

Article

Strategies of a Wind–Solar–Storage System in Jiangxi Province Using the LEAP–NEMO Framework for Achieving Carbon Peaking Goals

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Abstract: Jiangxi Province relies heavily on thermal power and energy imports but is rich in natural resources, particularly lithium. This study explores strategies for advancing wind–solar–storage systems to help Jiangxi transition to a low-carbon energy structure. Using LEAP and NEMO models, four scenarios are examined: the reference (REF) scenario, new energy storage policy scenario (NPS), high wind–solar power capacity scenario (HWSS), and comprehensive optimization scenario (COS). Key findings show that the COS and HWSS offer significant advantages over the REF scenario and NPS in terms of energy storage efficiency, carbon emission reduction, and cost savings. By 2035, under the COS, wind and solar power share rises to 48%, reducing coal use by 5.9 million tons and electricity imports by 40.0 TWh compared to the REF scenario. Battery storage utilization increases by 1499.8 GWh, nearly four times that of the REF scenario. This scenario also cuts CO₂ emissions by 16.8% and lowers cumulative social costs by 5.19 billion USD, delivering optimal economic efficiency. The study also identifies challenges such as high investment costs, underdeveloped business models, and low resource utilization, and recommends setting higher targets, implementing flexible solutions, promoting market reforms, and increasing R&D efforts, among other measures.



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Keywords: renewable energy integration; energy structure; energy storage; CO₂ reduction; social costs

1. Introduction

The global commitment to addressing climate change has driven countries to accelerate efforts to achieve carbon neutrality and carbon peak targets [1]. In this context, renewable energy sources such as wind and solar have become crucial pillars in transforming traditional energy systems [2]. However, the large-scale development of wind and photovoltaic power is hindered by obstacles like intermittency and volatility [3]. The wind–solar–storage system, which integrates wind and solar generation with energy storage systems, can address these issues, ensuring energy security and grid stability [4].

China's power system follows a centralized grid structure, with the State Grid Corporation of China and China Southern Power Grid Corporation overseeing the operation and dispatch of regional grids [5]. Inter-provincial energy exchanges are primarily governed by long-term agreements, though pilot spot market programs are being gradually introduced. Resource-rich regions, such as Inner Mongolia [6], rely on ultra-high-voltage transmission

networks to deliver electricity to the central and eastern load centers [7]. However, this system continues to face challenges including transmission losses, limited flexibility for cross-regional peak shaving, and issues like curtailment of wind and solar power in certain areas [8]. Jiangxi Province, located in the southeastern inland of China with over 70% of its land covered by hills and mountains [9], serves as a typical example of the difficulties in integrating renewable energy and upgrading the grid. In 2022, thermal power made up 79% of Jiangxi's total energy generation. The province relies heavily on imported coal, which accounts for 97% of supply and depends on external power transfers for about 20% of its electricity [10], highlighting significant energy security risks.

Therefore, it is crucial for Jiangxi Province to increase its renewable energy share. From 2016 to 2022, the installed capacity of wind and solar energy grew nearly fivefold, from 0.34 MW to 1.75 MW [11,12], with further growth expected due to continued policy support. Additionally, Jiangxi is rich in lithium resources, with the largest lithium mineral reserves in China as of 2022 [13]. The province has actively promoted integrated wind–solar–storage systems through its policies. In 2021, the Notice on the Competitive Selection of Additional Photovoltaic Power Generation Projects [14] encouraged the adoption of integrated solar–storage systems, requiring energy storage to be at least 10% of installed capacity for 1 h. In January 2024, the Development Plan for New Energy Storage in Jiangxi Province (2024–2030) [15] specified that by 2025 and 2030, the new energy storage production capacity in each city should reach 15% and 20% of the newly installed capacity of renewable energy, respectively. In March 2024, the Jiangxi Energy Bureau mandated peak-shaving capabilities for grid-connected projects, with storage standards rising from 10% to 20% [16]. These policies, which have evolved from encouragement to mandatory requirements and raised storage standards from 10% to 20%, present Jiangxi Province with a unique opportunity to advance wind–solar–storage systems in alignment with its carbon peak target. They focus on optimizing energy storage across generation, grid, and user levels, advancing various energy storage technologies, and enhancing system flexibility. Additionally, they emphasize integrating energy storage with renewable energy projects, fostering synergies with smart cities, and improving electricity market and storage pricing mechanisms to ensure safe and efficient operations. However, several challenges remain in implementing the system, including the high upfront costs of energy storage technology, inadequate grid infrastructure capacity, and limited policy incentives [17]. In view of the above, this study aims to explore the role of wind–solar–storage systems in Jiangxi Province in terms of energy structure, environmental impact, and economic feasibility under the carbon peak target. The goal is to provide strategic guidance for improving renewable energy integration, promoting a low-carbon transition, and supporting Jiangxi in building a more sustainable and cost-effective future energy system.

In recent years, integrating wind power, solar power, and energy storage systems has become critical for enhancing renewable energy utilization, reducing costs, and achieving carbon neutrality. Various studies have explored this integration from different perspectives, including system scheduling, techno-economics, and market dynamics. Lu et al. [18] evaluated solar power integration with energy storage in the context of China's carbon neutrality goals, finding it cost-competitive and grid-compatible. Zhu et al. [19] optimized wind–solar–storage scheduling to improve photovoltaic utilization and storage efficiency. Zhang et al. [20] studied hydro–wind–solar–storage systems, while Zeng et al. [21] developed a revenue-sharing model for green power markets. Additionally, Srinivasan et al. [22], Ahmed and Khalid [23], and Misak et al. [24] focused on predictive models for renewable energy integration, addressing grid uncertainties and optimization. Fan et al. [25] optimized scheduling for a wind–photovoltaic–pumped-storage system to maximize revenue

and minimize emissions. Gbadega and Balogun [26] proposed energy storage coordination to enhance stability and efficiency in grid-connected renewable systems. While these studies provide valuable insights, they primarily emphasize technological integration and its outcomes. Furthermore, many are based on idealized scenarios or resource-rich regions, overlooking the complex interactions between policy changes, grid constraints, and mineral resource availability in more resource-constrained areas like Jiangxi.

Unlike resource-rich provinces (e.g., Inner Mongolia), Jiangxi represents a “middle-ground” scenario: it has moderate renewable potential [27], but faces grid constraints and heavy reliance on external energy. This makes its experience relevant to regions worldwide that struggle with balancing dispersed renewable resources, storage economics, and grid modernization—such as mountainous areas in Southeast Asia or coal-dependent regions in Eastern Europe. Nevertheless, research on Jiangxi’s power and energy sectors remains limited. For instance, Gao et al. [28] investigated the impact of wind power integration on grid voltage stability, using doubly fed generator sets as a case study. Le et al. [29] assessed Jiangxi’s capacity to integrate new energy resources across generation, transmission, storage, and load using the entropy weight and TOPSIS methods. Tang et al. [30] explored the interactions between enterprises and governments in achieving carbon peak and neutrality goals through Bayesian Nash equilibrium theory.

