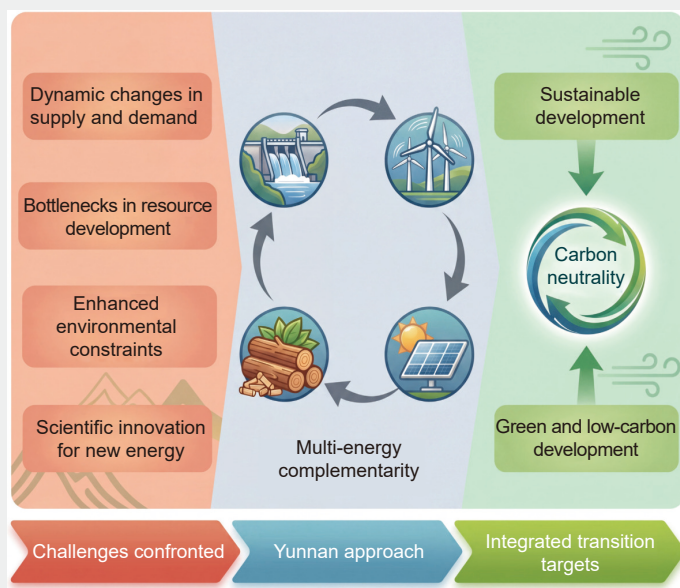


The integrated transition to carbon neutrality of ecologically fragile plateau areas

Wenze Zhang^{1,2}, Yang Liu^{1,2,*}, Zhiting Chen³, Qihang He^{1,2}, Wei Du^{1,2,*}, Jianwu Shi¹

ABSTRACT

As a clean energy hub with abundant hydro, wind, solar, and biomass resources, and serving as an ecological shield in Southwest China, Yunnan Province holds strategic importance in regional energy system transformation toward carbon neutrality. However, it currently confronts challenges such as disruptions to power supply–demand balance, resource development bottlenecks, and heightened environmental constraints, highlighting the need to balance growth with sustainability. This study reviews Yunnan’s energy resource potential, spatial-temporal characteristics, development constraints, as well as recent advances in implementation approaches and innovation deployment. A hydropower-centered, multi-energy complementary system emerges as a key pathway for Yunnan’s energy transition. By fostering positive economic and environmental synergies through multi-energy integration, technological innovation, and ecological conservation, the “Yunnan approach” may offer a valuable case example for regional low-carbon transformation.



Yunnan Province pursues carbon neutrality through a hydropower-centered, multi-energy complementary system, thereby providing a replicable model for the sustainable clean energy transition in ecologically fragile plateau regions.

KEYWORDS

Clean energy transition; multi-energy complementary system; regional low-carbon transformation; renewable energy integration; provincial carbon neutrality strategy; Yunnan

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1. Introduction

As a national ecological security barrier in southwestern China and a pivotal hub connecting South and Southeast Asia, Yunnan Province stands out for its exceptional biodiversity and extensive forest coverage. These natural endowments solidify Yunnan's status as one of the country's most abundant climate-dependent resource areas. Leveraging this inherent advantage, the province has proactively responded to the State Council's Guidelines on Strengthening System Mechanisms and Policy Measures for Energy Green and Low-carbon Transition by integrating clean energy development into its policy agenda. The commitment is further operationalized in the Yunnan Province Ecological Civilization Construction Pioneer Plan (2021–2025), which explicitly prioritizes clean energy deployment, outlining capacity targets and spatial layouts of photovoltaic and wind power projects while ensuring preferential resource allocation. Additionally, the province has pioneered integrated models such as “new energy generation + rural revitalization + agro-rural synergy”, reflecting a holistic approach to sustainable development^{1,2}. These efforts are critical to unlocking the substantial growth potential of clean energy resources, including hydro, wind, solar, and biomass, which play a strategically vital role in accelerating the low-carbon transformation of Yunnan's regional energy structure.

Strong policy support from both national and provincial authorities has created a favorable environment for developing Yunnan's climate-dependent energy resources. As of August 2025, the province's installed capacity of renewable energy has exceeded 150 gigawatts (GW), accounting for 90% of its total power generation capacity and ranking first in China by scale. Hydropower, photovoltaic, and wind power constitute the core pillars of Yunnan's clean energy generation, consistently maintaining a share of over 85% in total electricity output³ and far exceeding the global average level of 30.8% as reported by the International Energy Agency (IEA)⁴. According to Yunnan's development roadmap, the province aims to establish a national-level demonstration zone for new power systems by 2030. Key targets include achieving total energy production of around 220 million tons of standard coal equivalent, installed capacity exceeding 200 GW, and ensuring non-fossil energy accounts for no less than 46% of total energy consumption⁵.

