Policy Effects and Optimized Pathways for the Development of Wind and Solar Energy in Guangxi's Low-Carbon Energy Transition

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ABSTRACT

In the context of the global pursuit of carbon neutrality, the energy transition of Guangxi's power sector is crucial to regional sustainable development and to China's "dual-carbon" strategy. Relying on the Low Emissions Analysis Platform (LEAP) model, this paper simulates the evolution of Guangxi's energy mix and emission-reduction potential from 2022 through 2060, constructing a Baseline Scenario (BAS), a Policy Support Scenario (PSS), and a Deep Emission Reduction Scenario (DES), focusing on rapid development pathways for wind and solar energy. The scenario simulation results show that although Guangxi's energy structure continues to improve under the BAS scenario, coal-fired power generation still reaches 92.3 TWh by 2060, constituting about 23% of total electricity generation of 397.3 TWh. Wind and solar energy generation grow to 128.3 TWh and 115.9 TWh, respectively, jointly accounting for about 62% of total generation. Under the PSS scenario, renewable energies expand rapidly, with wind and solar energy reaching 255.9 TWh and 194.3 TWh, respectively, by 2060, jointly constituting about 76% of total electricity generation of 591.6 TWh. Compared to the BAS, emissions of major pollutants (CO_2, CO, NO_x, SO_2, and PM2.5) are reduced by about 21%, highlighting the importance of policy incentives in clean energy expansion. Under the DES scenario, Guangxi exhibits a high-penetration renewable energy development pattern. By 2060, solar energy further increases to 415.5 TWh, while wind energy reaches

219.7 TWh; together, they account for about 82% of total electricity generation of 773.2 TWh. Over the same period, coal-fired power generation sharply declined to 63.9 TWh, accounting for only 8.3% of the total. Compared to the BAS, Greenhouse Gas (GHG) emissions and air pollutant emissions under the DES decrease by nearly 80%, fully demonstrating the central supporting role of renewable energy in realizing carbon-neutrality targets. On this basis, the study proposes key strategies for renewable energy development in Guangxi, including building a multi-energy complementary system integrating wind, solar, hydropower, and energy storage; accelerating the deployment of energy storage facilities and flexible regulating power sources; implementing smart grid upgrades to enhance renewable energy integration; and improving market-oriented trading mechanics of renewable electricity while strengthening the local manufacturing layout of wind and photovoltaic equipment.

Keywords-Guangxi province; LEAP model; low-carbon energy transition; wind energy; solar energy

I. INTRODUCTION

Due to global warming, limiting temperature rise to 1.5°C requires rapid and deep reductions in Greenhouse Gas (GHG) emissions [1]. In response, the Chinese government has pledged to achieve carbon peaking before 2030 and carbon neutrality before 2060. Carbon neutrality refers to achieving net-zero GHG emissions through balancing emissions with removals, which imposes significant challenges on the transformation of China's energy system, through a combination of emission reductions and carbon sequestration [2]. As China's energy system has long been dominated by fossil fuels [3], industrial provinces such as Guangxi are under increasing pressure to achieve deep emission reductions. The total carbon emissions in Guangxi in 2020 were 270 million tons (Mt), significantly higher than those in 2015, of which emissions related to electricity consumption account for nearly 32% [4]. In the context of China's carbon neutrality strategy, the power sector plays a central role in emission reduction. Increasing the share of renewable energy, particularly wind and photovoltaic power, and accelerating the construction of a clean and low-carbon energy system will contribute to carbon peaking and neutrality [5].

According to the China Electricity Council, electricity demand in Guangxi has maintained steady growth. Official statistics show that the total electricity consumption increased significantly between 2016 and 2022, accompanied by a continuous rise in peak loads and installed capacity. In terms of generation structure, thermal power still accounts for a dominant share, while hydropower remains an important component of the regional energy mix. Although renewable energy capacity, particularly wind and photovoltaic power, has expanded rapidly, local power generation has not yet fully met growing demand. As a result, Guangxi continues to rely on interprovincial power transmission within the China Southern Power Grid framework and the West-to-East Power Transmission project.

From the perspective of resource endowment, national assessments conducted by the China Meteorological Administration (CMA) indicate that Guangxi possesses favorable solar radiation conditions compared with many inland provinces [6]. Wind energy resources are mainly concentrated in the Beibu Gulf coastal areas and mountainous regions. The national wind energy resource survey conducted in 2004 identified parts of Guangxi as relatively wind-rich areas with exploitable potential [7]. Subsequent detailed assessments further quantified this potential. The Guangxi Wind Energy Resource Detailed Survey and Assessment Report, completed by the Guangxi climate center, employed observational tower measurements and numerical simulations to evaluate spatial wind resource distribution and technical development potential, providing important data for regional wind power planning [8].

At the national level, large-scale development of wind and photovoltaic power enables carbon neutrality. The DNV Energy Transition Outlook China 2024 projects that wind and solar power will account for a substantial share of China's electricity generation by mid-century under accelerated transition scenarios [9]. Distributed development strategies can enhance the system efficiency and the regional adaptability of renewable deployment in China [10]. However, the intermittency and variability of wind and solar power pose challenges to power system operation and scheduling. Reductions in aerosol emissions under China's carbon neutrality pathway can enhance surface solar radiation and wind speeds, thereby increasing the technical potential of solar and wind energy generation [11].

In the evolution of the energy system toward carbon neutrality, the gradual reduction of fossil fuel dependence is expected to significantly increase the share of wind and photovoltaic power in China's electricity generation mix. Scenario analyses indicate that wind and solar energy will play a dominant role in the future power system under carbon neutrality pathways [12]. Driven by national carbon-neutral strategic policies, the installed capacities of wind and photovoltaic power have continued to expand, and their integration into regional grids in southern China is accelerating.

However, large-scale grid integration of photovoltaic and wind power introduces significant operational challenges. High penetration of variable renewable energy increases intermittency and forecast uncertainty, thereby intensifying balancing requirements and complicating generation scheduling and economic dispatch [13]. Accurate renewable power forecasting is therefore considered a critical prerequisite for secure and efficient system operation. Advanced forecasting approaches, including machine-learning-based prediction models, can effectively reduce forecast errors and improve operational coordination between renewable generation and conventional units [14-15]. Beyond forecasting, the integration of renewable energy significantly affects optimal power flow and dispatch strategies. Reviews on renewable-integrated power systems highlight that traditional deterministic dispatch models are insufficient under high uncertainty conditions and must be replaced or enhanced by stochastic and robust optimization frameworks [16]. These advanced dispatch methods are essential for maintaining system reliability while minimizing operational costs in grids with high renewable penetration. In addition, the grid-integration characteristics of wind and photovoltaic power impose new technical requirements on voltage regulation and reactive power support. Reactive power planning plays an important role in maintaining voltage stability, mitigating power quality issues, and ensuring secure system operation in renewable-rich networks [17-19].

