Impacts of Renewable Energy Strategy on Electricity System and Carbon Emmissions in Hunan Province of China

Caixia Yang

A Thesis Submitted in Partial Fulfillment of Requirements for
degree of Doctor of Philosophy in Electrical and Computer Engineering
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ABSTRACT

This study explores the impacts of renewable energy strategies on the electricity system and carbon emissions in Hunan province, China, with a focus on the challenges posed by limited renewable energy resources and the carbon peak target. Using the Low Emission Analysis Platform (LEAP) model, three scenarios (BAS, MED, and HIG) were analyzed to assess the impacts between 2022 and 2035. The analysis aimed to examine trends in electricity demand, power generation adjustments, emission reduction potentials, and policy frameworks. The results indicate that under the HIG scenario, coal-fired power generation would decrease by approximately 20%, leading to an estimated reduction of 50 million tons of CO2 emissions. The study suggests that strategies such as industrial restructuring, widespread adoption of energy storage technologies, and smart grid implementation could help Hunan achieve its carbon peak target 3 to 5 years earlier than under the BAS scenario. Key policy recommendations include: a) accelerating the phase-out of coal-fired power; b) supporting the development of natural gas power; c) promoting energy storage and distributed energy systems; and d) enhancing carbon market mechanisms. These strategies aim to optimize the electricity mix, enhance renewable energy integration, and improve system flexibility. Overall, this interdisciplinary study offers valuable insights into operational research, technological innovation, and the sustainable energy transition, contributing to the realization of carbon reduction goals in regions with limited renewable energy resources.

Keyword : Renewable Energy, Power System Optimize, Scenario Analyze, Low Emission Analysis Platform, Carbon Reduction

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Chapter 1 Introduction

I. Overview

Global climate change has become one of the major challenges facing the world today. Scientists unanimously agree that climate change is caused by human activities, mainly due to the significant emissions of greenhouse gases resulting from the extensive use of fossil fuels, particularly carbon dioxide (CO2) emissions. The rise in global temperatures leads to consequences such as rising sea levels, frequent extreme weather events, and loss of biodiversity, significantly impacting human society and natural ecosystems. According to the consensus of international climate scientists, greenhouse gas emissions are a primary cause of these issues. Specifically, the increase in greenhouse gases like carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), contribute to the rising global temperatures, rising sea levels, and frequent extreme weather events. International legal documents such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement call on countries to take proactive measures to reduce greenhouse gas emissions and limit global warming to within 2 degrees Celsius [1]. In order to mitigate the process of climate change, governments and international organizations worldwide are taking various measures, one of which is promoting energy transition, gradually reducing reliance on fossil fuels, and transitioning towards cleaner and more sustainable energy sources. Renewable Energy (RE) is considered a crucial component of this energy transition since it does not emit greenhouse gases, making it widely recognized as the key to achieving a low-carbon economy and environmental sustainability [2].

As the world's largest energy consumer and one of the major greenhouse gas emitters, China faces severe energy and environmental challenges. The heavy reliance on traditional energy sources such as coal and fossil fuels has resulted in serious air pollution and greenhouse gas emissions, putting significant pressure on the environment and public health. In response to the energy and environmental crises and to achieve sustainable development, the Chinese government has gradually prioritized the development of renewable energy to reduce carbon emissions, mitigate environmental pollution, and promote high-quality economic growth. As a responsible major country, the Chinese government has formulated a series of emission reduction targets to deal with global climate issues. In 2015, the Chinese government announced that it will reach the peak of carbon dioxide emissions by 2030 and will reduce the intensity of carbon dioxide emissions by 60-65% compared with 2005. At the 75th meeting of the United Nations General Assembly on September 22, 2020, Chinese President Xi announced that China will strive to achieve the peak of carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060 [3]. In the "13th Five-Year Plan," China proposed the concept of an energy revolution with the goal of establishing a clean, low-carbon, safe, and efficient energy system by 2050 [4]. Over the past two decades, China has made substantial progress in expanding renewable energy generation and lowering the cost of renewable energy, achieving the targets set in the "13th Five-Year Plan" ahead of schedule. In 2021, the National Energy Administration of China issued the "14th Five-Year Plan for the Development of Modern Energy System," which outlined the overall objectives for renewable energy development [5]. By 2025, the share of non-fossil energy consumption is targeted to reach about 20%, and the proportion of non-fossil energy in electricity generation is expected to reach about 39%. Additionally, there is a target for a cumulative reduction of 18% in carbon dioxide emissions per unit of GDP over the five-year period. Beyond 2025, on the basis of achieving a non-fossil energy consumption share of 25% by 2030, further significant increases in the share of non-fossil energy are envisaged, with renewable energy becoming the main source of electricity generation.

Hunan Province, located in southern China, is blessed with abundant water resources and favorable natural conditions. It is also an economically and culturally significant region. With the continuous progress of industrialization and urbanization, the energy demand in Hunan Province has been steadily increasing. However, the excessive reliance on traditional fossil fuels such as coal and petroleum has brought about a series of issues, including environmental pollution and energy security concerns, posing severe challenges to the ecological environment and sustainable development of the society. Firstly, with the rapid economic development and continuous improvement in living standards across the province, the total energy consumption in 2019 reached 160 million tons of standard coal, representing a 10.3% increase compared to 2015, with an average annual growth rate of 2.5% [6].

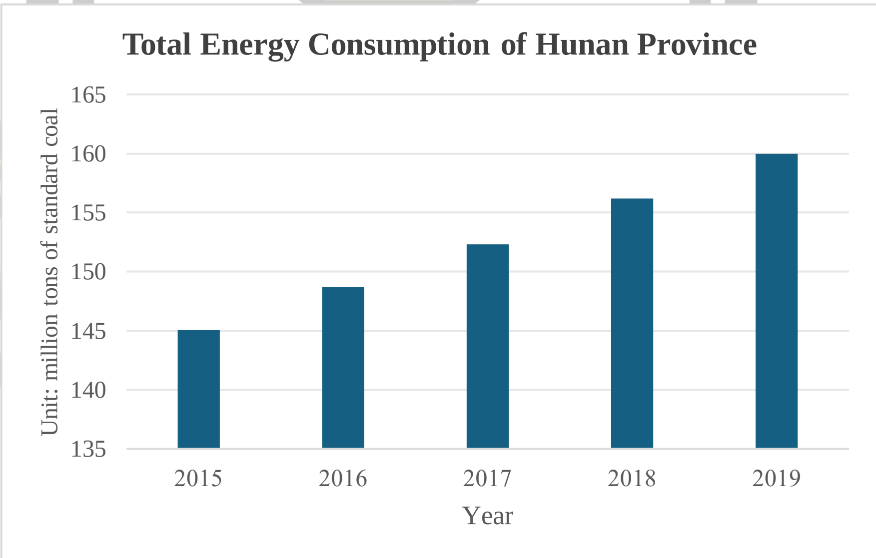


Figure 1 2015-2019 Total Energy Consumption in Hunan Province

Secondly, the energy structure in Hunan province remains relatively singular, relying mainly on traditional coal energy. The proportion of clean energy in the energy structure is relatively low. In 2019, coal consumption accounted for 55.09% of the total energy consumption, and oil fuel consumption accounted for 18.96% of the total energy consumption, leading to high carbon emissions and air pollution issues. It is essential to further promote the development and utilization of clean energy to achieve sustainable energy development.

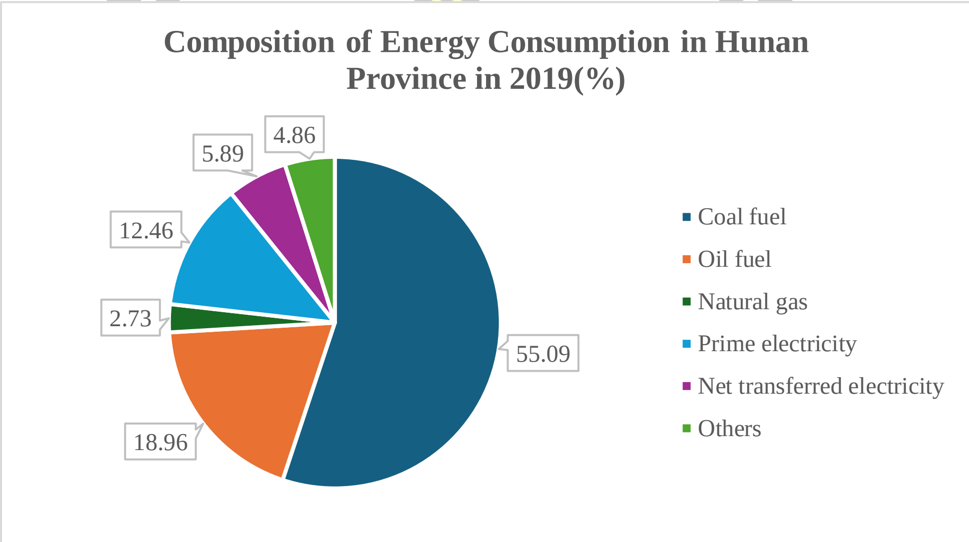


Figure 2 Energy consumption structure in Hunan Province in 2019

In China, 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 [7]. Therefore, the green transformation of this sector is central to meeting China's carbon peaking target. According to the China Electric Power Annual Report [8], the electricity consumption data for Hunan Province is shown in Table 1 and Figure 3. Hunan Province is a southern inland in China with limited energy resources. Since 2015, due to rapid economic development and a sharp increase in population, electricity consumption in Hunan Province has maintained a high growth rate. In 2015, Hunan's total electricity consumption was 1,447 GWh, which rose to 2,235 GWh by 2022, marking a 54.5% increase compared to 2015, at an average annual growth rate of 7.78%. Additionally, the secondary industry accounts for the majority of the province's electricity consumption, reflecting the dominant role of industrial production in driving energy demand. However, in recent years, growth in the secondary industry has slowed slightly due to industrial restructuring. Meanwhile, the tertiary industry has experienced the fastest growth in electricity consumption, nearly doubling from 24.2 GWh in 2016 to 44.4 GWh in 2022. This highlights the increasing importance of the service sector in Hunan's economy. Residential electricity consumption also saw significant growth, increasing by 65.6% from 2015 to 2022, driven by accelerated urbanization and improved living standards. In contrast, the primary industry has maintained relatively low and stable electricity demand, indicating limited changes in energy use within the agricultural sector.

Table 1 Electricity Consumption in Hunan 2016-2022 (Unit: GWH)

Year	Total	Primary industry	Secondary industry	Tertiary industry	Residential industry
2016	158.3	1.8	93.5	24.2	38.7
2017	1581.5	1.9	88.6	26.6	40.8
2018	174.5	1.5	98.1	29.0	45.8
2019	186.4	1.6	98.7	35.0	50.9
2020	192.9	1.7	103.0	34.8	53.2
2021	215.4	2.1	113.6	41.9	57.6
2022	223.5	2.6	112.3	44.4	64.1

Furthermore, the per capita energy consumption has notably risen. In 2015, the per capita electricity consumption was 1999 kilowatt-hours, while in 2019, it reached 2547 kilowatt-hours, showing a growth of 27.4% compared to 2015, with an average annual growth rate of 6.2%.

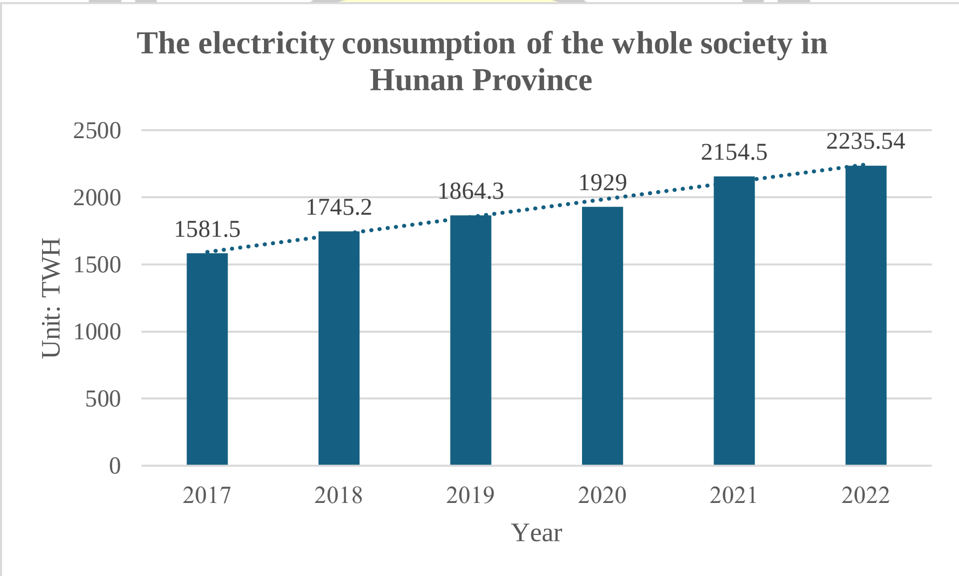


Figure 3 2017-2022 Electricity consumption in Hunan Province

Despite this growth, the province remains heavily reliant on coal-based power generation. In 2022, Hunan's energy generation consisted primarily of thermal power (61.39%), followed by hydro-power (27.28%), wind power (9.8%), and solar power (1.54%) [9]. The reliance on thermal power has brought about a continuous increase in fossil fuel consumption, which means more severe carbon emissions and air pollution.