In summary, while extensive research has been conducted on the integration of wind, solar, and energy storage systems globally, policy-driven studies are limited, and there is a lack of in-depth analysis specifically for Jiangxi Province. This study innovatively evaluates the feasibility of various wind–solar–storage policy scenarios under carbon peak constraints in Jiangxi, using real data to analyze their impacts on renewable energy structure, costs, and carbon emissions. The goal is to provide targeted strategies and policy recommendations for regions with similar challenges, optimize energy structure, and facilitate the transition to a low-carbon, sustainable energy future in Jiangxi and beyond.

2. Methodology

2.1. Model Framework

This study employs the Low Emissions Analysis Platform (LEAP) and the Next Energy Modeling (NEMO) model as its research methodology. LEAP is an energy planning tool developed by the International Institute for Applied Systems Analysis (IIASA), primarily used for evaluating the long-term development of energy systems. LEAP–NEMO is an extension module of LEAP. Developed by SEI and integrated into LEAP in May 2020, the open-source energy system optimization tool NEMO enables the inclusion of energy storage capacity in long-term power system capacity expansion simulations [6,31]. LEAP is a widely used tool for strategic decision-making, long-term planning, and evaluating the effectiveness of policies. Regarding carbon emission pathways, Zou et al. [32] examined public building emissions in Changsha and proposed adaptive energy-saving strategies suited to areas with hot summers and cold winters. Cai et al. [33] utilized the LEAP model to analyze carbon peaking and neutrality pathways for a state-owned power generation enterprise in China, emphasizing the influence of carbon pricing and technological progress on emission reductions. Reza et al. [34] conducted a feasibility assessment of a low-carbon energy system in the Java–Bali region of Indonesia using the LEAP model, outlining a roadmap for net-zero emissions. The application of the LEAP–NEMO model is relatively less widespread. Handayani et al. [35] used the LEAP–NEMO model to simulate 100% renewable energy integration in Cambodia, Laos, and Myanmar, emphasizing the critical role of storage technologies in balancing supply and demand. Similarly, Teola et al. [36] developed a LEAP-based model for the Luzon grid incorporating utility-scale energy

storage (BESS), underscoring its importance in capacity expansion and grid flexibility for sustainable power systems.

The LEAP–NEMO model typically includes key assumptions, demand, transformation, etc. The structure of the LEAP–NEMO model in this paper is shown in Figure 1. This paper considers both pumped hydro storage and lithium-ion battery storage for energy storage. However, the analysis primarily focuses on battery storage due to Jiangxi Province’s strategic advantage in lithium resources and the rapid development of battery storage technology. Therefore, the “new energy storage” mentioned later in the paper refers specifically to battery storage.

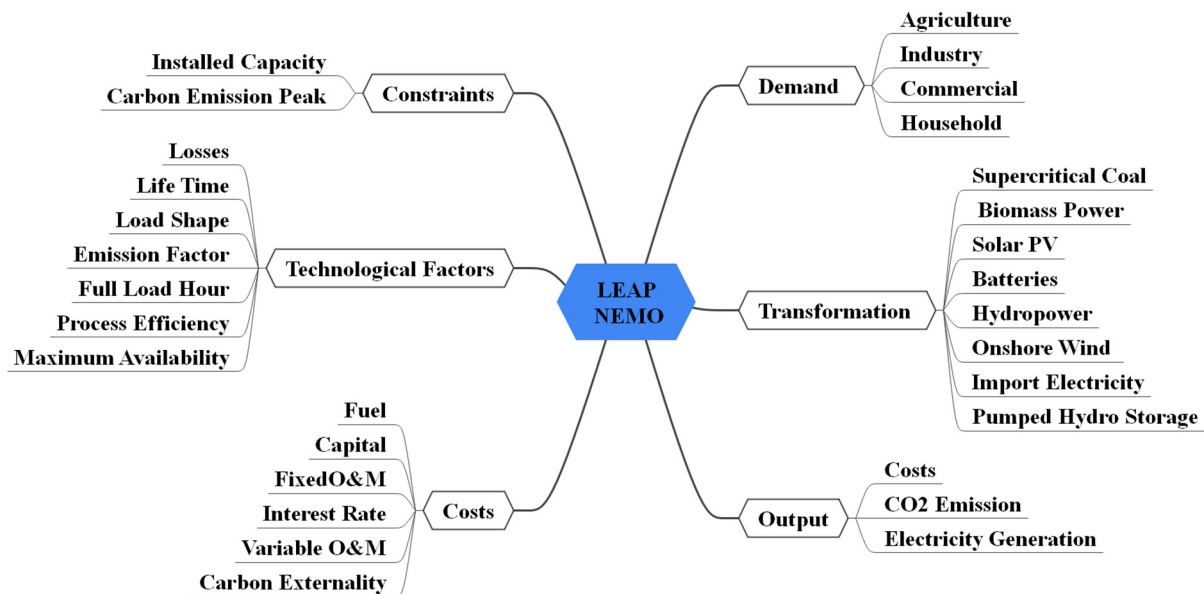


Figure 1. LEAP–NEMO model construction.

2.2. Scenario Design and Data Consideration

Based on historical data from 2013 to 2022 [37], the regression curve between the regional GDP of Jiangxi Province and the total electricity consumption of the society is shown in Figure 2. To ensure the accuracy of the fitting curve, a quadratic polynomial was used for the data fitting in this calculation. Assuming a 5% GDP growth rate for Jiangxi Province, using regression analysis, it is estimated that electricity demand will reach 316.9 TWh (trillion watt-hours) by 2035.

The load shape is obtained from online data [38]. To calculate the actual annual hourly availability of solar and wind power generation in Jiangxi Province, data from a wind farm and a solar power plant in the province are used and adjusted using Formula (1). The hourly availability of wind and solar power are illustrated in Figure 3.

$$Availability = \alpha \times \frac{P_{actual}(t)}{P_{rated}} \quad (1)$$

where α is an adjustment factor to adjust the availability of wind or solar power generation to match the actual conditions in Jiangxi Province. By analyzing the region’s historical generation data [7,8], the annual average availability is calculated and compared with the average availability of wind farms or solar power plants. The adjustment factor is the ratio of these two averages.

$P_{actual}(t)$: The actual power generation per hour (MW).

P_{rated} : The system’s rated power (MW).

