Policy-Oriented Carbon Neutrality Pathways in Shanxi's Power System: A LEAP-Based Scenario Analysis

Guangyao Zhu
College of Electrical Engineering, Hunan Mechanical and Electrical Polytechnic, China
zhuguangyao@gmail.com

Xiao Yao
College of Electrical Engineering, Hunan Mechanical and Electrical Polytechnic, China
65010363003@msu.ac.th

Hai Yang
College of Electrical Engineering, Hunan Mechanical and Electrical Polytechnic, China
yanghai@foxmail.com

Buncha Wattana
Electrical and Computer Engineering Research Unit, Faculty of Engineering, Mahasarakham University, Thailand
buncha.w@msu.ac.th (corresponding author)

Received: 31 October 2025 | Revised: 24 November 2025 and 8 December 2025 | Accepted: 11 December 2025

DOI: https://doi.org/10.48084/etasr.15902

ABSTRACT

With China's carbon peak and neutrality targets in sight, the low-carbon transformation of carbon-intensive power systems becomes increasingly important for realizing China's national emission reduction targets. Based on the Low Emission Analysis Platform (LEAP) model, this study presents the first policy-driven multi-scenario LEAP analysis of Shanxi's power system, analyzing the transition paths of the power system in Shanxi Province under different policy scenarios, and further quantifies the changes in generation structure, fossil energy consumption, and major air pollutant emissions. Under the Reference Scenario (REF), coal power still contributes about 78% of total generation in 2060, with fossil energy consumption and CO_2 emissions continuing to increase. In the Policy-Driven Scenario (PDS), the gradual expansion of renewable energy reduces CO_2 emissions by roughly 100 million tons compared with REF. Under the Carbon Neutrality-Target Scenario (CNS), the share of coal power declines to around 11% in 2060, renewable output rises to nearly 1,000 TWh (terawatt-hours), and major air pollutants drop by 86.3% compared with REF. These results suggest that stronger policy measures, especially those promoting renewable energy and related supporting technologies, are essential for guiding Shanxi toward a carbon-neutral power system.

Keywords-Shanxi Province; carbon neutrality; policy pathways; Low Emission Analysis Platform (LEAP) model; scenario analysis

I. INTRODUCTION

China is the world's largest energy consumer and carbon emitter, and coal has always played a vital role in its energy structure [1]. In 2020, the total energy consumption was about 498 million tons of standard coal, of which coal accounted for approximately 56.8% [2]. Along with the extensive use of coal, high carbon intensity, low energy efficiency, and environmental pollution have also emerged as major challenges. In order to solve these problems, China proposed a series of "dual carbon" goals with the target of peaking carbon emissions by 2030 and reaching carbon neutrality by 2060 by developing renewable energy, promoting clean coal utilization, and adjusting the energy structure [3, 4].

In 2023, Shanxi, one of China's largest coal-producing provinces, extracted about 1.37 billion tons of raw coal, accounting for nearly 29% of national total [5, 6]. Coal has long dominated Shanxi's power system. According to the statistics in 2022, the installed capacity of coal power accounted for more than 60% of the province's total installed capacity, and coal consumption in the electricity sector represented over 50% of the province's total energy consumption [7]. Such high dependence on coal leads to high carbon emissions and limits the development of renewable energy. It is estimated that in 2022, the province's energy-related CO_2 emissions were approximately 521.5 million tons [8], accounting for about 4.1% of China's total emissions [9]. To promote energy transition and meet the "dual-carbon" strategy, Shanxi successively implemented the Carbon Peak Implementation Plan [10] and the 14th Five-Year Renewable Energy Development Plan [11]. By 2030, the province aims for non-fossil energy consumption to reach 18% of total energy use, and renewable electricity generation to exceed 60%. In addition, it is planned that the installed capacity of wind and solar will reach about 80 GW in 2025 and 120 GW in 2030.

However, under the background of energy transition and "dual carbon", it is still necessary to scientifically evaluate the carbon reduction potential of the power system under different policy and development scenarios, and ensure the energy security and economic benefits of the country. Taking the electricity sector of Shanxi as the research object, this study uses the Low Emission Analysis Platform (LEAP) model to establish multiple future scenarios, including baseline, policy-driven, and carbon-neutral scenarios. Through a quantitative analysis of the impact of different policy measures and changes in power generation structure on CO_2 emissions, this study explores the feasible path to achieve carbon neutrality in Shanxi's power system. The research results not only provide a scientific basis for formulating provincial energy planning and carbon mitigation policies, but also provide a reference for energy transition and carbon reduction in other coal-dependent regions.