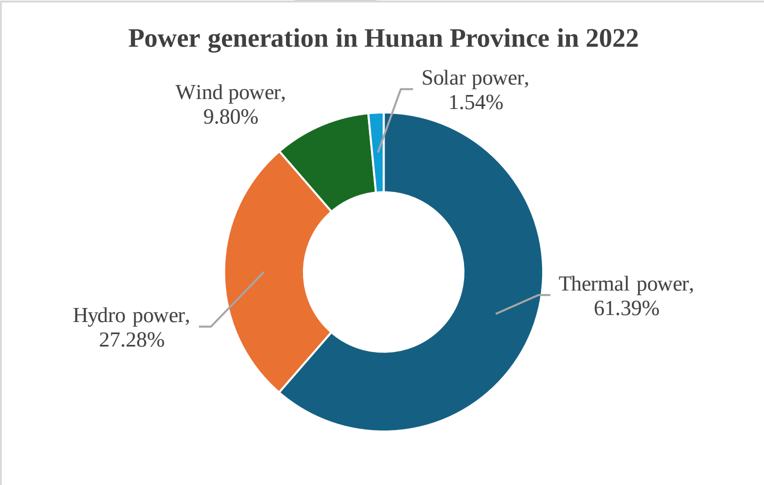


Figure 4 Power generation in Hunan Province in 2022

Under the superimposed influence of strong economic growth momentum and extreme weather in Hunan Province in recent years, the tension between energy supply and demand in Hunan has become increasingly prominent. Based on the status quo of lack of coal, no oil, no gas, Hunan's energy dependence on foreign energy remains high, and the situation of maintaining power supply in the medium and long term is severe. "Hunan Province Energy Development Report 2021" shows that in 2021, the electricity consumption of the whole society in Hunan Province as high as 215.454 TWH, an increase of 11.7% year-on-year. The gap between power generation and electricity consumption has reached 49.594 TWH. Its own power generation is insufficient, and naturally the degree of external dependence continues to deepen. From 2017 to 2021, Hunan Energy's external The degree of dependence is 78%, 82.4%, 81.6%, 81.2%, and 82.9%, respectively, and continues to operate at a high level. Among them, in 2021, 36.06 TWH of foreign power will be imported into Hunan, with an average annual growth rate of 21.4% for two years.

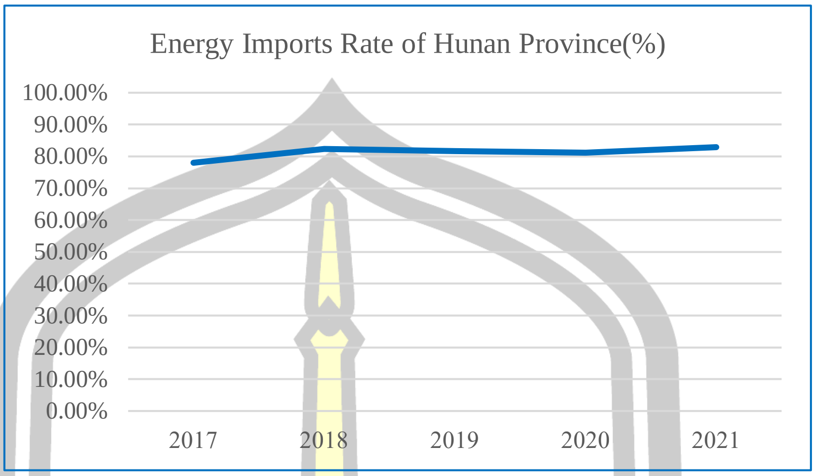


Figure 5 Energy Imports of Hunan Province

The reliance on thermal power has brought about a continuous increase in fossil fuel consumption, which means more severe carbon emissions and air pollution for power sector. During the 13th Five-Year Plan period (2015-2020), the average annual growth rate of carbon emissions from the power sector in Hunan stood at approximately 1.53%. The carbon emissions for Hunan province were showed in Table 2, the data is sourced from the China Carbon Accounting Database (CEADs) [10]. The total carbon emissions of Hunan Province in 2019 were about 438 million tons, and the carbon emission intensity was about 0.779 tons/10,000 yuan, which is lower than the national carbon emission intensity of 0.993 tons/10,000 yuan.

Table 2 Carbon emissions in Hunan 2015-2022 (Unit: Million metric tonnes)

Year	Carbon Emissions in Power Sector	Total Carbon Emissions
2015	83.4	410.6
2016	74.6	406.4
2017	64.1	408.5
2018	108.7	414.5
2019	107.9	438.5
2020	102.9	420.5
2021	115.0	443.2

Hunan Province has identified renewable energy strategies as a key lever for the low-carbon transition of its electricity system, implementing a series of policies to drive the shift toward cleaner energy and significantly reduce carbon emissions. Guided by national policies, Hunan Province has introduced measures that profoundly impact the optimization of its electricity system and the achievement of carbon reduction goals. In 2017, the Hunan Provincial Government issued the "13th Five-Year Plan for Renewable Energy Development" [11], the proposal aimed to limit the average annual growth rate of energy consumption in the province to not exceed 2.9%

by 2020. Additionally, it targeted to cap the total energy consumption at 178.5 million tons of standard coal and reduce energy consumption per unit of GDP by 16% compared to 2015 levels. In May 2022, the Hunan provincial government issued the "13th Five-Year Plan for Renewable Energy Development" [12], it is projected that the installed capacity of renewable energy power generation would reach around 44.5 GW, comprising 18 GW of hydroelectric power and 26.5 GW of non-hydro renewable energy sources. The proportion of renewable energy power consumption would reach about 18.5%, and non-fossil energy consumption accounts for more than 22% of total fossil fuel consumption. In 2023, the General Office of the Hunan Provincial People's Government released the "Hunan Province New Power System Development Plan" [13], proposing that by 2030, the installed capacity of clean energy sources such as photovoltaic and wind power would become the main power generation installed capacity, and the overall power system would be transformed into a clean and low-carbon direction to support the whole country. The anticipated installed capacity of wind power and photovoltaic power generation is set to reach 40 GW, which would be approximately 2.7 times the installed capacity in 2022. The power structure would be accelerated to become cleaner, and the installed capacity of non-fossil energy has reached 73.9 GW, and the proportion of non-fossil energy installed capacity has reached 63% until the year of 2030.

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 [14]. 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 [15]. While the province is rich in water resources, hydro-power development has largely reached its limit, making further development challenging and costly [16]. 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. Given these constraints, Hunan province's successful low-carbon transition is of national importance.

Despite geographic limitations, such as low photovoltaic and wind energy utilization efficiency and near-saturation of hydropower development, these policies have provided robust support for Hunan's electricity system restructuring and carbon reduction efforts. The large-scale development of solar and wind energy and the optimization of grid and power dispatch systems are crucial in overcoming these challenges. This study focuses on the low-carbon transition of Hunan's electricity system, designing various renewable energy scenarios to analyze their specific impacts on the electricity structure and carbon emissions. The findings would offer scientific evidence for the low-carbon transition of Hunan's electricity sector and provide replicable pathways for green development in other resource-constrained regions.

II. Research Objectives

To comprehensively evaluate the effects of renewable energy policies on power generation and carbon emissions in Hunan Province, focusing on the challenges of structural adjustments in the electricity system and achieving carbon peak targets. We focus on four key areas:

1. Power Generation and Structure:

Examine how power generation and its composition evolve under renewable energy policies, with a focus on renewable energy integration, capacity expansion, and overall growth.

2. Energy Consumption and Structure:

Assess changes in energy consumption patterns and structures driven by renewable energy policies, highlighting their impact on clean energy development and supply-demand imbalances.

3. Carbon Emission Trends:

Analyze carbon emission trajectories across different energy sources and sectors, quantify reductions attributable to renewable energy policies, and identify the timing and pathways for achieving carbon peaking.

4. Policy Effectiveness and Sensitivity:

Evaluate the effectiveness of renewable energy policies in meeting carbon peak targets through sensitivity analyses, providing insights into uncertainties and guiding policy adjustments.

Through this comprehensive investigation, the study aims to offer a detailed understanding of the interplay between renewable energy policies, power generation dynamics, and carbon emissions, contributing to the advancement of low-carbon energy transitions in Hunan Province and beyond.

III. Scope of Research

The scope of this study is to analyze the impact of renewable energy policies on power generation and carbon emissions in Hunan Province during the period 2022-

2035. In this time frame, we will focus on the implementation and effect of renewable energy policies in Hunan Province, as well as the impact on the power generation industry and carbon emissions.

IV. Research Value

This study offers a comprehensive analysis of the implementation and actual impact of renewable energy policies in Hunan Province, focusing on their effects on the power generation industry and carbon emissions. By examining the efficacy and benefits of these policies, the research highlights significant academic and practical value in the following aspects:

(1) Scientific Evaluation of Renewable Energy Policy Effects

Hunan Province has implemented a series of policy measures to promote renewable energy development, yet the actual outcomes of these policies require rigorous, objective assessment. This study will analyze the policies' implementation, their impact on the power generation industry, and associated changes in carbon emission levels. Such an analysis will help uncover the real effects of these policies in fostering renewable energy development and reducing carbon emissions. Furthermore, it will provide valuable insights for government decision-making and policy optimization.

(2) Empirical Support for Energy Transition and Carbon Emission Reduction

As global pressure to limit carbon emissions increases, energy transition and emission reduction have become critical priorities for governments worldwide. Hunan Province's experience with renewable energy policies offers important demonstration value for national energy transition strategies and emission reduction efforts. This research will provide empirical evidence for policymakers, guiding the design and implementation of effective policies that support energy transitions and align with carbon neutrality goals.

(3) Advancing the Regional Renewable Energy Industry

This study delves into how renewable energy policies in Hunan Province have influenced the power generation sector and carbon emissions, offering insights into policy execution and effectiveness. These findings can guide governments and enterprises in crafting targeted development strategies, optimizing resource allocation, and fostering the sustainable growth of the renewable energy industry. A thorough assessment of policy impacts will also help refine incentive mechanisms and support measures, encouraging greater investment in renewable energy projects.

(4) Expanding Research on Renewable Energy Policies

While existing research on renewable energy policies often emphasizes macro-level effects, economic impacts, and environmental benefits, there is a lack of localized, granular studies. By analyzing the specific impacts of Hunan Province's renewable energy policies, this study fills this gap, introducing new perspectives and methodologies for renewable energy policy research. The findings will enhance the academic understanding of localized policy impacts and inspire innovative approaches for researchers and policymakers in the field.

This study aims to illuminate the actual effects and potential challenges of renewable energy policies on power generation and carbon emissions in Hunan Province. It seeks to provide a scientific foundation for policy development, support regional energy transformation, and contribute to carbon emission reduction and sustainable development goals. Simultaneously, the research will enrich the renewable energy policy literature, offering fresh perspectives and practical insights for academic and policy communities, thus driving progress in the field and its applications.

V. Thesis Organization

This research is divided into 5 chapters, the specific content of each chapter is as follows:

Chapter One: Introduction. Firstly, it introduces the research background, research objectives and significance of the article, considers the challenges of global climate change and the needs of sustainable development, and discusses the importance of studying the impact of renewable energy policies on power generation and carbon emissions in Hunan Province.

Chapter Two: Literature review. Renewable energy impact analysis research: analysis of relevant research using models such as LEAP to assess the impact of renewable energy policies on power generation and carbon emissions in different regions.

Chapter Three: , Research methods. Provide an overview of the LEAP model, explaining its components, data requirements, and how it is used for analyzing energy systems. Explain the data collection process and the sources of data used to calibrate and validate the LEAP model for the study. Design different scenarios, detail the different policy scenarios that will be simulated in the LEAP model, including variations in renewable energy targets, incentives, and other policy measures.

