 to 400 TWh (BAS), 387.2 TWh (EPS), and 375 TWh (APS) by 2035. Although total electricity generation would be the lowest under the APS scenario, it would also have the lowest electricity demand among the scenarios, with a greater emphasis on energy efficiency and low-carbon transition.

In terms of installed capacity, the APS scenario would exhibit significantly higher total installed capacity compared to BAS and EPS, with the highest share of renewable energy, indicating greater energy production efficiency and carbon reduction potential. Under the BAS scenario, coal power would remain dominant, with an installed capacity of 35.7 GW in 2035, although its share would gradually decrease. Wind and solar power installations would grow modestly, reaching 18 GW and 25 GW, respectively. In the EPS scenario, renewable energy installations would increase substantially, with solar and wind power reaching 32 GW and 23 GW, and storage capacity reaching 3.3 GW. The APS scenario would demonstrate the most proactive low-carbon transition, with solar and wind power installations rising to 41 GW and 27 GW, respectively, and storage capacity reaching 7 GW, significantly surpassing the other scenarios.

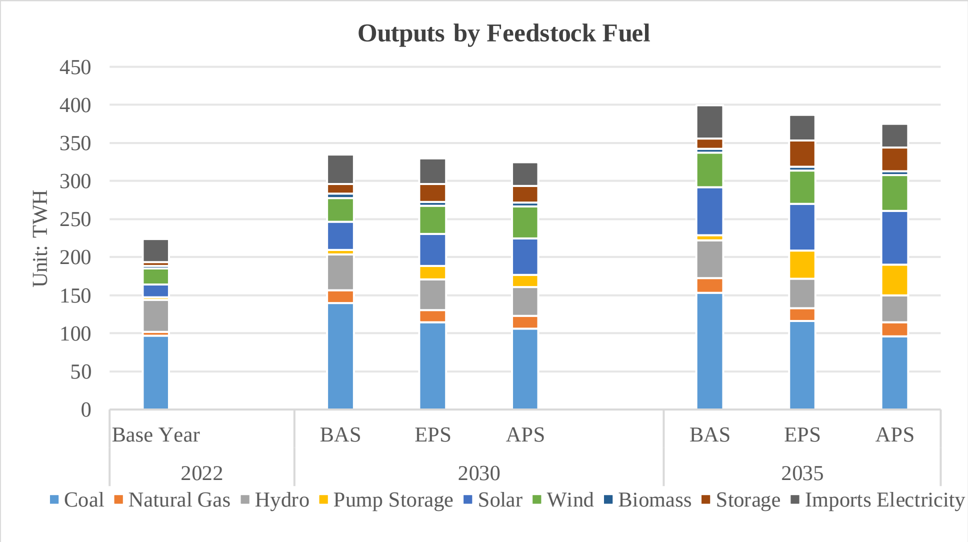


Figure 4: Power generation under three scenarios from 2022 to 2035

In terms of power generation structure, coal power would remain dominant in the BAS scenario, with electricity generation reaching 153.3 TWh by 2035. While its share would gradually decline, it would remain a core energy source. In contrast, coal power generation would decrease to 115.9 TWh in the EPS scenario and further to 95.9 TWh in the APS scenario, reflecting the restrictive effect of enhanced policy measures on coal power. Renewable energy would grow significantly, particularly solar and wind energy. By 2035, solar power generation would increase to 62.6 TWh, 61.5 TWh, and 71.2 TWh in the BAS, EPS, and APS scenarios, respectively, making it the fastest-growing energy source. Wind power generation would reach 45.1 TWh, 44.2 TWh, and 46.9 TWh across the scenarios, showing stable growth and positioning wind energy alongside solar power as leading renewable energy sources.

Energy storage, as a critical flexibility resource, shows significant growth in generation capacity in the APS (Automated Power System) scenario. By 2035, pumped storage generation capacity is expected to increase to 36.8 TWh and 40.4 TWh in the EPS and APS scenarios, respectively, far surpassing the 6.9 TWh in the BAS scenario. This highlights the importance of flexible resources in carbon reduction pathways.

