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Renewable energy strategy impacts on electricity system and carbon emissions in Hunan Province of China

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Abstract: This study investigates the impact of increasing renewable energy capacity on the power industry in Hunan Province, China, focusing on power demand, electricity generation, and CO2 emissions reductions. Using the Low Emission Analysis Platform (LEAP) model, five scenarios (BAU, RES, HEF, HST, and COP) were developed to assess the effects of renewable energy strategies from 2022 to 2035. The analysis considered renewable energy growth, energy storage, and efficiency improvements. The Comprehensive Optimization Scenario (COP) emerged as the most optimal, achieving a 48% share of renewable energy, 17% energy storage, and 23% efficient coal use, leading to significant CO2 emissions reductions while ensuring system flexibility and reliability. The study concludes that the COP scenario is the most effective in supporting a low-carbon transition and maintaining energy security. Practical implications include the need for policy support in areas such as diversified energy storage, distributed energy systems, V2G/V2X technologies, and smart grid development to enhance renewable energy integration and ensure sustainable development in Hunan.

Keywords: *CO2 Emissions Energy policy, Power system prediction, Renewable energy planning, Scenario analysis.*

1. Introduction

Energy and environmental challenges are major global issues. To address these crises and promote sustainable development, China is advancing renewable energy initiatives aimed at reducing carbon emissions and mitigating pollution. Hunan Province, which has limited energy resources, has experienced rapid economic growth and population increases since 2015, leading to a significant rise in electricity consumption. From 2015 to 2022, electricity consumption in Hunan grew by 54.5%, outpacing the growth of electricity generation. This disparity resulted in a low self-sufficiency rate and increased reliance on imported electricity. By 2021, the gap between generation and consumption had reached 496 GWh [1]. Hunan's electricity generation is heavily dependent on coal, with thermal power accounting for 61.39% of the total in 2022, followed by hydropower, wind, and solar. The continued use of fossil fuels has contributed to rising carbon emissions and worsened air pollution. Between 2015 and 2020, carbon emissions in Hunan's energy sector grew at an average annual rate of 1.53%, with fossil fuel combustion responsible for about 95% of emissions in 2020 [2]. In response to these challenges, Hunan has been expanding renewable energy generation. Guided by national policies, the provincial government aims to reduce dependence on fossil fuels and promote clean energy. The 13th Five-Year Plan (2017) set targets to control energy consumption growth and reduce energy consumption per unit of GDP [3]. The 14th Five-Year Plan for Renewable Energy, released in 2022, set a goal of 44.5 GW in renewable energy capacity by 2025, with 18 GW from hydropower and 26.5 GW from non-hydro sources, aiming for 18.5% renewable energy consumption [4]. By 2030, the province plans to increase

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clean energy capacity to 40 GW, with wind and photovoltaic power becoming the primary generation sources. Non-fossil fuel energy is expected to account for 63% of the total capacity [5].

In the context of the global energy transition, Hunan Province, representing central China, plays a pivotal role in energy structure adjustment and low-carbon development. Although the province has made significant achievements in economic and social development in recent years, its energy structure is still heavily dependent on coal-fired power, resulting in increasing energy security risks and carbon emissions. At present, the development of renewable energy in Hunan remains relatively limited, with coal-fired power continuing to dominate electricity generation. This situation has led to substantial carbon emissions and air pollution, highlighting the urgent need for effective energy transition strategies. To address these challenges, this study designs five scenarios (BAU, RES, HEF, HST, COP) tailored to Hunan's specific circumstances, aiming to systematically analyze the comprehensive impacts of renewable energy development strategies on electricity demand, power generation structure, energy security, and CO_2 emission reduction potential in the province.

Numerous studies have employed various power generation and energy demand modeling tools for assessments in different regions. Some investigations have analyzed electricity generation from renewable energy sources by considering socio-economic and technological factors [6]. Several research endeavors have concentrated on energy pricing and energy security Salite, et al. [7]. Sweeney, et al. [8] highlighted the significance of probabilistic forecasting for wind and solar energy in conjunction with user-customized products, while AlKandari and Ahmad [9] proposed an integrated deep learning model to enhance the accuracy of solar power forecasting. Additionally, multiple researchers have directed their attention toward policy analysis. For instance, Chen, et al. [10] elucidated the role of renewables in mitigating China's CO_2 emissions, and subsequent studies by Zou, et al. [11] and Hu, et al. [12] utilized the LEAP model to investigate regional carbon peaking strategies. On an international scale, Misila, et al. [13] and Amo-Aidoo, et al. [14] explored renewable energy adoption in Thailand and Ghana, respectively, providing valuable insights for developing nations. Furthermore, Li, et al. [15] examined cross-province electricity trade emissions within China, while Salem, et al. [16] and Zhou, et al. [17] proposed a combined forecasting model for the electricity consumption in Hunan Province. Despite the extensive body of research focusing on renewable energy generation assessments across various regions, the majority of these studies emphasize generation technologies and single-factor analyses. Consequently, a systematic examination of the comprehensive impacts of renewable energy policies on power system operations, the dynamics of carbon emissions, and regional energy transitions in Hunan Province remains insufficiently addressed. Through a multidimensional analysis of different scenarios, this study reveals the impact of renewable energy policies on power system operations under varying technological developments and market conditions, providing theoretical support for optimizing energy policies. The innovations of this study are reflected in the following aspects:

(1) This study considers three dimensions-policy, technological progress, and market changes-integrating them into a multi-scenario analysis framework. This approach provides a systematic method for the comprehensive evaluation of regional power system development.

(2) The study explores the transitional role of coal power in the energy transition process, emphasizing its importance in ensuring energy security. This helps policymakers find a balance between accelerating energy transformation and maintaining energy security.

(3) The research investigates the key role of energy storage technologies in enhancing grid flexibility and promoting renewable energy integration. It further reveals how energy storage improves the stability of the power system and the efficiency of renewable energy utilization.

(4) Based on the energy characteristics and development needs of Hunan Province, this study designs scenario analyses tailored to the region. The findings not only have local applicability but also provide valuable insights for energy development in central China.

(5) This study provides quantitative analysis to guide government policies for low-carbon energy development, helping to formulate more scientific and rational policy measures. This can contribute to

achieving the goal of efficient, secure, and low-carbon energy development in Hunan Province and central China.

Through in-depth analysis and scenario forecasting, this study aims to provide theoretical support for optimizing energy policies in Hunan Province, aiding the implementation of energy transition and low-carbon development strategies.

2. Materials and Methods

2.1. Low Emission Analysis Platform (LEAP) Model

Various methodologies have been employed in the literature to evaluate energy and environmental impacts, encompassing econometric modeling, gray system theory, artificial neural networks, scenario analysis, combined forecasting, and other approaches. For instance, Chen, et al. [18] proposed an autoregressive model to predict gas flow. Ceribasi, et al. [19] employed the IPAT model to analyze the effect of climate change on the energy produced by hydroelectric power plants. Hu and Wang [20] applied a neural-network-based gray forecasting approach to predict electricity consumption. Among these methods, such as those presented in Zheng, et al. [21]; De Marcos, et al. [22] and Raihan, et al. [23] econometric models grounded in economic theory reveal the relationship between human activities and energy consumption; however, they tend to overlook the non-economic factors influencing energy consumption, such as technological innovation and policy changes. Moreover, while gray system models have been utilized for energy prediction research, as demonstrated in Moonchai and Chutsagulprom [24]; Khan and Osińska [25] and Ding, et al. [26] they are often inadequate for addressing complex nonlinear systems and external disturbances. The scenario analysis model is widely employed to assess the impacts of policy and technological changes on energy systems by constructing diverse scenarios. The LEAP model, a scenario-based analysis model, stands out as a robust and adaptable software system that is used for integrated energy planning and evaluating climate change mitigation strategies. The LEAP model has been employed in several studies to assess energy and environmental impacts, as detailed in Rivera-González, et al. [27]; Wang, et al. [28]; Masoomi, et al. [29]; Ren, et al. [30] and Wattana, et al. [31]. The flexibility and comprehensiveness of the LEAP model render it a crucial tool in energy-related research and decision-making.