However, the development of these resources confronts significant challenges, including spatiotemporal heterogeneity and multifaceted constraints. Specifically:

Shift in supply-demand dynamics. The electricity market is transitioning from a state of general overcapacity to one characterized by seasonal and periodic tightness. This trend is further amplified by widening peak-to-trough demand differentials, driven in part by global climate change.

Resource development bottlenecks. The depletion of large-scale hydropower reserves has exacerbated the structural power imbalance between flood season surpluses and dry season shortages. Meanwhile, limited cross-basin peak-shaving capacity intensifies long-term supply security pressures.

Enhanced environmental constraints. Yunnan's mountainous terrain significantly limits available land for energy infrastructure development, resulting in frequent spatial conflicts with agricultural land, urban planning zones, and ecological conservation red lines. The expansion of non-fossil energy consumption is further constrained by land availability issues and stringent environmental protection requirements.

Facing the pressures of intensified global climate change and China's “dual carbon” goals, Yunnan Province must address a critical challenge: how to scientifically increase the proportion of non-fossil energy consumption through innovation-driven planning while ensuring ecological security. This challenge is pivotal for achieving the province's green and low-carbon transformation.

2. Yunnan's climate-dependent energy resources and their developmental constraints

2.1 Development prospects of climate-dependent energy resources

Yunnan possesses exceptional climate resource endowments, with hydro, wind, solar, and biomass energy mutually complementing each other, thereby forming the core competitive advantage of its clean energy development (see Fig. 1). According to statistics⁶, the province's technically exploitable capacity of green electricity is more than 200 GW, accounting for 20% of China's national total and ranking among the highest in the country. Specifically:

Hydropower resources reach approximately 128 GW of technically exploitable capacity, ranking the second highest nationally. A foundational clean energy system has been established, with mega-projects such as Baihetan and Wudongde hydropower stations serving as its core infrastructure.

Wind energy reserves reach 123 GW, primarily located in river canyons (e.g., Jinsha, Nujiang and Lancang) and its northwestern and southeastern regions. Covering 11.5% of provincial territory, these zones benefit from high-altitude terrain effects that boost energy capture efficiency. However, current development utilization remains limited to 16% of total capacity.

Solar energy resources are also abundant in Yunnan, with the Tropic of Cancer traversing its southern region and an average annual sunshine duration of 2,200 hours. The annual solar energy equivalent is 7.31 billion tons of standard coal, driving photovoltaic utilization

hours above the national average (i.e., 1,439.1 hours).

Biomass energy potential in Yunnan is further amplified through comprehensive light energy integration. By utilizing abundant agricultural and forestry residues such as crop straw and sugarcane bagasse along with livestock manure, waste-to-energy conversion can establish a circular economy-based emission reduction pathway. Pu'er City serves as an illustrative case, with an annual output of 1.35 million tons of recyclable crop straw⁷, providing abundant raw materials for biomass fuel production in sectors including forestry, coffee processing, and nut cultivation. Compressing these agricultural wastes into biomass pellet fuels creates a clean, high-efficiency energy alternative that can effectively substitute traditional fossil fuels. Similarly, Kunming City has pioneered a biomass-based baking method primarily using tobacco stalks. Pellet fuel composed of 70% tobacco stalks exhibits significantly lower sulfur and ash content after combustion compared to coal⁸, substantially reducing energy consumption and carbon emissions.

The coordinated integration of the above four energy sources has created a “hydro-wind-solar-biomass” complementary energy model. This model effectively compensates for hydropower generation deficits during dry periods through intelligent scheduling of wind, photovoltaic, and biomass power generation. This strategic approach has achieved three key benefits: stabilizing the power generation output profile, enhancing energy supply system resilience, and reducing dependence on fossil fuels.