In recent years, numerous studies have explored pathways for China to achieve carbon peaking and carbon neutrality based on energy models and scenario analysis. For example, authors in [12] studied China's carbon peaking and carbon neutrality goals, pointing out that the Chinese government has committed to achieving carbon emissions peaking before 2030 and striving to achieve carbon neutrality before 2060. Authors in [13] developed an innovative system dynamics model, combined with scenario analysis, to simulate the trajectory of carbon emissions and carbon absorption in China, providing quantitative support for achieving carbon peaking and carbon neutrality goals. Meanwhile, scholars have also focused on the regional differences in national energy transition, emphasizing the different needs of the eastern coastal and central-western regions in energy structure optimization and carbon reduction policy implementation [14, 15]. Nevertheless, national-level research mainly focuses on macro-level averages, with limited analysis of the differentiated policy effects on individual provinces or specific energy structure regions.

At the provincial level, in coal-rich provinces such as Shanxi, Shaanxi, and Inner Mongolia, high dependence on coal leads to carbon emissions well above the national average. In recent years, the decarbonization potential of Shanxi has been studied with various modeling frameworks. Authors in [16] used the LEAP model to calculate carbon emissions from 2019 to 2035. Under the baseline scenario, carbon emissions in 2035 were projected to reach 1.6462 billion tons, whereas under the energy structure optimization and efficiency improvement scenario, carbon emissions would peak in 2028 and drop to 652,900 million tons, indicating that structural optimization and efficiency improvements are crucial for Shanxi. Authors in [17] constructed carbon source and carbon sink scenarios for Shanxi Province from 2020 to 2060 and found that increasing forest carbon sinks can reduce net emissions. System dynamics analysis results also show that optimizing power generation structure and developing renewable energy can slow emissions [18]. Advanced technology pathways, such as Carbon Capture and Storage (CCS), can reduce the decarbonization burden under high coal dependence conditions and make carbon neutrality possible [19]. However, most of these studies focus on single-scenario projections or isolated interventions, and do not provide a systematic multi-scenario analysis that integrates power system structure with policy measures. In contrast, this study develops multiple policy-driven scenarios for Shanxi's power system and evaluates both carbon emissions and co-benefits of major air pollutants (SO_2, NO_x, PM2.5), providing a comprehensive assessment that integrates policy measures with the power system structure. Building on previous provincial LEAP studies, the analysis explicitly incorporates policy considerations and pollutant co-benefits, demonstrating the value of a policy-driven multi-scenario approach.

In terms of methods, the LEAP model has been widely used at the national and provincial levels to evaluate the impact of policies, energy structure changes, and advanced technology paths under different scenarios. Authors in [20] developed six LEAP scenarios for China's future electricity demand and emissions, providing valuable insights for future energy planning. Authors in [21] applied the LEAP model to the coal-based Sichuan-Chongqing power system and found that structural optimization and efficiency improvement were highly significant. Authors in [22] applied the LEAP model to study the development pathway of wind and solar power in Hunan Province. Their results show that carbon neutrality can only be achieved by continuously expanding wind and solar capacity while improving energy-storage technologies and grid infrastructure. These findings also offer important references for Shanxi and other coal-dependent regions in energy planning and carbon-emission reduction. These studies provide important methodological and empirical references; however, most concentrate on other provinces or sectors and rarely examine Shanxi's power system through a multi-scenario, policy-integrated approach.

Although the above studies have provided a good theoretical basis and certain practical references, there are still few comprehensive studies on the emissions reduction path of Shanxi's power system, especially the quantitative simulation of multiple scenarios. Therefore, it is of significant scientific importance to systematically construct the baseline scenario, policy scenario, and carbon neutrality scenario, carry out quantitative analysis based on the LEAP model, and evaluate the impact of different strategies on power structure and CO_2 emissions, which provides an important basis for energy planning and carbon emissions reduction policies in Shanxi Province and other coal-dependent provinces.

II. METHODOLOGY

A. Model Structure

This study builds a LEAP-based power system model for Shanxi Province, as illustrated in Figure 1, taking 2020−the first year of the 14th Five-Year Plan−as the base year and 2060 as the simulation horizon. Gross Domestic Product (GDP) growth is selected as the main driving variable. The future electricity demand is projected by fitting the historical relationship between GDP and electricity consumption. In addition, Shanxi's electricity exports are included in the demand side projections.