This paper utilizes the LEAP scenario analysis tool to assess the impacts of increased renewable energy generation on the electricity generation industry and the environment in Hunan Province. The model can be subdivided into multiple layers, each involving different sets of data. Figure 1 shows the structure of the LEAP analysis framework and model for Hunan Province. The primary outputs of the model include energy demand prediction, electricity generation by different energy types, energy CO_2 emission and sensitivity analysis.

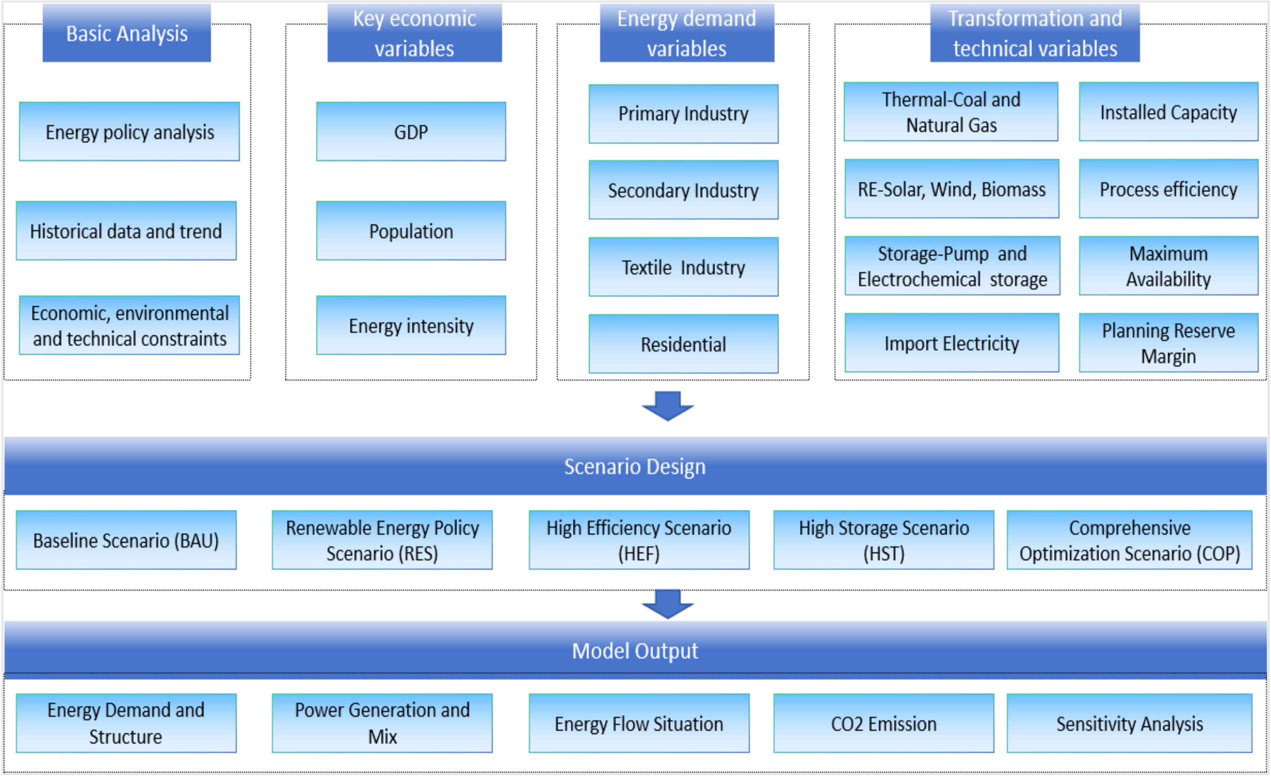


Figure 1.
LEAP framework and model.

2.2. Scenario Development

This study designs five scenarios (BAU, RES, HEF, HST, COP) to comprehensively analyze the potential impacts of renewable energy strategies on electricity generation in Hunan, considering varying levels of renewable energy development, energy storage enhancement, and efficiency improvements. The scenarios also take into account the role of coal-fired power in ensuring energy security. The descriptions of the scenarios are shown in Table 1, and detailed experimental capacity data for different scenarios are shown in Appendix Table A1.

- Baseline Scenario (BAU): This scenario assumes that current policies and technologies remain unchanged, with electricity demand continuing to grow. Under this scenario, the limited increase in renewable energy capacity means coal-fired power will continue to play a key role in balancing the electricity supply and demand. This represents a "business-as-usual" trajectory without significant policy or technological interventions.
- Renewable Energy Policy Scenario (RES): This scenario emphasizes a significant increase in wind and solar power generation capacity, in line with government medium- and long-term plans, aiming to reduce dependence on coal-fired power. While renewable energy capacity grows, there are no substantial improvements in energy storage or efficiency, leading to a reduced but still present reliance on coal power.
- High Efficiency Scenario (HEF): The focus of this scenario is on improving the efficiency of both coal-fired and renewable energy generation. By reducing coal consumption per unit of electricity, the overall system efficiency is enhanced. In this scenario, renewable energy capacity increases according to government plans, and coal-fired power usage is reduced due to the efficiency improvements in both coal and renewable energy technologies.

- High Storage Scenario (HST): This scenario emphasizes the development of energy storage technologies to enhance grid flexibility and facilitate peak shaving. Energy storage improvements allow for greater integration of renewable energy, further reducing dependence on coal-fired power. While renewable energy capacity increases, coal-fired power use is reduced as energy storage provides better grid management and supports higher renewable energy consumption.
- Comprehensive Optimization Scenario (COP): The COP scenario integrates elements from the renewable energy policy, high efficiency, and high storage scenarios. The aim is to maximize the utilization of renewable energy, significantly improve energy generation efficiency, and expand energy storage capacity, while gradually phasing out coal-fired power. This scenario strives to optimize the electricity system comprehensively, transitioning towards a low-carbon, efficient, and sustainable energy system.

Table 1.
Key scenario descriptions.

Scenarios	**Description**	**Key features**
Baseline Scenario (BAU)	Assumes current policies, technologies, and installed renewable energy capacities remain unchanged. As electricity demand grows and renewable energy increases are limited, coal-fired power capacity needs moderate expansion to meet the demand.	- Renewable energy capacity: Limited increase. - Coal-fired power capacity: To meet the electricity balance needs. - Efficiency: No improvement. - Energy storage: No increase.
Renewable Energy Policy Scenario (RES)	Significant increase in wind and solar capacity, prioritizing renewable energy utilization and reducing coal power output.	- Renewable energy capacity: Increased according to the government's medium and long-term plans [32]. - Coal-fired power capacity: Reduce increase rates according to the government's plans [5]. - Efficiency: Refer to BAU. - Energy storage: Refer to BAU.
High Efficiency Scenario (HEF)	Improvement in coal-fired and renewable power generation efficiency to reduce coal consumption per unit of electricity and enhance operational efficiency.	- Renewable energy capacity: Increased according to the government's short-term plans [4]. - Coal-fired power capacity: Reduce increase rates according to the government's plans [5]. - Efficiency: Significant improvement in coal-fired and renewable energy technologies according to the government's plans. - Energy storage:Refer to BAU scenario.
High Storage Scenario (HST)	Increased energy storage capacity and efficiency to enhance peak-shaving and further reduce coal power output.	- Renewable energy capacity: Increased according to the government's short-term plans. - Coal-fired power capacity: Reduce utilization rates. - Efficiency: Refer to BAU. -Energy storage: Gradually increased according to the government's medium and long-term plans [33].
Comprehensive Optimization Scenario (COP)	Combines high renewable, high storage, and high-efficiency coal scenarios to maximize renewable energy utilization and minimize coal power output.	- Renewable energy capacity: Increased according to the government's medium and long-term plans. - Coal-fired power capacity: Gradually phase out. - Efficiency: Significant improvement in coal-fired and renewable energy technologies according to the government's plans. - Energy storage: Gradually increased according to the government's medium and long-term plans [33].

