Analysis of Wind-Solar Power Development and Policy Strategies for Carbon Neutrality in Hunan Province

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ABSTRACT

Against the backdrop of global carbon neutrality, the energy transition in Hunan's power sector is crucial. This study employs the Low Emissions Analysis Platform (LEAP) model analysis to evaluate the electricity production structure and environmental impacts under three scenarios: Baseline Scenario (BAS), Policy Support Scenario (PSS), Deep Emission Reduction Scenario (DES), focusing on the development of wind and solar energy. The results indicate that the increasing installed capacity of wind and solar power significantly improves Hunan's power generation structure and environmental conditions. By 2060, under the PSS scenario, wind and solar power will have achieved an installed capacity of 128 GW, contributing 23.6% to electricity generation, while pollutant emissions (CO_2, NO_2, SO_2, $PM_{2.5}$) will have been reduced by 21% compared to the BAS scenario. Under the DES scenario, wind and solar power capacity will have risen to 251 GW, with solar generation having reached 212 TWh, while thermal power's share will have declined to 9.8%. Pollutant emissions will have decreased by nearly 80% compared to the BAS scenario. Furthermore, the study proposes targeted strategies to address challenges in Hunan's wind and solar development, including the establishment of integrated wind-solar energy storage systems, the advancement of smart grid infrastructure, and the development of a market-oriented trading system for wind and solar power. These strategies aim to enhance infrastructure, improve technology integration, and establish a resilient and economically viable renewable energy framework, ensuring Hunan's successful achievement of carbon neutrality goals.

Keywords-Hunan province; LEAP model; carbon neutrality; renewable energy; wind power; solar power; power production structure; environmental impact

I. INTRODUCTION

As climate concerns intensify, achieving carbon neutrality has become a central objective for nations striving for sustainable development [1]. China has set ambitious targets: to have peaked carbon emissions by 2030 and to have reached carbon neutrality by 2060. These goals require a fundamental transformation of the energy sector and rapid advancements in low-carbon technologies [2]. Carbon neutrality entails balancing CO_2 emissions with removal measures, ultimately achieving net-zero emissions [3] In October 2022, the Provincial Party Committee and Government issued the Hunan Carbon Peak Implementation Plan, identifying the power sector as critical for emission reduction [4]. The plan emphasizes optimizing the energy mix, expanding clean energy sources, and prioritizing wind and solar power. Accordingly, this study explores pathways for Hunan's power sector to achieve carbon neutrality through renewable energy initiatives and provides actionable recommendations for long-term sustainability.

According to China Electric Power Yearbook (2021, 2022), Hunan's electricity demand steadily increased from 1,495.65 TWh in 2016 to 2,235.54 TWh in 2022, reflecting a significant annual growth rate [5-6]. Despite the rising generation capacity, meeting demand remains a challenge. In 2022, power generation primarily relied on thermal power (1,194 TWh) and hydropower (603 TWh), while wind and solar energy expanded significantly, increasing their share in the energy mix from 3% in 2016 to 13.9%. Installed wind and solar capacity reached 9 GW and 6.36 GW, respectively, comprising 26.1% of the total energy mix. These clean energy sources reduced Hunan's reliance on thermal power, however, local generation still falls short [7]. As a result, Hunan imported approximately 48 TWh of electricity in 2022, representing 21.4% of the total consumption. To achieve carbon neutrality, the province must further develop solar and wind energy transition to a more sustainable energy structure, and reduce dependency on external electricity imports. Hunan possesses significant potential for solar and wind energy development. The province experiences an annual average temperature of 16 °C-18 °C with 1300-1800 sunshine hours and total solar radiation levels ranging from 3,384.7 to 4,372.0 MJ/m^2 [8]. The theoretical solar reserves are estimated at (7.164-9.25) × 10^{14} MJ, with an exploitable solar energy of approximately 0.238 × 10^{14} kWh [9]. For wind energy, the theoretical reserves are approximately 500 GW, with 50 GW located in regions where the annual average wind power density exceeds 130 W/m^2 [10]. These wind resources are concentrated in southern, southwestern, and eastern Hunan, as well as around Dongting Lake.