From the perspective of carbon peaking and carbon neutrality strategies, promoting low-carbon power system transformation through technological innovation, system flexibility enhancement, and optimized dispatch mechanisms will enable achieving regional decarbonization targets [20]. Therefore, considering Guangxi's growing renewable capacity and increasing grid integration scale, it is necessary to systematically evaluate the impacts of large-scale photovoltaic and wind power development on power system operation, dispatch optimization, and voltage stability. The present study aims to analyze these impacts under carbon peaking and carbon neutrality goals and to explore feasible optimization pathways for enhancing system flexibility and supporting a secure low-carbon transition.

While numerous studies have employed the Low Emissions Analysis Platform (LEAP) model for energy transition analysis at the national level in China, there is a significant knowledge gap regarding provincial-level heterogeneity, particularly for regions like Guangxi with unique resource endowments and cross-border strategic importance. Previous provincial-level LEAP studies often focus on single-pathway projections and lack a comprehensive integration of policy-driven incentives with technology-driven pathways. Moreover, the synergistic effects between carbon reduction and the mitigation of multiple air pollutants (co-benefits) are seldom quantitatively evaluated within a localized framework.

This study contributes to the literature by developing a high-resolution, Guangxi-specific LEAP model and designing three differentiated policy scenarios (Baseline Scenario (BAS), Policy Support Scenario (PSS), and Deep Emission Reduction Scenario (DES)). The novelty of this work lies in its integrated analytical framework that simultaneously evaluates energy structure transformation, multi-pollutant emission reduction (including CO_2, SO_2, NO_x, and PM2.5), and the associated co-benefits. By bridging the gap between national-level strategic goals and provincial-level implementation constraints, this study provides a more granular and multi-dimensional assessment of low-carbon transition pathways, offering specific quantitative policy implications tailored to Guangxi's transition toward a carbon-neutral power system.

II. METHOD

A. Model Structure

This study develops an integrated energy–power system model based on the LEAP. LEAP is a bottom-up, scenario-driven accounting framework widely applied in long-term energy system analysis, climate mitigation assessment, and policy evaluation. The platform enables detailed representation of energy demand, transformation processes, and resource supply under alternative socio-economic and policy assumptions [21]. The LEAP model is a widely used tool for energy system planning, sustainable development assessment, environmental impact analysis, and policy formulation. In terms of demand-side analysis, LEAP is capable of effectively simulating changes in energy demand and trends in GHG emissions, and it is well-suited for evaluating alternative policy scenarios [22, 23].

The methodological rigor of this study is grounded in high-resolution data calibration and localized parameter settings. The base year (2022) data for Guangxi's power sector, including installed capacity, electricity generation by fuel type, and transmission losses, were strictly calibrated against the Guangxi Statistical Yearbook 2023 and the China Electric Power Industry Statistics. To ensure the accuracy of emission projections, technology-specific emission factors for CO_2, NO_x, and SO_2 were adopted based on the Intergovernmental Panel on Climate Change (IPCC) guidelines, adjusted for the average thermal efficiency of Guangxi's coal-fired fleet.

The scenario differentiation logic is based on varying levels of policy intervention and technological advancement. In the PSS and DES scenarios, renewable energy growth rates (wind and solar) are justified by the official "14th Five-Year Plan for Energy Development in Guangxi" and the "Action Plan for Carbon Peaking before 2030". Specifically, this work assumed a higher learning rate for electrochemical storage and offshore wind technologies in the DES scenario, reflecting accelerated cost reductions. Furthermore, to address the inherent uncertainty in long-term projections, a sensitivity analysis was conducted to evaluate the impact of fluctuating load growth rates and fuel prices on the overall transition pathway. This multi-layered approach ensures that the model results are not only theoretically sound but also practically relevant to Guangxi's specific energy landscape.

LEAP links the final energy demand, technology characteristics, and primary energy supply through a scenario-based simulation structure. On the demand side, energy consumption is projected as a function of activity levels and energy intensity. On the transformation side, electricity generation is modeled through explicit representation of installed capacity, process efficiency, plant availability, and emission factors. This structure allows for consistent tracking of energy balances, fuel substitution pathways, and associated GHG and air pollutant emissions [24]. Based on this modeling logic, an energy–power system framework for the Guangxi Zhuang Autonomous Region is constructed, incorporating key socio-economic drivers (Gross Domestic Product (GDP), population, and industrial structure), sectoral electricity demand modules (primary, secondary, tertiary, and residential sectors), power conversion parameters (installed capacity, reserve margin, process efficiency, availability, and emission coefficients), and primary energy resource inputs (coal, natural gas, wind, solar, and hydropower).

Scenario design is implemented to reflect alternative development pathways, enabling the comparative analysis of power structure evolution and environmental outcomes. The model generates outputs, including total electricity demand, generation mix by fuel type, fossil fuel consumption, and air pollutant emissions (CO_2, CO, SO_2, NO_x, and PM2.5). The overall modeling framework is illustrated in Figure 1.

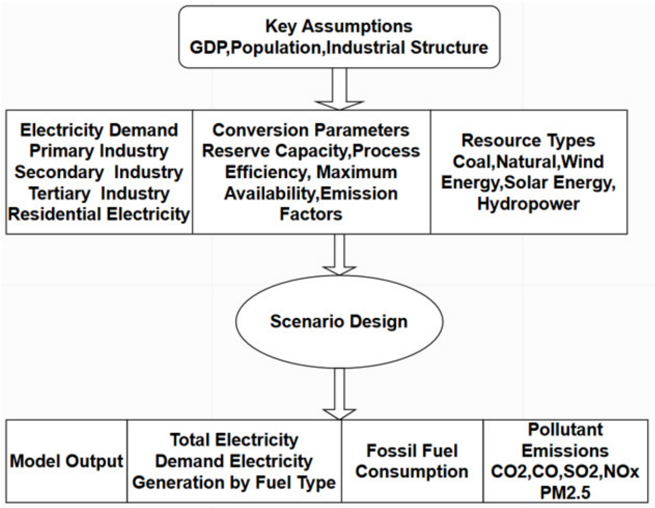

Fig. 1. LEAP model framework for Guangxi's power sector.