In addition to pumped storage, other energy storage technologies, such as electrochemical storage, will also play a significant role in enhancing grid stability and decarbonization efforts. Results show that between 2022 and 2035, the electricity released by storage in the EPS and APS scenarios will increase from 12.5 TWh and 24 TWh to 34.6 TWh and 31.3 TWh, respectively. Energy storage technologies effectively balance the intermittency of renewable energy sources, such as wind and solar power, reducing reliance on coal and natural gas generation, thus lowering carbon emissions.

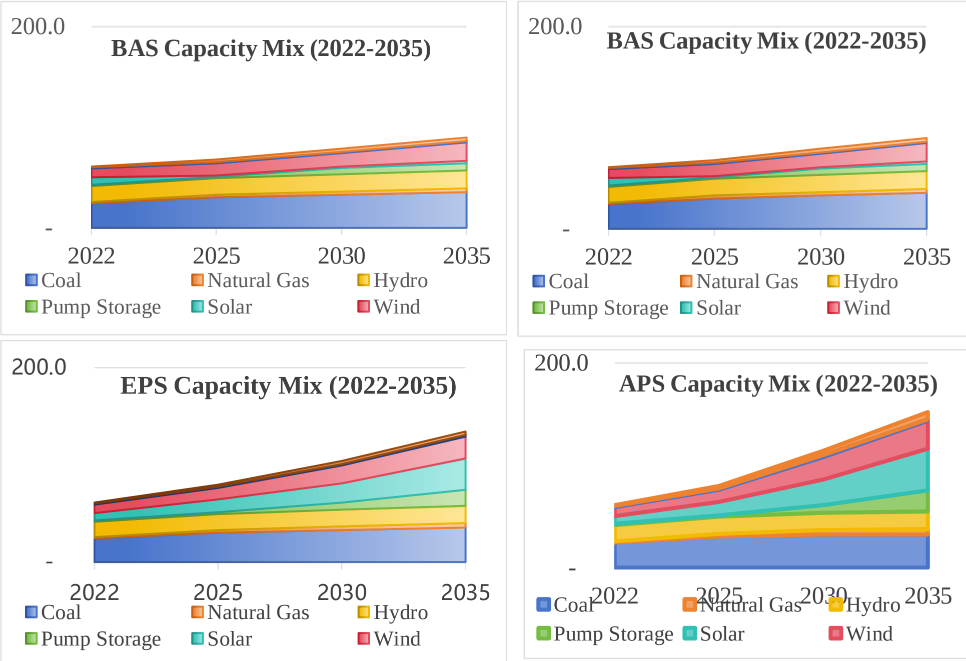
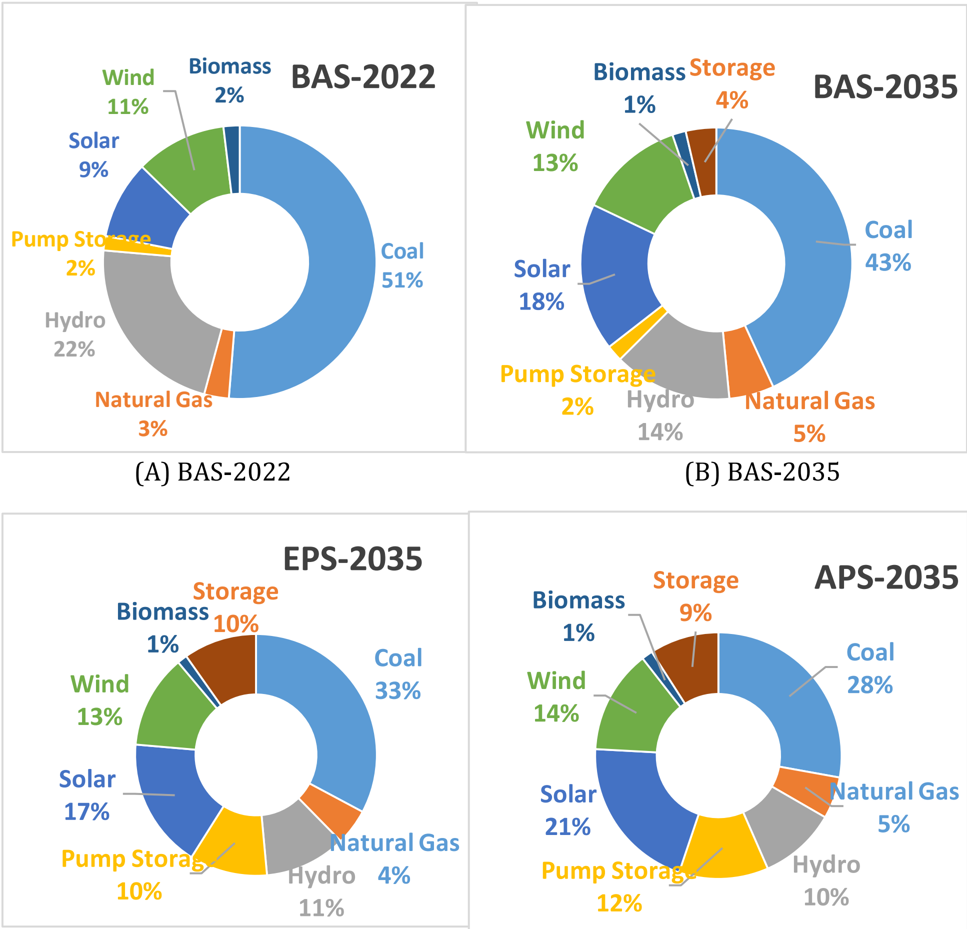