2.3. Key Assumptions and Data

This study necessitates the gathering of varied data, encompassing key assumptions, electricity demands, load profiles, electricity generation processes, and transmission and distribution data, among others. The key assumption data involve economic growth and population change in Hunan Province.

2.3.1. GDP Assumption

The historical data of GDP can be collected in the reference [34]. The Government Report indicates that the province aims to achieve an average annual GDP growth rate of over 6% between 2020 and 2025 [35]. In this research, the GDP growth rate for 2023-2035 is set at 6.5% according to government report.

2.3.2. Population Assumption

From 1995 to 2020, Hunan Province's population grew at an average annual rate of 3.96%. However, since 2023, with a global population decline and economic slowdown, the province has shown a trend of negative population growth. To address this issue, Hunan has implemented a three-child policy [36]. Given these factors, the province's population growth is expected to remain low in the future. This study uses the exponential smoothing method [37] to project the population from 2023 to 2035.

2.3.3. Other Data Consideration

Information regarding power generation by various energy sources and electricity-generating capacities can be found in the reference [38]. The target of energy installation capacity is available in [5, 39]. The detailed electricity load curve data for Hunan Province can be obtained from China Electricity Council [40]. The data relating to the efficiency of power plant technologies are available in reference [1]. The CO2 emission factors associated with the consumption of different energy types in the electricity sector are primarily sourced from the United Nations Intergovernmental Panel on Climate Change (IPCC) sixth assessment report scenario database, which includes data for Asia and China [41].

3. Results and Discussion

3.1. Power Demand Analysis

The electricity consumption in Hunan Province from 2023 to 2035 was estimated by analyzing consumption data from 2015 to 2022 using the elasticity coefficient method [42] regression analysis [43] and the energy consumption per unit of output method [44]. Growth rates were adjusted using a weighted average method, applying weight ratios of 0.4:0.2:0.4. The findings suggest that electricity consumption in Hunan Province will maintain medium to high growth, reaching approximately 335 billion kilowatt-hours by 2030 and about 400 billion kilowatt-hours by 2035, as illustrated in Figure 2.

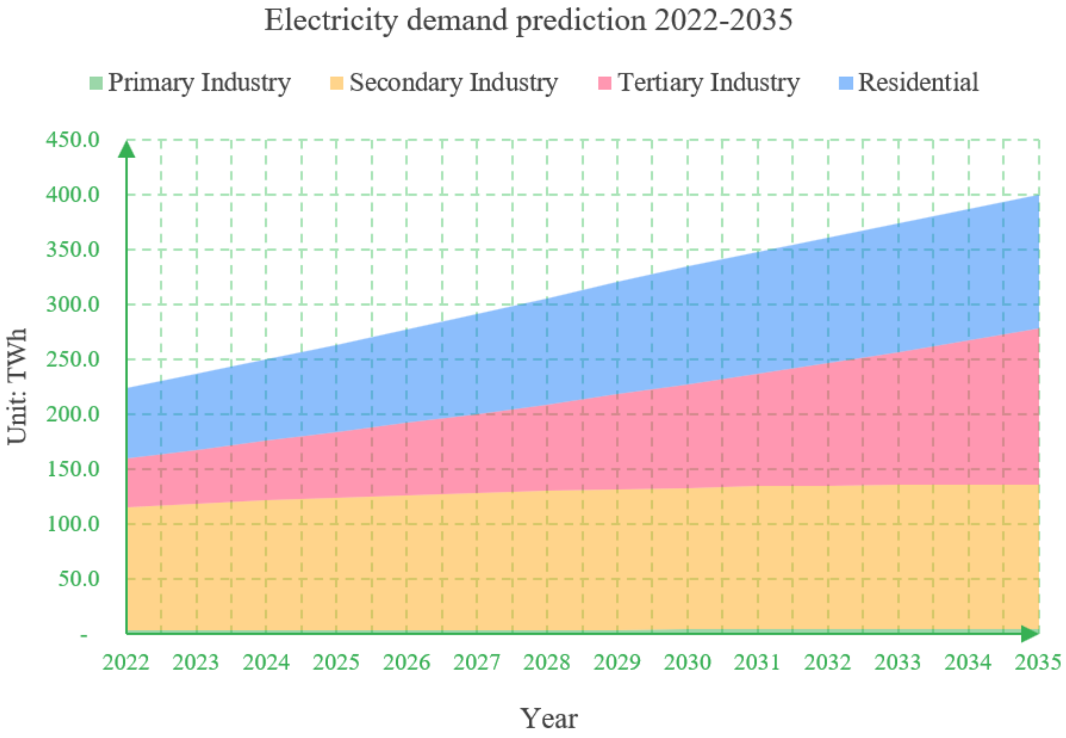


Figure 2.
Electricity demand prediction results in Hunan province from 2022 to 2035.

Based on the overall electricity demand forecast, total demand is expected to increase steadily, driven primarily by growth in the tertiary sector and residential electricity consumption. Electricity demand in the tertiary sector is projected to grow significantly, increasing from 44.4 TWh in 2022 to 142.1 TWh by 2035—nearly tripling—and becoming the main driver of overall demand growth. Meanwhile, residential electricity demand is also expected to rise steadily, from 64.1 TWh to 122.4 TWh, reflecting increased demand driven by population growth and improved living standards. In contrast, electricity demand in the primary sector shows only modest growth, rising from 2.7 TWh to 4.7 TWh, with little significant change. Demand in the secondary sector, while continuing to grow, is slowing, with projections indicating an increase from 112.3 TWh in 2022 to 130.8 TWh by 2035, suggesting a gradual stabilization in the sector's reliance on electricity.

Overall, future electricity demand growth will primarily stem from the tertiary sector and residential consumption, while the primary and secondary sectors will experience relatively smaller increases. This underscores the importance of rising service industry and residential demand as key considerations in the planning and operation of future electricity systems.

3.2. Electricity Production and Structure

Figure 3 illustrates electricity generation by fuel type across five scenarios—BAU, RES, HEF, HST, and COP—projected for the period from 2022 to 2035. Electricity generation is expected to rise significantly from 223.5 TWh in 2022 to over 400 TWh in 2035 across all scenarios, driven by increasing electricity demand and varying renewable energy expansion strategies.

Under the BAU scenario, coal-fired power generation sees the largest increase, growing from 97.1 TWh in 2022 to 155.0 TWh in 2035, representing a 60% rise. This reflects continued reliance on coal to meet growing demand, given the limited development of renewable energy and energy storage capacity. Renewable energy contributions, such as solar and wind power, grow modestly, with solar increasing by

264% (from 17.4 TWh to 63.3 TWh) and wind by 123% (from 20.4 TWh to 45.6 TWh). However, their overall share remains constrained in this scenario. Imported electricity, which starts at 3.0 TWh in 2022, increases to 4.5 TWh by 2035, reflecting a steady rise in external energy dependence.

The RES scenario prioritizes renewable energy expansion, leading to a notable reduction in coal-fired power reliance. By 2035, coal-fired generation declines to 108.3 TWh, a reduction of nearly 30% compared to the BAU scenario. Renewable sources, particularly solar and wind, exhibit significant growth, with solar generation reaching 97.7 TWh (a 462% increase from 2022) and wind generation rising to 64.3 TWh (a 215% increase).