B. *Data Consideration*

Year 2022 is selected as the base year, 2023 as the initial simulation year, and 2060 as the terminal year of the modeling horizon. The end year is aligned with China's national carbon neutrality target [25].

The permanent resident population of Guangxi reached 50.47 million at the end of 2022, including 28.09 million urban residents [26]. Considering the recent slowdown in urbanization growth and the broader demographic trend of population aging observed at the national level [27], this study assumes a gradual and moderate population decline starting from 2022. Under this assumption, the permanent population decreases to approximately 50.0 million by 2035 and further declines to around 48.0 million by 2060. This trajectory reflects a conservative demographic outlook consistent with regional development trends. In 2022, Guangxi's GDP was approximately RMB 2,630.09 billion, with the value-added shares of the primary, secondary, and tertiary industries accounting for about 16.2%, 34.0%, and 49.8%, respectively. Regarding assumptions on future GDP growth and industrial restructuring, this study assumes an average annual GDP growth rate of 4.0%–5.0% during 2023–2035, followed by a gradual slowdown to 2.0%–3.0% during 2035–2060. Meanwhile, the share of the secondary industry is projected to decline progressively, while the tertiary sector continues to expand, reflecting structural upgrading and service-oriented transformation trends [28].

Regarding the electricity demand projection, according to official statistics, Guangxi's total end-use electricity consumption in 2022 was approximately 221.7 TWh. Electricity demand in the model is projected as a function of socio-economic drivers, including GDP growth, population changes, industrial restructuring, and electrification trends, as depicted in Table I. Based on these assumptions, future electricity demand trajectories are simulated within the LEAP framework under different policy and structural transition scenarios.

TABLE I. PROJECTED ELECTRICITY DEMAND (TWh) FROM 2022 TO 2060

Year	Primary industry	Secondary industry	Tertiary industry	Resident	Others	Total
2022	5.1	137.1	13.7	46.9	18.9	221.7
2030	9.4	253.8	25.3	86.9	34.9	410.3
2040	14.5	392.0	39.1	134.2	54.0	633.7
2050	16.0	433.0	43.1	148.2	59.6	700.0
2060	17.7	478.3	47.6	163.7	65.9	773.2

Assumptions for power generation technologies and emissions: It is assumed that newly added coal-fired power generation in Guangxi will utilize ultra-supercritical and higher-efficiency units, while natural gas power generation will employ Combined Cycle Gas Turbine (CCGT) systems. At the same time, wind and solar power generation will develop rapidly.

C. *Scenario Construction*

To explore potential development trends in Guangxi under different policy and technological pathways, the current study constructed three scenario models: the Business-as-Usual Scenario (BAS), the PSS, and the DES. The design of these scenarios draws upon the autonomous region's and the national "dual carbon" goals, Guangxi's energy development plan, and the potential of Guangxi's renewable energy resources (Table II). According to the assumptions of this case, Table III shows the evolution of the generation of electricity in Guangxi in 2022, 2035, and 2060, divided by various generating technologies. Overall, both wind and solar grow substantially in any case, but the rates at which they grow and the structures that they fill will differ considerably between up and down scenarios. The BAS scenario has limitations on its uptake, rooted in land use and the conditions of wind and hydro resources, as well as the planned baseload of fossil generation in the region. While wind and solar generation grow, their growth is not rapid. By 2060, wind power generation will have grown from 29 TWh in 2022 to 128.3 TWh, and solar generation will have grown from 19 TWh to 115.9 TWh. While coal-fired power generation decreases from its 2035 peak, its scale, at 92.3 TWh in 2060, implies that fossil energy is nearly impossible to retire under this planned development pathway. In the PSS scenario, policy incentives generate sufficient demand such that by 2035, wind power and PV generation will have reached 104 TWh and 88.1 TWh, respectively, while by 2060 they will have been strongly driven up to 255.9 TWh and 194.3 TWh of generation each. Coal-fired generation will have decreased to 76.5 TWh with strict controls—the ideal scenario of PSS leans heavily on positive incentives. In the DES scenario, solar generation is on a deep emission-reduction trajectory under the carbon-neutrality constraints laid out, with solar generation increasing from 19 TWh in 2022 to 119.1 TWh by 2035 and on to 415.5 TWh in 2060, easily becoming the largest single source of generation in the system. Wind power generation also grows reliably, to 219.7 TWh in 2060.

Coal generation is on a path to reducing to a mere 63.9 TWh by 2060, with just enough retained ability to manage peak demand, and minimal destined for backup roles temporarily, in a gradual easing of fossil generation from its prior stage. Hydropower varies less between the scenarios and is all within a range of 63 to 63 TWh by 2060, in line with the reality that Guangxi has reached hydropower saturation. Nuclear generation is relatively small as a base, although it grows moderately well in both the PSS and DES results. For essential system balance and safety relative to fulfilling demand, all three scenarios draw on lightly imported electricity. The PSS and DES scenarios both encourage a deep low-carbon future since they significantly increase renewable generation while strongly discouraging coal generation. These two sets of scenarios indicate a potential technology pathway for Guangxi towards building a new-type power system led by renewable energy.

III. EMPIRICAL RESULTS AND DISCUSSION

A. Electricity Generation Mix

The structure of electricity generation demonstrates the energy transformation pathways of supply and the emission-reduction possibilities in Guangxi under different levels of policy intensity. Using the projected electricity generation (TWh) from 2022 to 2060, this study examines the evolution of Guangxi's power generation mix under a number of model scenarios: BAS, PSS, and DES. Overall, Guangxi's power generation system is expected to continue its transition toward greater diversification and cleaner energy sources.