China has made significant progress in wind and solar energy development; though, regional disparities exist. Authors in [11] highlighted that solar resources are abundant in the east and west, while wind power is concentrated in the north and northwest. Authors in [12] projected a sharp increase in wind and solar capacity by 2050, reducing fossil fuel reliance and strengthening sustainable energy support. However, authors in [13] emphasized that the intermittent nature of renewables complicates grid management, lowering coal power efficiency and increasing operational costs. Addressing this volatility is crucial for achieving carbon neutrality. Authors in [14] stated that reducing air pollution could enhance the renewable energy potential by improving solar radiation and wind speeds. Lower aerosol levels improve air quality, solar radiation, and wind speeds. In this transition, wind and solar power will play a dominant role in electricity production, replacing fossil fuels. Authors in [15] argued that despite the intermittency of issues, renewables offer clear carbon reduction benefits over coal power. In [16], it was further noted that as carbon neutrality policies advance, the deployment of wind and solar energy will become more stable and contribute significantly to regional power supply, particularly in eastern and southern China. Research on wind and solar energy in Hunan remains limited. In [17], a large-scale solar power deployment was analyzed, stressing the need for better forecasting and dispatch strategies to enhance integration into the grid. Similarly, authors in [18] examined wind power integration, emphasizing its role in voltage stability and reactive power support. Authors in [19] proposed a comprehensive approach, including industrial restructuring, green grid construction, and technological innovation, to achieve low-carbon transformation and peak emission reduction. Research on other regions also provide valuable insights. For example, authors in [20] identified infrastructure gaps and policy barriers in Xinjiang's wind energy sector, advocating for stronger government support and technological advancements. In [21], the Inner Mongolia's carbon neutrality strategy was studied, and renewable energy expansion, robust storage systems, and power supply diversification were proposed. The findings suggest that phasing out coal power can lead to substantial cost savings and emission reductions. The present study aims to analyze the impact of Photovoltaic (PV) and wind power development on Hunan's power system and its associated challenges. It will provide specific optimization strategies to support the province's low-carbon transition and its goal of achieving carbon neutrality.

II. METHODOLOGY

A. Model Framework

This study utilizes the LEAP model, a widely used tool for energy system planning, sustainability assessment, environmental impact analysis, and policy formulation. The LEAP model effectively evaluates the energy demand trends, Greenhouse Gas (GHG) emissions, and the impact of various policy measures. On the demand side, the LEAP model has been extensively applied to analyze energy consumption patterns and policy effectiveness. Authors in [22] studied Colombia's industrial, residential, transportation, and tertiary sectors, concluding that the transportation sector is the largest energy consumer. A study in China demonstrated through scenario analysis that enhanced energy-saving measures can significantly reduce terminal energy demand [23]. Similarly, authors in [24] projected that by 2030, carbon emissions in the central region of the Yangtze River Economic Belt will have surpassed those in the eastern region. Authors in [25] analyzed Shaanxi Province and found that improving terminal energy efficiency and adjusting industrial structures could lead to substantial emission reductions. Additionally, a study on an industrial park in Changsha showed that shifting the economic growth model has a positive effect on emissions reduction [26].

On the power generation side, research focuses on optimizing energy structure and supply technologies. Authors in [27] demonstrated that clean energy adoption and energy-saving policies in Nigeria can effectively reduce GHG emissions. Authors in [28] evaluated multiple power supply scenarios in Pakistan, finding that the Energy Efficiency and Conservation (EEC) scenario had the lowest investment cost and best aligned with sustainable development goals. Similarly, authors in [29] proposed strategies for optimizing Yunnan Province's energy structure in the context of supply-side reforms. Beyond energy demand and supply analysis, the LEAP model also addresses regional energy planning and policy integration. Authors in [30] examined air pollution reduction in Beijing and found that energy-saving policies help optimize the energy consumption structure. Additionally, authors in [31] emphasized the importance of regional coordination in energy planning within the Liaobin Coastal Economic Zone.

These studies highlight the LEAP model as a critical tool for energy and carbon emission scenario analysis. By supporting policymakers in evaluating policy impacts, the model plays a key role in achieving both global and local sustainability objectives. In this study, a LEAP model for Hunan province, illustrated in Figure 1, is developed to analyze electricity generation and its environmental impact. The model incorporates key inputs, such as GDP, population, and electricity demand across four sectors: primary, secondary, tertiary, and residential. The primary sector includes agriculture (farming, forestry, animal husbandry, and fishing), the secondary sector consists of manufacturing and construction, and the tertiary sector covers services, like transportation, finance, education, and tourism. The model also accounts for energy transformation factors, including merit order, process efficiency, and resource availability (coal, natural gas, wind, solar, biomass, and hydropower). It explores multiple scenarios by evaluating different capacity and generation mixes. The key outputs include total electricity demand, generation by fuel type, fossil fuel consumption, and pollutant emissions (CO_2, NO_2, SO_2, and $PM_{2.5}$).