In the HEF scenario, improvements in generation efficiency are emphasized. Coal-fired power output remains relatively high at 119.1 TWh in 2035 but benefits from enhanced efficiency, reducing coal consumption per unit of electricity. Solar and wind power also expand to 86.6 TWh and 66.4 TWh, respectively, representing increases of 398% and 226% compared to 2022. Imported electricity shows slight growth, reaching 6.2 TWh by 2035, suggesting a marginal increase in external energy support to complement efficiency improvements.

The HST scenario focuses on energy storage capacity expansion, with energy storage generation increasing substantially from 3.9 TWh in 2022 to 26.6 TWh in 2035. This scenario also includes a significant increase in pumped storage capacity, contributing 51.5 TWh in 2035. These advancements in storage capabilities reduce coal-fired power output to 89.4 TWh, down from 155.0 TWh in the BAU scenario. Solar power generation in this scenario grows to 66.5 TWh (an increase of 282%), and wind reaches 51.0 TWh (an increase of 150%). Imported electricity rises slightly to 6.5 TWh by 2035, reflecting the system's improved flexibility to manage external energy flows.

The COP scenario represents an optimal balance of high renewable energy deployment, enhanced storage systems, and improved efficiency. By 2035, coal-fired power output decreases to 92.0 TWh, the lowest among all scenarios, reflecting a 5% reduction compared to 2022. Solar and wind generation reach 91.5 TWh and 60.2 TWh, respectively, representing increases of 426% and 195%. Energy storage contributions grow to 20.8 TWh, supplemented by 45.4 TWh from pumped storage. Imported electricity remains at a modest level of 6.3 TWh, highlighting a strategy that focuses on maximizing domestic renewable energy resources while maintaining limited energy imports to ensure system reliability.

Overall, the analysis reveals that renewable energy sources, particularly solar and wind, exhibit significant growth across scenarios, with the COP scenario achieving the most balanced and sustainable power generation mix. The growth rates of renewable energy generation, combined with reductions in coal-fired power, highlight the potential for integrated policies and technological advancements to facilitate a low-carbon energy transition. For example, by 2035, solar power generation grows by approximately 264% in the BAU scenario, 462% in the RES scenario, and 426% in the COP scenario, while wind power grows by 123%, 215%, and 195%, respectively. Imported electricity remains a relatively small but stable component in all scenarios, reflecting its role as a supplemental energy source rather than a primary driver of system changes. These results underscore the critical role of comprehensive optimization in achieving a sustainable and reliable energy future.

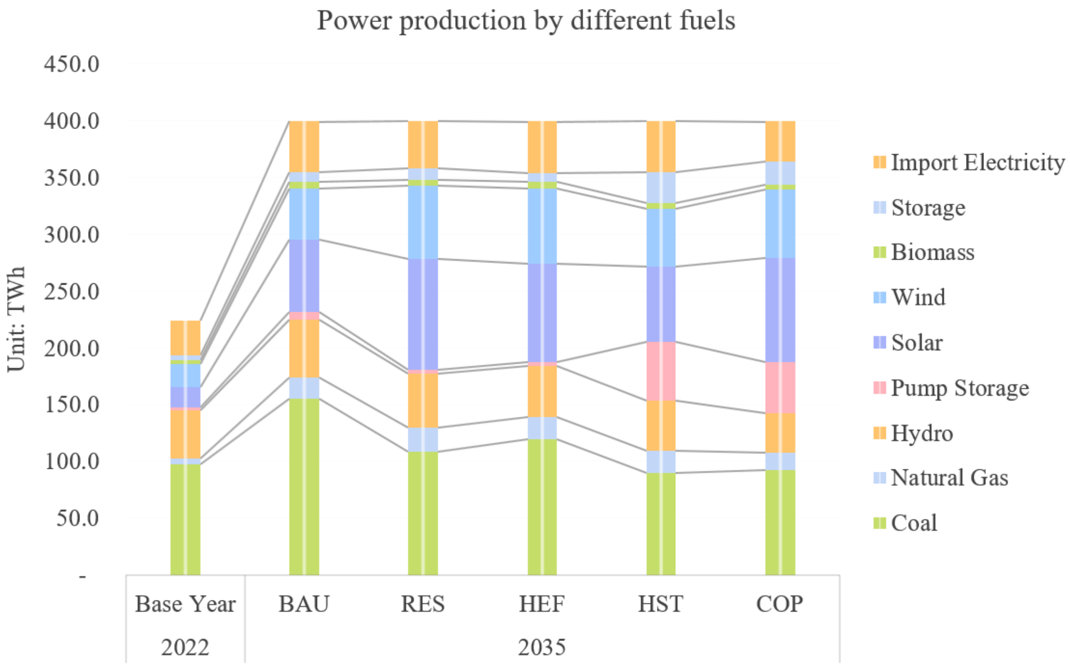


Figure 3.
Electricity generation by fuel types from 2022-2035

Figure 4 illustrates the electricity generation proportion by fuel type across five scenarios—BAU, RES, HEF, HST, and COP—projected for the period from 2022 to 2035. The comparative analysis of energy structures across different scenarios highlights the significant impact of transition strategies and decarbonization goals on the shares of coal, renewable energy, and storage.

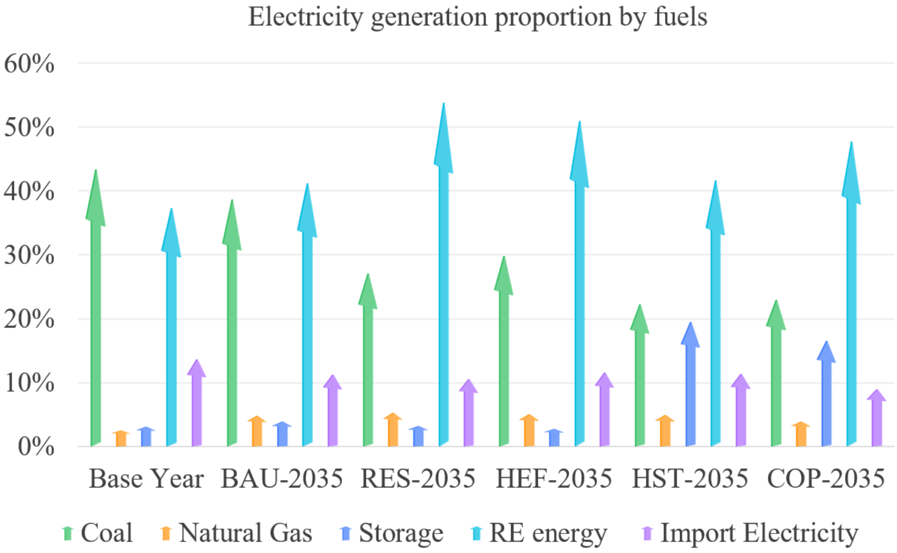


Figure 4.
Electricity generation structure from different fuel type 2022-2035.

In the baseline scenario (BAU), the share of coal decreases slightly to 39%, while renewable energy accounts for 41%, and storage remains at 4%. This indicates that without substantial policy support or technological advancements, traditional fossil fuels will continue to dominate power supply, with limited growth in renewables and storage.

In the Renewable Energy Policy Scenario (RES) and High Efficiency Scenario (HEF), renewable energy shares rise significantly to 54% and 51%, respectively, leading all other scenarios. Meanwhile, coal's share declines to 27% in the RES scenario and 30% in the HEF scenario. These results demonstrate that promoting renewable energy expansion through policy measures or improving energy efficiency can significantly reduce coal dependency and enhance renewable energy utilization. However, storage shares in these scenarios remain limited at 3%-4%, suggesting that system flexibility continues to be constrained.