Under the BAS scenario, Guangxi's power generation mix shows a transition characterized by a decline in the share of coal-fired power, a rapid growth in wind and solar power, a gradual decline in the share of hydropower, and a relatively stable share of nuclear. The power generation for coal-fired power increases from 107.0 TWh in 2022 to 130.7 TWh in 2035 and declines to 92.3 TWh by 2060, during which the share of electricity generation reduces from 48.0% in 2022 to 40.1% (2035); and further falls of 23.2% by 2060. This indicates that coal-fired power, under the BAS, continues to perform a certain role in providing base-load security, but its position as "king" is weakened. Wind power generation rises rapidly, from 29.0 TWh in 2022 to 66.6 TWh in 2035 and 128.3 TWh in 2060. Its share of total electricity generation increases from 13.0% to 20.5%, and then to 32.3% in 2060, making it one of the important incremental powers under BAS. As exploitable resources become more exhausted, growth is probably steadier in that later period, with solar power continuously increasing its share of generation. Solar electricity generation in total grows from 19.0 TWh in 2022, reaches 55.9 TWh by 2035, and jumps to 115.9 TWh by 2060. Its share of total generation is first 8.5%, rises to 17.2%, and increases to 29.2% in 2060, contributing to optimizing the power generation structure. Hydropower development conditions are close to resource limits. Its generation is relatively stable in the medium-term and then declines slightly. Its share declines from 27.4% in 2022 to 19.6% by 2035 and to 13.3% by 2060. Nuclear power has changed little in scale of power generation. Its share remains consistently within about 2%–3%, hence it has a relatively minor overall impact on generation. Overall, in the BAS scenario (absent strong binding emission-reduction policies), the Guangxi power system continues to rely on traditional energy sources as an important support, but the rapid expansion of solar power will change generation in a dramatic way and lay the groundwork for subsequent energy transition.

In the PSS scenario, there is a doubling of wind and solar power and a rapid decline in coal-fired generation, reflecting adjustments in electricity demand and supply. By 2060, coal-fired power generation will have dropped to 76.5 TWh, with its share falling from 48.0% in 2022 to 12.9%. The coal power's dominant role in the electricity system is weakened, and coal power plays a supporting role by assisting the system. On the other hand, renewable energy is expanding. Wind power generation reaches 255.9 TWh in 2060, accounting for about 43.3% of the total generation, and becomes the power source with the largest generation capacity in Guangxi. Solar power generation reaches 194.3 TWh, and its share rises to about 32.8%. It provides strong support for the low-carbon transformation of the power system. Compared to a strong wind scenario, in which technical and policy constraints have a weakening effect, the strong wind and solar scenario is more conducive to the phase-down of coal power and the coordinated substitution by wind and solar energy, thus greatly accelerating Guangxi's pace toward a low-carbon and cleaner electricity system.

Under the DES Scenario, solar power becomes the absolute mainstay. According to the scenario forecast, with a deep decarbonization target, the overall energy structure in Guangxi becomes lighter. By 2060, coal-fired power generation will have dropped to 63.9 TWh, and its share of total generation will have been further reduced from the original 48.0% in 2022 to about 8.3%. In the power system, coal power serves as the core leading energy source and gradually plays a supporting auxiliary role. At the same time, solar power generation focuses on this aspect. Its output will increase rapidly from the original 19.0 TWh in 2022 to 415.5 TWh in 2060, accounting for about 53.7% of the total power generation, becoming the core leading energy source in the Guangxi system. Wind power will expand on a large scale simultaneously, reaching 219.7 TWh of generation by 2060 and increasing its share to about 28.4%, providing a significant supporting power source mix, which, together with solar energy, makes up an important basis for Guangxi's deep decarbonization.

Overall, in the effect of deep emission reduction policies and technological advancements, the expeditious steps are towards low-carbon solar energy and large supporting wind power, to support Guangxi's carbon neutrality goal. From the perspective of energy structure, the system will show the prominent features of a high-renewable system. This study estimates a scenario that depicts an extreme transformation pathway under the strongest policy constraints and with key technological breakthroughs, through which Guangxi's energy system evolves toward deep decarbonization. Specifically, under this scenario, the combined share of non-fossil energy generation—wind, solar, hydro, and nuclear power generated—could reach approximately 91.7% by 2060, as Guangxi approaches the near-complete decarbonization of its power system.

TABLE II. KEY FEATURES OF ENERGY TRANSITION PATHS UNDER DIFFERENT POLICY SCENARIOS FROM 2022 TO 2060

Scenarios	Scenario features
BAS: Business-as-Usual Development Path, 2022–2060	No policy measures beyond those currently in place (business as usual). The energy system follows a natural evolutionary path: electricity generation gradually climbs from 223 TWh to 397.3 TWh by 2060. Key trends: Existing coal-fired power is extended, peaking at 130.7 TWh by 2035. Power generation from existing coal falls much more slowly, comprising 23.2% (92.3 TWh) of total generation by 2060. Renewable energy (solar and wind) grows, but does not reach a majority share of generation, reaching at 61.5% by 2060. Generating capacities for hydropower and nuclear power also train off towards the upper limit of their potential. Key features: This scenario illustrates the pace of transition that would occur if the evolution of the energy system were left mainly to the market, resulting in some structural adjustment in the market but little reduction in carbon emissions.
PSS: Accelerated Transition Pathway, 2022–2060	A smooth, policy-supported route to carbon neutrality: total electricity generation rises steadily (up 66% overall) to 591.6 TWh by 2060. Core trends in this scenario: Coal-fired power generation peaks in 2035 at 178.7 TWh and then falls steeply, dropping to 12.9% of the total (76.5 TWh) by 2060. Wind and solar form a growing 'monoculture', yielding 450.2 TWh, or 76.1% of the total electricity: a radical restructuring of the energy system. This demonstrates the pace and scale of renewables rollout achievable with policy support.
DES: Leading Pathway toward Carbon Neutrality, 2022–2060	This scenario adopts the most ambitious emissions reduction targets assuming the greatest policy support and technological advances. Total electricity generation is at its highest, peaking at 773.2 TWh by 2060. Core trends: Coal-fired power plummets quickly, with its share falling to just 8.3% (63.9 TWh) by 2060. Solar power will have rapidly expanded to 415.5 TWh by 2060, becoming the largest source of generation. Wind and solar combined contribute over 82% of the total generation; almost 92% of the total generation comes from non-fossil sources. Key characteristics: This is a fully decarbonized power system, which would require truly innovative approaches to grid flexibility, energy storage, and electricity network capacity and infrastructure.