Figure 5: Installed capacity change under three scenarios from 2022 to 2035

By 2035, electrochemical storage capacity in the APS scenario is expected to reach 2.5 TW, providing key support for peak shaving and valley filling while enhancing the reliability of renewable energy integration. The deployment of diverse storage technologies, including compressed air storage, flywheel storage, and thermal storage, will further improve the grid's adaptability to renewable energy fluctuations. For Hunan Province, imported electricity would remain vital in balancing energy supply and demand across all scenarios. In 2035, imported electricity would amount to 44.4 TWh, 34 TWh, and 30.8 TWh under the BAS, EPS, and APS scenarios, respectively. This would reflect a decreasing reliance on imported electricity as the share of renewable energy increases, enabling local power generation to meet a larger portion of demand.

Overall, the APS scenario would demonstrate the most aggressive low-carbon transition. With a higher share of non-fossil energy generation, larger-scale energy storage deployment, and reduced reliance on imported electricity, the APS scenario would offer enhanced carbon reduction capabilities and energy efficiency, providing a clear pathway toward achieving carbon peaking and neutrality goals.

By analysing the data shown in Figure 6, it can be observed that the share of electricity generation by different energy sources would exhibit significant changes across the scenarios, reflecting the direction of energy structure adjustments and the potential for a low-carbon transition. In 2022, coal-fired power accounted for 50% of total electricity generation, serving as the dominant energy source. Under the BAS scenario, by 2035, the share of coal-fired power would decline to 43%, though it would still dominate. In the EPS and APS scenarios, the share of coal-fired power would decline further to 33% and 28%, respectively, indicating a significant reduction. In all scenarios, the share of natural gas power generation would remain at 5% by 2035, representing only a slight increase compared to 2022. This would suggest that natural gas would continue to serve primarily as a transitional energy source without a significant expansion. As renewable energy development and energy storage deployment would progress, coal-fired power would gradually cede its position to low-carbon energy sources while maintaining its role in system regulation and as backup power.



(A) BAS-2022 (B) BAS-2035

(c) EPS-2022 (d) APS-2035

Figure 6: Electricity Generation Share by Fuel Types

Additionally, the proportion of renewable energy generation would continue to rise. In 2022, solar power accounted for 9% of total electricity generation, and by 2035, it would reach 18% (BAS), 17% (EPS), and 21% (APS). Wind power would grow steadily from 10% in 2022 to 13% (BAS and EPS) and 14% (APS) by 2035. Hydropower, which accounted for 22% of total electricity generation in 2022, would decline to 14% (BAS), 11% (EPS), and 10% (APS) by 2035, indicating that its development potential would be nearing saturation, with limited room for future growth.