Chapter Four: Research Results. Present the simulated results from the LEAP model for different policy scenarios, comparing the changes in electricity generation capacity, electricity generation structure, carbon emission and the energy mix with the baseline scenario. Discuss the findings from the impact analysis and their implications for renewable energy policy formulation and implementation in Hunan Province.

Chapter Five: Research Conclusions. Summary of findings: Recap the key findings from the impact analysis on electricity generation and carbon emissions in response to renewable energy policies. Contributions and significance: Highlight the contributions of the research to the understanding of renewable energy policy impact and its implications for sustainable development in Hunan Province. Future research directions: Suggest potential areas for further research and improvements in the analysis methodology.

By following this structure, the paper ensures a systematic and comprehensive exploration of the topic, offering both academic value and practical insights.

Chapter 2 Literature Review

I. Overview of Energy and Environmental Impact Prediction Models

To assess the impacts of renewable energy policies on electricity generation, greenhouse gas (GHG) emissions, and PM2.5 emissions in Hunan Province, developing a provincial-level energy model is crucial. Numerous studies have utilized various tools for modeling power generation and energy demand to conduct similar assessments across different regions. Research institutions and scholars in China and abroad have successively developed various energy, economic and environmental models. At present, the carbon emission prediction models can be divided into "top-down" and " bottom-up " models in terms of modeling methods [17,18].

Table 3 Classification of Energy and Carbon Emission Prediction Models

Model Type	Model Category	Representative Models
top-down	Index Decomposition Models	LMDI (Logarithmic Mean Divisia Index), Kaya Identity, STIRPAT Model
	Macroeconomic Models	CGE (Computable General Equilibrium) Model, Environmental-Economic Models
	Integrated Assessment Models	MESSAGE, GCAM, AIM, IMAGE, MERGE, PAGE
	Econometric Models	Logistic Growth Models, EKC (Environmental Kuznets Curve) Hypothesis
	Time-series Models	ARIMA (Auto-Regressive Integrated Moving Average)
	Structural Models	CGEM (Computable General Equilibrium Model)
bottom-up	Energy Systems Models	LEAP (Long-range Energy Alternatives Planning), MARKAL, TIMES, MESSAGE
	Dynamic Energy Optimization	MARKAL/TIMES, EFOM (Energy Flow Optimization Model), MESSAGE
	Technology Investment Models	PETERSEN Model, SIM (Simulation Model)
	Optimization Models	GAMS (General Algebraic Modeling System), OMEGA Model
	Machine Learning Models	ANN (Artificial Neural Networks), CNN (Convolutional Neural Networks), RNN (Recurrent Neural Networks)
	Input-Output Models	SAM (Social Accounting Matrix), IO Model
	Sectoral Models	NEMS (National Energy Modeling System), EPPA (Emissions Prediction and Policy Analysis)
	Agent-based Models	ABM (Agent-Based Models for energy systems)

The top-down model mainly predicts the energy system through macroeconomic index data. The advantage is that the data is highly available, and it can simply and intuitively reflect the impact of various driving factors on energy consumption and carbon emissions. The disadvantage is that the prediction analysis is macroscopic, cannot be refined to various energy types in various industries, and cannot reflect the specific optimization process of energy consumption and carbon emissions. Such models mainly include Logistic model, Kaya identity, STIRPAT model, EKC assumption, LMDI model, etc.

The bottom-up model mainly uses detailed and dispersed data of energy production, conversion, terminal consumption and other links to analyze the energy system in detail, and can carry out detailed analysis and simulation on the impact of technological progress. The disadvantage is that the data availability is poor, and experience After the data is decomposed by the method, it is easy to cause the conclusion to be distorted, and it is easy to ignore the impact of changes in other fields on the energy field. This type of model mainly includes the LEAP model, the dynamic energy optimization model, etc.

Currently, the most commonly used models include econometric models, grey system theory, artificial neural networks, scenario analysis, combination forecasting, and others.

1. Econometric model

Econometric models are based on the theoretical knowledge of statistics, mathematics, and economics. They utilize time-series data or panel data to study the relationships between various factors of human activities. In the field of energy forecasting, econometric models based on past development trends mainly include models such as the IPAT (I = Human Impact, P = Population, A = Affluence, T = Technology) model, STIRPAT (stochastic: impacts by regression on population, affluence, and technology) model, regression models, and elasticity analysis. Due to their mature theories and simple application, these models have been widely used in energy forecasting. For instance, Moslemi Z [19] established an ARIMA model model for energy demand forecasting to predict USA's primary energy demand from 2005 to 2020. Huang, L. etc. [20] analyzed the impact of various lifestyles on energy consumption and CO2 emissions. Wen, L. etc. [21] improved the STIRPAT model to predict my China's energy consumption and CO2 emissions. CONG X [22] using the STIRPAT model to predict future energy consumption and CO2 emissions in Hunan and various regions (Shanxi, Chongqing, Jiangsu, Beijing-Tianjin-Hebei and other regions). Econometric model is greatly affected by economic factors and is not suitable for unstable economic environments. The influence of other non-economic factors is ignored.

2. Gray system theory

Gray system theory, is a mathematical framework used for analyzing systems with insufficient or limited information. Developed by Professor Deng Julong in the 1980s, this theory is particularly useful when dealing with systems that lack complete data or are affected by uncertainties. The gray system theory focuses on forecasting, modeling, and decision-making in situations where traditional statistical methods may not be applicable due to data limitations. It aims to bridge the gap between deterministic and stochastic models, making predictions and analyses more feasible for systems with uncertain and incomplete information. Gray system theory has found applications in fields such as economics, engineering, environmental science, and social sciences. Its ability to handle limited data and uncertainties makes it a valuable tool for decision-making and forecasting in situations where traditional methods may fall short. Wang, H. and his colleagues [23] applied an improved grey forecasting model to predict China's energy consumption and CO2 emissions. They found that compared to the GM and ARMA models, the non-linear grey Bernoulli model (NGBM-OP) provided more accurate prediction results. Additionally, Ding, S., & Zhang, H. [24] employed the grey relational analysis method to identify CO2 emission. But in the case of a large amount of data, there may be a large error. For complex nonlinear systems, the prediction results may not be accurate enough.

3. Artificial neural network

In recent years, with the rapid rise of artificial intelligence technology, artificial neural network models have gradually gained attention from researchers in the field of energy and the environment. These models have been applied to research on energy demand, energy consumption, and pollution emission predictions. For instance, Faruk Kılıç etc. [25] used the Artificial Neural Networks to forecast the electricity capacity and electricity generation values of wind and solar energy in Germany from 2000-2020. Rahman, M. M. [26] employed artificial neural networks (ANNs), for renewable energy time series prediction, emphasizing the importance of accurate forecasting in addressing energy sustainability, fossil fuel shortages, and rural electrification through hybrid renewable energy systems. Reference [27-29] proposed an ANN-based methodology for energy and carbon prediction of different sectors.

4. Scenario analysis method

Energy demand and consumption scenario analysis is a systematic approach to assessing the impact of different scenarios or scenarios on energy demand and consumption. This analytical approach aims to explore and predict future changes in energy demand and consumption, based on factors such as different assumptions, policies, technological advances, and economic trends. By creating multiple scenarios, it is possible to better understand the impact of different factors on energy demand and consumption, and provide a reference for decision makers when formulating policies and planning. Commonly used scene analysis methods include: Long-range Energy Alternatives Planning System (LEAP), MARKAL/TIMES model, MESSAGE model, etc. For instance, Buncha S etc. [30] applied the LEAP model to analyze the impacts of electricity generation from renewable energy on the Thai electricity industry. Xin Zou etc. [31] applied the LEAP model to forecast the CO_2 emission trends in Shanxi Province from 2019 to 2035 under different scenarios and identify the conditions for achieving the goal of reaching the CO_2 emissions peak in 2030. Guang xiao Hu etc. [32] proposed propose a revised LEAP model by which to achieve sustainable urban energy planning with the minimum economic cost, and draw a Sankey energy flow map for a postindustrial city(Shenzhen). A. Amo-Aidoo etc. [33] applied the LEAP to demonstrate how appropriate renewable energy policy can drive solar energy development in Ghana, the historical data from 2013 to 2018 was used to project electricity demand and supply from 2019 to 2030 in Ghana. Wang J. etc. [34] proposed six development scenarios of Beijing to build a simulation model and scientifically forecast Beijing's future energy usage trend by using the LEAP software. Pemika Misila etc. [35] analyzed potentials of GHG emission reduction during 2015-2050 from utilization of renewable energy and increasing energy efficiency using the Long-range Energy Alternative Planning system(LEAP) model. Troy B.Felver etc. [36] applied the LEAP model to assess the effectiveness of climate change-related energy policy options in Azerbaijan, to make sure whether Azerbaijan can meet its Paris Agreement commitments. Dr. Tauseef Aized etc. [37] used LEAP to forecast demand and supply assessing the validity of electricity generation scenarios, environmental emissions and cost of electricity production, optimization scenario have been developed to assess the validity of different parameters of cost, environment and generation.

5. Combined forecasting

In order to enhance the reliability of predictions, some scholars have proposed combination forecasting methods. They believe that each forecasting method has its own advantages and disadvantages, and different perspectives and applicabilities are considered in each method. By combining multiple forecasting methods, the reliability of predictions can be effectively improved [38]. With the rise of combination forecasting theory, an increasing number of researchers have applied combination forecasting methods in the field of energy prediction. For example, Rui Chen etc. [39] developed a combined model based on LEAP model and econometric model to forecast the energy demand of Hunan Province from 2012 to 2030. Peng Wang etc. [40] used the LMDI to divide the total energy consumption growth of three industries from 2006 to 2015 in Hunan Province into scale effect, structure effect and efficiency effect, and used the LEAP model to predict the energy consumption from 2016 to 2040 in Hunan Province. Yan Li etc. [41] used combined model based on multivariate Linear Regression and BP Neural Network to forecast the electricity consumption in Hunan province. Qingyou Yan etc. [42] used Index Decomposition Analysis (IDA) model to discover the driving factors behind CO_2 emission changes at the provincial level, such as carbon emission factor, energy intensity, and economic activity factor. In addition, the Slack-based Model (SBM) is used to identify which provincial power grids should be allocated with a higher (lower) CO2 reduction burden. Wang chunchun etc. [43] used Multilayer-hierarchical Logarithmic Mean Divisia Index, M-H LMDI) to retrospectively decomposed and analyzed the changes in energy consumption and total CO2 emissions in Fujian Province from 2000 to 2015, in addition, the LEAP model was used to forecast the energy consumption and C02 emissions in Fujian Province from 2016 to 2030. Xuan Zhou etc. [44] adopted dynamically changing ECEF to calculate carbon emissions, which improves the accuracy of carbon emission measurement, and established a LEAP-SEDU model for pre-primary, primary and secondary schools in Shanghai, and used the Kaya-LMDI method to analysis the key drivers' effects on educational buildings' carbon emission, which can be used as a reference for similar studies.

Each energy analysis method has its advantages and disadvantages, and the analysis of advantages and disadvantages is shown in Table 4.

Table 4 Comparison of different energy analysis methods

Method	**Advantages**	**Disadvantages**
Econometric model	➢ Econometric Models Based on economic theory, reveals the relationship between human activities and energy consumption. ➢ Uses historical data for modeling, accurate for short-term energy demand and consumption predictions. Mature theory, relatively simple to use, suitable for stable economic environments.	➢ Pronounced impact from economic factors, not suitable for unstable economic conditions. ➢ Ignores other non-economic factors affecting energy consumption, such as technological innovation, policy changes. ➢ May result in significant errors when predicting long-term energy demand and consumption.
Grey System Theory	➢ Applicable for prediction with insufficient or incomplete data, provides reasonable predictions when data is lacking. ➢ Considers interrelationships between data, suitable for correlated data series. ➢ Relatively simple, low computational cost.	➢ Potential for significant errors when dealing with larger datasets. ➢ Less accurate for complex nonlinear systems. Does not account for nonlinear factors and external disturbances.
Artificial Neural Networks	➢ Able to handle complex nonlinear relationships, suitable for various influencing factors in energy systems. ➢ Improved accuracy through training, suitable for long-term predictions. ➢ Adaptive learning ability, can adapt to changing data and environments. Requires a large amount of training data, strong dependence on data.	➢ Subjective choices for network structure and parameters, requires specialized knowledge. ➢ Complex training process, higher computational cost.