TABLE III. ELECTRICITY GENERATION (TWh) BY FUEL TYPE

Fuel Type	Base Year	BAS		PSS		DES	
	2022	2035	2060	2035	2060	2035	2060
Hydro-power	61	63.7	53	89.3	56	111.4	62.9
Coal	107	130.7	92.3	178.7	76.5	217.1	63.9
Wind	29	66.6	128.3	104	255.9	139.2	219.7
Solar	19	55.9	115.9	88.1	194.3	119.1	415.5
Nuclear	7	8.7	7.9	12.8	9	16.1	11.2

B. Fossil Fuel Consumption

Considering the existing energy development situation and related research in Guangxi, Guangxi is short on coal resources, and its coal supply in the electricity sector is heavily dependent on the external power sector. Reducing coal consumption and improving the energy self-sufficiency rate are central to improving energy security in the region and achieving a low-carbon transition. The pathways for coal consumption in Guangxi's power sector under the different development scenarios are shown in Figure 4 and the corresponding analysis.

Under the BAS scenario, coal consumption increases from 26,286.7 KTOE in 2022, peaks at 32,119.9 KTOE in 2035, and then begins to gradually decline, still reaching a high level of 22,674.5 KTOE in 2060. This reflects the reality that, given the lack of strong intervention from policies, the growing demand for electricity will underpin a dependence on mine mouth coal, which will decline only slowly over the long term. Under the PSS scenario, the region implements clean energy policies and drives a structural transformation of the energy system. Coal consumption peaks at a higher level of 43,893.7 KTOE in 2035, and then declines rapidly to 18,782.3 KTOE by 2060, a reduction in coal consumption of about 17.2% compared with the BAS scenario.

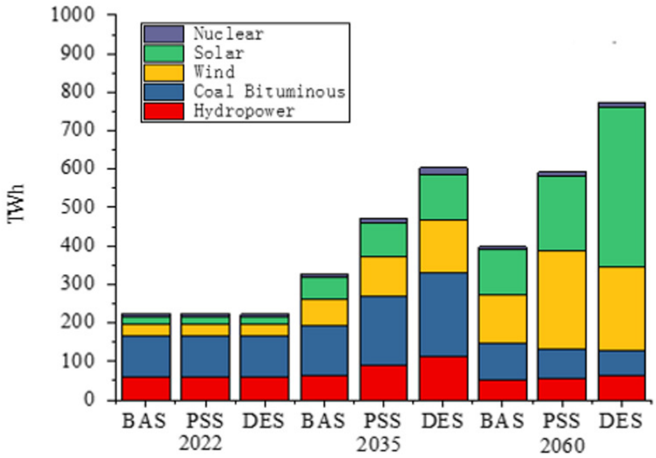

Fig. 2. Power generation under different scenarios.

The DES scenario involves the most extensive transformation of the energy system to achieve carbon neutrality, with coal consumption peaking in 2035 at 53,339.2 KTOE, reflecting the transitional role of coal power in maintaining system stability as renewable energy generation enters its absolute leading status, and then falling sharply to only 15,702.4 KTOE in 2060, the lowest among this level and about 30.7% reduction from the BAS scenario. In terms of the cumulative total consumption from 2022 to 2060, the DES scenario (213,680.2 KTOE, the strongest transition efforts) exceeds both the PSS scenario (194,622.7 KTOE) and the BAS scenario (168,853.2 KTOE). The reasoning is that the transition to a renewable-dominant energy system requires maintaining supply reliability and grid stability, for which coal-fired generation is still necessary until flexible, large-scale renewable integration and storage technologies mature. Thus, despite DES's long-term benefits in emissions reduction and coal minimization, the transition phase entails significant coal use, explaining the higher cumulative coal consumption. This shows one logic of the deep decarbonization pathway that, in order to reshape and clean up the power system at its core, there is no way around burning some coal to support a stable and smooth transition.

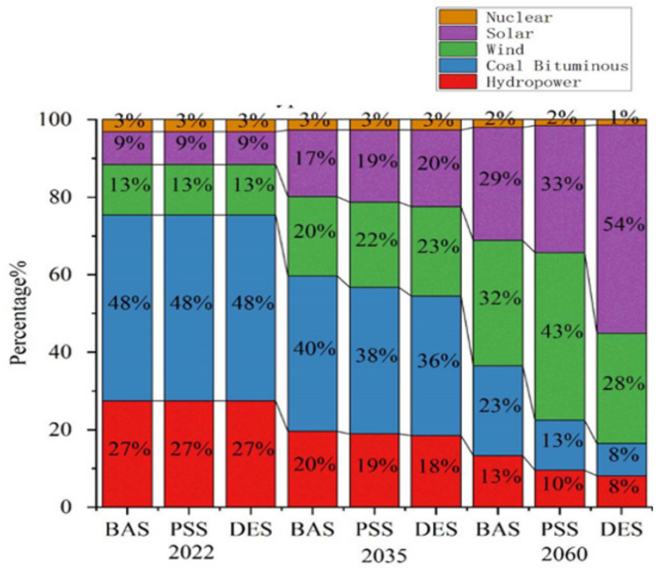

Fig. 3. Electricity generation share for technology type.

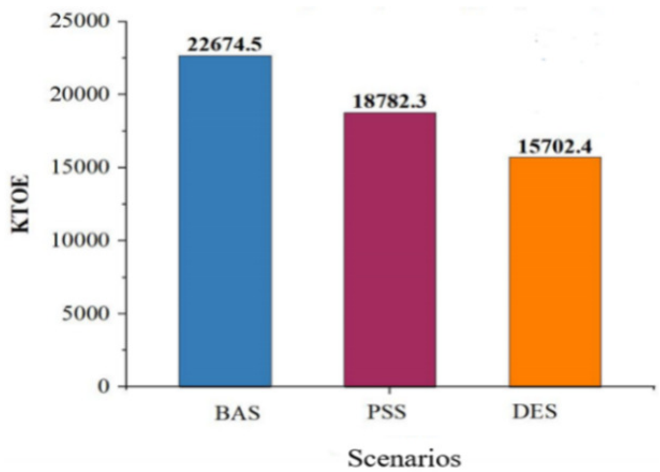

Fig. 4. Fossil fuel consumption in 2060.