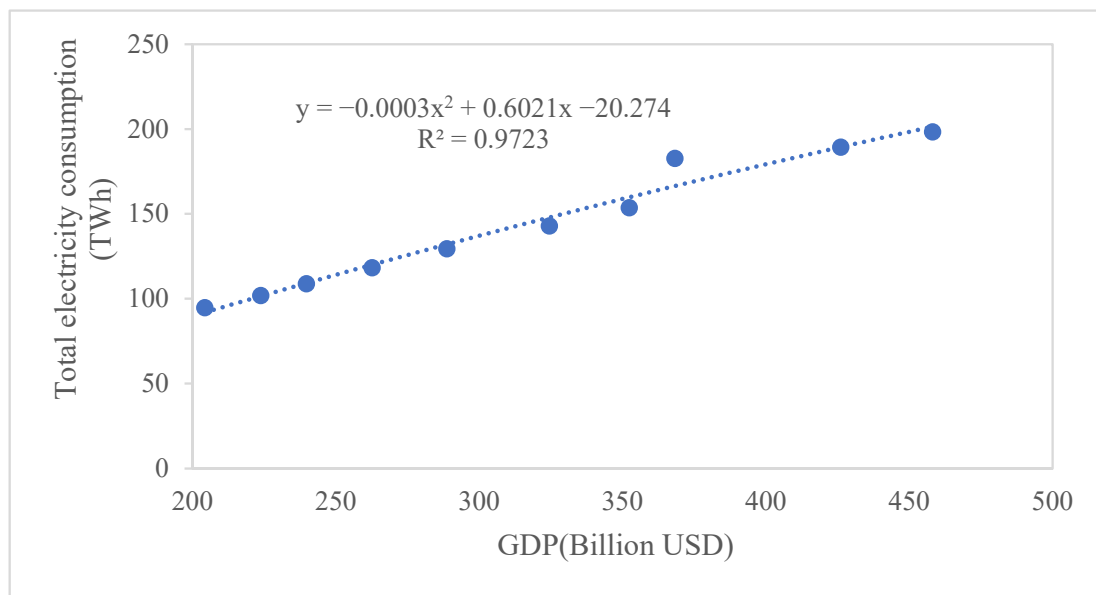


Figure 2. The regression curve between the regional GDP of Jiangxi Province and the total electricity consumption of the society.

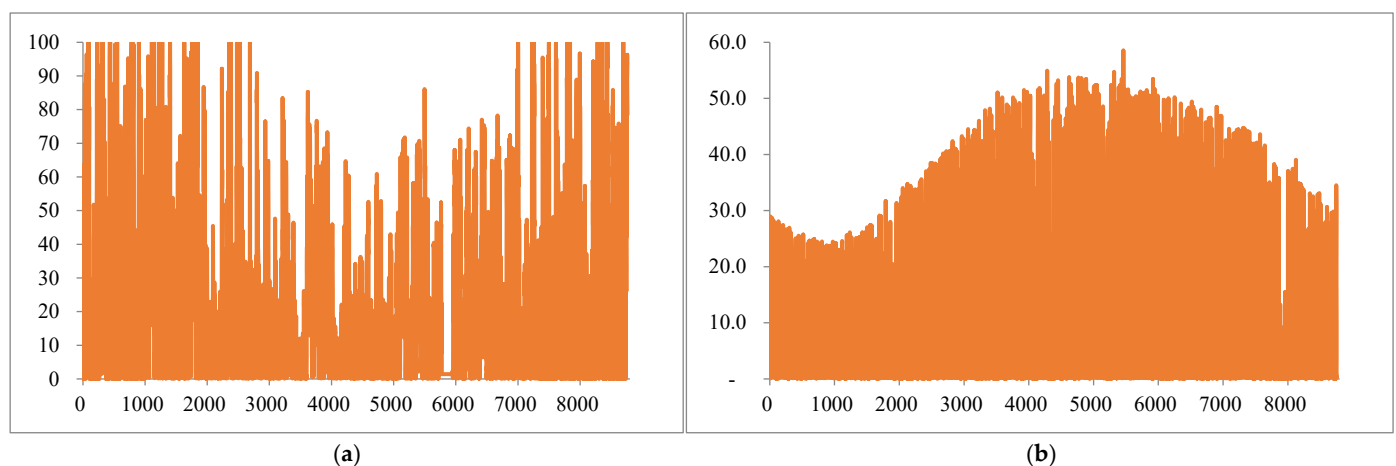


Figure 3. Hourly availability of wind and solar power. (a) Wind availability (%); (b) solar availability (%).

The CO₂ emission factor is derived from Intergovernmental Panel on Climate Change (IPCC) standards [39]. The carbon price will rise annually, reaching \$30 per ton by 2035 [40]. The losses, maximum availability, and process efficiency are verified based on the 2021–2022 China Electricity Yearbook [11,12]. Costs and lifetime are validated through relevant literature [35,36,41–45], as shown in Table 1. Assuming the battery energy storage duration is no less than 2 h per day, the battery's full-load hours are set to 730 h per year.

This study is grounded in a comprehensive analysis of the internal and external environment of Jiangxi Province. It employs scenario simulation methods to explore potential future development trends, selecting 2022 as the base year and 2035 as the end year. To analyze the feasibility of policies and the utilization rate of energy storage, four scenarios are developed: the reference (REF) scenario, the new energy storage policy scenario (NPS), the high wind and solar power installed capacity scenario (HWSS), and the comprehensive optimization scenario (COS). The specific assumptions for each scenario are outlined in Table 2. The four scenarios are designed to comprehensively assess the future development

of Jiangxi Province’s energy system, evaluating feasibility and impacts under various policy and technological conditions. The REF serves as the baseline, reflecting current policies and energy development plans, offering a point of comparison for the other scenarios. The NPS explores the effects of more proactive energy storage policies, focusing on how rapid storage expansion can enhance the hourly utilization of renewable energy. The HWSS assumes a substantial increase in wind and solar power capacity, coupled with progressively stricter carbon emission limits, highlighting the impact of high wind and solar penetration on grid stability and storage demand. The COS integrates technological advancements and policy support, assuming significant increases in the installed capacity of solar, wind, and storage, alongside stricter CO₂ emission regulations, aiming to demonstrate an optimized, cost-effective energy system. By exploring these four scenarios, the study provides valuable insights into how different development pathways can influence energy structure and storage utilization, guiding future energy planning.

Table 1. Characteristics of technologies.

Technology	Life Time (Year)	Maximum Availability (%)	Process Efficiency (%)	Interest Rate (%)	Capital Cost (\$/kW)	Fixed O&M Cost (\$/kW)	Variable O&M Cost (\$/MWh)	Fuel Cost (\$)
Supercritical coal	30	48	45	5	3112	71.8	7.3	109.3/ton
Biomass power	30	20	40	5	2149	47.9	3.0	-
Solar PV	30	variable	23	5	435	14.4	2.0	-
Hydropower	50	23	80	5	1793	37.7	6.5	-
Onshore wind	30	variable	40	5	714	42.2	2.0	-
Batteries	10	90	90	5	237	34.1	2.3	-
Pumped hydro storage	50	13	65	5	824	50.0	5.0	-
Import electricity	30	100	100	5	-	-	-	65/MWh

Table 2. Main constraints of the four scenarios.