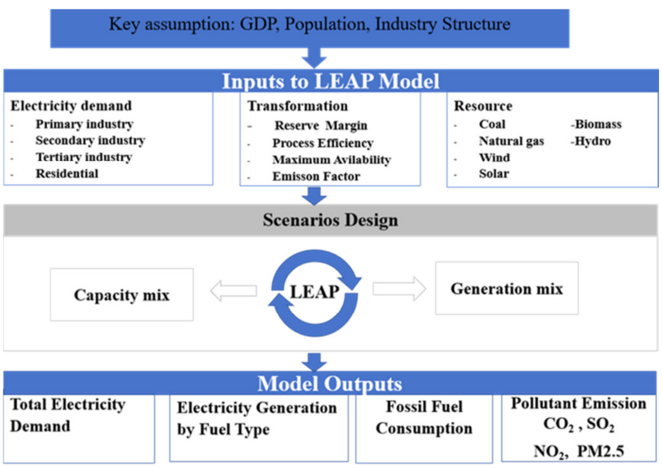

Fig. 1. LEAP Model for Hunan Province.

B. Data Consideration

Due to data update delays, 2022 was selected as the base year, with 2023 having been chosen as the first simulation year and 2060 as the final year. The projections are based on historical data from the Hunan Statistical Yearbook (2016-2022) [32]. Hunan Province's population is expected to decline, that is to have reached approximately 64.85 million by 2030 and 53.3 million by 2060. Meanwhile, GDP is projected to grow at an annual rate of 5%. As the industrial structure evolves, the share of the secondary industry will gradually decline, while the tertiary industry will expand. In the current work, residential electricity consumption was estimated using linear regression analysis based on historical trends. Based on the advancements in energy-saving technologies, the growth rate of residential electricity demand is expected to have slowed between 2030 and 2060. Table I presents the projected electricity consumption from 2023 to 2026. By 2060, the total electricity demand of Hunan province is estimated to have reached 828.9 TWh. For 2023, the projected electricity consumption is 237.3 TWh, exceeding Hunan's actual consumption [33] by just 0.9%. This minimal error, within an acceptable range, confirms the reliability of the model's data.

TABLE I. ELECTRICITY CONSUMPTION FORECAST (TWH)

Base Year	Primary Industry	Secondary Industry	Tertiary Industry	Residential	Total
2022	2.7	112.3	44.4	64.1	223.4
2030	3.5	148.4	71.3	110.2	333.5
2040	6.1	187.2	124.6	130.2	447.8
2050	11.3	223.8	221.5	150.2	606.8
2060	20.6	244.9	393.1	170.2	828.9

This study assumes the adoption of supercritical technology for the coal-fired power and Combined Cycle Gas Turbine (CCGT) technology for natural gas-fired power, alongside the large-scale expansion of wind and solar power. The merit order prioritizes non-fossil energy over thermal power generation. To simplify the analysis and focus on core variables, the impact of economic conditions on the results is excluded. Process efficiency, maximum availability, and historical installed capacities for different fuel types are sourced from the China Electric Power Statistical Yearbook (2017–2022), published by the China Statistical Publishing House. The emission factors for CO_2, NO_2, and SO_2 are based on IPCC standards. Additionally, the $PM_{2.5}$ emission factor for raw coal used in power generation is 12 g/kg, following the Guidelines for Compilation of Emission Inventory of Atmospheric Fine Particulate Matter ($PM_{2.5}$) Sources (Trial) [34].

C. Scenario Development

This study defines three scenarios:

- BAS: Assumes all energy types continue growing at the 2016 - 2022 trend under the existing technological conditions.
- PSS: Based on Hunan's 2023 Development Plan for the New Power System [7], prioritizing wind and solar energy expansion within the carbon neutrality framework.

- DES: Focuses on low-carbon power system transformation, restricting thermal power to peak shaving while minimizing carbon emissions.

A detailed comparison of these scenarios is provided in Table II.