Overall, regarding the BAS, PSS, and DES scenarios, the coal consumption of Guangxi's power sector condenses in the peak time, the peak level first rises and then falls, and the final consumption level shows a tiered decline. It demonstrates the following proactive pathway of Guangxi's low-carbon and rich energy structure planning under climate change and the great threat to energy independence. Although in the short term there may be systemic challenges due to deep transformation, in the long-term, dependence on imported fossil energy will be greatly reduced, and energy security will be strengthened.

C. Greenhouse Gas Pollutant Emissions

Reducing the use of fossil energy can greatly reduce the emission of GHG and conventional air pollutants and improve regional air quality. Looking at different scenarios, it can be observed that the emissions of major pollutants from Guangxi's power sector are going to diverge. Under the BAS scenario, where the energy structure transformation is slow, and coal power is dominant for a long time, pollutant emissions from Guangxi's power sector increased significantly in the medium-term period. By 2035, emissions of CO_2, CO, SO_2, NO_x, and PM2.5 increased to 235.3 Mt, 130.7 kt, 2,091.9 kt, 784.5 kt, and 523.0 t, respectively. By 2060, emissions fell slightly as some outdated coal-fired units were gradually eliminated, but CO_2, CO, SO_2, NO_x, and PM2.5 were still 166.1 Mt, 92.3 kt, 1,476.7 kt, 553.8 kt, and 369.2 t, respectively, and were much higher than the 2022 levels. This means that, without policy and technological upgrades, Guangxi's power system will find it difficult to realize a substantial cleansing.

In the PSS scenario, wind and solar installed capacity, driven by policy, continues to grow, and the proportion of coal power also gradually increases, thus alleviating the restraining difficulty of pollutant emission. By 2060, CO_2 emissions shrink to 137.6 Mt, down to 17.2% from the BAS scenario; CO emissions decline to 76.5 kt, down to about 17.1%; while the emissions of SO_2, NO_x, and PM2.5 are reduced to 1,223.3 kt, 458.7 kt, and 305.8 tons, respectively, being all down by about 17% from the BAS scenario. However, as coal burning is still a relatively large proportion of the foundation in the power system, the overall emission level is still higher than in 2022, demonstrating that moderate-intensity policies alone are no longer enough to support a soaring emission reduction.

Under the DES, motivated by the strictest emission reduction policies, "great adjustment" of the energy structure and mutual synergy between the advancement of clean power generation and cleaning treatment technologies, the emission dregs of Guangxi's power sector peak by 2035, and fall continuously thereafter. By 2060, they further reduce to 115.1 Mt, down about 30.7% from the BAS scenario; CO emissions drop to about 63.9 kt, down about 30.8%; and emissions of SO_2, NH3N, and PM2.5 fall to 1,022.7 kt, 383.5 kt, and 255.7 t, respectively, with the reduction rate being more than 30%. A high proportion of non-fossil energy substitution makes it possible to reduce the monopolistic position of coal power in the power system and realize the multi furnishing with emission reduction.

Overall, the comparisons from these scenarios show that the natural evolution path alone is insufficient for effective pollution control and deep emission reductions in power generation in Guangxi province to concurrently achieve sustained improvements in air quality and carbon reduction outcomes. The region must pursue the path represented by the DES scenario, of/including strong control over new fossil fuel projects and the rapid, large-scale development of renewable energy, alongside reinforcing emission constraints and technology innovation mechanisms to give strong backing for the region's carbon peak and carbon neutrality targets.

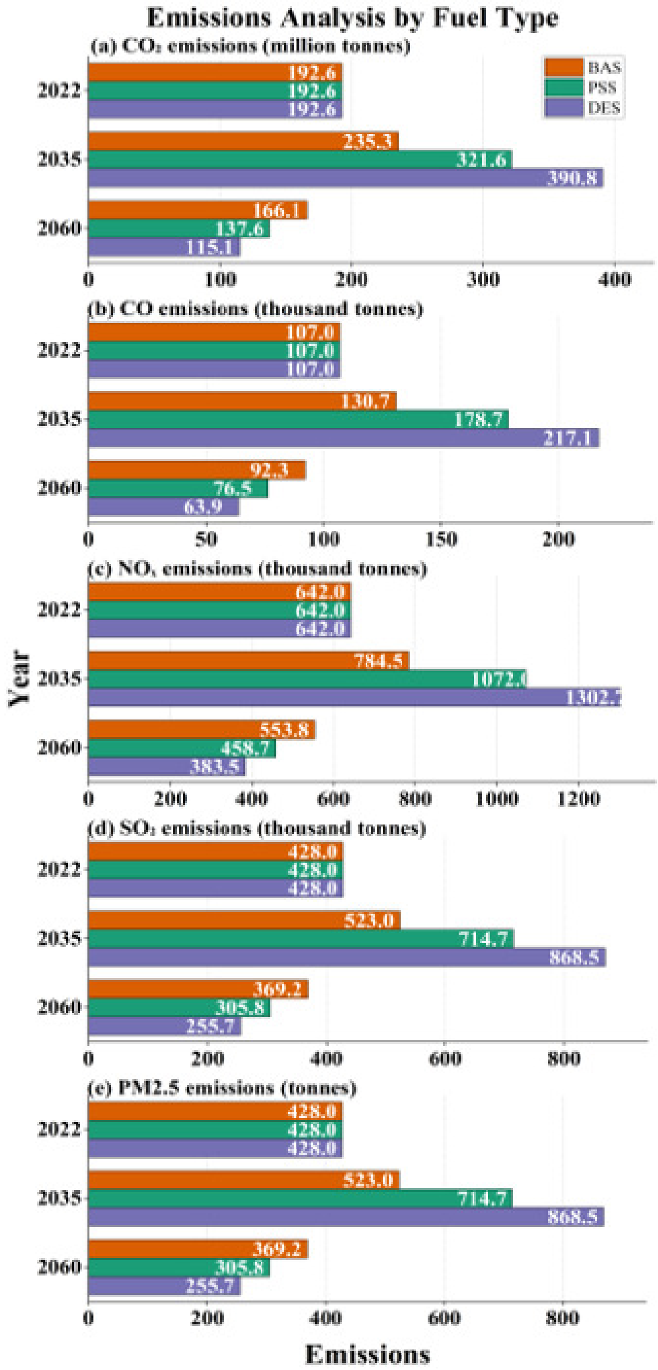

Fig. 5. GHG pollutant emissions forecast from 2020 to 2060.