Meanwhile, the share of flexibility resources such as energy storage and pumped storage would grow significantly, particularly in the EPS and APS scenarios. In these scenarios, the share of energy storage would exceed 10%, while pumped storage would reach 12%, highlighting their important role in supporting the integration of high shares of renewable energy into the power grid. In the APS scenario, the total share of non-fossil fuels would reach 66%, a significant increase compared to 53% under the BAS scenario. This would demonstrate that policies and technological advancements would drive the adoption of higher shares of renewable energy and flexibility resources, thereby improving the overall low-carbon level of the energy system.

4.3 Fossil Fuel Consumption

From Table 3, it can be observed that the use of fossil fuels in electricity generation would show an increasing trend from 2022 to 2035, but the reduction effects would be significant under different scenarios (EPS and APS). According to the BAS scenario, fossil fuel consumption would grow from 8,782.90 kilotons of oil equivalent (KTOE) in 2022 to 14,821.70 KTOE by 2035, indicating that overall demand would continue to rise. Under the moderate reduction scenario (EPS), fossil fuel consumption would decrease by 2,535.1 KTOE (a reduction of 16.4%) by 2030 compared to the 2022 level of the BAS scenario, and by 4,436.1 KTOE (a reduction of 22.8%) by 2035. In the higher reduction scenario (APS), the reduction would be even greater, with fossil fuel consumption expected to decrease by 3,151.6 KTOE (a reduction of 21.3%) by 2030, and by 6,222.6 KTOE (a reduction of 33.4%) by 2035. These observations indicate that as reduction efforts strengthen, the use of fossil fuels would gradually decrease significantly. The APS scenario would have the highest reduction efforts, reflecting that technological advancements and policy interventions could substantially reduce reliance on fossil fuels, thereby promoting the electricity industry's transition toward greener and low-carbon development.

Table 3: Consumption of Fossil Fuels for Electricity Generation over the Period 2022– 2035

Year	BAS	Change from BAS Scenario (KTOE)	
		EPS	APS
2022	8,782.90	-	-
2030	13,470.00	-2,535.1 (-16.4%)	-3,151.6 (-21.3%)
2035	14,821.70	-4,436.1 (-22.8%)	-6,222.6 (-33.4%)

(1) Carbon Emissions: The total CO2 emissions and trends for the Hunan electricity sector under the three scenarios are shown in Figure 7. In the BAS and EPS Scenario, from the "14th Five-Year Plan"(2020-2025) to the early stages of the "15th Five-Year Plan"(2025-2030) coal-fired power would still be needed to supplement electricity demand, and CO2 emissions would not peak before 2030. Under the Baseline Scenario, CO2 emissions would continue to rise, with the peak expected after 2035 at 134.8 million tons. In the EPS Scenario, CO2 emissions would peak in 2033 at 103.4 million tons. The APS Scenario demonstrates a faster pace of carbon reduction. CO2 emissions would peak in 2030 at 94.6 million tons, with an average annual growth rate of about 3%. After reaching the peak, CO2 emissions would enter a plateau phase and begin to decline. By 2035, emissions are expected to fall to 86.8 million tons, which would be the lowest among the three scenarios.

It can be concluded that only under the APS scenario would be able to achieve carbon peaking by 2030 for Hunan's power system compare to EPS and BAS scenario. Therefore, this study recommends the Accelerated Peak Scenario (APS) as the prioritized path for low-carbon development in the Hunan electricity sector.