The Manwan Water-Light Integration Project developed by Huaneng Lancang River Company serves as a prime example of this model. By integrating 75 megawatts (MW) of photovoltaic capacity with the Manwan Hydropower Station and utilizing its rapid regulation capabilities, the project effectively mitigates photovoltaic volatility, achieving a 6% improvement in hydropower efficiency and the transmission channel utilization rate of 92%⁹. From December 2024 to May 2025, during Yunnan's most severe drought on record, the photovoltaic project achieved a cumulative power generation of approximately 180 million kWh, effectively filling about 20%–25% of the power supply gap of Manwan Hydropower Station in the dry season¹⁰. During overcast and cloudy weather over the same period, the 189 MW wind power supporting the Miaowei-Gongguoqiao hydro-wind-solar hybrid integration base stably supplied about 40%–60% of the power deficit caused by insufficient PV output, ensuring stable delivery of 750 MW of new energy from the base¹¹.

2.2 Spatial-temporal patterns

In Yunnan Province, climate-dependent energy resources exhibit significant spatiotemporal distribution characteristics as well as pronounced annual extreme seasonal

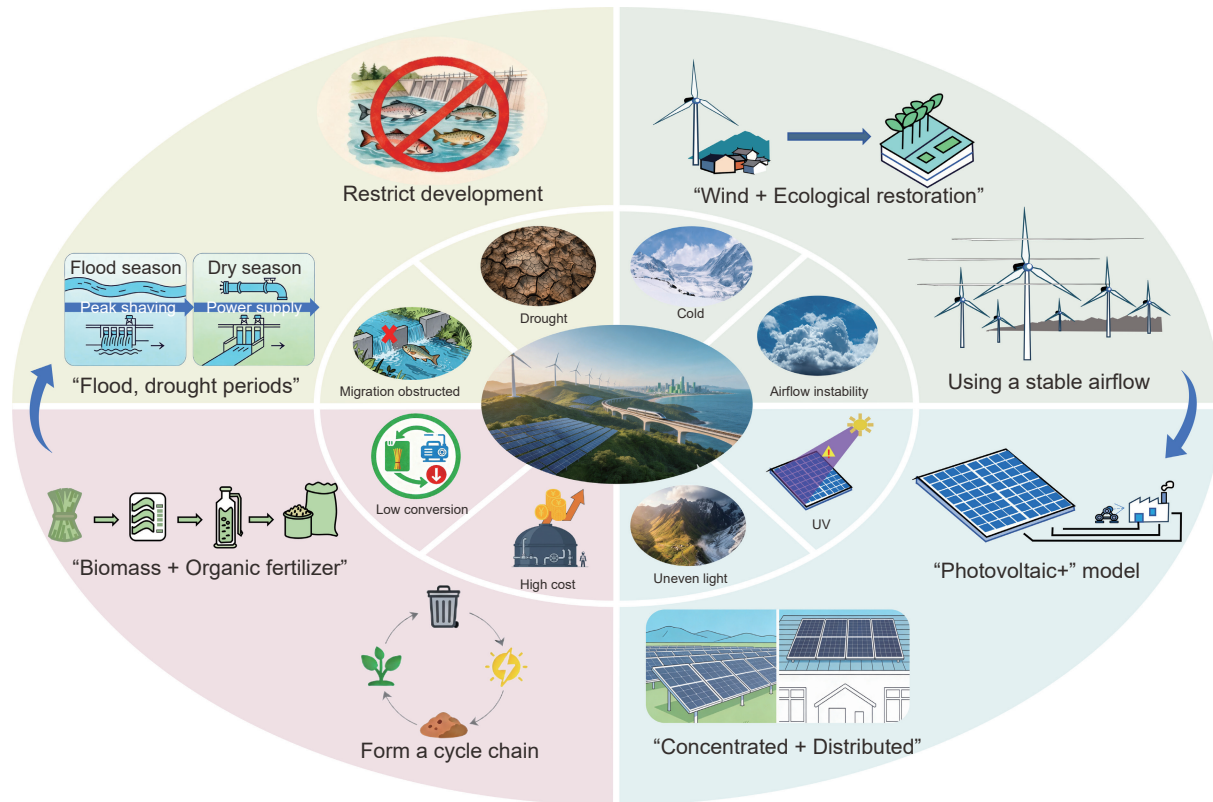


Fig. 1. Complementary model of hydro, wind, solar, and biomass energy resources.

fluctuations. Yunnan Province's climate-dependent energy resources are a double-edged sword, offering immense potential for renewable energy development while presenting significant challenges due to their spatiotemporal diversity and extreme seasonal fluctuations. By embracing hybrid energy systems, expanding cross-regional transmission infrastructure, and leveraging advanced technologies, Yunnan can transform these challenges into opportunities.