			REF	NPS	HWSS	COS
Installed Capacity (GW)	Wind and Solar	2025	31.0	31.0	32.5	34.0
		2030	60.0	60.0	68.0	72.0
		2035	90.0	90.0	108.0	118.0
	Batteries	2025	1.0	1.5 *	1.5 *	3 *
		2030	2.0	3.0 *	3.0 *	6.0 *
		2035	3.0	6.0 *	6.0 *	12.0 *
Carbon Emission		2030 vs. 2022: +10% †, 2035 vs. 2030: −5% *	2030 vs. 2022: +5% †, 2035 vs. 2030: −5% *	2030 vs. 2022: 0% †, 2035 vs. 2030: −5% *	2030 vs. 2022: −5% †, 2035 vs. 2030: −5% *	

Notes: * Marked as a mandatory lower limit. † Marked as a restrictive upper limit. Unmarked numbers: preset target values.

The REF scenario is primarily based on the Jiangxi Province Carbon Peak Implementation Plan [46] and the 14th Five-Year Energy Development Plan for Jiangxi Province [47]. By 2025, the installed capacity of new energy storage systems is expected to reach 1 GW. The target for solar power capacity exceeds 24 GW, while wind power capacity is projected to reach 7 GW. By 2030, the installed capacity of pumped hydro storage plants is projected to reach 10 GW. The combined wind and solar power generation capacity is anticipated to reach 60 GW, while biomass power generation is expected to reach approximately 1.5 GW.

The NPS builds upon the REF scenario by including the targets for new energy storage development outlined in the Jiangxi Province New Energy Storage Development Plan (2024–2030) [15]. By 2025, the scale of new energy storage deployment should account for

at least 15% of the newly added renewable energy capacity. By 2030, this proportion should increase to at least 20%. By 2035, the goal is to achieve an installed capacity of over 6 GW, with the new energy storage duration being no less than 2 h per day.

The HWSS assumes that by 2035, the total installed capacity of solar and wind power will increase to 108 GW, with progressively stricter carbon emission limits.

The COS projects that by 2035, the installed capacity of solar and wind power will reach 118 GW, while battery energy storage capacity will grow to 12 GW, accompanied by stricter carbon dioxide emissions regulations. By 2035, the battery energy storage duration will be no less than 4 h per day. With the increase in energy storage capacity, the annual average utilization hours of wind and solar power will improve [48]. By 2035, considering the sunlight conditions and geographical constraints of Jiangxi Province, the utilization hours are expected to rise by 5%. Due to technological advancements, the capital costs of both solar and wind energy will decrease by 30%, while those of batteries will decrease by 50%. Given the battery lifespan of ten years, fixed O&M cost of batteries will be designed in phases, remaining unchanged from 2022 to 2026, decreasing by 10% annually from 2027 to 2031, and increasing by 10% annually from 2032 to 2035.

3. Results and Discussion

3.1. Power Generation Structure

By comparing the power generation structures across different scenarios from 2022 to 2035 (Figure 4), it is evident that future power demand will continue to grow, resulting in a steady increase in total power generation. By 2035, the total power generation reaches 331.1 TWh. Considering a 4% loss, total power generation slightly surpasses electricity demand. With the development potential of hydropower nearly saturated, its generation remains stable across all scenarios. The share of thermal power generation declines across all scenarios, aligning with the carbon peak and carbon neutrality policy goals. However, the rate of decline varies among scenarios. In the REF scenario, thermal power generation reaches 129.7 TWh in 2035, accounting for 39.2% of total power generation. In the NPS, with stricter carbon dioxide emission controls, thermal power generation amounts to 125.7 TWh by 2035, accounting for 38% of total power generation. Accordingly, imported power accounts for 20.3% and 21.5% of total electricity in the REF scenario and NPS, respectively. In the HWSS and COS, wind and solar power generation experience significant growth. By 2035, solar and wind generation reaches 123.2 TWh (37.1%) in the HWSS, with thermal power and imported electricity shares decreasing to 35.2% and 16.5%, respectively. In the COS, solar and wind generation increases further to 158.8 TWh (48.0%), while the shares of thermal power and imported electricity drop to 32.7% and 8.2%, respectively, contributing to an optimized energy structure. It is evident that, with the ongoing optimization of the energy structure, Jiangxi Province has successfully reduced its dependence on external electricity while significantly strengthening its energy security. Additionally, auxiliary energy sources such as pumped storage and biomass energy show growth, enhancing the diversity and stability of the power system.

3.2. Energy Import

Reducing energy imports can enhance energy security and decrease dependence on external energy supplies. Jiangxi Province has a high dependence on imports for electricity generation, and reducing import volumes is crucial for the province. Table 3 illustrates the trends in coal and electricity imports related to electricity generation under different scenarios. According to the energy balance table of Jiangxi Province (2018–2022) [10], it is assumed that coal import dependency stays constant at 97%. Coal imports show a slight increase before gradually declining. In contrast, electricity imports rise significantly,

reaching 67.0 TWh by 2035, reflecting limited progress in energy transition. A comparison of the NPS, HWSS, and COS reveals substantial differences in energy imports. By 2035, coal imports in the NPS decrease by 1 million tons relative to the REF scenario, while the HWSS and COS achieve larger reductions of 3.5 million tons and 5.9 million tons, respectively, reflecting greater efficiency in reducing coal dependence in the latter two scenarios. In the same year, electricity imports in the NPS increase by 4.0 TWh compared to the REF scenario, whereas the COS reduces electricity imports by 40 TWh, a 60% decrease, demonstrating its superior capacity to leverage local renewable energy. While both the NPS and HWSS show progress in reducing coal imports, the COS stands out for its more significant reduction in energy imports, achieved through optimizing energy structures and improving efficiency, offering a more sustainable pathway.

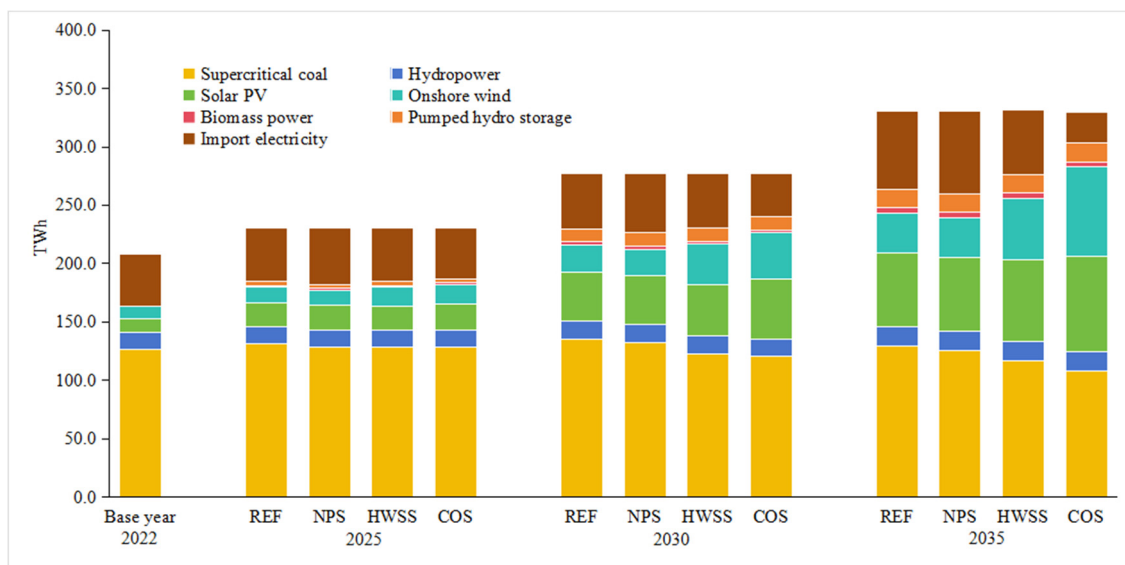


Figure 4. Power generation structure from 2022 to 2035.