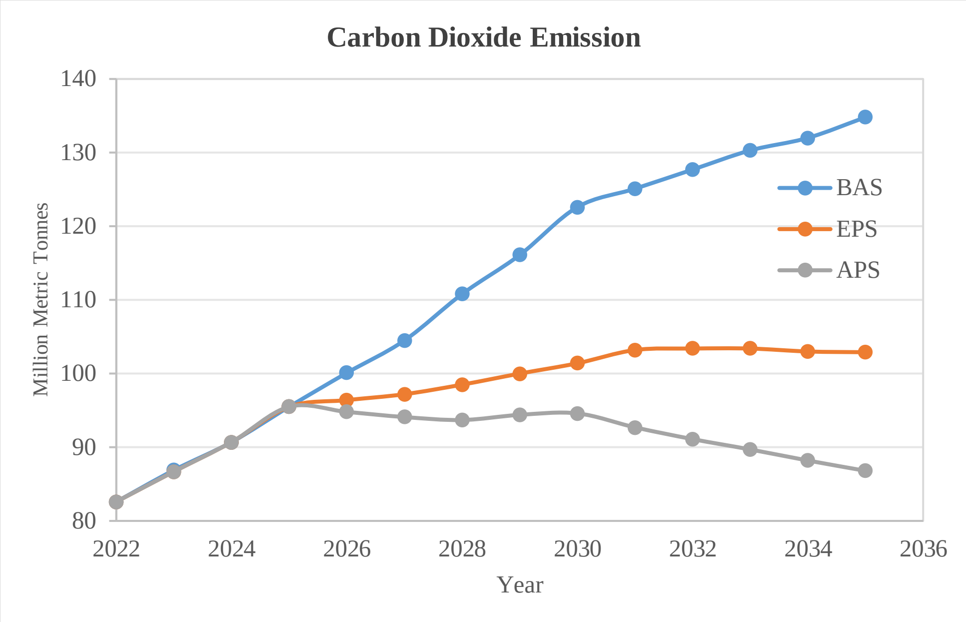


Figure 7: CO2 Emission Results under three Scenarios

Table 4 compares the CO2 emissions under different scenarios, in the EPS, it is expected that by 2030, CO2 emissions would be reduced by approximately 28 million tons compared to BAS and by 6.8 million tons compared to the APS. By 2035, the APS scenario would have CO2 emissions reduced by approximately 48 million tons compared to BAS and by 16.1 million tons compared to the EPS.

Table 4. CO2 Emissions from Electricity Generation over the Period 2022– 2035

Year	BAS	Change from BAS Scenario (Million Metric Tonnes)	
		EPS	APS
2022	82.60	-	-
2030	122.60	101.4 (-21.2%)	94.6 (-28%)
2035	134.80	102.9 (-31.9%)	86.8 (-48%)

(2) Carbon Emission Structure: An analysis of the carbon emission structure in the electricity sector of Hunan Province's peak carbon process is conducted by examining the sources of carbon emissions, as shown in Figure 8. This section focuses primarily on direct carbon emissions from the province's power generation sector. The main source of carbon emissions in Hunan's electricity industry is coal-fired power generation, followed by natural gas power generation. Reducing coal-related carbon emissions is the core strategy for achieving a low-carbon transition across all scenarios. In contrast, natural gas emissions remain relatively stable, indicating that its role is mainly as a backup power source with minimal contribution to carbon reduction strategies.