IV. POLICY RECOMMENDATIONS

Based on the quantitative projections from the scenario analysis, this study proposes a targeted policy framework designed to address the unique challenges of Guangxi's energy transition. To overcome localized constraints and leverage regional advantages, the following policy recommendations are put forward:

- Fostering the high-quality development of wind and solar power. In planning and approving wind and solar projects across Guangxi, the region must prioritize the "Beibu Gulf Offshore Wind Power Base" and large-scale "Photovoltaic + Karst Restoration" projects in northern and western Guangxi. Instead of a generic approach, Guangxi should leverage its unique karst topography to develop decentralized wind power in mountainous areas that are unsuitable for traditional agriculture. Following a path of combined centralized and distributed development: in industrial clusters like Liuzhou and Guigang, rooftop photovoltaic projects should be mandatory for new industrial parks to enhance local renewable energy consumption capacity.

- Building a multi-energy complementary system integrating wind, solar, and Guangxi's significant existing hydropower resources. By utilizing the cascaded hydropower stations on the Hongshui River as flexible "regulating reservoirs," the intermittency of new wind and solar additions can be effectively buffered. Judging from the simulation results, Guangxi should accelerate the deployment of pumped hydro storage (such as the Longan and Tiandeng projects) to serve as a regional energy buffer. Taking advantage of the complementary relationship between wind and solar energy on the daily and seasonal scales, the integration should focus on the coastal-mountainous synergy, where coastal wind peaks during the winter and spring, while inland solar is most productive during the summer.

- Enhancing the flexibility and operational regulation capacity of the power system. Under the DES scenario, where variable renewable energy (wind and solar) exceeds 450 TWh by 2060, system balancing and dispatch complexity increase significantly. Therefore, Guangxi should prioritize the development of advanced dispatching systems and flexible regulation resources, including energy storage and demand-side response, to ensure system stability. The adoption of coordinated control strategies, such as virtual power plants, can further improve the aggregation and management of distributed energy resources [29]. In particular, leveraging Guangxi's geographical position as a gateway to the ASEAN region, cross-regional power exchange and coordinated dispatch mechanisms can be strengthened to enhance system flexibility and integration efficiency [30]. In addition, integrating distributed photovoltaics in urban centers such as Nanning with decentralized wind power in northern mountainous areas can enhance spatial complementarity and reduce variability impacts. The establishment of localized manufacturing clusters for wind turbines and photovoltaic equipment in Qinzhou and Beihai can also help reduce system costs and support large-scale renewable deployment.

- Advancing market-oriented development mechanisms for wind and solar energy. Guangxi should align with the national unified power market development process, accelerate the improvement of green power trading mechanisms, and promote the full participation of renewable energy in market transactions. Specific measures include prioritizing the participation of wind and photovoltaic projects that have achieved grid parity in the power market; fully reflecting the emission reduction value of green electricity in the linkage mechanisms between carbon markets and power markets; and forming reasonable green electricity prices through market-based pricing mechanisms to guide sustained investment from social capital into the renewable energy sector.

In short, through the implementation of the above policies, Guangxi will achieve a new-type power system with solar and wind as the main pillars, supported by energy storage and pumped hydro storage, and backed by smart grids as the core safeguard, which will provide solid support for the deep decarbonization and carbon neutrality of the regional power system.

V. CONCLUSION

This research conducts a systematic analysis of the development paths of the wind and solar industries in Guangxi in the context of carbon neutrality goals. It also demonstrates the characteristics of the transformation of power industry structure and the difference of environmental impact between three scenarios, namely, Baseline Scenario (BAS), Policy Support Scenario (PSS), and Deep Emission Reduction Scenario (DES). To a certain extent, the stronger the scenario constraints, the greater the tendency for Guangxi's power system to transform from a fossil fuel-based power system to a renewable energy-dominant power system. The DES scenario is the preferred one for power structure adjustment. By 2060, the share of coal-fired power generation drops rapidly from around 48% in 2022 to about 8.3%, going from the power source of choice to a back-up and peaking service provider, while wind and solar power generation grow rapidly and are consistent with green development results, having the strongest renewable energy integration capacity. Fossil fuel consumption drops significantly in PSS and DES scenarios. Greenhouse Gas (GHG) pollutants' (CO_2, CO, SO_2, NO_x, and PM2.5) emissions are lower than in the BAS scenario, fully reflecting the environmental benefits brought by the renewable energy transition from the perspective of pollution and carbon co-benefits.

From the scenario simulation results, a series of implementable policy recommendations are proposed, including: maximizing the utilization of Guangxi's wind and solar resources through scientific planning; accelerating the coordinated deployment of flexible regulation resources, such as energy storage and pumped hydro storage, to improve system stability; utilizing smart grids and digital dispatch technologies to enhance grid operational efficiency and renewable energy consumption levels; and, at the same time, accelerating the marketization of green electricity and improving the linkage mechanisms between the power and carbon markets to create a stable market environment for renewable energy development. This study integrates Guangxi's distinctive resource endowment, topography, and power system structure to design region-specific energy transition scenarios and developmental pathways.

The technical pathways and policy frameworks proposed provide valuable insights not only for Guangxi but also for other regions in southern China and areas worldwide with similar resource conditions and energy transition challenges. Future work can help build upon this work by incorporating more specific time-series data and regional differentiation information to conduct a broad range of assessments, from various perspectives, such as economic feasibility, social equity, and system resilience, to ensure a smooth and sustainable transition in Guangxi's power system.

DECLARATION OF COMPETING INTERESTS

The authors declare that there are no competing interests.

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DATA AVAILABILITY

The datasets used in this study (e.g., energy policy and planning, renewable energy resources, and energy statistical reports) are publicly available and can be accessed through the corresponding references cited in the manuscript [5-9, 25-28].

REFERENCES

[1] V. Masson-Delmotte *et al.*, "Climate change 2021: the physical science basis," *IPCC-Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 2391, 2021, https://doi.org/10.1017/9781009157896.

[2] P. R. Shukla *et al.*, "Climate Change 2022: Mitigation of Climate Change", *IPCC-Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2022, https://doi.org/10.1017/9781009157926.

[3] Z. Liu *et al.*, "Challenges and opportunities for carbon neutrality in China," *Nature Reviews Earth & Environment*, vol. 3, no. 2, pp. 141–155, 2022, https://doi.org/10.1038/s43017-021-00244-x.