Method	Advantages	Disadvantages
Scenario Analysis	➢ Able to consider interactions among multiple variables and factors, providing comprehensive prediction results. ➢ Reveals potential development trends under different scenarios, aiding decision-makers in devising responses for different situations. ➢ Able to assess policy and technology changes on energy systems by constructing different scenarios.	➢ Requires substantial data and parameters, constructing complex scenario models may increase uncertainty. ➢ Subjectivity when selecting scenarios, leading to biased prediction results. ➢ Complex and time-consuming for complex energy systems.
Combination Forecasting	➢ Able to amalgamate strengths of multiple forecasting methods, enhancing reliability and accuracy of predictions. ➢ Overcomes limitations of individual methods, suitable for various prediction scenarios. ➢ Reduces prediction risk, diminishes errors and uncertainties.	➢ Requires balancing and selection of multiple forecasting methods, potentially adding complexity to predictions. ➢ Subjectivity and uncertainty when determining weights and combination methods. ➢ Differences between methods might lead to prediction result deviations.

II. Research on Energy and Environment in Hunan

Hunan Province, as an important economic region in China, has made significant progress in energy and environmental research. Historical studies have focused on areas such as energy structure, consumption trends, environmental impacts, and policy analysis. These efforts provide a solid foundation for understanding the challenges and opportunities in transitioning to a low-carbon energy system. Reference [45] developed a system dynamics model of the Water-Energy-Food-Society-Economy-Environment (WEF-SEE) nexus to assess the impacts of policy goals on the WEF-SEE system in Hunan Province from 2021 to 2035. It reveals synergies and trade-offs between policies and provides comprehensive policy recommendations to promote sustainable development. Reference [46] examines the impact of large-scale new energy integration on the Hunan power grid, identifies issues in the current grid-connected operation and management model, and proposes optimization measures to ensure safe, stable grid operation and support high-quality new energy development. Reference [47] analyzes the relationship between industrial pollution and economic growth in Hunan Province from 2000 to 2018, using the Environmental Kuznets Curve (EKC) model, and identifies key driving factors such as industrial technology, energy efficiency, structure, economic size, and population, highlighting the role of economic size in driving industrial pollution.

While substantial progress has been made, existing research often lacks a comprehensive analysis of the interplay between renewable energy strategies, electricity system dynamics, and carbon emissions. Most studies focus on isolated aspects, such as resource potential or policy impacts, without integrating them into a cohesive framework. This study addresses this gap by analyzing how renewable energy strategies influence the electricity system and carbon emissions in Hunan Province. Understanding this relationship is critical for supporting the province's low-carbon transition, ensuring energy security, and achieving national carbon neutrality goals.

III. Introduction of LEAP model

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. Moreover, 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 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 [48], Thailand [49], and Pakistan [50]. Sahabuddin and Khan [51] applied the LEAP model to analyse the power generation scenarios of Bangladesh. Other studies involved renewable energy planning [52]; Reference [53] optimization of energy storage, Reference [54] used LEAP model to research carbon emission forecasting. These results indicate the capabilities of LEAP in formulating emission reduction plans, thus providing scientific basis for energy transitions and carbon reduction targets.

The fundamental principle of the LEAP model is to establish an energy system model that comprehensively analyzes energy supply, conversion, and consumption processes while taking into account environmental, economic, and social factors. Driven by the long-term needs of energy planning, the LEAP model can predict future energy demand and supply and assess the impacts of various policies, technologies, and market factors on the energy system. The core of the LEAP model is a dynamic and simulation system composed of energy flows, technological innovations, policy interventions, and other factors. This comprehensive analysis of the energy system is achieved through mathematical modeling and data analysis.

The LEAP model possesses several important functions and characteristics, making it a powerful tool for energy planning and policy formulation:

Comprehensiveness: The LEAP model can comprehensively consider multiple aspects of the energy system, including energy supply, conversion, and consumption, covering different types of energy and their interrelationships.

Long-Term Planning: The LEAP model is primarily designed for long-term energy planning, allowing users to formulate energy policies spanning several years or even decades. This facilitates the consideration of long-term development trends and technological innovations by researchers and decision-makers.

Scenario Analysis: The LEAP model supports scenario analysis, enabling researchers to study variations in the energy system under different assumptions. This allows researchers to assess the impacts of different policies, technologies, and market factors on energy supply and consumption, thereby formulating robust policy scenarios.

Sustainable Development: The LEAP model focuses on the sustainable development of energy. It helps evaluate the comprehensive impacts of energy policies on the environment, economy, and society. Users can set environmental indicators in the model, such as greenhouse gas emissions, air pollutant emissions, etc., to assess policy impacts on the environment.

Flexibility: The flexibility of the LEAP model makes it suitable for analyzing energy systems in different countries, regions, and contexts. It can be customized based on the geographic, economic, and energy characteristics of various locations, leading to wide-ranging global applications.

The basic components of the LEAP model include the following key modules:

Energy Supply Module: This module describes different sources of energy, including fossil fuels (such as oil, natural gas, coal), renewable energy (such as solar, wind, hydropower), nuclear energy, etc. The model incorporates data on the production, imports, prices, and other relevant information for various energy sources, forming the foundation for energy supply analysis.

Energy Conversion Module: This module considers energy conversion processes, such as electricity generation, transmission, and distribution. The model can analyze the efficiency, costs, environmental impacts, and other factors associated with different energy conversion technologies, evaluating the stability and reliability of the electricity system.

Energy Consumption Module: This module describes energy consumption across different sectors, industries, and uses, including industrial, transportation, residential, and agricultural sectors. The model can analyze consumption trends, structural changes, and disparities among different consumption sectors.

Environmental Impact Module: Given its focus on sustainable development, the LEAP model includes a crucial environmental impact module. This module can consider the environmental indicators affected by energy consumption, such as air pollution, greenhouse gas emissions, water resource utilization, etc., providing support for sustainable development.

Policy Intervention Module: This module is used to consider the impacts of various policies and government interventions on the energy system. The model can analyze policy effectiveness, such as energy efficiency improvement policies, renewable energy promotion policies, carbon emission limitation policies, etc., assisting decision-makers in formulating scientifically sound energy policies.

In summary, the LEAP model is a powerful tool for energy planning, characterized by comprehensiveness, flexibility, and sustainability. Its applications in the energy field contribute to the formulation of scientifically sound energy policies, the promotion of sustainable development of energy systems, addressing the challenges of climate change, and providing robust support for energy planning and decision-making. This research utilizes the LEAP-Hunan scenario analysis tool to assess the impacts of increased renewable energy generation on the electricity generation industry and the environment in Hunan Province.

Chapter 3 Methodology

I. Framework

The LEAP-Hunan model can be subdivided into multiple layers, each involving different sets of data. The electricity consumption sectors are categorized into primary industries (including agriculture, forestry, animal husbandry, and fisheries), industry, services, and the residential sector. The principal sources of electricity generation in Hunan Province encompass thermal power, hydropower, wind power, solar power, and biomass power generation. Figure 6 shows the structure of LEAP-Hunan analysis framework and model for Hunan Province. The primary outputs of the model include electricity generation by different energy types, primary energy consumption, as well as emissions of CO_2, SO_2, and PM2.5.

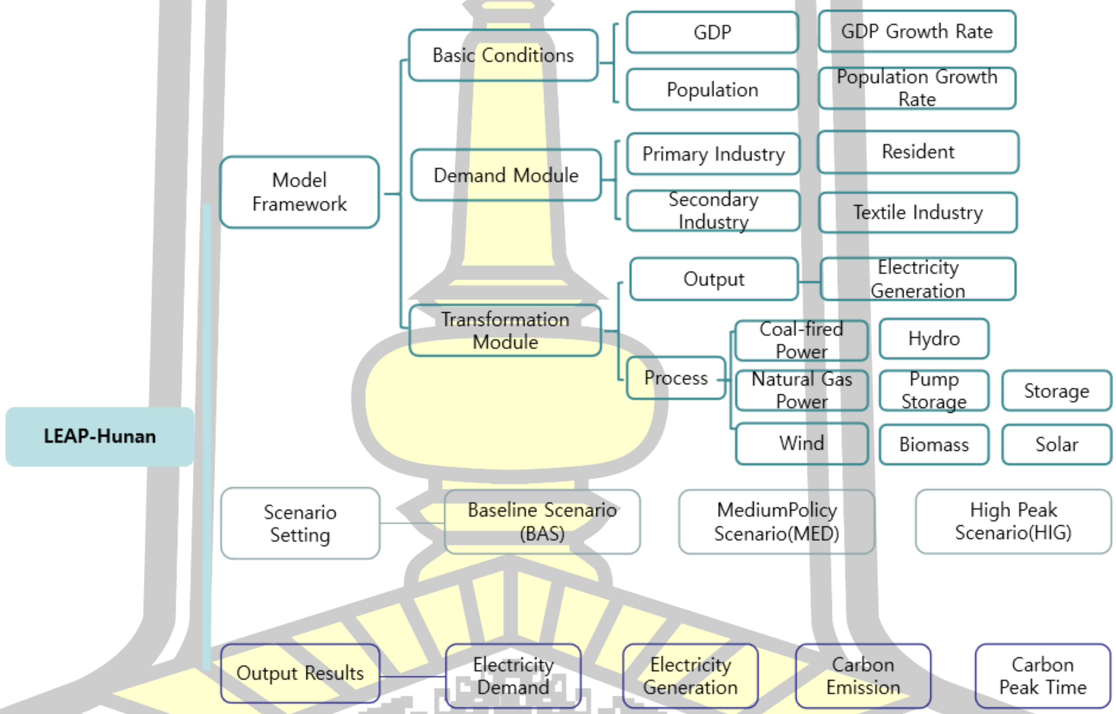


Figure 6 LEAP-Hunan framework

Before forecasting, in order to set the rate of change of the predictor variables more rationally, the forecasting cycle is divided into three time periods: 2022-2025, 2026-2030, 2031-2035, of which 2022 is the base year, and the changes of the factors in the four time periods are set on the basis of 2022. Models can be divided into layers, each involving different data and concerns. Below is the model structure, divided into layers and listing the main data required for each layer.

Level 1: Basic Data and Scenario Settings

At the top layer of the model, set the basic data and scenarios, including the name of the model, research area, time range, etc. At this level, this study defines three scenarios in the context of different new energy policies.

Level 2: Economic and Demographic Data

This level involves data on economic growth and population change in Hunan Province. In this study, relevant economic and demographic data such as GDP, industrial output value, and population growth rate need to be collected.

Level 4: Electricity Production Module

At this level, the focus will be on electricity production, including power generation by different energy types, with a focus on thermal power, hydropower, wind power, solar power, and biomass power generation in Hunan Province, collecting power generation capacity, efficiency, and renewable energy for various energy sources. installed capacity data. These data will be used together with electricity demand data to simulate electricity production.

Level 4: Energy Demand Module

This level is concerned with the forecasting of electricity demand and primary energy demand. This research needs to collect historical electricity demand data, divide the electricity sector into primary industry (including planting, forestry, animal husbandry, by-products and fisheries), secondary industry (including industry and construction), tertiary industry (including transportation, service and others), residential industry, and collect the electricity demand of these four industries. Consider new energy policies, especially the push for renewable energy sources (eg solar, wind), and growing demand for electricity.

Level 5: CO2 Emissions Module

This level focuses on the prediction of CO2 emissions. Data on CO2 emission factors for different energy types need to be collected. These coefficients will be combined with energy consumption data to calculate CO2 emissions.

Level 6: Results and Analysis

At this level, the forecast results under different scenarios are analyzed, including electricity demand, electricity production, primary energy demand and CO2 emissions. These results will be used to assess the impact of new energy policies, understand the potential of renewable energy in the electricity supply, and trends in CO2 emissions.

II. Current Status and Data Consideration

1. Current Status of Renewable Energy in Hunan Province

Since the 18th National Congress of the Communist Party of China, new energy power generation such as solar energy, wind energy, and biomass energy has developed rapidly in large-scale industries in Hunan, from 631 million kwh in 2012 to 6.069 TWH in 2016, an increase of 9.6 times and an average annual growth rate 176.1% [55]. Since entering the "14th Five-Year Plan", Hunan Province has vigorously developed new energy power generation such as wind power and photovoltaic power generation. The green development of electric power mainly characterized by new energy power generation has accelerated significantly, and the installed capacity of wind power and photovoltaic power generation has grown rapidly year by year, as shown in Figure 7.