Temporally, the availability of climate-dependent resources exhibits seasonal fluctuations. In the dry season (November to May of the following year), watershed precipitation declines by 65%–80%, runoff reduces to 30%–40% of rainy season levels, and hydropower generation drops by 50%–70% compared to the rainy season¹². However, this dry period coincides with peak generation periods for wind, solar, and biomass energy. For example, during the dry season, solar radiation intensity increases significantly, with a daily average of 5.8–6.5 kWh·m⁻² which is 30%–40% higher than that in the rainy season. This enhancement boosts photovoltaic efficiency to 18%–22%, elevating power generation by 25%–30%^{13,14}. Meanwhile, biomass energy derived from agricultural waste (e.g., straw) peaks at 60%–70% of annual supply during harvest months (October to February), with straw yields averaging 3.5–4.5 tons per hectare^{15,16}. Co-generation systems (35%–40% efficiency) or biogas production (0.8–1.2 m³ methane kg⁻¹ of waste) can mitigate seasonal energy gaps. In winter (December to February

of the following year), the average wind speed reaches 5.8–7.2 m·s⁻¹, 40%–60% higher than rainy season levels, allowing wind turbines to achieve 2,200–2,500 annual utilization hours¹⁷, indicating the optimal period for wind power expansion. When the wind speed reaches 2.0–3.0 m·s⁻¹ in winter, wind power compensates for 25%–40% of the hydropower output deficit, while solar energy contributes 8%–15%. The combined wind and solar power offsets 33%–55% of the deficit, with the remaining shortfall covered by the regulating capacity of hydropower reservoirs. The power system adopts a scheduling strategy of “hydropower priority regulation, full-generation wind power supplementation, and auxiliary support from photovoltaic power”¹⁸.

Spatially, resource distribution in Yunnan Province exhibits a strong coupling with topographic characteristics. The Jinsha and Lancang Rivers collectively constitute the strategic core of Yunnan's hydropower landscape, contributing over 85% to the province's total resources¹⁹. Specifically, the surface water resources of the Jinsha River reach 28.476 billion cubic meters (see Fig. 2), with individual plants within these systems achieving capacities in the millions of kW, exemplified by the 16-million-kW Baihetan Hydropower Station. Wind energy resources are predominantly concentrated in canyon and mountain-pass areas, particularly within the Nujiang and Lancang River canyon systems of northwestern Yunnan. These regions exhibit average annual wind speeds of 6.5–8.5 m·s⁻¹ with energy densities exceeding 300 W·m⁻²,

comprising 65%–70% of the province's total wind energy reserves and representing priority zones for wind power development²⁰. Solar energy resources predominantly cluster in southern low-latitude plateau regions of Yunnan, such as Honghe, where annual sunshine duration reaches approximately 2,234 h·y⁻¹ (see Fig. 2). These areas exhibit annual sunshine durations of 2,200–2,500 hours and daily radiation intensities of 5.8–6.5 kWh·m⁻² per day, collectively accounting for 55%–60% of the provincial solar resources and offering ideal conditions for large-scale photovoltaic installations. Complementing the solar power generation base in this episode, biomass energy resources are extensively distributed across the major agricultural zones of central and southern Yunnan. The annual agricultural waste output exceeds 20 million tons, constituting 80% of the provincial biomass feedstock supply. Specifically, in Honghe Prefecture, the annual production of crop straw reaches 2,465,751.46 tons. This spatiotemporal heterogeneity necessitates a precise development strategy, prioritizing wind power in the northwest, focusing on photovoltaics in the southern plateau, and promoting the comprehensive biomass utilization in key farming regions, thereby maximizing overall resource efficiency.

2.3 Developmental constraints

Although Yunnan Province holds substantial potential for climate-dependent energy resources development, it still confronts multiple constraints.