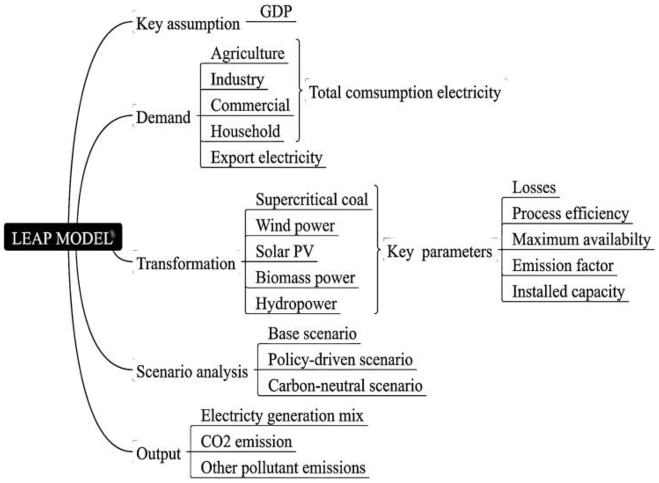


Fig. 1. LEAP model for Shanxi Province.

For the power generation sector, five technologies are considered, including supercritical coal-fired power, wind power, solar photovoltaic power, biomass power, and hydropower. Each technology is characterized by a loss rate, process efficiency, maximum availability, emission factor, and installed capacity to simulate the operational characteristics and efficiency variations. Based on these technical parameters and generation outputs, the final power generation structure and CO_2 and other major air pollutant emissions (SO_2, NO_x, PM2.5) are calculated. The impacts of different scenarios and policy measures on emission reduction are analyzed to provide a scientific basis for formulating an optimal low-carbon transition and carbon neutrality pathway for Shanxi's power system.

Furthermore, to simplify the model structure, the LEAP model developed in this study does not include economic feedback mechanisms, detailed grid constraints, or unit-level operational scheduling. As a result, the model focuses primarily on analyzing the evolution of supply and demand across different energy sources, structural adjustments, and the effects of policy scenarios on energy development trends, rather than capturing electricity market price fluctuations or fine-grained grid operations. Although this simplification introduces certain limitations for short-term operational analysis or grid security assessment, it remains well-suited for medium- and long-term energy planning and evaluating the effectiveness of policies. In addition, the simplification enhances computational efficiency, allowing for faster and more systematic assessment of the potential impacts of policies and technological options across multiple scenarios and sensitivity analyses. Model validation was performed by comparing the simulated baseline-year electricity generation and emissions with official statistics. The deviations were within 3–5%, indicating acceptable model accuracy for scenario analysis.

B. Data Consideration

Based on the "14th Five-Year Plan for National Economic and Social Development of Shanxi Province and the Long-Range Objectives Through 2035" [23] and the Shanxi Statistical Yearbook (2011–2020) [24], it is assumed that Shanxi's GDP will increase by 6% per year during 2021–2025, 5% during 2026–2030, and 4% during 2031–2060. Taking into account the fact that Shanxi's electricity exports accounted for about 50% of total electricity consumption during 2011–2020 according to the China Electric Power Yearbook [25], and using the fitted GDP–electricity elasticity relationship from 2011–2020 (Figure 2), the total electricity consumption in Shanxi during 2021–2060 can be calculated, reaching about 785.8 TWh (terawatt-hours) in 2060. In addition, based on historical data, the share of exported electricity is assumed to remain at approximately 50% of total electricity consumption.

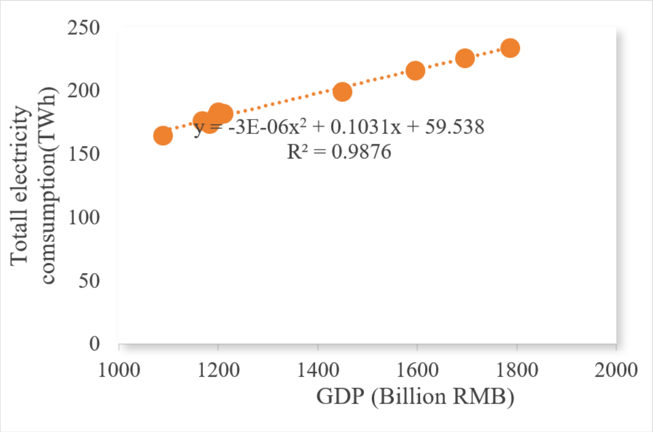


Fig. 2. Regression curve between Shanxi Province GDP and total electricity consumption from 2011–2020.

The transmission and distribution loss rate for the Shanxi power system is set at 5%; the efficiency and maximum availability of each generation technology are obtained from the China Electric Power Yearbook; emission factors are referred from the Intergovernmental Panel on Climate Change (IPCC) standards embedded in the model. According to Guidelines for Compilation of Emissions Inventory of Atmospheric Fine Particulate Matter (PM2.5) Sources (Trial) [26], the PM2.5 emission factor of raw coal for power generation is set at 12 g/kg.