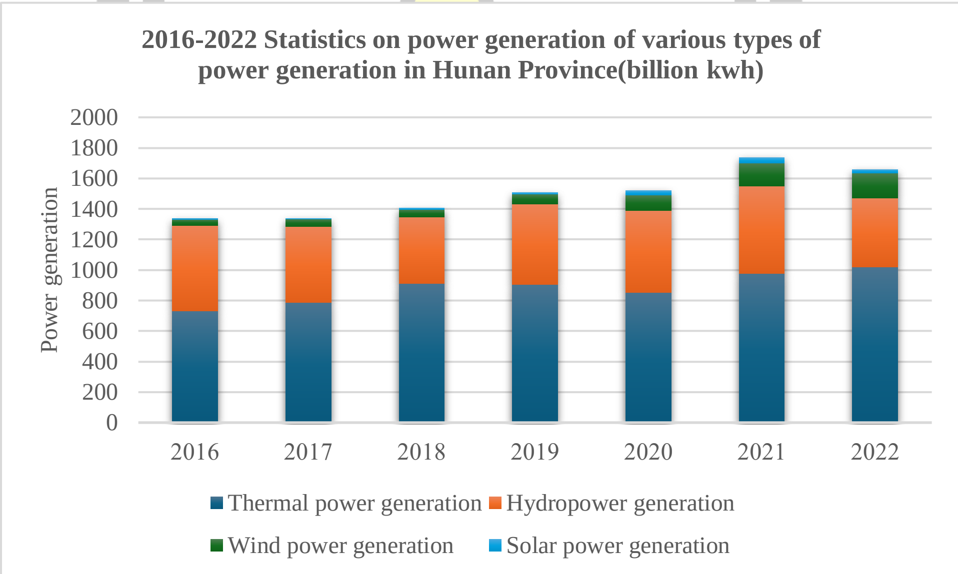


Figure 7 Statistics on power generation of various types of power generation in Hunan Province 2016-2022 (Unit: TWH)

(1) Utilization of water energy resources

Hunan Province is a relatively water-rich area. It is located in a humid and rainy area. The annual average rainfall is 1430mm, ranking seventh in the country. However, there is an obvious uneven distribution of water resources in time and space.) rainfall accounts for more than 70% of the whole year, the non-flood season (October to March of the following year) has relatively little precipitation, and there is a seasonal water shortage in some areas; in terms of space, the eastern and southern mountains are relatively abundant, and the central and northern hilly plains are relatively poor. The medium and large hydropower stations in Hunan Province are mainly distributed in the Xiangjiang River, Yuanjiang River, Zijiang River and Lishui

River, and most of the other small and medium-sized hydropower stations are located in the tributaries of the four rivers. In recent years, hydropower resources in Hunan Province have been fully developed. As of 2022, there will be a total of 4,231 small hydropower stations in the province, with a total installed capacity of 6.26 GW and an average annual power generation of 19.8 TWh.

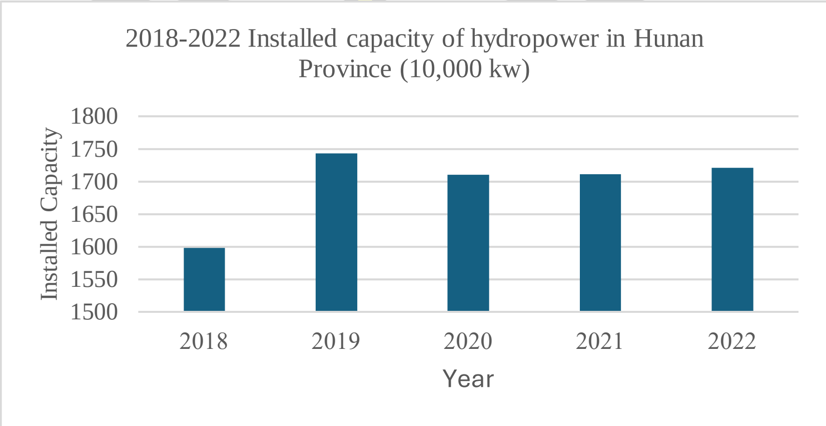


Figure 8 Statistics on installed capacity of hydropower in Hunan Province 2018-2022

(2) Wind energy development

Hunan Province is located in the south of China. Compared with the plains in the north, its geographical and climatic conditions may not be suitable for large-scale wind power development. However, with the advancement of technology and the promotion of renewable energy policies, Hunan Province has also made some progress in wind power generation. Some areas in Hunan Province have relatively rich wind energy resources, such as Western Hunan and Southern Hunan. In recent years, with the continuous maturity of wind energy technology and the active support of policies, the development of wind energy in Hunan Province has achieved remarkable results. The construction of wind farms continues to expand, the installed capacity of wind energy increases year by year, and the amount of wind power generation continues to increase, making positive contributions to the optimization of the energy structure. At the end of 2018, the installed capacity of wind power in Hunan exceeded 2.7 GW, and wind power generation was 5.10 TWH, a year-on-year increase of 15.7%. By the end of 2022, the installed capacity of wind power in the province will reach 9 GW.

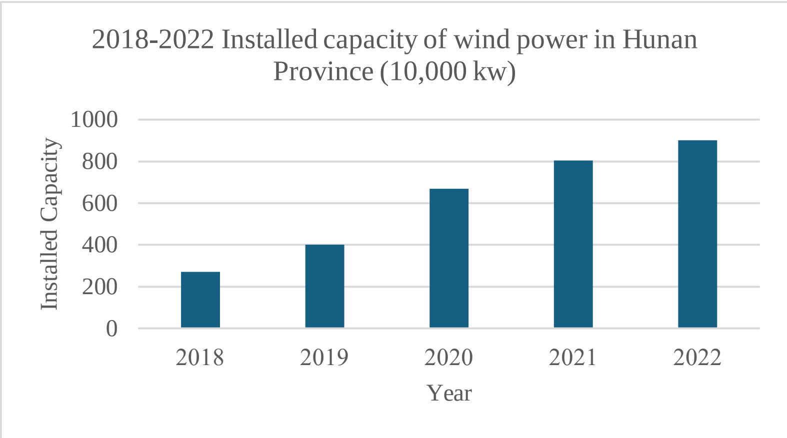


Figure 9 Statistics on installed capacity of wind power in Hunan Province (TWH)

(3) Solar energy development

In recent years, solar power generation has gradually emerged in Hunan. Distributed photovoltaic power plants have been promoted in rural areas and cities, converting solar energy into electricity and injecting new impetus into local energy supply. The government's incentive policies and technological progress have made solar power generation gradually commercialized, injecting new vitality into the development of renewable energy. Over the past five years, the installed capacity of solar power in Hunan Province has shown a steady growth trend. It has increased from 2.92 GW in 2018 to 6.36 GW in 2022, representing a significant increase.

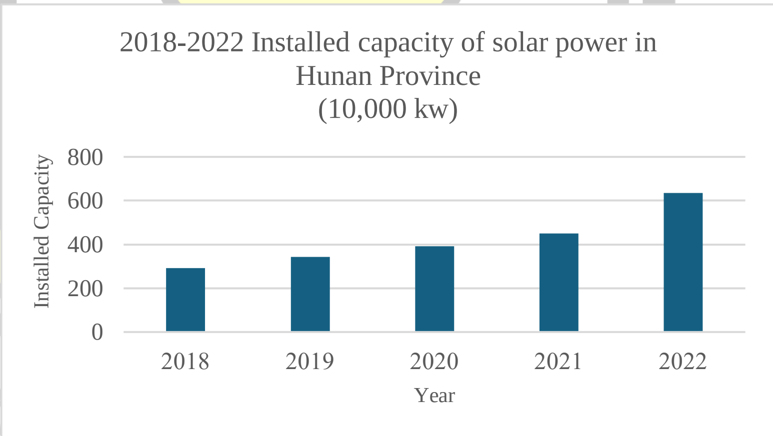


Figure 10 Statistics on installed capacity of solar power in Hunan Province (TWH)

(4) Biomass energy utilization

Hunan Province has developed agriculture and is rich in biomass resources such as crop straws. These resources have potential application prospects in the field of biomass energy. The use of biomass energy can not only reduce the pollution of rural domestic waste, but also add a clean choice to energy supply. In recent years, biomass power generation projects have gradually emerged to provide renewable energy support for rural areas.

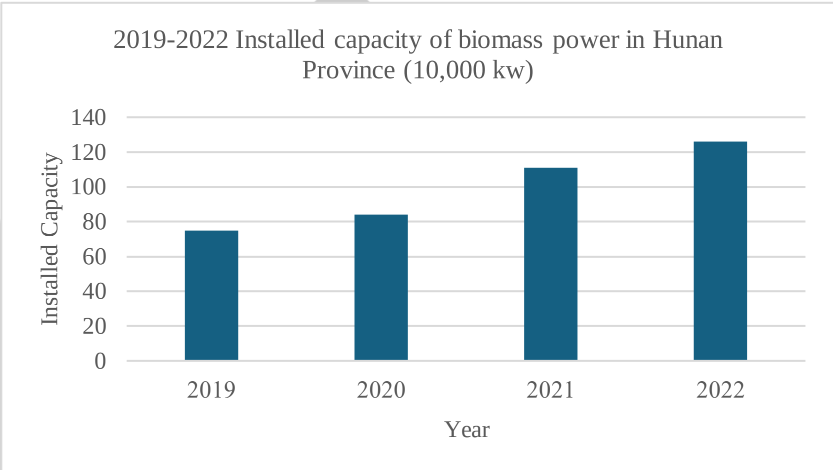


Figure 11 Statistics on installed capacity of biomass power in Hunan Province

To sum up, the development of Hunan Province in the field of renewable energy presents a positive trend. From water energy to wind energy, solar energy to biomass energy, various resources have been developed and utilized to varying degrees. The support of government policies, the promotion of technological innovation, and the increase in investment have jointly laid a solid foundation for the development of renewable energy in Hunan Province. However, we must also be aware that we still face challenges such as technical difficulties and market competition during the development process. In the future, the sustainable development of renewable energy in Hunan Province will require continuous optimization of policies, continuous improvement of innovation capabilities, and further improvement of the industrial chain.

2. Renewable Energy Policies and Targets of Hunan Province

In October 2021, the "Opinions of the Central Committee of the Communist Party of China and the State Council on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job of Carbon Peaking and Carbon Neutrality" was officially issued, 2030 and 2060 overall goals, and pointed out eight key strategies and three important safeguard measures.

Subsequently, the State Council issued the "Action Plan for Carbon Peaking by 2030", which further clarified the main goals at the national level during the two important transition periods of the "14th Five-Year Plan" and "15th Five-Year Plan", and clearly pointed out ten key tasks and forty-three Subdivided task blocks.

In the second half of 2022, according to the "Opinions of the Central Committee of the Communist Party of China and the State Council on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job of Carbon Neutrality for Peak Carbon Development" and the deployment requirements of the State Council's "Action Plan for Carbon Peak Before 2030", around The planning requirements of the "14th Five-Year Plan for National Economic and Social Development and the Outline of Long-term Goals for 2035" and "Implementation Opinions on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job of Carbon Neutrality at Peak Carbon" in each province , have formulated carbon peak implementation plans based on the actual situation in the province.

The vision of carbon neutrality puts forward higher and more urgent requirements for China's energy structure transformation, and the optimization and transformation of energy structure is an important condition and key measure to achieve the goal of carbon neutrality. In recent years, the Hunan provincial government has successively issued many energy policies to deal with energy and environmental crises, as shown in Table 5.

Table 5 Summary of policies and laws of renewable energy

Year	Laws, Policies, and Programs
2022	Notice from the Hunan Provincial Development and Reform Commission on the Implementation Plan for Promoting Green and Low-Carbon Transformation of Energy and Achieving Carbon Peak in Hunan Province [56]
2022	Notice from the Hunan Provincial People's Government on the Implementation Plan for Energy Conservation and Emission Reduction in the 14th Five-Year Plan in Hunan Province [57]
2022	Notice from the Hunan Provincial Development and Reform Commission on the Development Plan of Renewable Energy in the 14th Five-Year Plan in Hunan Province [12]
2021	Notice from the National Development and Reform Commission and the National Energy Administration on the Responsibility Weight of Renewable Energy Power Consumption in 2021 and Related Matters [58]
2021	Notice from the National Development and Reform Commission and the National Energy Administration on Encouraging Renewable Energy Generation Enterprises to Build or Purchase Peak Regulation Capacity and Expand Grid Connection Scale [59]
2020	Guiding Opinions of the National Energy Administration on the Implementation of the 13th Five-Year Plan for Renewable Energy Development [11]
2019	Notice from the National Development and Reform Commission and the National Energy Administration on Establishing and Improving Mechanisms to Ensure the Consumption of Renewable Energy Electricity [60]
2017	Notice from the Hunan Provincial Development and Reform Commission on the Thirteenth Five-Year Plan for Energy Conservation in Hunan Province

In July 2022, the Hunan Provincial Development and Reform Commission issued the "Hunan Province "14th Five-Year" Renewable Energy Development Plan", pointing out that Hunan Province should align with the overall national goals and combine our province's actual conditions to work hard during the "14th Five-Year Plan" period Realize the development goal of renewable energy "greater green contribution, wider application field, lower use cost, and better industrial structure". By 2025, the installed capacity of renewable energy power generation will reach about 44.5 million kilowatts, including 18 million kilowatts of hydropower and 26.5 million kilowatts of non-hydro renewable energy. The weight of renewable energy power consumption responsibility reaches about 18.5%, and non-fossil energy consumption accounts for more than 22% of the total primary energy consumption.