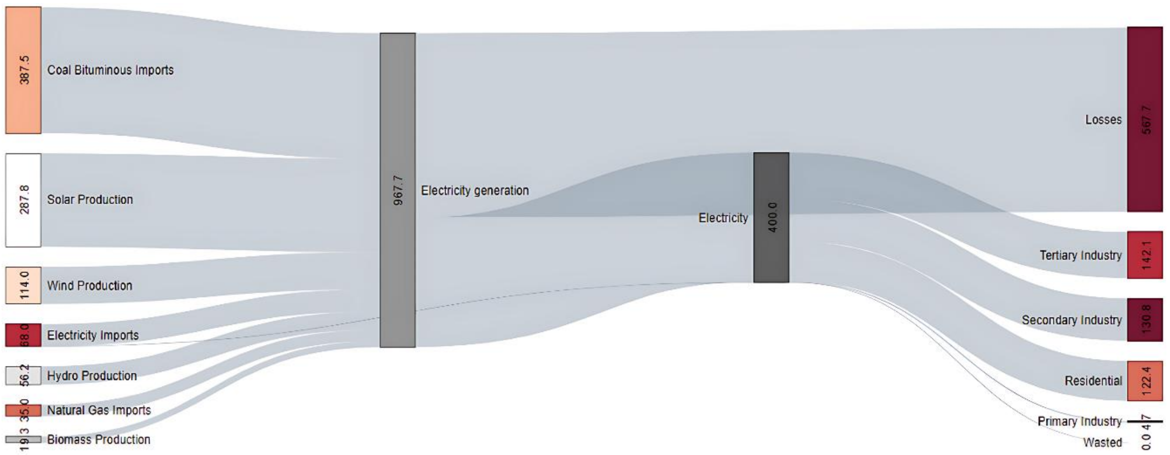
The High Storage Scenario (HST) and Comprehensive Optimization Scenario (COP) emphasize the critical role of energy storage in decarbonized power systems. In the HST scenario, storage's share increases substantially to 20%, reducing coal's share to 22%, while renewable energy accounts for 42%. In contrast, the COP scenario achieves a balanced approach with high storage, significant renewable energy, and efficient coal use, resulting in a storage share of 17%, renewable energy at 48%, and coal at 23%. The COP scenario optimally integrates renewable energy development and system flexibility, achieving the lowest reliance on coal while maintaining higher efficiency, presenting an ideal pathway for the energy transition.

3.3. Energy Flow

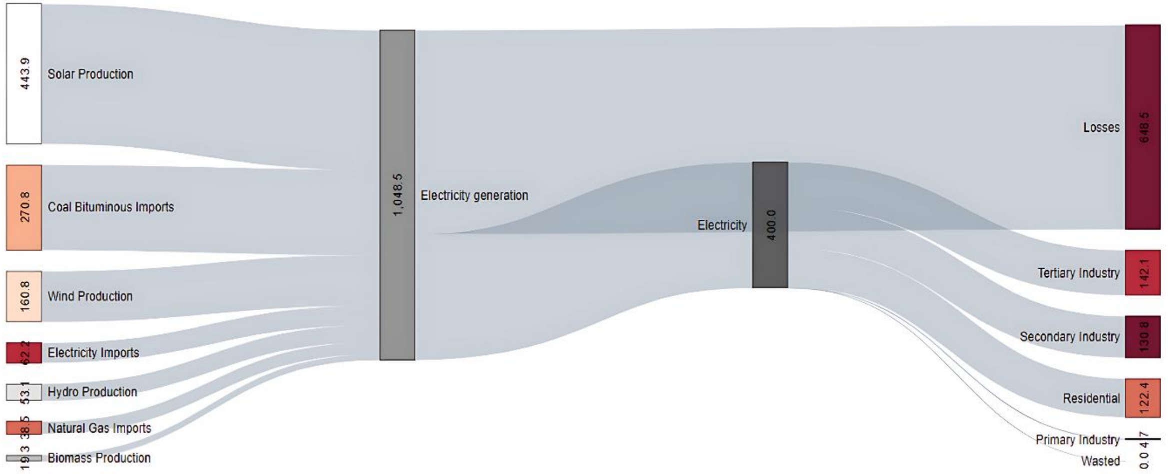
In analyzing the energy Sankey diagrams of the three typical scenarios (BAU-2035, RES-2035, and COP-2035), significant differences in energy flow, utilization efficiency, and carbon emissions emerge, as shown in Figure 5. In BAU-2035, reliance on traditional coal and fossil fuels remains predominant, with renewable energy making limited contributions. Energy utilization efficiency is low, and grid losses are substantial. Electricity consumption is heavily concentrated in the industrial sector, exemplifying a traditional model that prioritizes energy supply at the expense of high carbon emissions.

The RES-2035 scenario marks the beginning of a transition toward a low-carbon energy system. Renewable energy's share increases significantly, with wind, solar, and hydropower becoming key contributors. Reliance on fossil fuels decreases notably, while electricity imports rise to mitigate the intermittency of domestic renewable sources. Additionally, electricity consumption gradually shifts toward the service and residential sectors, mirroring economic structural adjustments. Although power generation efficiency and energy utilization improve, challenges persist in storage infrastructure and grid flexibility.

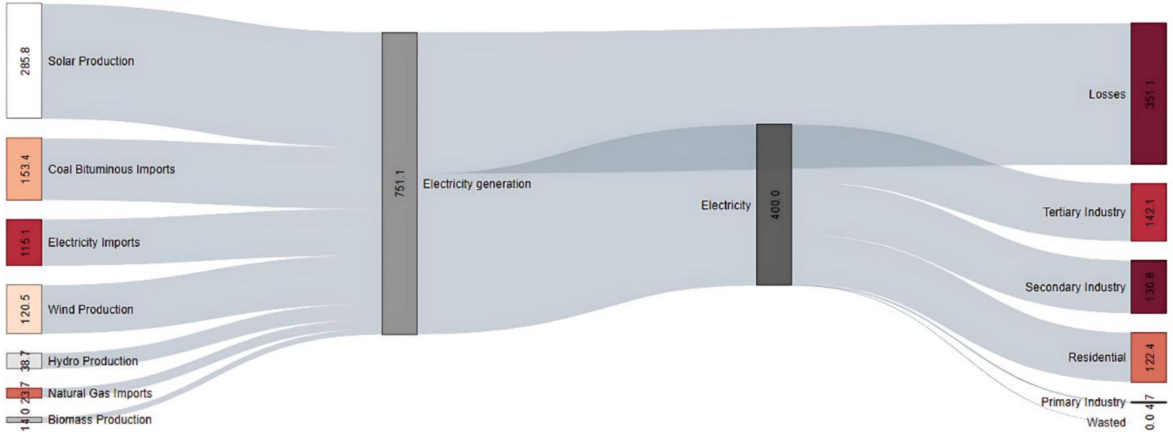
In COP-2035, the energy system and power generation efficiency are further optimized, achieving full decarbonization. Coal and natural gas are nearly phased out, with renewable energy dominating the supply. Grid losses are sharply reduced, and imported electricity plays a critical role in enhancing system flexibility and supporting decarbonization. Energy utilization efficiency reaches its peak. While this scenario represents an ideal and highly optimized energy system, it necessitates more robust solutions for managing renewable energy intermittency, advancing storage technologies, and bolstering policy support.



a.BAU-2035 energy Sankey diagram



b. RES-2035 energy Sankey diagram



c. COP-2035 energy Sankey diagram

Figure 4.
Sankey diagram of the Hunan power system in 2035 for the typical three scenarios

3.4. CO2 Emissions

Figure 5 illustrates the CO_2 emissions from electricity generation under different scenarios, revealing significant variations that underscore the impact of energy transition pathways and policy measures. Under the Business-As-Usual (BAU) scenario, CO_2 emissions rise from 83.0 million metric tons in 2022 to 136.3 million metric tons in 2035, an increase of 64.2%. This trend reflects continued reliance on fossil fuels and limited progress in transitioning to a low-carbon power sector without additional policy interventions.