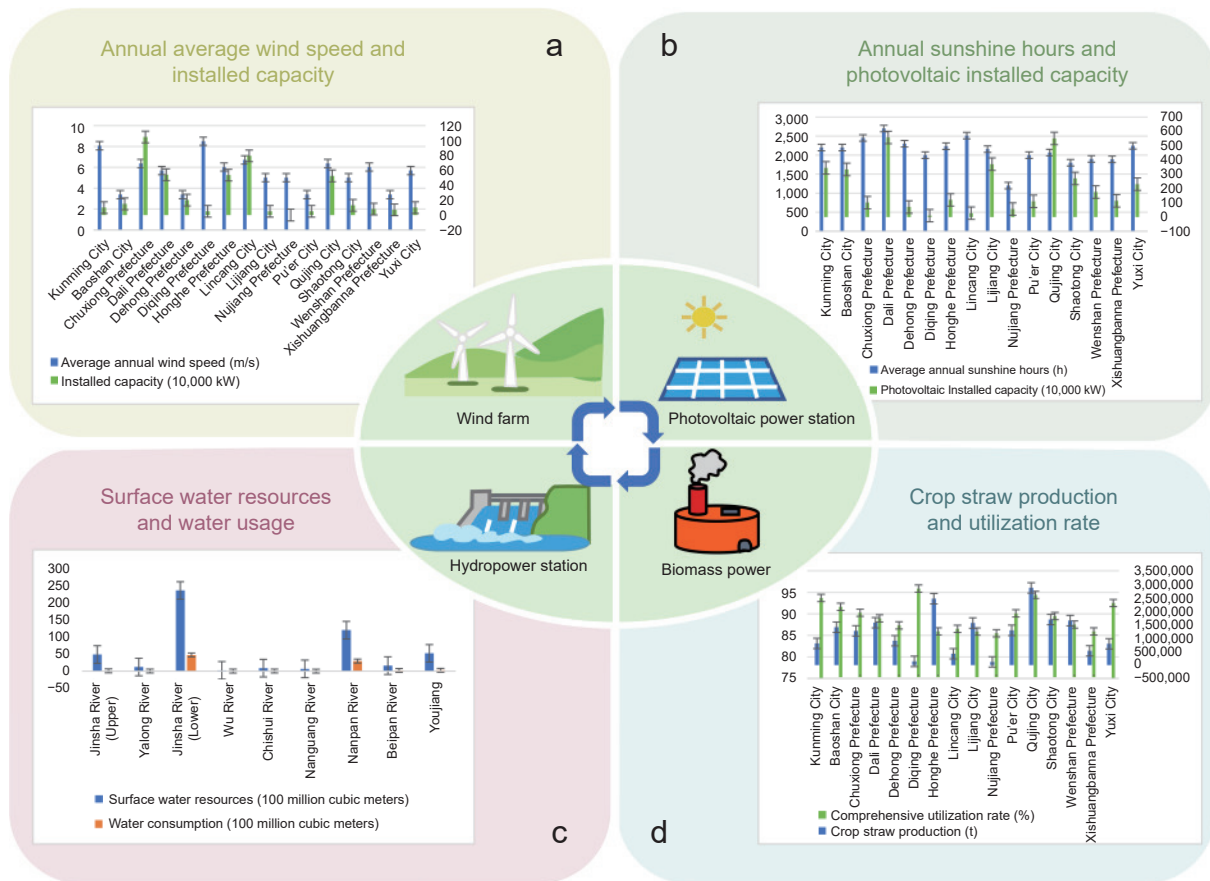


Fig. 2. The resource endowment and utilization levels in Yunnan Province.

Natural factor constraints

With mountainous terrain covering 88.6% of the province's area²¹ and the plateau sloping from the high northwest to the low southeast, an extreme altitude difference of up to 6,663.6 meters²² is created. The complex topography of Yunnan Province results in a highly uneven distribution of climate-dependent resources. Concurrently, seasonal variations in energy supply exacerbate the challenges associated with integrating renewable energy into the power grid. Transportation costs for these resources are substantially higher than in flatland regions, a disparity particularly pronounced in areas with underdeveloped infrastructure such as Pu'er City, Nujiang Prefecture, Diqing Prefecture, Zhaotong City, and Lincang City. Moreover, the steep terrain further inflates logistics expenses, e.g., the conventional collection radius for biomass can extend to 50.0 km²³, creating significant barriers to achieving optimal resource utilization efficiency.