Table 6 Target for renewable energy capacity in Hunan in 2025

Energy type	2020	Target 2025
Hydropower (GW)	1710	1800
Wind power (GW)	669	1200
Solar power (GW)	391	1300
Biomass power (GW)	85	150
Energy consumption ratio per unit GDP (GW)	461.69	397.05
Share of Non-fossil in electricity generation (%)	10.70%	22%

In November 2022, the Hunan Provincial People's Government issued a notice on printing and distributing the "Carbon Peak Implementation Plan in Hunan Province". Significantly improved, the growth of coal consumption has been strictly and reasonably controlled, the construction of new power systems has been accelerated, new progress has been made in the research and development, promotion and application of green and low-carbon technologies, green production and lifestyles have been widely implemented, and the policy system for green and low-carbon circular development has been further improved. By 2025, the proportion of non-fossil energy consumption will reach about 22%, and the energy consumption per unit of regional GDP and carbon dioxide emissions will be reduced to ensure the completion of the national target and lay a solid foundation for achieving the goal of carbon peaking.

During the "15th Five-Year Plan" period, the province's industrial structure adjustment made significant progress, a clean, low-carbon, safe and efficient energy system was initially established, a low-carbon development model in key areas was basically formed, and the energy utilization efficiency of key energy-consuming industries reached the international advanced level. The proportion of energy consumption has further increased, key breakthroughs have been made in green and low-carbon technologies, green lifestyles have become a conscious choice of the public, and the policy system for green, low-carbon and circular development is basically sound. By 2030, the proportion of non-fossil energy consumption will reach about 25%, the reduction of energy consumption and carbon emissions per unit of regional GDP will meet the national targets, and the goal of carbon peaking before 2030 will be successfully achieved.

III. 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 7. 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.

Table 7 Key scenario descriptions

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.
Medium Scenario (MED)	(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.
High Scenario (HIG)	(1) GDP growth rate, population, and industrial structure are further optimized based on medium- and long-term policies and MED. (2) The proportion of the third industry increased based on MED. (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.

(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) Medium 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) High 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.

IV. 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) [61]. According to the Hunan Provincial Government Work Report [62], 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 MED 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 [63]. Under the HIG 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 [61]. To alleviate the population crisis, Hunan Province has implemented a three-child policy [64], 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 [65] , 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 [8] . 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 [66] , regression analysis [67] , and the energy consumption per unit of output method [68] . 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 [69], by 2035, the proportion of consumption in the tertiary sector in the MED and HIG 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 MED scenario, which considers the medium-term planning objectives of the 14th Five-Year Plan. The HIG 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 energy storage, and hydrogen 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 8.

Table 8 Renewable energy capacity scenarios target for 2035

Module	Context	Year	Scenario		
			BAS	**MED**	**HIG**
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 13,000MW	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.
	Hydro Capacity (MW)	2035	Increase to 17,000 MW	Refer to BAS	Refer to BAS
Storage target	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.

Module	Context	Year	Scenario		
			BAS	MED	HIG
	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

5. Other Key Data

Detailed data on the electricity load curve for Hunan Province is sourced from the China Electricity Council [8]. The emission factors for CO2 generated by the consumption of various energy types in the electricity sector are primarily derived from Bofeng et al. (2023) and the Asia and China-specific data in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report Scenario Database [70]. 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 9 Related energy coefficient table

Energy type	Standard coal conversion factor	Carbon Emission factor
Raw coal	0.7143	1.9003
Coke	0.9174	2.8604
Crude	1.4286	3.0202
Kerosene	1.4714	3.0179
Diesel fuel	1.4571	3.0959
Gasoline	1.4714	2.9251
Fuel oil	1.4286	3.1705
Natural gas	1.3300	2.1622

V. Expected outputs

In this research, we present the anticipated outcomes of utilizing LEAP model to investigate the effects of varying renewable energy installed capacities on electricity generation, energy mix, reduction in fossil fuel consumption, and CO2 emissions in Hunan Province. The outputs discussed in this chapter are crucial for understanding the potential benefits and challenges associated with different renewable energy integration scenarios.

1. Future Electricity Generation

One of the primary expected outputs of this study is the projection of future electricity generation under different renewable energy capacity scenarios. By simulating the implementation of various renewable energy sources such as solar, wind, hydroelectric, and biomass, we will obtain insights into how each scenario contributes to the overall electricity generation capacity of Hunan Province. This analysis will help policymakers and stakeholders to anticipate the energy supply-demand dynamics and to formulate strategies for reliable and sustainable electricity generation.

2. Impact on Energy Mix

The study will also yield valuable information regarding the potential changes in the energy mix of Hunan Province based on different renewable energy capacity scenarios. The LEAP model will enable us to quantify the proportion of energy contributed by each renewable source and compare it with the contributions from conventional sources like coal, natural gas, and oil. This assessment will shed light on the diversification of the energy portfolio and the progress towards a cleaner and more sustainable energy mix.

3. Reduction in Fossil Fuel Consumption

An essential expected outcome of this research is the assessment of the reduction in fossil fuel consumption as a result of increased renewable energy integration. By contrasting scenarios with higher and lower renewable energy capacities, we can quantify the displacement of fossil fuel-based electricity generation. This information is crucial for understanding the potential decrease in dependence on finite and environmentally harmful resources, contributing to the province's energy security and reduced exposure to fuel price volatility.

4. CO2 Emission Impact

One of the most critical outcomes of this study is the estimation of the impact of different renewable energy capacity scenarios on carbon dioxide (CO2) emissions. The LEAP model allows us to calculate the CO2 emissions associated with each energy source and scenario, enabling a comprehensive assessment of the potential reductions in greenhouse gas emissions. This analysis will provide empirical evidence of the contribution of renewable energy to mitigating climate change and achieving regional emission reduction targets.

5. Policy Implications

The expected outputs will have profound implications for energy and environmental policies in Hunan Province. The insights gained from this research can guide policymakers in formulating strategies to promote renewable energy development, enhance energy security, and reduce carbon emissions. The results can serve as a foundation for designing incentives, targets, and regulations that accelerate the transition to a more sustainable energy system.

Chapter 4 Results and Discussion

I. Energy Demand

The energy demand projection data is shown in Figure 12, 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 MED and the HIG 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 MED and HIG 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 HIG, 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.

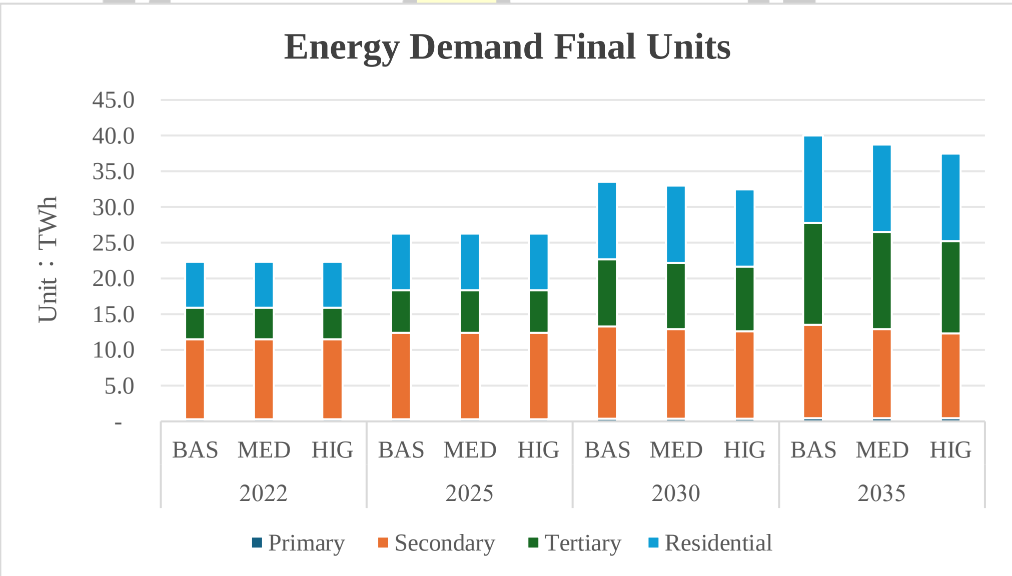


Figure 12 Electricity demand by sectors from 2022 to 2035

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 13. 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%. MED and HIG 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 MED and 9.0% under HIG. 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.

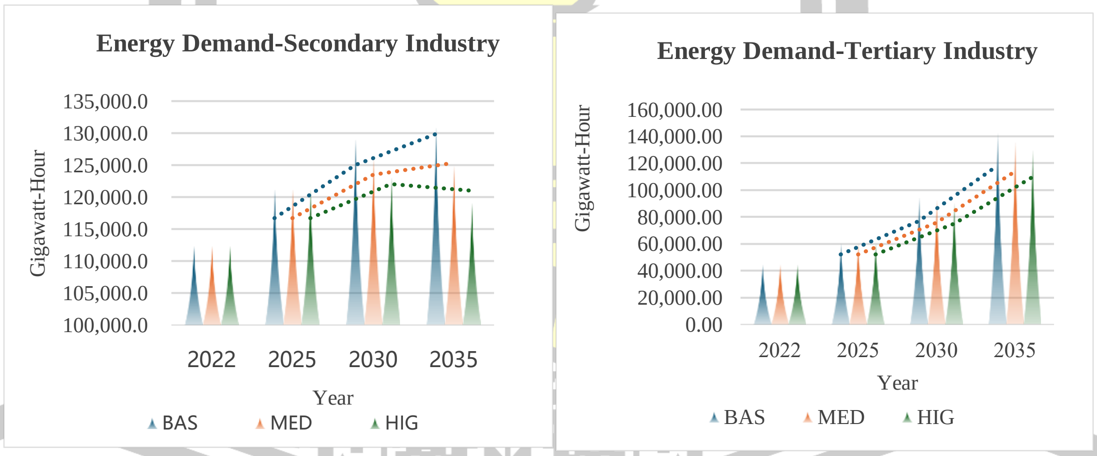


Figure 13 Trends in Electricity Demand for the Secondary and Tertiary Sectors under Different Scenarios

II. Electricity Generation and Capacity Mix

By analyzing the installed capacity and electricity generation data under the three scenarios (BAS, MED, and HIG), as shown in Figures 14 and 15, 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 (MED), and 375 TWh (HIG) by 2035. Although total electricity generation would be the lowest under the HIG 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 HIG scenario would exhibit significantly higher total installed capacity compared to BAS and MED, 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 MED 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 HIG 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.

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 MED scenario and further to 95.9 TWh in the HIG 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, MED, and HIG 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 HIG (Automated Power System) scenario. By 2035, pumped storage generation capacity is expected to increase to 36.8 TWh and 40.4 TWh in the MED and HIG 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 MED and HIG 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. By 2035, electrochemical storage capacity in the HIG 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, MED, and HIG 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 HIG 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 HIG scenario would offer enhanced carbon reduction capabilities and energy efficiency, providing a clear pathway toward achieving carbon peaking and neutrality goals.