In contrast, the Comprehensive Optimization Policy (COP) scenario achieves substantial emissions reductions. By promoting renewable energy development, advancing energy storage technologies, and retrofitting coal-fired power plants for greater flexibility, CO_2 emissions drop to 43.2 million metric tons by 2035, a 48% decrease from 2022. Notably, the 2035 emissions under the COP scenario are only 31.7% of those in the BAU scenario, highlighting the critical importance of coordinated policies in achieving low-carbon goals.

The High-Efficiency (HEF) and High-Storage (HST) scenarios demonstrate moderate emissions reductions. In the HEF scenario, focusing on energy efficiency improvements and optimization, emissions decline to 63.6 million metric tons in 2035, a 23.4% reduction from 2022. Meanwhile, the HST scenario, which emphasizes large-scale deployment of energy storage technologies to enhance system flexibility and renewable energy integration, sees emissions of 89.7 million metric tons, representing a modest 8.0% reduction. These outcomes suggest that relying on a single technological strategy limits emissions reduction potential, underscoring the need for comprehensive, integrated measures.

The Renewable Energy (RES) scenario increases the share of renewables but fails to significantly reduce coal dependency. Consequently, CO_2 emissions rise to 98.0 million metric tons in 2035, an 18.1% increase compared to 2022. This indicates that renewable energy expansion alone is insufficient to achieve meaningful carbon reductions.

In conclusion, the COP scenario emerges as the most effective pathway for emissions reduction, achieving a substantial decrease in carbon emissions while maintaining energy supply and demand balance. The continued emissions growth in the BAU scenario highlights the urgency of systematic reduction policies to meet carbon neutrality targets. While the HEF, HST, and RES scenarios mitigate emissions to some extent, they fall short of the performance achieved by the COP scenario. To ensure a sustainable low-carbon future, the power sector must adopt a holistic approach integrating policy, technology, and market mechanisms to accelerate renewable energy development, transform traditional energy systems, and advance energy storage innovation.

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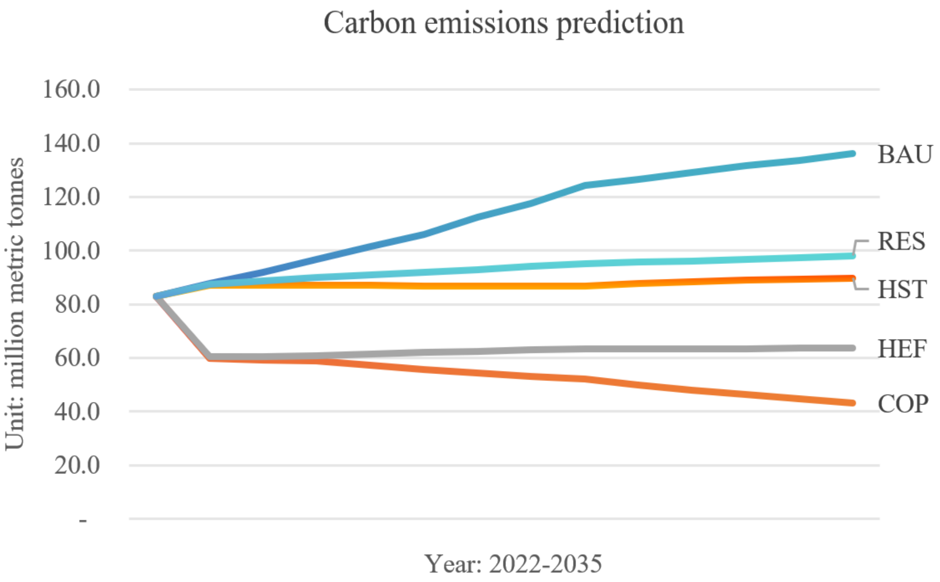

Figure 5.
CO2 emissions from electricity generation in the years 2030 and 2035.

3.5. Sensitivity Analysis

To assess the robustness and reliability of the research findings, a sensitivity analysis was conducted on the key parameters of the energy transition pathway in Hunan Province. The analysis focused on the variations of parameters such as economic growth, the rate of technological progress in renewable energy, carbon emission factors for coal and natural gas power generation, and the development of energy storage. These parameters were adjusted in the Baseline Scenario (BAU), Renewable Energy Policy Scenario (RES), High Efficiency Scenario (HEF), High Storage Scenario (HST), and Comprehensive Optimization Scenario (COP), to evaluate their impact on energy demand, renewable energy deployment, and carbon emissions.

Economic growth is a critical factor influencing energy demand and carbon emissions. In this study, the potential impact of economic fluctuations was simulated by adjusting the GDP growth rate by ±2%. The results showed that higher economic growth (+2%) would lead to a 1.4% increase in energy demand by 2035, raising it from 400 TWh to 405.6 TWh, thus increasing coal consumption and reducing the share of renewable energy. Conversely, slower economic growth (-2%) would reduce energy demand to 394.4 TWh, leading to an increased share of renewable energy. In the BAU scenario, GDP growth intensified the reliance on coal, while in the COP scenario, the government's strong policy push for renewable energy deployment helped offset the impact of economic fluctuations, maintaining a relatively balanced energy structure. The carbon emission factors for coal and natural gas power generation were also assessed with a 1% annual reduction to evaluate their impact on overall emissions. The results showed that reducing the carbon emission factor would lead to approximately 3.2% cumulative CO_2 emissions reduction, highlighting the key role of cleaner coal technologies and higher operational efficiency in emissions reduction. This adjustment indicates that even moderate improvements in coal-fired power generation technologies can play a significant role in reducing carbon emissions while increasing renewable energy share.

The sensitivity analysis also assessed the impact of policy changes on the energy transition. Simulations of changes in government policies, such as the pace of renewable energy deployment and the speed of coal power reduction, were conducted to understand their role in the future energy landscape. The analysis results showed that, especially in the HEF and COP scenarios, strong policy interventions help maintain the trajectory of a low-carbon transition, even in the face of economic fluctuations and technological uncertainties.

4. Policy Implications

This section explores the challenges posed by the increasing penetration of renewable energy into the power sector and the corresponding countermeasures. Although this study focuses on Hunan Province, the challenges and policy measures discussed are equally applicable to other regions in China, as well as internationally, to power systems that rely on renewable energy. These studies and strategies are particularly valuable for regions facing rapid growth in electricity demand and energy structure transitions. Furthermore, the research can be expanded to explore cross-border power interconnections, enhancing regional power cooperation and optimizing resource allocation.

The above results indicates that a high proportion of renewable energy generation in Hunan Province will have favorable impacts on the province's electricity and energy sectors. For instance, increasing the share of renewable energy generation will help increase the electricity generation proportion from renewable energy and reduce fossil fuel combustion in Hunan, as well as decreasing the reliance on traditional energy sources such as coal and natural gas and diversifying the energy generation structure. Moreover, further reducing fossil fuel usage will help decrease air pollution and greenhouse gas emissions in Hunan Province, contributing to the achievement of Hunan's carbon emission targets, which include reducing energy consumption per unit of regional GDP and ensuring the fulfillment of national targets for CO_2 emission reduction. It is worth noting that promoting the use of renewable energy in power generation will enhance local energy resources, particularly in relation to the utilization of solar and biomass energy. Solar and biomass energy generation in Hunan Province can be more widely distributed to regions via techniques such as rural photovoltaic power generation. This will provide local investors and communities with opportunities to participate in renewable energy generation in the form of distributed generation. It appears that the increase in local energy generation supports the development of distributed generation, thereby contributing to the improvement of energy security in Hunan Province, especially in terms of decentralization.

However, this transition will inevitably pose some challenges to Hunan's power system, as the existing power structure is primarily designed for traditional thermal power generation technologies, mainly including issues related to reliability, flexibility, grid infrastructure, power dispatching, and management.