Referring to the China Electric Power Yearbook and the China Energy Statistical Yearbook, the proportion of hydropower in Shanxi's power generation is very limited, and the installed capacity has nearly reached its upper limit.

Meanwhile, the development of biomass power generation is still in its initial stage. Shanxi Province is situated in inland North China, with mountains, hills, and plateaus accounting for the majority of its territory [24]. Wind resources are not uniformly distributed and are mainly concentrated in the northern and northwestern highland areas, including Datong, Shuozhou, and Xinzhou. In the southern and southeastern areas, wind speed is relatively low, and it is hard to develop large-scale wind power projects [27, 28]. By the end of 2020, the total installed capacity of wind power in Shanxi Province reached 19.74 GW and ranked fourth in China [25]. Based on the national estimates and historical data, the technically exploitable onshore wind power installed capacity in Shanxi is estimated to be about 80–100 GW [29].

In contrast, Shanxi Province has extensive land resources, including large areas of idle and barren land, and most rooftops are available for Photovoltaic (PV) deployment. According to historical data, the annual full-load hours of PV are 1,100–1,400 h, which rank among the highest in China [30]. Assuming the PV installation density is 20–45 MW/km^2 and sufficient available area (for example, the 13,941 km^2 of "most suitable areas" for centralized PV assessed in [31]), the PV installation capacity can theoretically reach more than 600 GW.

To improve model transparency and replicability, the key parameters used in the LEAP model are summarized in Table I.

TABLE I. THE KEY PARAMETERS IN THE LEAP MODEL

Parameter		Value	Source
Losses		5%	[24, 25]
Efficiency	Supercritical coal	41%	
	Wind power	25%	
	Solar PV	18%	
	Biomass power	50%	
	Hydropower	80%	
Maximum availability	Supercritical coal	51.8%	
	Wind power	14.3%	
	Solar PV	16.4%	
	Biomass power	50%	
	Hydropower	24%	
Emission factor	CO_2	25.8 × FractionOxidized × (CO_2/C), t/TJ	IPCC standard
	SO_2	SulfurContent × (1-SulfurRetention) × (SO_2/S), kg/kg	
	NO_x	300 t/TJ	
	PM2.5	12 g/kg	[26]
Limited capacity	Hydropower	2.2 GW	[24, 25]
	Wind power	80-100 GW	[27-29]
	Solar PV	600 GW	[30, 31]

C. *Scenario Design*

In this study, to evaluate the influence of wind and other renewable energy development on the regional energy structure and carbon emissions in Shanxi Province, three representative scenarios are designed: Reference Scenario (REF), Policy-driven Scenario (PDS), and Carbon Neutrality-Target Scenario (CNS). The REF scenario assumes that renewable energy continues to develop in a manner consistent with past trends and reflects the evolution of energy demand and structure under inertial growth. The PDS scenario is based on the REF scenario and takes into account the Carbon Peak Implementation Plan [10] and 14th Five-Year Energy Development Plan [11]. By 2025, the total installed capacity of wind and solar power is estimated to reach around 80 GW, including 30 GW of wind power, and increase to 120 GW by 2030. Besides, the installed capacity of biomass power generation is expected to reach 1 GW in 2025. This scenario analyzes the energy structure and carbon emissions under policy implementation by optimizing wind power, solar power, and biomass power generation.

The CNS scenario aims to achieve the carbon peaking and neutrality targets, and assumes that a large amount of fossil energy will be substituted by 2060. The maximum feasible installed capacity of wind, solar, and biomass power is considered, and flexible grid operation and carbon reduction measures are assumed to reduce emissions as much as possible. All scenarios are simulated using the LEAP model, and the above scenarios take into account the characteristics of wind resources, load demand, and energy transition policies in Shanxi Province. The specific installed capacities for each scenario are summarized in Table II.

TABLE II. INSTALLED CAPACITY (GW) OF TECHNOLOGIES

Generation technology	**Base year**	**REF**		**PDS**		**CNS**	
	2020	**2030**	**2060**	**2030**	**2060**	**2030**	**2060**
Supercritical coal	68.9	90.0	195.0	77.5	165.0	58.8	26.5
Hydropower	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Wind	19.7	33.0	80.0	40.0	80.0	46.0	80.0
Solar	13.1	45.7	100.0	80.0	200.0	150.0	600.0
Biomass	0.6	1.0	2.2	1.4	3.8	2.8	30.0