Table 3. Imported coal and transferred electricity for the power sector.

		REF	NPS	HWSS	COS
Coal (Million tons)	2022	33.6			
	2030	37.0	(−0.9)	(−3.4)	(−4.2)
	2035	35.4	(−1.0)	(−3.5)	(−5.9)
Electricity (TWh)	2022	45.0			
	2030	47.3	(+3.5)	(−1.4)	(−10.7)
	2035	67.0	(+4.0)	(−12.2)	(−40.0)

Notes: The number in brackets indicates the changes in energy import from the REF scenario.

3.3. Storage Utilization

This study selects data from the COS in 2035, which represents the optimal energy mix, to better analyze the role of energy storage in the power system. The data for the year are meticulously divided into 730 series, with each day split into daytime and nighttime periods. This approach provides a clearer representation of the daily power generation structure. As shown in Figure 5, the results highlight the generation characteristics of various energy sources and the crucial role of energy storage systems across different periods. Battery systems are particularly active in May, June, July, and October. These systems play a vital role in “peak shaving and valley filling” by discharging power during peak demand periods and absorbing surplus power during low-demand periods. This capability mitigates fluctuations caused by wind and solar generation, enhancing system

stability and reliability. However, during the highest peak load periods of the year, reliance on external power supply becomes inevitable, reducing the effectiveness of battery energy storage. This underscores the critical need for Jiangxi Province to improve power dispatch and strategic planning, focusing on optimizing energy reserves and distribution during peak demand periods. It also emphasizes the importance of scaling up renewable energy generation to enhance the reliability and resilience of the power system. Thermal power generation remains central to Jiangxi's electricity system, providing reliability, particularly during demand peaks. Additionally, thermal power generation remains central to Jiangxi's electricity system, providing reliability, particularly during demand peaks. Hydropower, pumped hydro storage, and biomass energy also provide relatively stable electricity outputs year-round. Although their contribution is smaller, they supplement the system as clean and reliable energy sources.

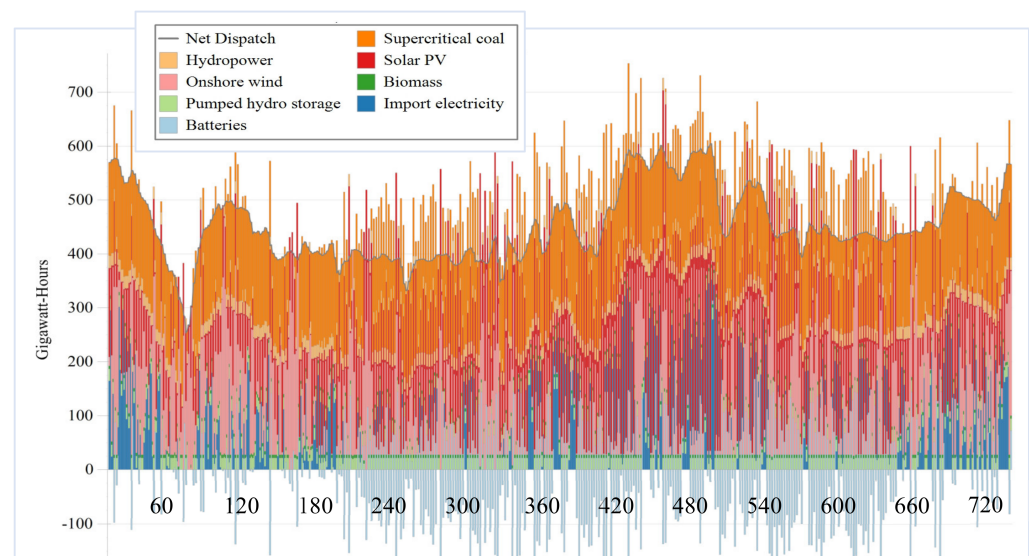


Figure 5. Daily energy generation of the COS in 2035.

As power generation in Jiangxi Province increases year by year, the annual energy discharge from new storage systems also increases steadily. As shown in Table 4, increasing the installed capacities of battery energy storage, solar, and wind power all lead to a higher utilization rate of battery energy storage. However, a comparison between the NPS and REF scenario reveals that even when battery energy storage capacity is doubled, the discharged energy from storage systems does not increase proportionally. In contrast, with the same installed capacity of 6 GW, the utilization rate of battery energy storage in the HWSS is nearly 1.5 times that in the NPS. This suggests that the discharge capacity of battery energy storage is influenced not only by its installed capacity but also by the generation of renewable energy, particularly solar and wind. This finding aligns with the conclusions of Gangopadhyay [49]. In the COS, due to the simultaneous growth of battery energy storage and solar–wind installed capacities, the discharged energy is nearly four times that of the REF scenario. As renewable energy generation increases, battery energy storage systems become more effective in stabilizing fluctuations in wind and solar power, thereby enhancing the overall stability and reliability of the power system. Jiangxi Province should better integrate energy storage development with solar and wind energy in its renewable energy plans.