TABLE II. KEY STRATEGIES OF THREE SCENARIOS

Scenario	Scenario features
BAS	- Capacity growth follows historical trends. - Installed capacity of pumped storage remains unchanged. - Planned reserve margin set at 15%.
PSS	-By 2025: - Wind and solar capacity will have reached 25 GW. - Hydropower, biomass, and pumped storage capacities will have reached 16.59 GW, 1.5 GW, and 3 GW, respectively. - By 2030: - Wind and solar capacity will have reached 40 GW. - Hydropower, biomass, and pumped storage capacities will have reached 17 GW, 2 GW, 10.4 GW, and 4.5 GW, respectively. - Planned reserve margin will have increased to 20%.
DES	- Carbon emissions will have peaked by 2030. - By 2060, thermal power generation will have accounted for only 10% of total power generation. - Other settings will have remained the same as in the PSS. - Planned reserve margin will have gradually increased to 25%. - Carbon Capture and Storage (CCS) technologies are expected to have advanced significantly.

Table III presents the projected installed capacities of various power generation technologies under different scenarios, highlighting significant growth in renewable energy. Notably, in the DES scenario, solar power capacity will have increased from 6.4 GW in 2022 to 200 GW by 2060, while wind power will have remained capped at 51 GW due to development limitations. In the PSS scenario, wind and solar capacities are balanced in 2025, but solar power grows at a faster pace thereafter. Thermal power capacity will have increased in the BAS and PSS scenarios but will have remained stable in the DES scenario after having peaked at 27.8 GW in 2030, indicating a gradual phase-out of fossil fuels. In the BAS scenario, over 98% of Hunan's thermal generation relies on coal.

TABLE III. INSTALLED CAPACITY (GW)

Fuel Type	BAS			PSS		DES	
	2022	2030	2060	2030	2060	2030	2060
Thermal	25.9	35.0	108.0	31.5	66.1	27.8	27.8
Hydro-power	15.9	17.0	20.0	17.0	20.0	17.0	20.0
Wind	9.0	20.0	51.0	18.0	51.0	18.0	51.0
Solar	6.4	17.0	55.0	22.0	79.0	25.0	200.0
Biomass	0.7	1.1	3.7	2.0	5.0	2.0	5.0
Pumped Storage	1.2	1.2	1.2	10.4	64.2	10.4	64.2
Import	Fulfill electricity demand and ensure power equilibrium.						

However, in the PSS and DES scenarios, the coal-to-gas power ratio will have shifted to 9:1 by 2060, promoting energy diversification. Hydropower capacity will have grown steadily, while biomass energy will have remained limited due to resource availability and economic constraints. Pumped hydropower will have expanded rapidly in the PSS and DES scenarios, addressing renewable energy intermittency and enhancing grid stability.

III. EMPIRICAL RESULTS AND DISCUSSION

A. Diversification of Electricity Generation

Electricity generation reflects Hunan Province's energy supply potential, highlighting the scale and sustainability of power production. Figure 2 illustrates the projected power generation structure from 2022 to 2060 under the BAS, PSS, and DES scenarios. Total electricity generation is expected to have increased from 224 TWh in 2022 to 829 TWh in 2060, aligning precisely with the projected demand.