- One challenge is the instability of the current power system. According to some forecasts [45] by 2060, renewable energy in China could account for 80% of the total power generation. To accommodate this growth, it is essential to enhance the stability of the power system. However, the current power system still primarily relies on alternating current (AC) synchronous mechanisms. As the proportion of renewable energy and power electronic devices increases, the system's operating characteristics will undergo significant changes. Unlike traditional synchronous generators, these new energy sources do not provide sufficient system inertia, leading to increased vulnerability and a higher risk of system failures. Additionally, the generation of renewable energy is affected by natural conditions and weather, with a risk of supply unreliability under extreme weather conditions. For instance, Hunan Province mainly relies on hydropower as its renewable energy source. According to statistical data, from January to August 2023, due to drought and reservoir water levels falling, hydropower generation was 27 billion kWh, with a 42.3% decrease in hydropower output compared with that in 2022 [46]. Without sufficient backup capacity to balance these fluctuations, the grid may experience deviations, potentially leading to regional power outages.

- Another major challenge is the inflexibility of the current power system. Studies show that transforming our energy system towards one dominated by renewable energy comes with some challenges, as highly variable renewable energy shares increase system requirements for balancing supply and demand [47]. The volatility of renewable energy can cause significant fluctuations in power generation within a single day. Research indicates that by 2030, the maximum daily fluctuation in national renewable energy generation could reach 40 million kilowatts, potentially leading to multiple load adjustments and more frequent switching cycles within the system. Therefore, a more flexible power system is needed to accommodate these fluctuations. For instance, in Hunan Province, there is a significant difference between peak and off-peak electricity demand, with shortages during peak periods and surpluses during off-peak periods. Currently, wind and solar power generation cannot effectively adjust to load due to environmental constraints, and hydropower capacity is insufficient for peak shaving. This highlights the need for effective energy storage systems. However, Hunan's existing electricity storage capacity is very limited and cannot meet energy regulation needs. As of 2023, Hunan's storage capacity stands at 2.64 million kilowatts [48] accounting for only about 3.7% of the province's total installation capacity.
- The grid's infrastructure needs further upgrading. The integration of large amounts of distributed renewable energy, such as rooftop solar panels and small wind turbines, requires the grid to have advanced technologies to manage multiple access points and bidirectional power flows, as well as improved equipment to handle the instability caused by fluctuations in renewable energy generation. Additionally, as renewable energy planning advances, the existing grid needs to be expanded, and more power transmission lines need to be constructed. For example, in Hunan Province, wind and solar resources are primarily concentrated in the remote southern regions, while electricity demand is concentrated in the northern urban areas. By the end of 2019, although renewable energy accounted for 6.43% of the total power generation, curtailment issues persisted, with a curtailment rate of 1.80% [49]. This indicates that some renewable energy was not fully utilized. To address this problem, more transmission lines and substations need to be built, which requires significant investment and long-term planning.
- The transformation of the power generation structure presents challenges to the scheduling and management of the power sector. The volatility and unpredictability of renewable energy increase the complexity of grid scheduling, necessitating the adoption of more advanced algorithms and real-time management technologies. The rapid fluctuations in wind speed and solar radiation further complicate real-time scheduling and load matching. Despite the availability of various forecasting tools and models, errors in predicting renewable energy output persist, requiring real-time adjustments to generation plans to compensate for these uncertainties. As a result, scheduling systems must possess efficient data processing capabilities and rapid response mechanisms. The integration of renewable energy increases operational complexity and may impact system reliability. Grid operators must effectively assess and manage these risks to ensure the stability and security of the power supply.

To address the challenges posed by renewable energy to the power grid, Hunan Province has implemented a series of policy measures. First, the province has significantly advanced the construction of renewable energy infrastructure, including pumped storage power stations, wind power, and photovoltaic projects [50]. According to Hunan Province's "14th Five-Year Plan" energy project progress monitoring report [51] the province has approved the construction of eight pumped storage power stations with a total installation capacity of 11.8 million kilowatts, including the Pingjiang and Anhua Pumped Storage Power Station. Additionally, 18 pumped storage power stations in Hunan will be constructed, with their completion expected around 2030. To enhance power security and ensure stable electricity supply, the Hunan provincial government is accelerating the development of ultra-high-voltage (UHV) AC and DC transmission projects and expanding the scale of electricity imports [52]. To improve the smart grid level, Zhuzhou City is implementing a smart grid renovation plan by deploying smart meters and Advanced Distribution Management Systems (ADMSs) [53]. In terms of power regulation, Hunan Province is enhancing the configuration of emergency backup power and peaking power sources to improve the regulation capability of hydropower, wind power, and photovoltaic power to cope with fluctuations in renewable energy. In addition, the government is optimizing demand-side management by implementing electricity price reforms, encouraging industrial and residential users to shift their electricity consumption to off-peak periods.

In addition to initiating government policies to address transition challenges, this paper also proposes the following recommendations:

4.1. Accelerating the Construction and Optimization of Energy Storage Facilities

In Hunan province, it is recommended to further increase investment in energy storage technologies, particularly in regions that are rich in wind and solar resources, by constructing diversified storage facilities such as large-scale Battery Energy Storage Systems (BESSs), pumped hydro storage, and hydrogen storage technology. According to the authors of [54] BESS costs are expected to decrease significantly in the coming years. According to the Medium-to-Long-Term Plan for the Development of the Hydrogen Energy Industry (2021-2035), hydrogen energy is a crucial component of China's future energy system [55]. These facilities can effectively balance power supply and demand, release stored energy during peak periods, and alleviate grid pressure. Additionally, it is recommended to upgrade existing storage facilities to improve their charge–discharge efficiency, extend their lifespan, and reduce operational costs. To further promote the application of storage technologies, the government could introduce special subsidy policies and tax incentives to encourage businesses and individuals to install storage devices, fostering the development of the energy internet.

4.2. Encouraging the Development of Distributed Energy and V2G/V2X Technology

While vigorously developing distributed energy, Hunan Province should also focus on the widespread application of V2G (vehicle-to-grid) and V2X (vehicle-to-everything) technologies, especially in urban and rural power systems. By developing micro-grids and distributed energy systems, local self-sufficiency in power can be achieved, reducing the dependence on the main grid. V2G technology utilizes electric vehicle batteries as distributed storage units, enabling bidirectional energy and information transfer between vehicles and the grid. This technology is cost-effective, scalable, and safe, and can flexibly respond to power demand through interaction between electric vehicles and the grid, further enhancing grid stability and efficiency.

4.3. Promoting the Development of Smart Grid Technology

Over the past decade, smart grid technology has transitioned from virtual reality and conceptual stages to its actual implementation. For instance, China established a smart grid framework and planned a wide-area monitoring system in 2011 [56]. In promoting smart grid technology, Hunan Province can draw on successful domestic and international smart grid demonstration projects and develop practical development plans tailored to local electricity demand characteristics.

4.4. Optimizing Power Grid Infrastructure and Engineering Design

With the rapid development of renewable energy, the construction and maintenance of Hunan Province's power grid infrastructure have become particularly important. When designing and constructing the next generation of substations and transmission lines, it is essential to integrate advanced mechanical engineering technologies and smart design to enhance system performance and reliability. It is recommended to use high-strength materials and modular designs, which not only improve the equipment's resistance to wind and seismic activities but also extend its lifespan. Additionally, incorporating civil engineering techniques and smart design elements, such as sensors and monitoring systems, can enable real-time monitoring and fault warning for power equipment, thus reducing downtime and maintenance costs. In energy system design, it is essential to consider the integration of power and thermal energy systems. According to relevant research [57] optimizing resource scheduling and employing advanced optimization algorithms can enhance overall system efficiency. It is recommended to optimize the integration of energy systems by combining power systems with thermal energy systems, such as combined heat and power (CHP) and solar thermal systems. This approach can enhance energy conversion efficiency and reduce energy waste. For instance, utilizing CHP technology to simultaneously generate electricity and heat can significantly improve energy utilization. Additionally, integrating various forms of energy generation, such as wind, solar, and biomass, can further optimize resource use and enhance the system's overall efficiency through the synergistic effect of multiple energy sources. Deploying distributed generation and micro-grid technologies can strengthen system resilience, ensuring continued power supply even during natural disasters. Through these comprehensive optimization measures, the power grid in Hunan Province will be better suited to accommodate large-scale renewable energy integration while demonstrating enhanced resilience in the face of natural disasters.