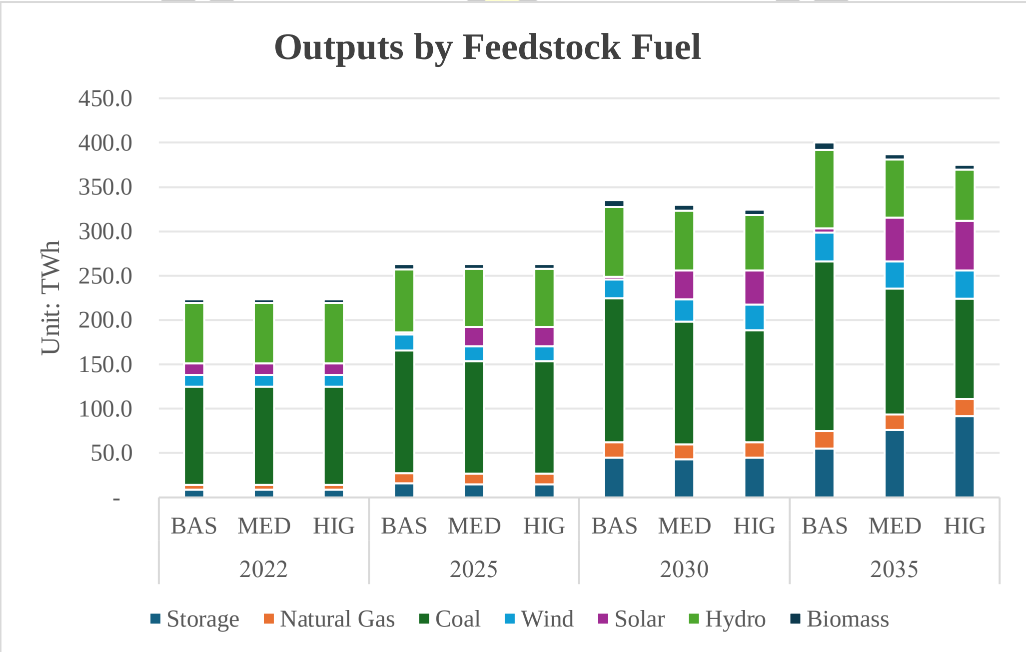
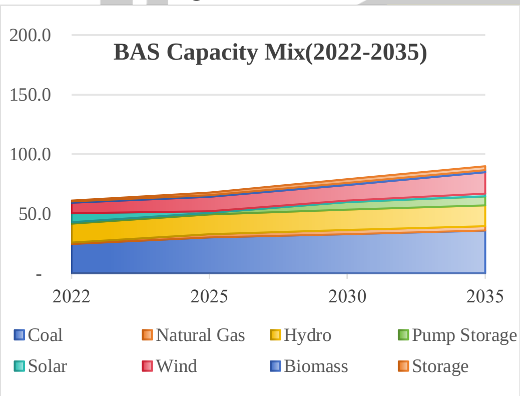
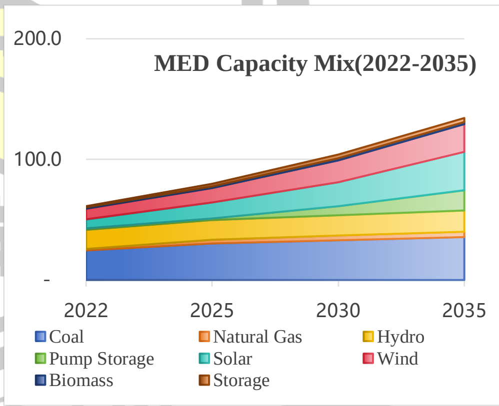


Figure 14 Power generation under three scenarios from 2022 to 2035





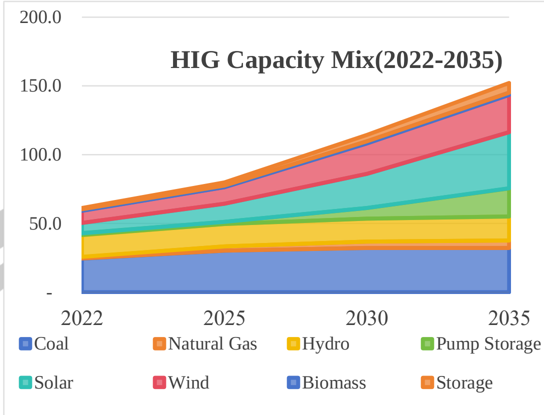
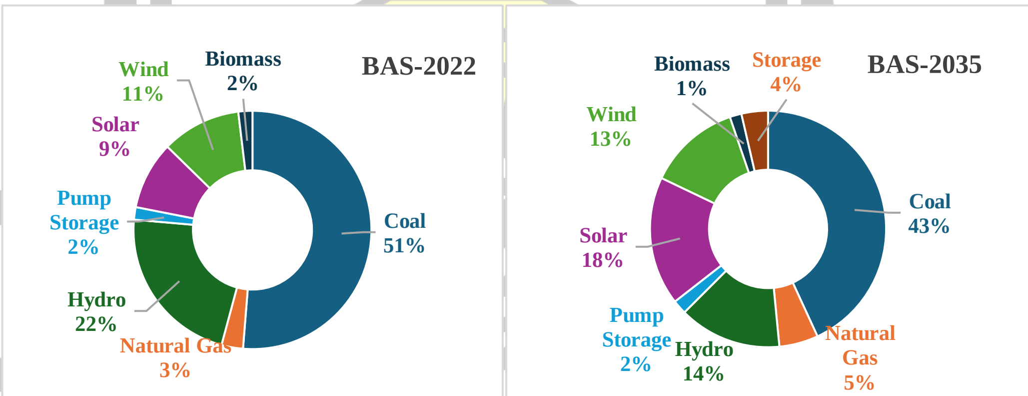
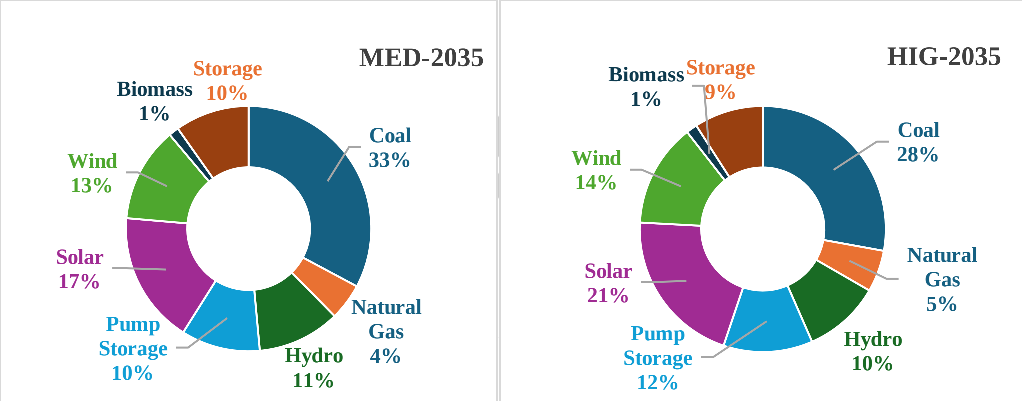


Figure 15 Installed capacity change under three scenarios from 2022 to 2035

By analyzing 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 MED and HIG 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) MED-2022 (d) HIG-2035

Figure 16 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% (MED), and 21% (HIG). Wind power would grow steadily from 10% in 2022 to 13% (BAS and MED) and 14% (HIG) by 2035. Hydropower, which accounted for 22% of total electricity generation in 2022, would decline to 14% (BAS), 11% (MED), and 10% (HIG) 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 MED and HIG 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 HIG 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.

III. Fossil fuel consumption in electricity sector

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 (MED and HIG). 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 (MED), 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 (HIG), 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 HIG 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 10 Consumption of fossil fuels for electricity generation over the period 2022–2035

Year	BAS	Change from BAS Scenario (KTOE)	
		MED	HIG
2022	8,782.90	-	-
2030	13,470.00	-2535.1(16.4%)	-3151.6(21.3%)
2035	14,821.70	-4436.1(22.8%)	-6222.6(33.4%)

IV. Carbon Emissions

The total CO2 emissions and trends for the Hunan electricity sector under the three scenarios are shown in Figure 17. In the BAS and MED 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 MED Scenario, CO2 emissions would peak in 2033 at 103.4 million tons. The HIG 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 HIG scenario would be able to achieve carbon peaking by 2030 for Hunan's power system compare to MED and BAS scenario. Therefore, this study recommends the High Scenario (HIG) as the prioritized path for low-carbon development in the Hunan electricity sector.

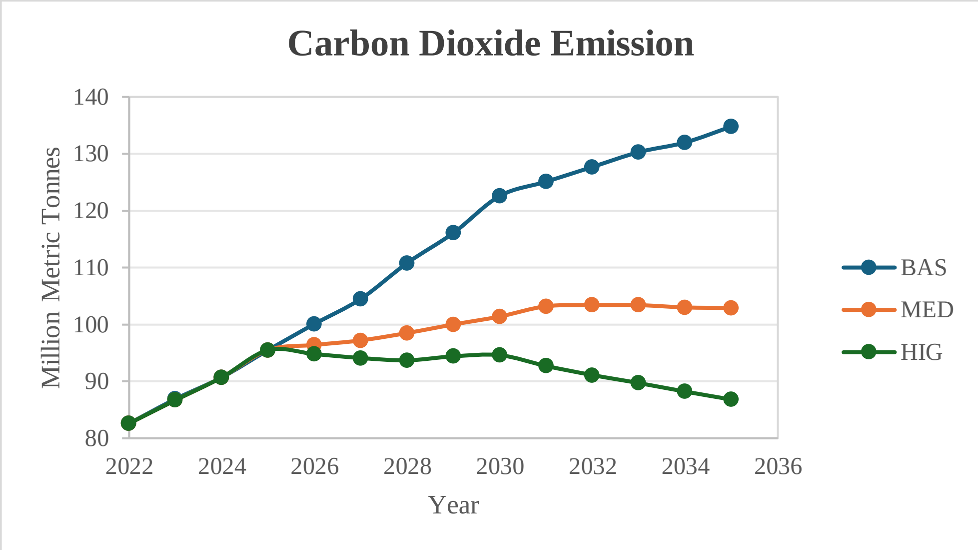


Figure 17 CO_2 Emission Results under three Scenarios

Table 11 compares the CO_2 emissions under different scenarios, in the MED, it is expected that by 2030, CO_2 emissions would be reduced by approximately 28 million tons compared to BAS and by 6.8 million tons compared to the HIG. By 2035, the HIG scenario would have CO_2 emissions reduced by approximately 48 million tons compared to BAS and by 16.1 million tons compared to the MED.

Table 11 CO_2 emissions from electricity generation over the period 2022– 2035

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

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 18. 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.

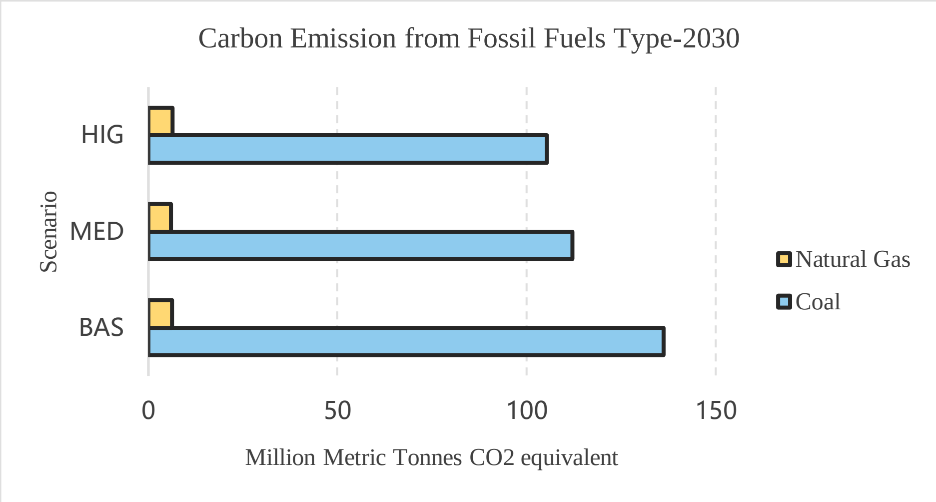


Figure 18 Carbon Emission Structure

V. PM2.5

Table 12 indicates that PM2.5 under the BAS scenario are projected to rise from 10,057 tonnes in 2022 to 16,789 tonnes in 2035. In 2030, the PM2.5 in the MED and HIG scenarios emissions will be 641 tonnes and 2,193 million tonnes lower than emissions in the BAS scenario respectively. In 2035, the PM2.5 in the MED and HIG scenarios will be 1,049 tonnes and 3,567 tonnes lower than emissions in the BAS scenario, respectively. PM2.5, consisting of fine particulate matter smaller than 2.5 micrometers, poses significant health risks when inhaled. These particles can penetrate deep into the lungs and enter the bloodstream, leading to respiratory and cardiovascular problems such as asthma, bronchitis, and heart disease. The results from the table indicate that there are differences in PM2.5 among different scenarios. In 2030 and 2035, the PM2.5 under the MED Scenario and HIG Scenario are lower than those under the BAS Scenario. There are differences in PM2.5 emissions among different scenarios. In 2030 and 2035, the PM2.5 under the MED Scenario and HIG Scenario are both less than those under BAS Scenario. This suggests that in the coming years, adopting different policies and measures will have a significant impact on PM2.5, and increasing renewable energy generation will effectively control and reduce PM2.5 emissions from electricity generation, benefiting the environment and human health.