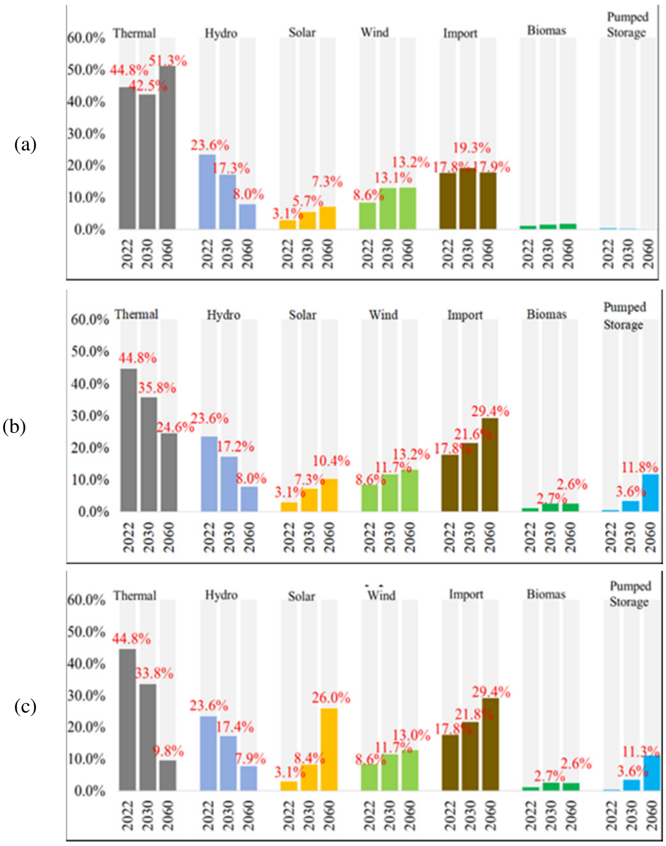

Fig. 2. Electricity production share in 2022-2060: (a) BAS, (b) PSS, and (c) DES.

In the BAS scenario, the share of coal power initially declines from 44.8% to 42.5% but will have rebounded to 51.3% by 2060. This fluctuation is largely due to the rapid expansion of wind power, which increased nearly fourfold between 2016 and 2021 [6]. As a result, wind power's share is projected to have risen from 8.6% in 2022 to 13.1% by 2030, before having stabilized due to resource limitations. Similarly, solar power is expected to have grown steadily from 3.1% to 7.3%. Meanwhile, hydropower will have reached its development ceiling, leading to a gradual decline in its share, while other energy sources will have remained relatively stable. In the PSS scenario, coal power's share drops sharply to 24.6%, while solar power increases to 10.4%. Compared to the BAS scenario, external power imports and pumped storage expand significantly, reaching 29.4% and 11.8%, respectively. This aligns with government plans to strengthen regional power interconnections, such as the Jingmen-Changsha 1,000 kV UHV line and Turpan-Hunan UHV project [35]. Under the DES scenario, thermal power's share drops drastically to 9.8%, serving mainly for peak load balance. Solar power will have become the dominant source, generating 212 TWh by 2060. Overall, Hunan Province is on track to transition to a low-carbon energy system, reinforcing the sustainable development of renewable energy in the coming decades.

B. Fossil Fuel Consumption

According to the Hunan Province Energy Development Report for 2021 [36], the province consumed approximately 167 million tons of standard coal in 2021, including 11.8 million tons of coal and 3.758 million tons used for power generation. However, only 7.2677 million tons were locally produced [37], with over 90% imported from other provinces. Reducing fossil fuel consumption is crucial for enhancing energy security and independence. Figure 3 portrays the fossil fuel consumption in 2060 (ktoe) across different scenarios. In the BAS scenario, total fossil fuel consumption will have risen sharply from 21,068.9 ktoe in 2022 to 89,321.2 ktoe by 2060, with coal lignite having accounted for 87,982 ktoe, the highest among all sources. This increase reflects the growing electricity demand and continued reliance on fossil fuels. In contrast, the PSS scenario projects a 21.2% reduction in total fossil fuel consumption by 2060 compared to the BAS scenario, with coal consumption having dropped to 38,559 ktoe. The DES scenario achieves the most significant reduction, cutting coal use further to 15,643 ktoe, a nearly 60,000 ktoe decline from the BAS scenario. Overall, fossil fuel consumption in the DES scenario will have dropped by 52% in 2030 and 80.5% by 2060, driven by policies promoting renewable energy and reduced fossil fuel dependence.

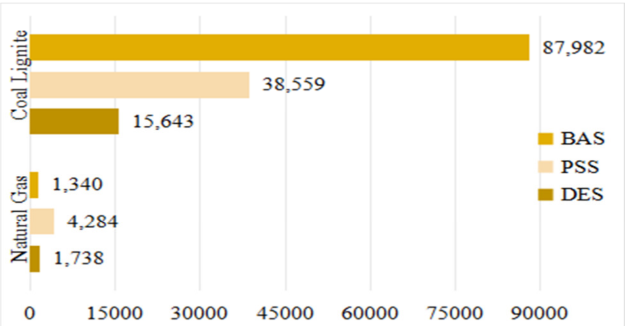

Fig. 3. The fossil fuel consumption by fuel types (ktoe) in 2060.