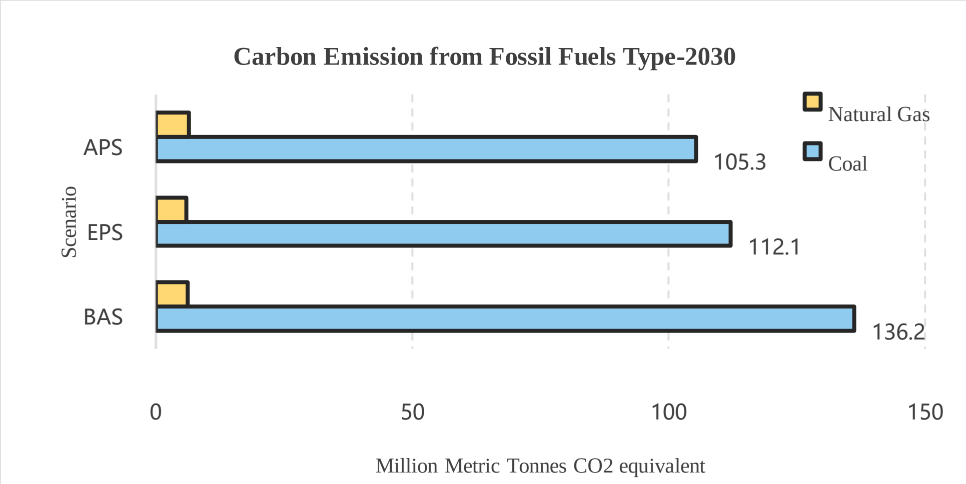


Figure 8: Carbon Emission Structure

4.4 Sensitivity Analysis

To evaluate the robustness of the research findings, this study conducted a sensitivity analysis on key parameters within the energy transition pathways of Hunan Province. The investigation investigated economic growth, renewable energy technological advancement, and coal and gas power carbon emission factors. These factors were adjusted to assess their effects on energy demand, renewable energy adoption, and carbon emissions in BAS, EPS, and APS scenarios. Adjusting GDP by ±2% for economic uncertainty showed that higher growth raised energy demand by 11.9% by 2035, while lower growth decreased it by 22%, impacting renewable energy shares. In the BAS scenario, stronger GDP growth increased fossil fuel use, while the APS scenario's robust policies stabilized energy mix despite variations. To account for technology developments, renewable energy efficiency advancement rates were 7% higher. Faster efficiency improvements led to a 4.5% increase in renewable energy generation by 2035, enabling earlier carbon peaking under the APS scenario. Technology delays slowed renewable energy uptake, boosting natural gas use. Additionally, cutting coal and gas power emission factors by 1% annually reduced CO_2 by 12.1%, highlighting cleaner coal technologies and operational efficiency. The sensitivity analysis emphasises timely technical advancements and consistent low-carbon transition plans. The APS scenario was more resilient to parameter variations, retaining carbon neutrality. These findings emphasise the necessity for adaptable energy solutions to manage uncertainty.

This study provides valuable insights into optimising Hunan Province's power industry under carbon emission constraints but has limitations. The LEAP-Hunan model relies heavily on accurate input data, with uncertainties in policy changes, technological progress, energy prices, and costs potentially affecting the findings. It also omits disruptions like extreme weather or global economic shifts that could impact energy dynamics. Additionally, while addressing demand-side reforms, renewable energy, and storage systems, the socio-economic effects of these transitions are not fully explored. Future research addressing these gaps could enhance the study's reliability and policy relevance.

5. Policy Implications

This section analyses the challenges and strategies in Hunan Province's green power transition. Although the focus is on Hunan, the findings are applicable to other regions in China and worldwide, especially in growing power systems with increasing demand. To speed up Hunan's carbon peaking, there is an urgent need to adopt an "Integrated Model of Demand-Side Reform, Energy Storage, and Renewable Energy". However, large-scale integration of renewables, distributed generation, and interactive devices into the grid raises complex issues. Hunan's renewable energy development changes its dynamic characteristic, and thus, brings high operational pressure to the power system. Fluctuations in wind and solar power affect the stability of grid frequency and voltage (Rakhmonov & Reymov, 2020). Such variations caused by extreme weather may be detrimental to the stability of the grid, which contradicts traditional stability analysis and control methods. Hence, Hunan needs to develop research and innovation in the areas of grid stability and emergency response.

Further, reliable electricity supply also creates new challenges. Variability of renewables makes scheduling and operation more complicated, particularly during winter and summer "dual-peak" periods when the demand usually exceeds supply. Although thermal and hydropower are there to stabilize supply, the large-scale integration of renewables has put strain on peak regulation, making it often necessary to curtail wind and solar supplies. Hunan needs to strengthen energy storage, utilize flexible power sources, and optimize grid scheduling to maintain supply reliability and stability.