III. RESULTS AND DISCUSSION

A. *Electricity Generation Mix*

The envisaged variation of Shanxi Province's power generation mix from 2020 to 2060 under the REF, PDS, and CNS scenarios is shown in Table III and Figure 3. Overall electricity generation is anticipated to grow from around 363.9 TWh in 2020 to more than 1,122.1 TWh in 2060, nearly tripling, reflecting ongoing growth in electricity demand. In 2020, coal and lignite accounted for the vast majority of generated electricity (85.6%), whereas wind, solar, hydro, and biomass contributed 7.8%, 4.5%, 1.3%, and 0.8% of total generation, respectively, indicating high dependence on fossil fuels and low penetration of renewable energy. In 2030, coal-fired power remains the largest generation source across all three scenarios (2020: 363.9 TWh; REF: 401 TWh; PDS: 348.9 TWh; CNS: 256.0 TWh), whereas renewable generation ranges from 100 to 260 TWh, which is 2–5 times that of 2020. By 2060, the differences between the three scenarios become significant. In the REF scenario, coal-fired power generation reaches 871.4 TWh (77.7%). In the PDS scenario, coal-fired power generation drops to 739.9 TWh, whereas solar and wind power generation increase to 247.6 TWh and 113.6 TWh, respectively. In the CNS scenario, coal-fired power generation drops sharply to 120.2 TWh (10.8%), representing approximately one-third of the 2020 generation. Total renewable energy generation is projected to be approximately 1,000 TWh. Limited by resource availability, wind power generation accounts for 10.2% of total electricity generation, whereas solar power generation dominates at 751.1 TWh (66.9%), approximately six times that of the REF scenario, and biomass power generation reaches 11.7% in the CNS scenario.

TABLE III. ELECTRICITY GENERATION FOR DIFFERENT SCENARIOS

Fuel type	**2020**	**2060**		
		Different scenarios		
	Base year (%)	**REF (%)**	**PDS (%)**	**CNS (%)**
Coal lignite	85.6	77.7	65.9	10.8
Wind	7.8	10.2	10.2	10.2
Solar	4.5	10.9	22.0	66.9
Hydro	1.3	0.4	0.4	0.4
Biomass	0.8	0.8	1.5	11.7

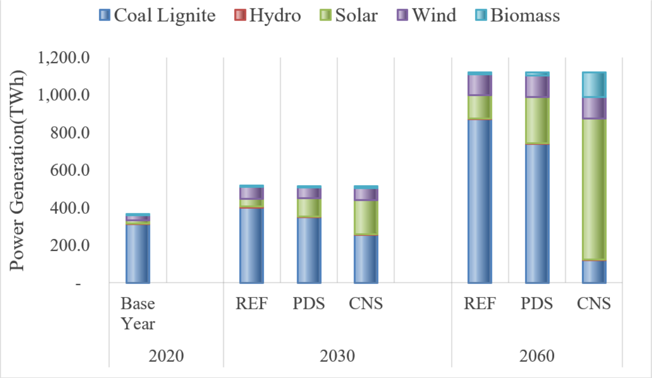


Fig. 3. Electricity generation mix from 2020 to 2060.

These results demonstrate significant differences in the system power mix across the different scenarios. Under the deep decarbonization scenario, the system undergoes a significant structural shift from a fossil fuel-dominated to a renewable energy-dominated system, with solar power taking a dominant position, wind power expanding moderately, and biomass power playing a secondary role. Overall, from renewable energy expansion to carbon neutrality, the power generation mix demonstrates decarbonization, diversification, and the increasing penetration of clean energy. Coal gradually loses its dominance, whereas the share of renewable energy continues to increase. This shift is driven by both policy and technology. The progress toward carbon peaking and carbon neutrality targets is strengthened, enhancing Shanxi Province's long-term energy security and sustainability.

B. Fossil Fuel Consumption

As a typical coal-producing province, Shanxi's fossil fuel consumption patterns have a significant impact on the achievement of national carbon emissions targets. Gradually reducing the use of fossil fuels and increasing the proportion of renewable energy constitute a core task for achieving low-carbon development. Table IV presents the projected fossil energy consumption in Shanxi Province under the REF, PDS, and CNS scenarios. Under the REF scenario, fossil fuel consumption is expected to increase from 6,535.5 KTOE (thousand tons of oil equivalent) in 2020 to 18,270 KTOE in 2060, nearly tripling, reflecting sustained growth in energy demand. In the PDS, fossil fuel consumption decreases by 13.2% in 2030 and 15.1% in 2060 relative to REF, indicating that partial decarbonization measures can only moderately reduce reliance on fossil fuels. In contrast, under the CNS, fossil fuel consumption declines to 5,376.7 KTOE in 2030 (36.3% lower than REF) and further drops to 2,503 KTOE in 2060 (86.3% lower than REF). These results further demonstrate that only deep decarbonization policies, such as large-scale development of renewable energy, the gradual phase-out of coal-fired power generation, and improved energy efficiency, can transform the current energy system and reduce reliance on fossil fuels.