Natural gas consumption remains relatively low in the BAS scenario at 1,340 ktoe. However, as natural gas is expected to have accounted for 10% of the installed capacity in both the PSS and DES scenarios by 2060, its consumption increases. The PSS scenario projects natural gas consumption rising to 4,284 ktoe, while in the DES scenario, it remains more restricted, dropping to 1,738 ktoe due to the decline of thermal power generation. This suggests that natural gas serves as a transitional energy source, playing a key role in the policy-driven energy transformation. In summary, Hunan's energy transition is expected to significantly reduce fossil fuel dependence, particularly on lignite coal, while shifting toward a low-carbon, diversified energy structure. This transition enhances energy security and reduces reliance on external energy sources, aligning with Hunan's carbon neutrality goals.

C. Pollutant Emissions

Reducing fossil fuel consumption plays a critical role in lowering GHG and air pollutant emissions, thereby improving air quality. As shown in Figure 4, under the BAS scenario, emissions of CO_2, SO_2, NO_2, and $PM_{2.5}$ are projected to have reached 344.4 million tons, 3,256.5 thousand tons, 1,368.1 thousand tons, and 1,569.7 thousand tons, respectively, by 2060 -an approximate threefold increase from 2022.

This surge is attributed to the continued reliance on fossil fuels due to the absence of strong technical and policy interventions. In contrast, under the PSS and DES scenarios, emissions are expected to have decreased by 21% and 80%, respectively, compared to the BAS scenario by 2060, reflecting the reduction in fossil fuel use. In the PSS scenario, despite an expansion of wind and solar power, coal power remains a major electricity source, resulting in CO_2 emissions of 159.6 million tons. Emissions of SO_2, NO_2, and $PM_{2.5}$ will still double compared to 2022, reaching 1,421.2 thousand tons, 603.7 thousand tons, and 661.5 thousand tons, respectively. With advancements in Carbon Capture and Storage (CCS) technologies, the DES scenario projects CO_2 emissions having peaked in 2030 before having dropped to zero by 2060, while SO_2, NO_2, and $PM_{2.5}$ emissions will have fallen to 579.8 thousand tons, 244.9 thousand tons, and 288.3 thousand tons, respectively. This marks a significant reduction compared to the 2022 levels, demonstrating substantial progress toward a low-carbon energy system. However, achieving this transformation presents significant challenges for Hunan's power sector. To ensure the carbon peak and neutrality goals are met, the government must take decisive action by halting new fossil energy projects, implementing mandatory renewable energy consumption targets, and accelerating the shift toward clean energy.

IV. POLICY IMPLICATIONS

This paper has analyzed the power structure, fossil energy consumption, and environmental impacts of Hunan province under the BAS, PSS, and DES scenarios. Under the DES scenario, thermal power generation is projected to have accounted for 9.8% of the total electricity production by 2060, with fossil energy consumption having reduced by 80% compared to the BAS scenario. CO_2 emissions are expected to have peaked at 88 million tons in 2030 and gradually decline, ultimately having reached zero by2060, facilitated by advancements in CCS technologies. To achieve carbon neutrality in power production, Hunan must expand its installed renewable energy capacity, particularly for solar and wind power.