5. Conclusions

This study evaluates the impact of the renewable energy strategy on Hunan Province's power industry from 2022 to 2035, with a focus on key areas such as power demand, electricity production, and CO_2 emissions. It indicates that Hunan Province's electricity demand is expected to grow steadily over the next decade, driven primarily by the tertiary industry and residential consumption. By 2035, the demand from the tertiary industry will nearly triple compared to 2022. Electricity production will rise significantly across all scenarios, with renewable energy driving this growth. In the BAU scenario, coal remains the dominant energy source, while renewable energy, especially solar and wind, will significantly increase in the RES, HEF, and COP scenarios. The COP scenario offers the optimal low-carbon transition, reducing CO_2 emissions by 48% by 2035 through increased renewable energy and energy storage. However, the BAU scenario shows rising emissions due to continued reliance on fossil fuels, emphasizing the need for effective emission reduction policies. This analysis underscores the importance of policy support, renewable energy, and energy storage integration for future energy transformation. These benefits include enhancing the diversity of primary energy sources in electricity production, reducing reliance on fossil fuels, and promoting environmentally friendly electricity generation practices. However, despite the numerous benefits of renewable energy, Hunan Province's energy transition process also faces several challenges. For instance, the intermittency of renewable energy sources affects grid stability and flexibility, increasing the complexity of power system scheduling and management, while issues such as outdated technology and infrastructure pose significant threats to grid security. The sensitivity analysis also showed that economic fluctuations, such as changes in GDP growth, can significantly affect energy demand, renewable energy share, and carbon emissions. The results indicate that higher economic growth (+2%) will lead to an increase in energy demand from 400 TWh to 405.6 TWh by 2035, a 1.4% rise, which will increase coal consumption and reduce the share of renewable energy. Conversely, slower economic growth (-2%) will reduce energy demand to 394.4 TWh, increasing the share of renewable energy. Additionally, reducing the carbon emission factor by 1% annually is expected to result in a cumulative CO2 reduction of about 3.2%, highlighting the key role of cleaner coal technologies and higher operational efficiency in emission reduction. In response, the government has proposed a series of measures to promote the efficient use of renewable energy. To better implement government policies and alleviate the pressures brought by the energy transition, this paper suggests that the government should focus on accelerating diversified

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energy storage technologies, encouraging distributed energy and V2G/V2X technologies, promoting smart grid technology, and strengthening power grid infrastructure and engineering design to ensure energy security and sustainable environmental development.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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Table A1.
Detailed experimental capacity data for different scenarios (Unit: GW).

Scenario	**Context**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
BAU Scenario	Coal	24.5	24.5	26.5	28.1	30.2	30.5	30.7	31.9	32.4	33.5	34.1	34.6	35.1	35.2
	Natural Gas	1.2	1.2	2.0	2.1	2.6	3	3.2	3.2	3.2	3.5	3.5	3.5	3.8	3.8
	Hydro	15.9	15.9	16.1	16.3	16.5	16.6	16.7	16.8	16.9	17	17.1	17.2	17.3	17.4
	Pump Storage	1.20	1.2	1.3	1.4	1.6	1.7	1.8	1.9	2.1	2.2	2.2	2.3	2.3	2.4
	Solar	7.6	7.6	9.4	11.2	13	13.4	13.8	14.2	14.6	15	17	19	21	23
	Wind	8.8	8.8	9.9	10.9	12	12.2	12.4	12.6	12.8	13	14	15	16	17
	Biomass	1.1	1.1	1.2	1.4	1.5	1.5	1.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6
	Other Storage	0.8	0.8	1.2	1.6	2	2	2	2	2	2	2	2	2	2
RES Scenario	Coal	24.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5
	Natural Gas	1.2	2.9	2.9	3	3.2	3.4	3.6	3.8	4	4	4.1	4.2	4.3	4.4
	Hydro	15.9	16.4	16.4	16.5	16.6	16.7	16.8	16.9	17	17.1	17.2	17.3	17.4	17.6
	Pump Storage	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	Solar	7.6	9.4	11.2	13	15.4	17.8	20.2	22.6	25	28.2	31.4	34.6	37.8	41
	Wind	8.8	9.9	10.9	12	14	16	18	20	22	23	24	25	26	27
	Biomass	1.1	1.2	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	Other Storage	0.8	1.2	1.6	2	2	2	2	2	2	2	2	2	2	2
HEF Scenario	Coal	24.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5	26.5
	Natural Gas	1.2	2.9	2.9	3	3.2	3.4	3.6	3.8	4	4	4.1	4.2	4.3	4.4
	Hydro	15.9	16.4	16.4	16.5	16.6	16.7	16.8	16.9	17	17.1	17.2	17.3	17.4	17.6
	Pump Storage	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	Solar	7.6	9.4	11.2	13	14.4	15.8	17.2	18.6	20	22	24	26	28	30
	Wind	8.8	9.9	10.9	12	13.2	14.4	15.6	16.8	18	19	20	21	22	23
	Biomass	1.1	1.2	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	Other Storage	0.8	1.2	1.6	2	2	2	2	2	2	2	2	2	2	2
HST Scenario	Coal	24.5	26.5	26	25.5	25.3	25.1	24.9	24.7	24.5	24.3	24.1	23.9	23.7	23.5
	Natural Gas	1.2	2.9	2.9	3	3.2	3.4	3.6	3.8	4	4	4.1	4.2	4.3	4.4
	Hydro	15.9	16.4	16.4	16.5	16.6	16.7	16.8	16.9	17	17.1	17.2	17.3	17.4	17.6
	Pump Storage	1.2	1.2	1.4	1.6	2.7	3.9	5.1	6.2	7.4	10	12.6	15.2	17.8	20.3
	Solar	7.6	9.4	11.2	13	14.4	15.8	17.2	18.6	20	22	24	26	28	30
	Wind	8.8	9.9	10.9	12	13.2	14.4	15.6	16.8	18	19	20	21	22	23
	Biomass	1.1	1.2	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	Other Storage	0.8	1.2	1.6	2	2	2	2	2	2	3	4	5	6	7
COP Scenario	Coal	24.5	26.5	26	25.5	25.3	25.1	24.9	24.7	24.5	24.3	24.1	23.9	23.7	23.5
	Natural Gas	1.2	2.9	2.9	3	3.2	3.4	3.6	3.8	4	4	4.1	4.2	4.3	4.4
	Hydro	15.9	16.4	16.4	16.5	16.6	16.7	16.8	16.9	17	17.1	17.2	17.3	17.4	17.6
	Pump Storage	1.2	1.2	1.4	1.6	2.7	3.9	5.1	6.2	7.4	10	12.6	15.2	17.8	20.3
	Solar	7.6	9.4	11.2	13	15.4	17.8	20.2	22.6	25	28.2	31.4	34.6	37.8	41
	Wind	8.8	9.9	10.9	12	14	16	18	20	22	23	24	25	26	27
	Biomass	1.1	1.2	1.4	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.7	1.7	1.7	1.7
	Other Storage	0.8	1.2	1.6	2	2	2	2	2	2	3	4	5	6	7