TABLE IV. FOSSIL FUEL CONSUMPTION UNDER DIFFERENT SCENARIOS

Year	**REF (KTOE)**	**PDS (%)**	**CNS (%)**
2020	6,535.5	–	–
2030	8,440.7	(–13.2)	(–36.3)
2060	18,270.0	(–15.1)	(–86.3)

Notes: The values in parentheses indicate the change in fossil fuel consumption compared with the REF scenario.

C. CO_2 Emissions

Due to the carbon-intensive nature of coal, its consumption leads to the substantial emission of CO_2. As shown in Figure 4, the three scenarios exhibit markedly different trends of CO_2 emissions from 2022 to 2060. In the REF scenario, CO_2 emissions continue to increase from 253.6 million tons in 2022 to 708.9 million tons in 2060. Compared with the REF scenario, the rate of increase in CO_2 emissions in the PDS scenario is slower, indicating that the implementation of emission reduction policies can partially curb the growth of emissions. In contrast, the CNS scenario exhibits a clear decline in CO_2 emissions after 2030. CO_2 emissions continuously decrease to below 100 million tons in 2060. These results further indicate that large-scale renewable energy deployment, energy efficiency improvement, and the adoption of low-carbon technologies have substantial emissions reduction potential.

In addition, the corresponding data shown in Table V quantify the above differences. Compared with the REF scenario, CO_2 emissions in 2025, 2030, and 2060 under the PDS scenario decrease by 26.0 million tons, 43.1 million tons, and 107.1 million tons, respectively. Meanwhile, the corresponding reductions under the CNS scenario are much larger, with 39.1 million tons, 118.6 million tons, and 611.2 million tons (86.3%) in 2025, 2030, and 2060, respectively. This indicates that the deep decarbonization scenario could approach the zero-emissions level in 2060. However, it should be noted that even under the CNS scenario, the system is still not carbon neutral, and certain emissions remain. Therefore, in order to achieve the net-zero emissions level, additional negative emissions measures should be implemented to offset the remaining emissions. Specifically, negative emissions measures include Carbon Capture, Utilization, and Storage

(CCUS), Bioenergy with Carbon Capture and Utilization and Storage (BECCS), and carbon sinks.

TABLE V. CO_2 EMISSIONS OVER THE PERIOD 2022–2060 (MILLION TONS)

Year	REF	PDS	CNS
2022	253.6	–	–
2025	293.8	(–26.0)	(–39.1)
2030	326.9	(–43.1)	(–118.6)
2060	708.9	(–107.1)	(–611.2)

Notes: The numbers in parentheses indicate the change in CO_2 emissions relative to the REF scenario.