Technological constraints

At the technical level, the high-altitude environment, where over 60% of areas exceed elevations of 2,000 meters, places rigorous demands on equipment weather resistance. Extreme daily temperature swings (ranging from -15°C to 35°C), coupled with intense ultraviolet radiation, lead to equipment failure

rates that are 30%–40% higher than those under standard operating conditions^{24,25}.

Moreover, while multi-energy complementary systems rely on advanced energy storage technologies, their current implementation faces significant gaps. Pumped-storage facilities have achieved only 35% of their planned capacity²⁶, and electrochemical energy storage systems exhibit energy densities of $180\text{ Wh}\cdot\text{kg}^{-1}$ ²⁷, which were insufficient to accommodate the dynamic demand and fluctuations inherent to renewable energy integration.

The development of biomass energy confronts critical efficiency and economics challenges. Specifically, straw gasification processes yield calorific values as low as $5.0\text{--}6.0\text{ MJ}\cdot\text{m}^{-3}$ ²⁸. Biogas engineering projects incur operational and maintenance costs of 2.7–3.0 yuan per cubic meter which are 6.75–7.5 times higher than those associated with coal-fired power generation²⁹. These cost and efficiency constraints severely limit the economic viability of biomass energy deployment.

Policy constraints

At the policy and market mechanism level, renewable energy development faces persistent challenges. A notable example is the 30% reduction in national subsidies for biomass energy in 2023, which has widened the subsidy

gap in the biomass power generation industry to an estimated 40–50 billion yuan³⁰. This gap exacerbates debt pressure on enterprises, potentially forcing the shutdown of aging or high-cost machine sets that have operated for over 15 years³¹. Consequently, the investment return cycle for biomass projects have been extended to 8–10 years. Despite these constraints, the green certificate trading market remains vibrant, with Yunnan's biomass energy green certificate trading volume accounting for approximately 9.3% of the national total in the first half of 2025³².

Ecological constraints

The ecological protection framework in Yunnan Province faces substantial developmental constraints, primarily due to the extensive coverage of ecological red zones around 29.6% of the provincial land area and a 40% overlap with planned hydropower development zones³³. Hydropower expansion in the Jinsha River Basin has particularly impacted aquatic ecosystems, causing blockage of fish migration pathways and triggering a 12%–20% decline in biodiversity³⁴. Additionally, biomass resource utilization exacerbates environmental challenges. Field straw removal for energy production may cause measurable soil degradation, with soil carbon storage decreasing by 1.2–1.8 tons per hectare over three consecutive years of operation³⁵.

3. Recent advances in climate-dependent resources utilization in Yunnan Province

3.1 Ecological sustainability in hydropower hubs

During high-water periods, the system prioritizes peak shaving to minimize water waste, whereas dry seasons employ cross-basin water transfers to prevent coal-fired plant restarts due to supply shortages. According to operational data from China Huaneng's Yunnan branch, the cascade hydropower stations on the Lancang River significantly enhance flood-season peak-shaving and supply stability through precise dispatching. By utilizing multi-year regulation reservoirs such as Xiaowan and Nuozhadu, the system achieves a daily output variation of up to 11 GW, which is equivalent to the peak-shaving capability of 11 GW-scale pumped-storage power stations³⁶. However, the current power system faces dual challenges: insufficient hydropower output during dry seasons and the financial unviability of thermal power as a reliable backstop. This over-reliance on a relatively singular power mix poses significant risks to energy security³⁷. At the policy level, Yunnan has strengthened ecological management of small and medium hydropower, restricted development in ecologically sensitive areas, and integrated hydropower carbon trading with watershed protection, thereby creating a feedback loop for emission reduction benefits. According to the "Yunnan Province Small Hydropower Station Ecological Flow Management Measures", for the 1,906 small hydropower stations under 50,000 kilowatts across the province, it is required to ensure ecological flow downstream and to clearly define responsibilities for discharge, monitoring, and supervision³⁸.