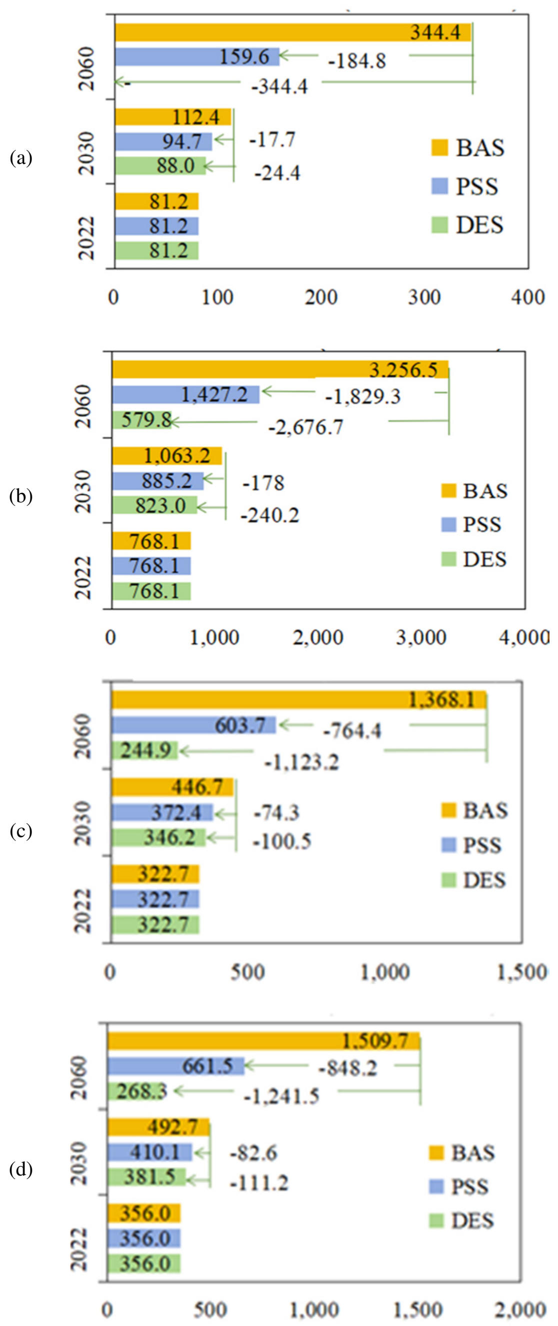

Fig. 4. Pollutant emission forecast from 2022 to 2060: (a) CO_2 (million tons), (b) SO_2 (thousand tons), (c) NO_2 (thousand tons), (d) $PM_{2.5}$ (thousand tons).

As of May 2024, according to the Hunan Regulatory Office of the National Energy Administration, the province's installed capacity for new energy has reached 24.61 GW (10.06 GW wind and 14.55 GW solar), already surpassing initial targets [38]. Given this process, this study proposes higher renewable energy targets:

1) Installed Capacity

- Wind power capacity of 18 GW and solar power capacity of 25 GW by 2030.
- Solar power should have made up more than 40% of the total installed capacity by 2060.
- Thermal power capacity should not have exceeded 28 GW by 2030 and should have been limited to 10% of the total installed capacity by 2060.

2) Electricity Generation

- By 2030, wind and solar power should have contributed at least 20% of the total generation, with fossil fuel-based generation having been capped at 35%.
- By 2060, solar power should have generated over 25% of electricity, with non-fossil energy sources having accounted for at least 60%.

3) Carbon Emissions

- Carbon emissions should have been capped at 95 million tons by 2030.

B. Challenges in Renewable Energy Development

The Hunan Provincial Government has actively promoted solar and wind power development through various policies, including setting capacity targets for PV and wind power, the construction of key renewable energy projects, and the exploration of PV+ models, such as agriculture-PV and forest-PV [37, 39-40]. These initiatives aim to accelerate the transition toward clean energy and reduce reliance on fossil fuels. However, Hunan faces numerous challenges in scaling up wind and solar energy. One of the most significant obstacles is the limited availability of wind and solar resources. The province's annual utilization hours for wind power are only 2,000, while solar power utilization is even lower at 900 hours -significantly below national averages [41]. These constraints limit the overall energy output and economic feasibility of renewable projects. Additionally, geographical constraints pose major difficulties for renewable energy development. Hunan relies on mountainous wind power and composite PV systems, such as agriculture-PV and forest-PV, which involve higher technical complexities and development costs. Moreover, in southern Hunan, wind, solar, and hydropower resources overlap, creating land-use conflicts that further complicate project planning. Environmental concerns have also led to the cancellation of 31 wind power projects, totaling 1.48 GW, due to conflicts with ecological reserves and military land [41].

Another challenge is the inherent intermittency and instability of wind and solar power, which makes balancing electricity supply and demand more difficult. Peak-shaving capabilities are insufficient, meaning the province struggles to manage fluctuations in energy generation. Reports indicate that Hunan's peak-to-valley load difference rate has reached nearly 60%, the highest in the State Grid system, making it increasingly difficult to maintain grid stability. Despite a 1.5x increase in wind power capacity and a 3.2x increase in PV capacity since 2020, during winter electricity demand peaks, wind and solar power contributed only 5% of the total electricity supply. As a result, the province still relies heavily on external power transfers and local coal power to ensure energy security [42]. Furthermore, grid infrastructure limitations present another significant challenge. As Hunan accelerates its transition to a new power system, the grid network has yet to fully adapt to the flexible integration of distributed wind and PV energy, raising concerns about power system security. The high penetration of renewable energy also places pressure on the grid and requires significant investments in modernization and energy storage. Additionally, the cost of absorbing high-capacity installations and maintaining system stability is expected to rise, which may in turn affect electricity prices in Hunan Province [42].