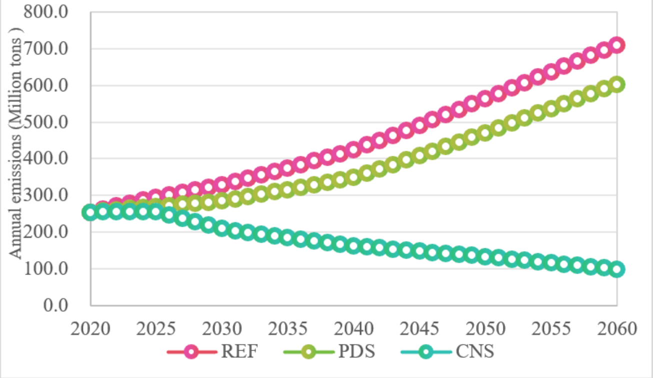


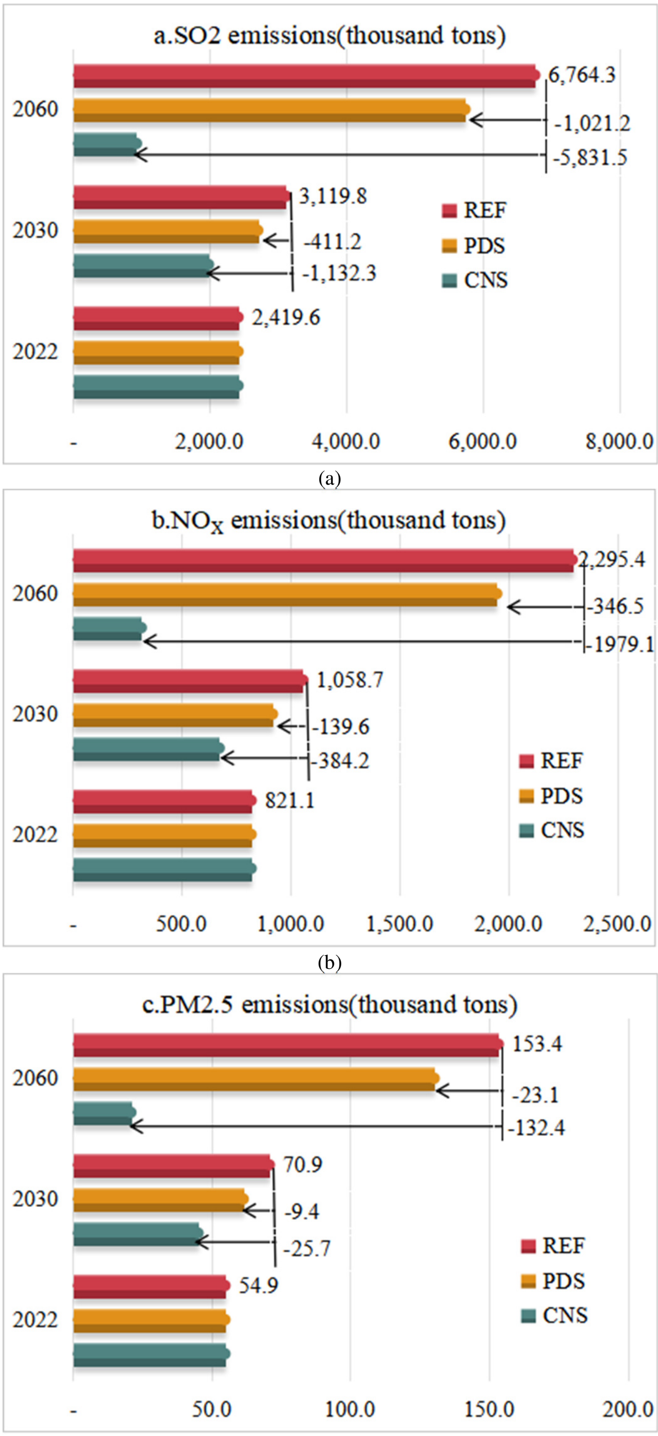
Fig. 4. CO_2 emissions trends under different scenarios from 2020 to 2060.

D. Other Pollutant Emissions

The excessive consumption of fossil fuels also leads to serious environmental problems, including air pollution, greenhouse gas emissions, and ecological damage. In particular, the air quality and ecological environment of Shanxi Province have already been affected by its over-reliance on coal energy. Emissions of SO_2, NO_x, and PM2.5 display marked differences across the three scenarios (Figure 5). In the absence of policies, emissions increase steadily from 2,419.6 kt (thousand tons), 821.1 kt, and 54.9 kt in 2022 to 6,764.3 kt, 2,295.4 kt, and 153.4 kt in 2060, respectively. These results further reveal that continued dependence on coal and other high-sulfur and nitrogen fuels significantly aggravates air pollution, acid deposition, and related environmental and health impacts.

The PDS attenuates the growth of these emissions, with 2030 and 2060 emissions decreasing compared with REF by 411.2 kt and 1,021.2 kt for SO_2, 139.6 kt and 346.5 kt for NO_x, and 9.4 kt and 23.1 kt for PM2.5, demonstrating the partial effectiveness of clean energy substitution and policy implementation. Further reductions in emissions can be achieved through the implementation of CNS, with 2030 and 2060 emissions decreasing compared with REF by 1,132.3 kt and 5,831.5 kt for SO_2, 384.2 kt and 1,979.2 kt for NO_x, and 25.7 kt and 132.4 kt for PM2.5.

These reductions are attributed to the optimization of energy structure, reduced dependence on coal, widespread use of low-sulfur and low-nitrogen fuels, and large-scale substitution with renewable energy. These results reveal that additional air quality benefits can only be achieved through accelerated ultra-low emissions technology deployment, coordinated energy production and consumption management, integrated multi-pollutant and carbon emissions reduction strategies, and regional clean energy interconnections, to achieve both environmental sustainability and energy transition goals.



(a)

(b)

(c)

Fig. 5. Other pollutant emissions forecast from 2020 to 2060: (a) SO_2 emissions, (b) NO_x emissions, (c) PM2.5 emissions.

IV. POLICY RECOMMENDATIONS

Scenario analysis reveals that Shanxi is currently in the midst of an energy transition. Compared with the REF Scenario, coal power will still compose 77.7% of electricity generation in 2060. Fossil energy consumption and CO_2 emissions are still increasing because of high coal dependence and carbon intensity pressures. The PDS shows that coal use and emissions will be reduced moderately, reflecting the partial effectiveness of current renewable policies. The power structure will only change significantly under the CNS: the share of coal power drops to 10.8%, and the share of solar power rises to 66.9%. Total CO_2 emissions are also reduced by 611.2 million tons compared with REF. Therefore, deep decarbonization not only needs large renewable deployment but also needs integrated policy support, technology breakthroughs, and efficiency improvements. In addition, changes in SO_2, NO_x, and PM2.5 emissions also reflect considerable co-benefits for air quality.