[4] C. Zhou, X. Lin, R. Wang, and B. Song, "Real-Time Carbon Emissions Monitoring of High-Energy-Consumption Enterprises in Guangxi Based on Electricity Big Data," *Energies*, vol. 16, no. 13, 2023, Art. no. 5124, https://doi.org/10.3390/en16135124.

[5] China Electricity Council (CEC), "China Electric Power Yearbook 2023", Beijing, China: China Electric Power Press, 2023.

[6] China Meteorological Administration, "China Wind and Solar Energy Resource Assessment Report", China Meteorological Press, 2018.

[7] Guangxi Meteorological Bureau, "National Wind Energy Resource Survey Results", 2004.

[8] Guangxi Meteorological Center, "Guamgxi Wind Energy Resource Detailed Survey and Assessment Report", 2011.

[9] DNV, "Energy Transition Outlook China 2024", 2024.

[10] B. Sun, Y. Yu, and C. Qin, "Should China focus on the distributed development of wind and solar photovoltaic power generation? A comparative study," *Applied Energy*, vol. 185, pp. 421–439, Jan. 2017, https://doi.org/10.1016/j.apenergy.2016.11.004.

[11] Y. Qin *et al.*, "Amplified positive effects on air quality, health, and renewable energy under China's carbon neutral target," *Nature Geoscience*, vol. 17, no. 5, pp. 411–418, 2024, https://doi.org/10.1038/s41561-024-01425-1.

[12] S. Zhou, Y. Wang, Y. Zhou, L. E. Clarke, and J. A. Edmonds, "Roles of wind and solar energy in China's power sector: Implications of intermittency constraints," *Applied Energy*, vol. 213, pp. 22–30, Mar. 2018, https://doi.org/10.1016/j.apenergy.2018.01.025.

[13] R. H. Inman, H. T. C. Pedro, and C. F. M. Coimbra, "Solar forecasting methods for renewable energy integration," *Progress in Energy and Combustion Science*, vol. 39, no. 6, pp. 535–576, Dec. 2013, https://doi.org/10.1016/j.pecs.2013.06.002.

[14] S. Syama, J. Ramprabhakar, R. Anand, V. P. Meena, and J. M. Guerrero, "A novel hybrid methodology for wind speed and solar irradiance forecasting based on improved whale optimized regularized extreme learning machine," *Scientific Reports*, vol. 14, no. 1, 2024, Art. no. 31657, https://doi.org/10.1038/s41598-024-83836-z.

[15] X. Zhao, "A novel digital-twin approach based on transformer for photovoltaic power prediction," *Scientific Reports*, vol. 14, no. 1, 2024, Art. no 26661, https://doi.org/10.1038/s41598-024-76711-4.

[16] D. K. Molzahn *et al*., "A Survey of Distributed Optimization and Control Algorithms for Electric Power Systems," *IEEE Transactions on Smart Grid*, vol. 8, no. 6, pp. 2941–2962, Nov. 2017, https://doi.org/10.1109/TSG.2017.2720471.

[17] C. Kumar, M. Lakshmanan, S. Jaisiva, K. Prabaakaran, S. Barua, and H. H. Fayek, "Reactive power control in renewable rich power grids: A literature review," *IET Renewable Power Generation*, vol. 17, no. 5, pp. 1303–1327, Apr. 2023, https://doi.org/10.1049/rpg2.12674.

[18] A. Mohammed, E. K. Sakr, M. Abo-Adma, and R. Elazab, "A comprehensive review of advancements and challenges in reactive power planning for microgrids," *Energy Informatics*, vol. 7, no. 1, Aug. 2024, Art. no. 63, https://doi.org/10.1186/s42162-024-00341-3.

[19] G. Pierrou and X. Wang, "The Effect of the Uncertainty of Load and Renewable Generation on the Dynamic Voltage Stability Margin," in *2019 IEEE PES Innovative Smart Grid Technologies Europe* (*ISGT-Europe*), Bucharest, Romania, Sept. 19 – Oct. 02, 2019, pp. 1–5, https://doi.org/10.1109/ISGTEurope.2019.8905575.

[20] H. Yang, B. Chen, S. Xiang, J. Liu, and E. Ackom, "Distributionally robust optimal dispatch modelling of renewable-dominated power system and implementation path for carbon peak," *Computers & Industrial Engineering*, vol. 163, Jan. 2022, Art. no. 107797, https://doi.org/10.1016/j.cie.2021.107797.

[21] C. G. Heaps, LEAP: The Low Emission Analysis Platform. Stockholm Environment Insitute, 2024, https://leap.sei.org/.

[22] M. McPherson and B. Karney, "Long-term scenario alternatives and their implications: LEAP model application of Panama′s electricity sector," *Energy Policy*, vol. 68, pp. 146–157, May 2014, https://doi.org/10.1016/j.enpol.2014.01.028.

[23] S. C. Bhattacharyya and G. R. Timilsina, "A review of energy system models," *International Journal of Energy Sector Management*, vol. 4, no. 4, pp. 494–518, 2010, https://doi.org/10.1108/17506221011092742.

[24] Y. Huang, Y. J. Bor, and C.-Y. Peng, "The long-term forecast of Taiwan's energy supply and demand: LEAP model application," *Energy Policy*, vol. 39, no. 11, pp. 6790–6803, Nov. 2011, https://doi.org/10.1016/j.enpol.2010.10.023.

[25] "Working guidance for carbon dioxide peaking and carbon neutrality in full and faithful implementation of the new development philosophy". The State Council of the People's Republic of China. https://www.gov.cn/zhengce/2021-10/24/content_5644613.htm.

[26] Guangxi Bureau of Statistics, "Guangxi statistical yearbook 2023", China Statistics Press, 2023.

[27] National Bureau of Statistics of China, "China statistical yearbook 2023", China Statistics Press, 2023.

[28] NDRC, "The 14th Five-Year Plan for national economic and social development of the People's Republic of China", 2021.

[29] Z. Ullah, Arshad, and J. Ahmad, "The Development of a Cross-Border Energy Trade Cooperation Model of Interconnected Virtual Power Plants Using Bilateral Contracts," *Energies*, vol. 15, no. 21, 2022, Art. no. 8171, https://doi.org/10.3390/en15218171.

[30] "Integrating Solar and Wind in Southeast Asia: From Potential to Policy," IEA, https://www.iea.org/reports/integrating-solar-and-wind-in-southeast-asia.