C. Policy Recommendations

In light of the challenges faced in expanding wind and solar power in Hunan, the following recommendations aim to drive sustainable development and ensure energy security:

- Promote the high-quality development of wind and solar power [43]. The government should ensure a balanced approach to the development of both distributed and centralized renewable energy projects. When approving new wind and solar projects, authorities must consider resource endowments, ecological constraints, and spatial carrying capacity [43]. Distributed wind power projects should be encouraged in land-scarce areas, while rooftop PV systems on privately owned buildings should be promoted to reduce land-use conflicts.
- Establish an integrated development model for wind, solar, and energy storage. To enhance grid stability and mitigate the intermittency of renewable energy, Hunan should adopt a comprehensive energy system that integrates wind power, solar power, pumped hydro storage, and electrochemical storage [10]. According to PSS and DES scenario projections, by 2060, installed capacities for pumped hydro storage and battery storage should have reached 64.4 GW and 3.5 GW, respectively. The strategic deployment of these storage solutions in key areas -Dongting Lake, central Hunan, and southern Hunan- will help stabilize the hydropower output and ensure smooth grid integration of wind and solar energy.
- Advance smart grid and Power system intelligence. Hunan should expand its efforts in intelligent power management through the implementation of advanced technologies. In June 2024, the Xiangjiang New Area Virtual Power Plant (VPP) became Hunan's first successful AI-driven power optimization system, using IoT, advanced control technology, and information communication systems to aggregate and regulate distributed power sources, storage, and adjustable loads [44]. During summer peaks, this system can dynamically adjust electricity supply from 50,000 to 100,000 kW. Building on this innovation, Hunan can promote Smart PV by combining solar energy development with ecological restoration and energy storage technologies, creating an integrated platform that covers all aspects of power station operation, maintenance, and management. Additionally, Smart Wind Power initiatives can be pursued through predictive maintenance.
- Facilitate the marketization of solar and wind power. Currently, in Hunan, the cost of centralized solar PV development is approximately 3.3 yuan per watt, while the cost of distributed development is around 2.9 yuan per watt, indicating that the solar and wind energy have reached grid parity. According to the National Unified Electricity Market Development Blueprint, by 2029, a fully integrated national electricity market will have been established. Therefore, Hunan province should accelerate the commercialization of solar and wind power, establishing a comprehensive green electricity trading mechanism. For example, priority should be given to organizing wind and solar companies with expiring subsidies or grid parity projects to participate in trading their electricity; carbon offset rules should consider the decarbonization properties of green electricity; and the trading price of green electricity should be determined through market-driven mechanisms.

V. CONCLUSION

This study utilized the Low Emissions Analysis Platform (LEAP) model to analyze the development pathways for wind and solar power in Hunan province, aiming to achieve carbon neutrality. By evaluating the power generation structure and its environmental implications under three scenarios: Baseline Scenario (BAS), Policy Support Scenario (PSS), Deep Emission Reduction Scenario (DES), the findings highlight that the DES scenario achieves the most significant reduction in thermal power, with its share having declined to 9.8% by 2060, while ensuring the highest level of renewable energy integration. Furthermore, the PSS and DES scenarios substantially reduce fossil fuel consumption, leading to notable decreases in CO_2, SO_2, NO_2, and $PM_{2.5}$ emissions, reinforcing the environmental benefits of transitioning to renewable energy sources. This study's novelty lies in its scenario-specific energy transition pathways, tailored to Hunan's unique resource endowments and industrial structure. The research identifies key challenges in the transition, including high development costs, limited peak-shaving capacity, and integration barriers, while providing actionable strategies to address them.

To facilitate the transition, this paper proposes:

- Strategic planning to maximize wind and solar resource utilization.
- Enhancing system stability through the integration of energy storage solutions.
- Optimizing grid efficiency with smart grid technologies.
- Accelerating the green electricity marketization and establishing robust trading mechanisms.

These findings have significant policy implications, emphasizing the importance of leveraging Hunan's local resources to gradually phase out coal-fired power, promote renewable energy development, and integrate advanced technologies, such as energy storage systems. This research provides a roadmap for Hunan to establish an efficient, low-carbon, and sustainable power generation system while offering valuable insights for energy transitions in central China's resource-rich regions. For future research, more granular data should be used to evaluate economic feasibility, social equity, and multidimensional factors to ensure a balanced and sustainable energy transition.

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