Southeast Asian countries offer valuable lessons for Hunan Province. For example, the Philippines' National Renewable Energy Program (NREP) focuses on decentralized renewable energy systems, such as solar microgrids, to address the challenge of limited grid coverage in remote areas (Fulton et al., 2017). Similarly, Vietnam's National Green Growth Strategy provides targeted subsidies for wind and solar power development, which has significantly accelerated the deployment of renewable energy (Trinh, 2022). These experiences highlight the importance of regional cooperation and innovation in overcoming infrastructure challenges. Hunan Province could draw inspiration from these examples to optimize its energy mix. And Vietnam's targeted subsidy models could serve as a guide for designing financial incentives to promote energy storage technologies and distributed generation in Hunan.

To address these challenges, this study proposes the following policy recommendations:

(1) Accelerate the optimization and transformation of coal power through large-scale clean coal projects.

Hunan Province should accelerate the transformation of coal power, promote the construction of large-scale clean coal projects, strictly control the approval of new coal power projects to ensure the coal power installed capacity limit is not exceeded, and increase efforts to eliminate outdated coal power units while optimizing the generation and heating efficiency of existing coal power plants. First, conduct field investigations focused on pollutant emissions, coal consumption efficiency, and local heating needs to identify specific coal power units for phased decommissioning. Second, surplus coal power units in certain regions should be strategically decommissioned and stored as emergency backup power to address potential power shortages during summer heat waves and winter heating periods. Third, the combined upgrades for energy saving, carbon reduction, flexibility, and heating must be strictly enforced. These efforts will accelerate the modernization of coal power plants, with a focus on reducing coal consumption in power units using more than 300 grams of standard coal per kilowatt-hour. Fourth, competitive power generation policies should be developed to promote the elimination of inefficient coal plants. Fifth, a "generation rights trading" system should be adopted to encourage the replacement of smaller units with larger, more efficient ones. Lastly, energy-saving monitoring platforms should be leveraged to promote energy conservation and efficiency improvements in coal power enterprises.

(2) Develop natural gas power generation moderately to provide stable power supply and flexible peak-shaving capabilities.

As coal power remains stable and the rapid development of wind and solar energy continues, the key issue facing Hunan’s power system is no longer insufficient base-load capacity but rather the inability to ensure peak power supply due to the combined effects of load peaks and the volatility of renewable energy output. Natural gas power generation, with its fast start-up and flexible operation, can provide stable electricity supply while also meeting heating demands, serving as a transitional energy source to help Hunan achieve its "carbon peak" and "carbon neutrality" goals. Although Hunan's natural gas power generation capacity is currently small and lags behind major power provinces like Guangdong and Jiangsu, it is crucial to implement the natural gas power generation targets set in the 14th Five-Year Plan. Priority should be given to cities with high electricity demand, such as Changsha, Yueyang, and Zhuzhou city, to build a series of natural gas power plants, enhancing the flexibility and stability of the power system and optimizing the energy structure.

(3) Accelerate the research and demonstration of forward-looking electricity technologies.

Hunan Province has abundant hydropower resources, with hydropower accounting for a high proportion of the overall electricity supply. However, seasonal fluctuations can lead to imbalances between electricity supply and demand. Therefore, efforts should focus on promoting advanced energy storage technologies, both short-term and long-term, to improve hydropower's peak-shaving capabilities, mitigate seasonal fluctuations, and ensure supply reliability and stability. Drawing inspiration from the Philippines’ success with decentralized solar micro grids, Hunan Province should prioritize the development of distributed energy systems in remote areas. This approach can enhance energy accessibility and grid resilience, particularly in mountainous regions. Targeted subsidies, similar to Vietnam’s, should be designed to encourage investments in wind and solar power projects, as well as advanced energy storage technologies. Geothermal energy, as a clean and renewable energy source, holds significant development potential. Hunan should expedite research on geothermal technologies and promote their application in heating, industrial production, and electricity generation. Additionally, hydrogen energy technologies also offer promising prospects, especially for long-distance storage and transportation and addressing industrial energy demand. Hunan should strategically invest in innovative hydrogen research and demonstration projects to build technological reserves and a comprehensive industry chain. Moreover, the coordinated development of distributed energy and micro grid systems represents a key strategy for improving grid stability and enhancing resilience, especially in remote areas.

(4) Strengthen the carbon technology and carbon market systems in Hunan, while establishing a comprehensive green, low-carbon development framework.