3.2 Plateau wind farms

Yunnan Province's plateau features complex terrain that has shaped unique local wind fields. Although wind energy development remains in its initial phase, its carbon mitigation potential is increasingly recognized through large-scale initiatives. For instance, the repowering projects of the Luoping Mountain, Qilong Mountain, and Fengle wind farms have been incorporated into the National Energy Administration's Wind Farm Repowering and Decommissioning Implementation Plan for 2025. Upon completion of site upgrades, these projects are projected to reduce carbon dioxide emissions by approximately 344,500 tonnes annually³⁹. However, renovation efforts face critical challenges, including the discontinued production of most original turbine components, which leads to procurement difficulties and limited replacement options. Furthermore, wind farm safety and reliability are declining, exacerbating risks associated with equipment performance and operational maintenance⁴⁰. At the policy level, Yunnan

prioritizes the deployment of wind turbines with high wind resistance and environmental adaptability. For instance, the Phase II project of the Daibu Wind Power in Huize, Qujing City, Yunnan Province, adopts "jumbo" highland mountain turbines with a single unit capacity of 6.7 megawatts and a hub height of 140 meters; segmented tower sections and digital twin hoisting technology are applied to cope with complex terrain and strong winds⁴¹. Additionally, wind energy projects are integrated with ecological restoration, such as through "wind power + vegetation restoration" initiatives in high-altitude regions, thereby enhancing carbon sequestration and fostering co-benefits for emission reduction. Here in Yunnan Province, an exemplary model of harmonious coexistence between advanced technology and nature is demonstrated. Shade-tolerant medicinal herbs and economic crops such as marigolds are planted in the intervals between wind farms; an ecological tourism route, "Painted Wind Turbines, Alpine Meadows," has been developed, establishing a "wind above, farming below" model⁴².

3.3 "Photovoltaic+" integrated model

At the policy level, the Yunnan government advocates the "photovoltaic+" integrated model⁴³. For example, it integrates agricultural land use with vegetation coverage to enhance efficiency and carbon sequestration, forming a closed-loop system of "power generation-emission reduction-carbon sequestration". The Mojiang Lianzhu 235 MW photovoltaic power station exemplifies this approach through its scientific design of the height, density, and spacing of PV arrays, which provides effective shading for tea plants below, enhancing tea leaf quality. Once fully operational, the station will annually supply approximately 376 million kWh of clean electricity, reduce carbon dioxide emissions by about 290,000 tons, and deliver substantial economic and social benefits⁴⁴. However, photovoltaic agriculture faces challenges such as inadequate technical support for solar-agriculture integration, poor infrastructure, and weak operational entities. There is an urgent need to explore new models and mechanisms for "photovoltaic plateau-characteristic agriculture" to create a win-win scenario for both sectors⁴⁵.

3.4 Biomass resources

As a major agricultural province, Yunnan actively promotes the "biomass energy + organic fertilizer" model in Qujing and Honghe cities, creating a "planting waste-energy-fertilizer" circular chain to mitigate agricultural non-point source pollution⁴⁶. For example, Qilin District in Qujing City is promoting projects that utilize vegetable waste leaves and green circular planting techniques⁴⁷. However, during the promotion of these new models, a common cycle emerges: immature technology drives up costs, high costs reduce profitability, poor profitability dampens market enthusiasm, and

low enthusiasm further impedes technology adoption and concept updates. Policy-wise, subsidies for biomass cogeneration projects encourage enterprise participation, while inclusion in the renewable energy quota system enhances market competitiveness. Against the backdrop of a 30% reduction in biomass industry subsidies, Yunnan Province will comprehensively implement the new energy security strategy of "Four Revolutions and One Cooperation" during the 15th Five-Year Plan period. To achieve the target of ensuring non-fossil energy accounts for no less than 46% of total energy consumption by 2030, the province will accelerate the green and low-carbon transformation of both energy production and consumption. It will enhance the supply capacity of green and low-carbon energy while accelerating the cultivation of new-quality productive forces within the green energy sector⁴⁸. Consequently, Yunnan Province has instituted a standardized management mechanism for comprehensive straw utilization project funds. Each key county receives five million yuan from central or provincial sources, with this mechanism guaranteeing the provision of requisite local matching funds⁴⁹. For instance, Dehong Prefecture's Finance Bureau has explicitly incorporated comprehensive straw utilization funds within its annual budget and directed county-level fiscal authorities to allocate corresponding matching funds⁵⁰.