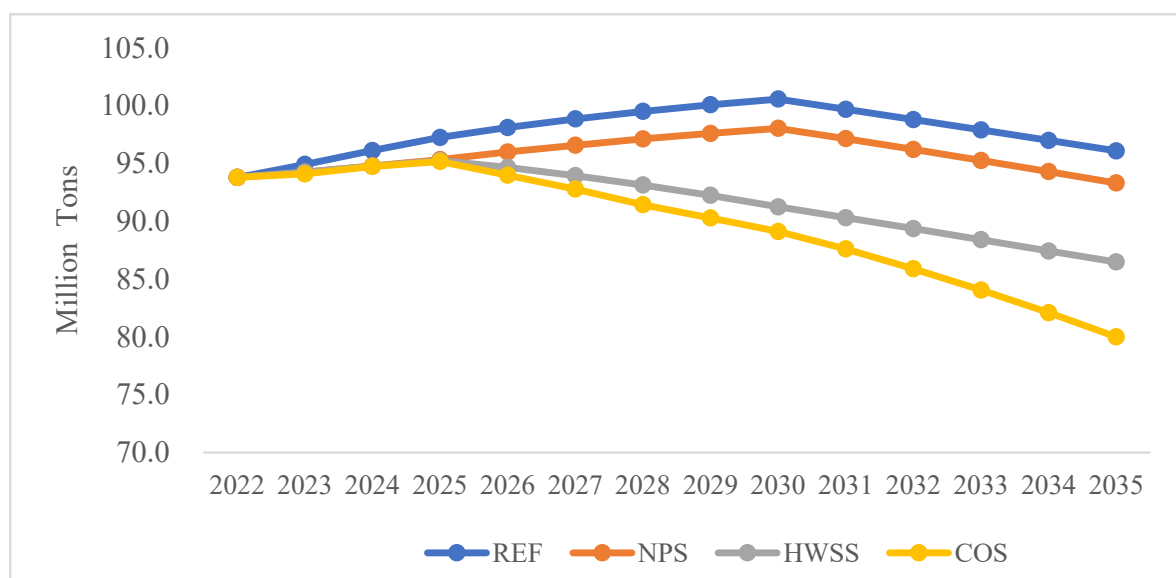
Table 4. Discharge amount of batteries under different scenarios (GWh).

	REF	NPS	HWSS	COS
2022	32.3	-	-	-
2025	98.3	(+8.6)	(+19.7)	(+210.5)
2030	400.2	(+92.0)	(+98.0)	(+519.0)
2035	611.4	(+260.2)	(+545.2)	(+1499.8)

Note: The number in brackets indicates the changes in battery discharge from the REF scenario.

3.4. CO₂ Emission

The consumption of fossil fuels inevitably impacts the environment, and this study primarily focuses on CO₂ emissions. Figure 6 illustrates the CO₂ emission trends under different scenarios from 2022 to 2035. All four scenarios peak in carbon emissions before 2030, in line with national carbon emission targets. In the REF scenario, carbon emissions peak in 2030 at 101.2 million tons, with carbon intensity reaching 3 tons per million USD of GDP, a reduction of nearly 90% from 2005 levels, consistent with China's commitments under the Paris Agreement [50]. However, each scenario shows notable differences in carbon peak timing and reduction levels. The HWSS and COS reach their carbon peak ahead of schedule, in 2025, demonstrating that a significant increase in wind and solar capacity can expedite carbon peaking. As shown in Table 5, by 2035, CO₂ emissions in the HWSS and COS are reduced by 9.6 million tons and 16.1 million tons, respectively, corresponding to a 10.0% and 16.8% decrease compared to the REF scenario. This further highlights the significant role of optimizing renewable energy share and leveraging energy storage systems in long-term carbon emission reduction.

**Figure 6.** CO₂ emission of different scenarios over the period 2022–2035.**Table 5.** CO₂ emissions from electricity production over the period 2022–2035 (million tons).

	REF	NPS	HWSS	COS
2022	93.8	-	-	-
2025	97.3	(−2.0)	(−2.0)	(−2.1)
2030	101.2	(−2.6)	(−9.3)	(−12.1)
2035	96.1	(−2.8)	(−9.6)	(−16.1)

Notes: The number in brackets indicates the changes in CO₂ emissions from the REF scenario.

3.5. Costs

The role of social cost is to guide society toward balancing economic development, environmental protection, and social equity while providing a scientific foundation for sustainable development [31]. Social cost encompasses private and external costs. This paper considers social costs including capital costs, fixed operation and maintenance costs (fixed O&M), variable operation and maintenance costs (variable O&M), import electricity fuel cost, and additional environmental costs from CO₂ emissions (as illustrated in Figure 7). Analyzing the trends in social costs across the REF scenario, NPS, HWSS, and COS reveals distinct growth patterns. The REF scenario and NPS are policy-driven, while the HWSS optimizes installed capacity without altering costs, resulting in minimal differences in cumulative social costs across the four scenarios. The REF scenario shows the steepest increase, with cumulative social costs projected to reach approximately 110.5 billion USD by 2035. Compared to the REF scenario, cumulative social costs in the NPS and HWSS are reduced by 510 million USD and 1.73 billion USD, respectively. The COS, which incorporates technological advancements, shows the greatest reduction in cumulative social costs, down by 5.19 billion USD relative to the REF scenario, with the largest contributions from the decrease in thermal power generation and external power procurement costs. Therefore, although investments in new energy storage generally increase costs, strict limitations on thermal power generation and CO₂ emissions can effectively mitigate social costs.

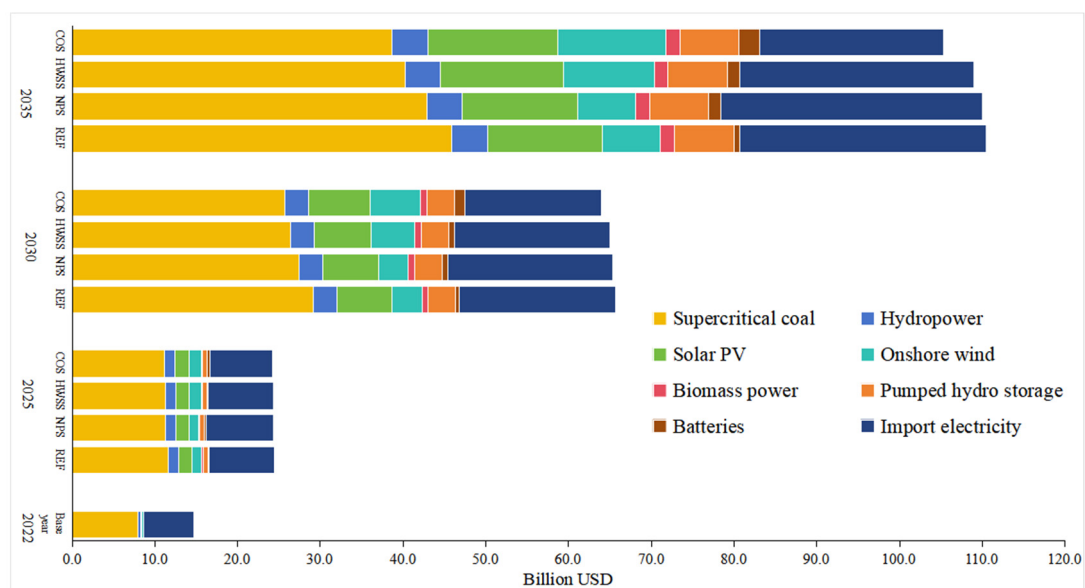


Figure 7. The cumulative social costs under different scenarios from 2022 to 2035.

To evaluate the impact of capital cost changes on the cumulative social cost in the COS for 2035, a sensitivity analysis was performed, comparing scenarios with varying levels of capital cost reductions (Figure 8). The results show that these changes have less than a 0.3% effect on the cumulative social cost. Despite significant reductions in battery energy storage capital costs, their small share in the overall system limits their impact on total costs. This suggests that, under the COS, the contribution of battery energy storage to social cost changes is minimal. Future policies should prioritize the large-scale deployment and cost reduction of wind and solar energy, while optimizing energy storage development.