Building on Vietnam's example of integrating renewable subsidies with carbon market incentives, Hunan could establish complementary mechanisms that simultaneously promote renewable energy deployment and carbon trading. Such an approach would align financial incentives with emission reduction goals, fostering a more dynamic and effective carbon market. Focus on improving CO2 emission control, particularly in the power sector and coal-fired plants. Prioritize the deployment of advanced carbon technologies such as Integrated Gasification Combined Cycle (IGCC) combined with Carbon Capture, Utilization, and Storage (CCUS) and multi-production systems. These measures intend to significantly decrease CO2 emissions and support the deployment of zero-carbon energy. Hunan should take advantage of the national carbon trading market in its carbon governance. Improve carbon accounting, reporting, and product footprint systems for greater transparency and efficiency. Establish a robust mechanism for market trading to motivate the reduction of CO2 and innovation and regulatory change in the electrical sector. These activities are essential in meeting China's carbon peak and neutrality goals.

6. Conclusion

This study uses the LEAP-Hunan model to optimise Hunan Province's power industry under carbon emission limitations in three scenarios to meet the 2030 carbon peaking target. Industrial restructuring, renewable energy integration, and sophisticated energy storage are crucial to regulating electricity consumption and decreasing emissions, according to the research. This paper proposes a "Integrated Model of Demand-Side Reform, Energy Storage, and Renewable Energy" a novel approach to carbon neutrality and modern power system difficulties. Its core contribution is the new, innovative methodological approach toward the representation of the resource-constrained region subject that has been understudied. The LEAP-Hunan model is adopted for this research to investigate the energy structure, policy environment, and resource constraints in Hunan Province. Such an approach will facilitate a rigorous investigation of how demand-side reforms, renewable energy integration, and energy storage could optimise the power system within carbon constraints. The paper also places much emphasis on demand-side reforms, an area which is normally neglected in mainstream research. Through energy efficiency measures and flexible demand-side management, it is demonstrated that these are complementary strategies for renewable energy integration and energy storage solutions. Together, they constitute a harmonious pathway toward meeting carbon reduction targets. Furthermore, the study rigidly tests the integration of renewable energy sources with energy storage technology, a topic rarely explored within power system optimization studies. The combination approach here spotlights potential for mitigating the intermittency of renewables and ensuring grid stability thus offering practical solutions to meeting the challenges of dynamic systems. To address intermittency of renewable energy, along with flexibility in the grid, the study suggests optimizing clean coal power plants, development of natural gas as flexible backup, and integration of smart grids with digital technologies. Increased policy support and innovative new market mechanisms are imperative for making the transition possible into a low-carbon energy system.

This paper provides practical measures to reconcile supply and demand with lower emissions, in support of energy security and long-term sustainable development. Its findings support policy design and infrastructure investments that align with the goals of sustainability. This framework will be invaluable for planning energy in resource-constrained regions. Future work should follow these directions: First, the power transition model must be improved to incorporate multi-scale modelling techniques that would help optimize input parameters and minimize uncertainty. Second, exploring the integrated application of advanced technologies, such as clean coal, hydrogen energy, and energy storage, to balance economic feasibility with sustainability. Third, analysing the impact of extreme weather events and global economic fluctuations on energy systems, while expanding research on inter-regional energy collaboration, to provide coordinated technological and economic solutions for achieving low-carbon transitions and sustainable development goals.

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Appendix

Appendix Table: Overview of Names and Abbreviations of Hunan Province

Name	Abbreviations
China Bureau of Statistics	CBS
China Electricity Council	CEC
Communist Party of China Changsha Municipal Committee & Changsha Municipal People's Government	CPCCMC & CMPG
Hunan Provincial Bureau of Statistics	HNBS
Hunan Provincial Department of Industry and Information Technology	HNDI&T
Hunan Provincial Development and Reform Commission	HNDRC
Hunan Provincial Grain and Material Reserves Bureau	HNGMRB
Hunan Provincial Health Commission	HNHC
Hunan Provincial People's Government Website	HNPGW