3.5 Technology empowerment

By optimizing top-level design, Yunnan is accelerating the deployment of cutting-edge technologies such as smart grids, virtual power plant dispatching, distributed resources, large-scale energy storage, hydrogen utilization, and carbon capture, utilization, and storage. These efforts aim to stabilize renewable energy volatility, reduce carbon emissions from backup power, and enhance the power system's economic efficiency, controllability, and security. Under this policy, Yunnan became the first province in China to operate a green electricity virtual power plant, participating in the regional electricity spot market launch. By December 2025, 20 certified virtual power plants were connected in Yunnan, aggregating over 11,000 users with a total capacity exceeding 22 GW and an adjustable regulation capacity of over 2.3 GW⁵¹. These two core indicators ranked first nationwide compared with data from key provinces such as Zhejiang and Shandong⁴⁸.

At the equipment upgrading level, to mitigate intense ultraviolet radiation and temperature fluctuations in high-altitude regions, the primary structure of the fault monitoring device for the distributed transmission line employs polyether ether ketone composite to resist thermal stress cracking; the surface coating prepared by spraying a nano-silica/PTFE composite coating achieves over 99% ultraviolet absorption; internally, aerogel and paraffin-wax phase change material constitute a thermal

barrier, maintaining internal temperatures above -10°C at an ambient temperature of -30°C . This increases the low-temperature startup success rate from 50% to 100% and extends the service life by a factor of three⁵².

3.6 Market mechanisms

Yunnan leverages market mechanisms and economic incentives to encourage user participation in demand response, peak load reduction, off-peak consumption, and precision electricity consumption. In 2024, Yunnan Province conducted its first power demand response. The invited peak-shaving response achieved an actual response of 1.2878 GW (implementation rate: 128.78%). The invited valley-filling response reached 267,900 kW (133.95%). The real-time peak-shaving response delivered 633,900 kW (126.78%). Market incentives effectively guided users to actively shave peaks and fill valleys⁵³. However, Yunnan's provincial electricity transaction volume (215 billion kWh) lags behind that of Guangdong Province (510 billion kWh) and Zhejiang Province (420 billion kWh). This is attributable to the inherent quantitative gap in the total provincial electricity consumption base of Yunnan, as well as the insufficient trading activity and scale flexibility of its provincial-level market. Yunnan's market-oriented reform is dominated by annual medium and long-term transactions, and the spot market has yet to see extensive participation from residents and communities.

Simultaneously, Yunnan explores synergies between carbon trading and green finance, such as incorporating wind and photovoltaic emission reductions into the national carbon market, integrating green certificates with carbon accounting, and consolidating the Lancang-Mekong regional electricity market. The cumulative number of green certificates freely transferred for Yunnan's existing conventional hydropower has reached 243 million, ranking first nationwide, equivalent to a power volume of more than 243 billion kWh⁵⁴.

3.7 Social participation

Yunnan strengthens climate science education and encourages community involvement in distributed energy projects, fostering a "government-enterprise-public" emission reduction synergy to facilitate green energy transition. The Yunnan Power Grid Company Metering Center, through its Electric Power Science Popularization Experience Center, actively promotes energy-saving and carbon-reduction activities, including green electricity and green certificate education. Within the year, it hosted seven external learning visits, significantly enhancing public awareness of low-carbon practices⁵⁵. Yunnan Province has turned "Yunnan green electricity" into a public consensus through government information disclosure, media publicity and other means, with its public satisfaction rate surpassing the national average for nine consecutive years⁵⁶.

4. Conclusions

Yunnan's climate-dependent resources offer significant potential for innovative, integrated development models that encompass clean energy, ecological conservation, and agricultural sectors. However, this development faces challenges such as technological and funding constraints, land-use planning complexities, and market volatility risks. Through scientific planning and effective strategies that maximize its climate resource advantages, Yunnan can achieve a virtuous cycle between economic growth and ecological preservation. This approach will propel Yunnan onto a green, low-carbon, and sustainable development path, thereby contributing to the realization of China's "dual carbon" targets.

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Author contribution statement

Yang Liu: Conceptualization, Writing-Original Draft and Supervision. Wenze Zhang: Writing-Original Draft and Visualization. Zhiting Chen, Qihang He, Wei Du and Jianwu Shi: Writing-Review & Editing.

Data availability

Not applicable.

Use of AI statement

None.

Declaration of competing interest

Zhiting Chen is the employee of Kunming Power Supply Bureau, Yunnan Power Grid Co., Ltd. The other authors have no competing interests to declare that are relevant to the content of this article.

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