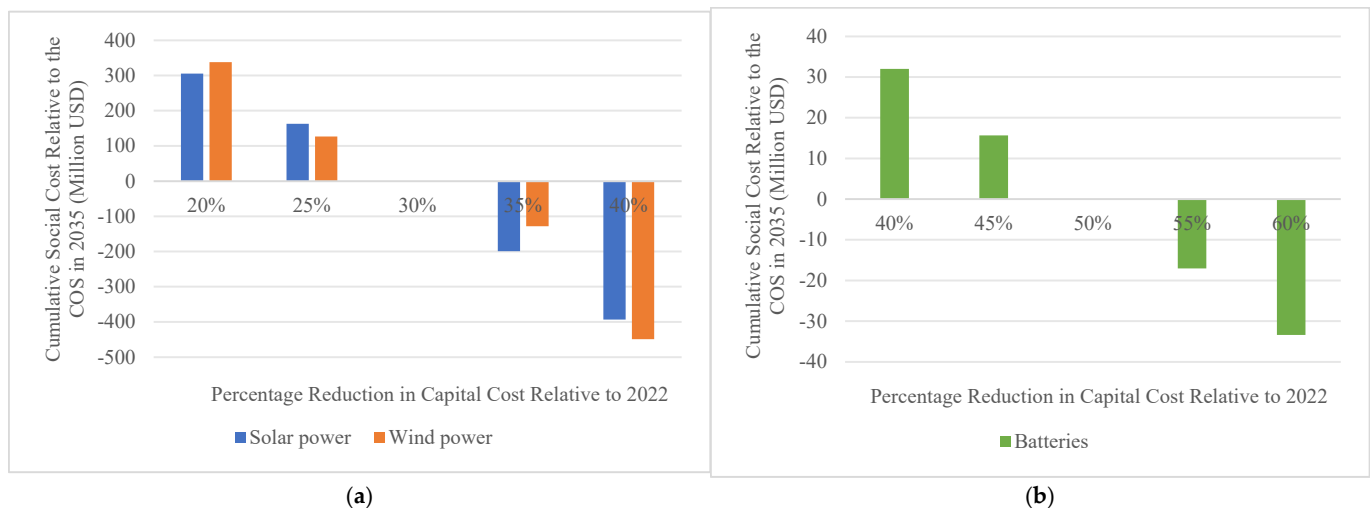


Figure 8. Sensitivity analysis of the COS in 2035. (a) Sensitivity analysis of solar and wind power costs; (b) sensitivity analysis of battery power costs.

In addition to social costs, the levelized cost of electricity (LCOE, USD/MWh) is a key metric for evaluating the economic feasibility of various power generation technologies [51]. This article refers to the cost per unit of electricity obtained by allocating the total cost of each generation technology (including capital costs, operation and fixed O&M costs, variable costs, fuel costs, etc.) over the period from 2022 to 2035, discounted at a rate of 5%. The LCOEs for different scenarios are compared in Table 6. The results indicate that the costs of hydropower, biomass, and pumped hydro storage remain stable, reflecting limited changes in deployment. The LCOE of supercritical coal-fired power fluctuates but stays relatively steady. In the COS, capital cost reductions for solar and wind energy lead to a \$4.7/MWh reduction for wind and \$2.7/MWh for solar compared to the REF scenario. The LCOE of battery storage falls from \$50.6/MWh in the REF scenario to \$25.7/MWh in the COS, reflecting the positive impact of technological advancements and policy incentives on cost optimization. Overall, policy support and technological advancements play a critical role in reducing energy production costs, particularly for renewable energy and storage technologies. However, wind power and battery energy storage still face cost pressures, necessitating further technological innovation and market support to enhance competitiveness.

Table 6. LCOE for different scenarios between 2022 and 2035 (USD/MWh).

	REF	NPS	HWSS	COS
Hydropower	29.1	-	-	-
Biomass power	60.9	-	-	-
Pumped hydro storage	69.4	-	-	-
Supercritical coal	50.4	(−0.3)	(−0.6)	(+0.2)
Solar PV	28.9	-	(+0.5)	(−2.7)
Onshore wind	29.5	-	(−0.9)	(−4.7)
Batteries	50.6	(−3.3)	(−3.3)	(−24.9)

Note: The number in brackets indicates the changes in levelized cost from the REF scenario.

4. Policy Implications

This study establishes a wind–solar–storage system for Jiangxi Province, integrating real-world data to explore the performance of various distribution and storage models in terms of structure optimization, import mitigation, supply stability, cost efficiency, and carbon emission reduction. The findings reveal that with increasing renewable energy

capacity, the share of thermal power in the generation mix declines significantly, thereby reducing Jiangxi's dependence on import energy sources. Expanding the distribution and storage system is crucial in enhancing generation stability. Compared to the REF scenario and NPS, the COS and HWSS offer significant advantages in battery energy storage utilization, carbon emission reduction, and cost savings. Under the COS, increased wind, solar, and battery energy storage capacity are expected to reduce carbon emissions by 16.8% by 2035, in contrast to the REF scenario, with a cumulative social cost reduction of 5.19 billion USD. In the short term, the government should implement stricter emission standards and phase out high-emission coal plants. Long-term, higher targets for wind, solar, and battery energy storage capacity should be set for 2035, in alignment with the COS, while fostering technological innovation and market mechanisms to achieve more efficient carbon reduction and cost savings.

Nevertheless, the development of the wind–solar–storage system faces significant challenges in Jiangxi Province. From a policy perspective, the mandatory integration of energy storage may face resistance from both government and market stakeholders, especially in the early stages. Investor interest could be limited due to the high cost of raw materials and the relatively short lifespan of battery energy storage systems, such as batteries [17]. Jiangxi's energy storage system is still in its early stages, and the lack of fully developed business models and market frameworks complicates policy implementation. Technically, the province's geographic limitations reduce the capacity factors of wind and solar power generation. According to solar radiation data, Jiangxi receives approximately 1200–1300 kWh/m² of solar radiation annually, with about 1100 h of sunshine per year [27]. While the theoretical capacity factor for solar energy is 12.5%, the actual figure is below 10%, and the wind energy capacity factor is around 22%. This inefficient resource utilization increases the cost and complexity of wind–solar–storage systems. Additionally, the introduction of energy storage systems adds complexity to grid management by increasing the number of nodes in the network. Financing remains another significant barrier. The long payback period for energy storage systems, coupled with limited financing options, could impede project development. Finally, the construction of large-scale wind–solar–storage systems may conflict with agricultural land, nature reserves, or other ecological zones, threatening bird habitats and impacting local vegetation and soil quality [52]. Public acceptance is also a challenge, as many residents are concerned about noise, visual pollution, and potential reductions in land value, leading to resistance that could delay project progress. These challenges are not unique to Jiangxi but are issues that need addressing nationwide and globally. As a frontrunner in renewable energy development, Jiangxi must proactively tackle these critical problems.