Table 12 PM2.5 emissions from electricity generation over the period 2022– 2035

Year	BAS	Change from BAS Scenario (Tonnes)	
		MED	HIG
2022	10,057	-	-
2030	14,201	-641 (-4.5%)	-2,193 (-15.4%)
2035	16,789	-1,049 (-6.2%)	-3,567 (-21.2%)

VI. SO2 emissions

Table 13 illustrates that SO2 emissions in the BAS scenario are projected to rise from 1,854.3 thousand tonnes in 2022 to 3,095.6 thousand tonnes in 2035. In 2030, the SO2 emissions in the MED and HIG scenarios would decrease 119.1 thousand tonnes and 404.9 thousand tonnes comparing to BAS scenario, respectively. In 2035, the SO2 emissions in the MED and HIG scenarios would reduce 193.5 thousand tonnes and 657.8 thousand tonnes comparing to BAS scenario, respectively. SO2 is a major air pollutant, and it is one of the main precursor substances that lead to the formation of acid rain. Acid rain causes great harm to soil, water bodies, and vegetation, further affecting human health. From the results, reducing the use of fossil fuels and promoting the transition of the energy industry to cleaner forms of energy can help reduce SO2 emissions and have significant benefits for the energy sustainability of the region.

Table 13 SO2 emissions from electricity generation over the period 2022– 2035

Year	BAS	Change from BAS Scenario (Thousand Tonnes)	
		MED	HIG
2022	1,854.3	-	-
2030	2,618.2	-119.1 (-4.5%)	-404.9 (-15.5%)
2035	3,095.6	-193.5 (-6.3%)	-657.8 (-21.2%)

VII. 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 analysis focused on three critical variables: economic growth, the advancement rate of renewable energy technologies, and the carbon emission factors of coal and gas power generation. Variations in these parameters were used to assess their impacts on energy demand, renewable energy deployment, and carbon emissions under the BAS, MED, and HIG scenarios. Firstly, GDP was adjusted by ±2% to simulate economic uncertainty. The results indicate that higher economic growth increased overall energy demand by 11.9% in 2035, whereas lower growth reduced it by 22%. This directly influenced the share of renewable energy. In the BAS scenario, higher GDP growth exacerbated dependence on fossil fuels. Conversely, under the HIG scenario, stronger policy interventions maintained a balanced energy structure despite economic fluctuations. Secondly, the advancement rate of renewable energy technology efficiency was adjusted by 7% to reflect potential technological progress or delays. Faster efficiency improvements led to a 4.5% increase in renewable energy generation by 2035, enabling earlier carbon peaking under the HIG scenario. In contrast, delays in technological progress slowed renewable energy adoption, significantly increasing reliance on transitional energy sources such as natural gas. Thirdly, the carbon emission factors of coal and gas power were reduced by 1% annually to assess their impact on overall carbon emissions. Lower emission factors resulted in a cumulative CO2 reduction of approximately 12.1%, highlighting the critical role of cleaner coal technologies and improved operational efficiency in emissions reduction. The sensitivity analysis underscores the importance of timely technological progress and consistent policy implementation in achieving low-carbon transition goals. Moreover, the findings reveal that the HIG scenario demonstrates greater resilience to parameter variations, maintaining the trajectory toward carbon neutrality even amid fluctuations in input assumptions. These results highlight the necessity of formulating adaptive energy strategies to effectively address uncertainties.

This study offers valuable insights into the optimization of Hunan Province's power industry under carbon emission constraints; however, several limitations should be acknowledged. First, as a bottom-up framework, the LEAP-Hunan model is highly dependent on the availability and precision of input data. Key parameters, including policy shifts, technological advancements, future energy prices, and technology costs, involve significant uncertainties that may influence the robustness of the findings. Second, the analysis does not explicitly incorporate potential disruptions, such as extreme weather events or global economic fluctuations, which could substantially affect energy demand and supply dynamics. Lastly, while the study integrates demand-side reforms, renewable energy deployment, and energy storage systems, it does not thoroughly examine the socio-economic implications of these transitions. Future research addressing these limitations could enhance the applicability and reliability of the results, providing a more comprehensive foundation for policy development.

VIII. Policy Implications

This section explores the challenges and corresponding strategies that Hunan Province faces during its green power transition. Although focused on Hunan, the study's findings and strategies also apply to other regions in China and globally, especially in rapidly transforming power systems with growing demand. Based on previous analysis, to ensure the peak of Hunan's power system is reached as quickly as possible, a combined pathway of "Integrated Model of Demand-Side Reform, Energy Storage, and Renewable Energy" must be implemented. While this model can effectively accelerate carbon peaking, the integration of large-scale renewable energy sources, distributed generation, and interactive devices into the grid introduces a series of complex challenges.

Firstly, the safe operation of the power system is under severe pressure. Located in southern-central China, Hunan Province has experienced significant changes in the dynamic characteristics of its power system as a result of renewable energy development. Notably, wind and solar power are subject to considerable fluctuations, which can impact grid frequency and voltage stability [71]. Under extreme climatic conditions, large-scale renewable energy variability can lead to unstable grid frequency and voltage, challenging traditional stability analysis and control theories. Therefore, Hunan Province must accelerate theoretical research and technological innovation to enhance grid emergency response capabilities and stability, ensuring the power system can cope with increasingly complex operating environments.

Secondly, the reliable supply of electricity faces new challenges. The variability and intermittency of renewable energy make electricity scheduling and operation increasingly complex, especially during the winter and summer "dual-peak" demand periods, when electricity demand often exceeds supply capacity. Although traditional thermal power and hydropower can balance supply during peak periods, the large-scale integration of renewable energy has strained peak regulation capabilities, leading to frequent wind and solar energy curtailments. To address this, Hunan Province should strengthen the construction of energy storage facilities, deploy flexible power sources, and improve grid scheduling mechanisms to ensure electricity 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 [72]. 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 [73]. 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 startup 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 microgrids, 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 microgrid 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 strategies aim to reduce CO2 emissions significantly and support the path toward zero-carbon energy. Hunan should implement carbon governance mechanisms by leveraging the national carbon trading market. Strengthen carbon accounting, reporting, and product footprint systems to improve transparency and efficiency. Establish a robust market trading mechanism to incentivize CO2 reduction through market-based mechanisms, supporting innovation and regulatory reforms in the electricity sector. These efforts are vital to achieving China's carbon peak and carbon neutrality goals.

Chapter 5 Conclusions

This study offers a comprehensive analysis of the impact of renewable energy generation on Hunan Province's power industry from 2022 to 2035, with a focus on key dimensions such as electricity production, fossil fuel consumption, and emissions of pollutants like PM2.5, CO_2, and SO_2. Through the use of the LEAP-Hunan model, this research takes a region-specific approach, addressing the unique energy structure, policy landscape, and resource limitations of Hunan Province. The findings not only contribute to the current body of knowledge in the field of power system optimization but also provide actionable insights that are relevant to regions with similar challenges in energy transition.

One of the major contributions of this study lies in its methodological approach, which addresses a critical research gap: the representation of resource-constrained regions in the modeling of energy transitions. This gap has been largely overlooked in existing research, where much of the focus has been on large, more economically developed regions with more accessible resources and infrastructure. By leveraging the LEAP-Hunan model, this study provides a nuanced, region-specific analysis that can serve as a valuable reference for other regions facing similar constraints. The study's findings emphasize that energy transition strategies must consider not only the availability of renewable resources but also the unique resource constraints, infrastructure capabilities, and economic and policy environments that shape energy systems at the regional level.

The study's focus on demand-side reforms is another critical aspect that differentiates it from more conventional studies. In many studies of power system optimization, the emphasis is placed primarily on supply-side solutions, such as increasing the share of renewable energy generation or improving grid flexibility. However, demand-side measures, including energy efficiency improvements and flexible demand-side management, are often overlooked. This study highlights the importance of these strategies, demonstrating that they are essential to complementing the integration of renewable energy and the deployment of energy storage technologies. By enhancing energy efficiency on the demand side, it is possible to reduce overall consumption, lower the strain on the power grid, and further reduce carbon emissions. Flexible demand-side management, such as demand response programs, can also help stabilize the grid during periods of high renewable energy generation or high demand, thus making the integration of renewables more feasible.

Furthermore, this research rigorously evaluates the integration of renewable energy sources with energy storage technologies—an area that remains underexplored in the existing literature on power system optimization. Renewable energy sources, especially wind and solar power, are inherently intermittent, with their output fluctuating based on weather conditions. This intermittency presents a significant challenge to grid stability and reliability. The study emphasizes that energy storage technologies, such as batteries or pumped hydro storage, play a vital role in mitigating this issue. By storing excess energy generated during periods of high renewable energy production, energy storage systems can ensure that there is a reliable supply of electricity during periods of low renewable output. The combination of renewable energy generation and energy storage technologies thus presents a promising solution to enhance grid stability and reduce reliance on fossil fuels.

To address challenges such as renewable energy intermittency and grid flexibility, the study proposes several strategic recommendations. First, optimizing the operation of clean coal power plants can provide the necessary backup power when renewable generation is insufficient. While coal power is traditionally associated with high carbon emissions, clean coal technologies, such as carbon capture and storage (CCS), can significantly reduce these emissions, making coal a more sustainable option in the short to medium term. Second, the development of natural gas as a flexible backup resource is recommended. Natural gas plants have lower carbon emissions than coal and can ramp up or down quickly in response to fluctuations in renewable energy generation, providing the necessary grid flexibility. Finally, the integration of smart grids, which use digital technologies to improve the monitoring, control, and optimization of the grid, is essential. Smart grids enable better coordination between renewable energy sources, energy storage systems, and flexible backup resources, ensuring a more efficient and reliable power system.

The findings of this study also highlight the importance of enhanced policy support and new market mechanisms in facilitating the transition to a low-carbon energy system. Policies that support renewable energy generation, energy efficiency, and the deployment of energy storage technologies are crucial for achieving carbon reduction goals. The study recommends that policymakers focus on creating an enabling environment for these technologies to thrive, through financial incentives, regulatory frameworks, and long-term planning. In addition, new market mechanisms, such as carbon pricing, capacity markets, and flexible electricity trading systems, are necessary to ensure that the costs and benefits of renewable energy, energy storage, and grid flexibility are properly reflected in market prices. Such mechanisms can help drive investments in clean energy technologies and create a more sustainable and economically efficient energy system.

Looking forward, there are several important avenues for future research that can build upon the findings of this study. First, there is a need to improve the power transition model by incorporating multi-scale modeling techniques. These techniques can help optimize input parameters, reduce uncertainty, and improve the accuracy of long-term projections. A multi-scale model could integrate regional, national, and global factors, providing a more comprehensive analysis of the impact of renewable energy integration on the power system. Additionally, incorporating advanced technologies such as hydrogen energy, clean coal, and energy storage into the modeling process would allow for a more holistic assessment of their potential role in achieving a low-carbon energy system.

Second, future research should explore the integrated application of advanced technologies to balance economic feasibility with sustainability. Technologies like clean coal, hydrogen energy, and large-scale energy storage hold great promise but also face significant economic and technical challenges. Investigating the synergies between these technologies and evaluating their potential in different contexts will be crucial for identifying practical pathways to a low-carbon energy future. This could involve analyzing the costs, performance, and scalability of these technologies, as well as assessing the potential for their widespread deployment in regions like Hunan.

Third, it is essential to consider the impact of extreme weather events and global economic fluctuations on energy systems. Climate change and economic volatility pose significant risks to the stability of energy systems, particularly in regions with high reliance on renewable energy. Future research could focus on modeling these risks and developing strategies for building resilience into energy systems, ensuring that they can continue to function effectively under challenging conditions. Moreover, expanding research on inter-regional energy collaboration could provide valuable insights into how neighboring regions can share resources and manage renewable energy variability more effectively, contributing to a more resilient and integrated power system.

In conclusion, this study provides valuable insights into the potential impacts of renewable energy generation on Hunan Province's power industry, offering practical recommendations for improving the sustainability and reliability of the region's energy system. By emphasizing demand-side reforms, energy storage integration, and flexible grid solutions, this research contributes to the growing body of literature on power system optimization and provides a roadmap for regions facing similar challenges in their transition to a low-carbon future. Through continued research and policy development, Hunan and other regions can achieve their energy transition goals while ensuring a stable, sustainable, and economically viable power system for the future..

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