In light of these challenges, the Jiangxi Provincial Government needs to implement a series of effective measures. Based on the previous analysis, this study proposes the following recommendations:

- Flexible and cost-effective solutions should be provided for battery energy storage capacity, such as allowing renewable energy projects to lease independent storage capacity, reducing upfront investment costs. Allowing projects in regions with energy consumption difficulties to lease storage nearby helps reduce logistics and infrastructure costs. Negotiating lease prices and signing long-term contracts make investments more predictable. Additionally, the government should increase financial subsidies for battery energy storage stations and user-side enterprises, drawing from the experiences of provinces and cities such as Hunan, Chongqing, and Anhui [53]. Taking Hunan Province as an example, the energy storage industry in Hunan has entered a stage of large-scale development. In 2023, the ratio of installed energy storage capacity to wind and photovoltaic generation capacity in Hunan reached 17.4% [54],

significantly surpassing the national average. To support this growth, Hunan has implemented key policies, including the “14th Five-Year Plan for Renewable Energy Development” [55], the “Hunan Province New Power System Development Plan Outline” [56], and the “Implementation Plan for Carbon Peaking” [57], establishing a strong policy foundation. Additionally, Hunan has introduced subsidy measures to promote advanced energy storage technologies and energy storage station development. These include a reward of 0.15 yuan per kWh for qualifying large-scale energy storage material enterprises based on their annual electricity consumption increase, and 0.3 yuan per kWh for energy storage station operators based on actual discharge amounts.

- Accelerating the market-oriented reform of electricity is also crucial. According to the National Development and Reform Commission’s “Regulations on the Supervision of Full Guaranteed Acquisition of Renewable Energy Power” [58], renewable energy projects should be divided into guaranteed acquisition and market transactions. This study suggests developing a robust green power trading strategy to enable all green energy to be traded online once quotas are met in Jiangxi. By introducing various trading forms such as real-time power markets and long-term contract markets, including intraday and weekly markets, the flexibility of supply and demand matching can be enhanced. At the same time, electricity prices can be dynamically adjusted to reflect market supply and demand, generation costs, and storage technology levels. Additionally, as Lin Boqiang [59] suggested, the green electricity market can be closely integrated with the carbon trading market to achieve mutual offset and recognition of carbon emissions. With reference to the previous analysis, carbon prices can be gradually increased, with an expected reach of \$30 per ton by 2035.
- A scientific and strategic layout of the solar–wind–storage system should be established, with strict supervision and approval processes. It is important to configure a reasonable installed capacity ratio for the wind–solar–storage system, without blindly increasing the energy storage proportion. Optimization algorithms, such as linear and integer programming [60], can be used to determine the optimal energy storage capacity and configuration. In regions with a high concentration of renewable energy projects, such as Yuanzhou in Yichun, Poyang in Shangrao, and Jinxian in Nanchang, centralized energy storage facilities are encouraged. In areas with optimal wind and solar power conditions like the Wugong and Wuyi Mountains [61], a higher energy storage ratio should be set to improve the utilization rate of energy storage. For distributed systems, such as rooftop photovoltaics, strict site selection reviews are necessary to ensure optimal resource conditions. Ongoing supervision and technical support should follow installation to improve generation efficiency and maximum availability.
- Efforts in technology research and development should be intensified. Through technologies such as big data, cloud computing, and artificial intelligence, precise forecasting and intelligent regulation of the power system can be achieved, ensuring its stable operation [62]. The power dispatch model for Jiangxi Province can take the form of a multi-stage coordinated dispatching framework [63], Stackelberg game models [64], and other advanced optimization algorithms. Additionally, the dispatch system should consider the energy storage battery lifespan to improve both cost efficiency and the long-term sustainability of the system [65].
- Land planning and management should be optimized by establishing land and ecological compensation mechanisms to safeguard the interests of all stakeholders. The government should mandate environmental impact assessments for all wind–solar–storage projects during the planning phase to minimize ecological disruption. To

improve public acceptance, the government should enhance transparency and social support through information disclosure, community engagement, and benefit-sharing mechanisms.

- The integrated development of wind–solar–storage systems, electric vehicles (EVs), and hydrogen energy should be promoted. Jiangxi Province should establish distributed wind–solar–storage systems, leveraging smart grids for real-time coordination with EV charging stations to prioritize clean energy use when wind–solar resources are abundant, drawing on successful models from Hainan [66] and Guangzhou [67]. Additionally, large-scale wind–solar–storage stations can incorporate electrolysis-based hydrogen production systems to convert surplus electricity into hydrogen, ensuring a stable supply of green power for hydrogen refueling stations for new energy vehicles.

To conclude, Jiangxi Province should integrate policies, technology, and market strategies. This will help advance the sustainable development of wind–solar–storage systems. The goal is to ensure economic efficiency, system stability, and a successful low-carbon transformation.

5. Conclusions

This study focuses on the critical tasks for achieving the “carbon peaking” goal in Jiangxi Province, exploring integration of the wind–solar–storage system and its application in the power sector. Based on the LEAP model, four scenarios were established: REF, NPS, HWSS, and COS. Through comparative analysis, the following conclusions were drawn. (1) Optimization of the energy structure and reduction of external dependence: In the COS, by 2035, the proportion of wind and solar energy increases to approximately 48.0%, while the share of coal-fired power decreases significantly. External coal and electricity imports are reduced by 5.9 million tons and 40 TWh, respectively, compared to the REF scenario. (2) Increased battery energy storage utilization and enhanced grid stability: In the COS, by 2035, battery energy storage discharge increases by 1499.8 GWh compared to the REF scenario, effectively enhancing grid stability. (3) Environmental improvement and reduced social costs: In the HWSS, CO₂ emissions decrease by 16.8% compared to the REF scenario, and cumulative social costs decrease by 5.19 billion USD, achieving optimal economic efficiency. Drawing from the above analysis, this study recommends accelerating the development of integrated wind–solar–storage systems. Additionally, this research identifies issues faced by Jiangxi Province, including high investment costs, inadequate business models, low utilization rates of wind–solar–storage resources, and challenges in dispatch. To address these problems, this study proposes measures such as setting higher installation targets, planning the gradual exit of coal power, providing more flexible and cost-effective options, promoting market-oriented electricity system reform, strategically planning power resources, and strengthening technological research and development, among others. Through these measures, Jiangxi Province can achieve a more efficient, economical, and lower-carbon energy transition. This would provide valuable insights and practical guidance for integrating renewable energy nationwide and achieving carbon peaking targets. Future research can further advance intelligent renewable energy integration technologies and enhance the efficiency and cost-effectiveness of energy storage systems. The aim is to enable smart renewable energy forecasting and efficient absorption, ultimately supporting Jiangxi Province in building a sustainable, low-carbon power system.

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