Although these opportunities exist, Shanxi still faces several challenges. First, technological and financial constraints may hinder rapid deployment of renewable energy and storage. This is because Shanxi has uneven distribution of resources, challenges in grid connection, and a lack of local technical capacity [32]. Second, Shanxi's economy and energy system are highly dependent on coal. Coal mining and coal power contribute significantly to its GDP and employment. Therefore, large-scale coal reduction may cause unemployment and social instability if proper retraining and social security measures are not implemented [33]. Third, environmental problems will persist. Coal use will still cause a large amount of SO_2, NO_x, and PM2.5 emissions, affecting public health and the environment [34, 35].

To address these challenges and promote a low-carbon power system, the following policy recommendations are proposed:

- Shanxi should decrease dependence on coal and increase investment in renewable energy. Energy investment should focus on solar and wind energy [36]. Large-scale onshore wind farms should be deployed in Lüliang and Xinzhou, and centralized PV plants should be deployed in Jinzhong and Yangquan. Financial incentives, such as feed-in tariffs and tax reductions, should attract more private and foreign investment. Finally, distributed energy systems combined with storage and demand-side response should increase accessibility and alleviate renewable fluctuations.
- Pumped hydro and large-scale battery storage should be deployed in wind- and solar-rich but load-remote areas, and distributed storage should be deployed in industrial centers. Market-based dispatch should enable storage to participate in peak shaving and emergency backup. This will improve grid flexibility and renewable energy integration [37, 38].
- Phased retirement of coal plants in coal-intensive areas should be carried out [39]. Vocational training and retraining should reorient coal workers towards renewable manufacturing, operation and maintenance, energy efficiency services, and green construction. Green industrial parks in the Taiyuan Economic and Technological Development Zone and Changzhi High-Tech Zone can promote green employment and enhance local development.
- Old coal plants in Datong, Yangquan, and Jincheng should be equipped with ultra-low emissions technologies [39] and real-time online monitoring to strictly control SO_2, NO_x, and PM2.5 emissions. Cross-region grid dispatch should promote the transmission of renewables and reduce dependence on fossil fuel reserves. Incorporating carbon targets in environmental impact assessments should strengthen enforcement.
- CCUS demonstration projects should be linked with coal power and mining in Jinzhong and Lüliang. Biomass and BECCS technologies, as well as forest carbon sink projects on the Loess Plateau, should be used to neutralize the remaining emissions. Carbon pricing and trading can enhance economic viability [40-42].
- Energy, environment, and economy policies should be coordinated through integrated planning, aligning the deployment of renewables, grid infrastructure, storage, and industrial transition with national carbon neutrality pathways. Pilot projects combining renewables, storage, and demand-side response can provide useful experience for large-scale implementation at the provincial level.

Overall, the energy transition in Shanxi should be a coordinated process across structural optimization, social justice, technological innovation, environmental regulation, and carbon reduction. Only through such comprehensive measures can carbon peaking and carbon-neutrality be achieved, air quality be improved, and sustainable socio-economic development be promoted. Shanxi can then serve as a model for other coal-dependent regions.

V. CONCLUSION

This study applies the Low Emission Analysis Platform (LEAP) model to track the transition pathways of the power system of Shanxi Province under various policy and development scenarios, and then calculates the changes in generation structure, fossil energy consumption, and key pollutant emissions. This research provides a comprehensive provincial-level modeling of Shanxi's power system transition, explicitly quantifying the impacts of different policy scenarios on coal dependency, renewable deployment, and emissions reductions.

The results show that under the Reference Scenario (REF), the proportion of coal power in total electricity generation remains 77.7% in 2060. Fossil energy consumption is expected to increase from 6,535.5 KTOE in 2020 to 18,270 KTOE, and CO_2 emissions are expected to rise from 253.6 million tons in 2022 to 708.9 million tons, indicating that the Shanxi power system still relies heavily on coal and faces significant carbon pressure. Under the Policy-Driven Scenario (PDS), electricity generation from coal decreases to 739.9 TWh, fossil energy consumption decreases by 15.1% compared with REF, and CO_2 emissions decrease by 107.1 million tons compared with REF, showing the partial mitigation effect of the current renewable energy policies. Under the Carbon Neutrality-Target Scenario (CNS), the proportion of coal falls to 10.8%, the generation of solar power reaches 751.1 TWh (accounting for 66.9% of total electricity), and the generation shares of wind and biomass reach 10.8% and 11.7%, respectively. Total renewable energy generation approaches 1,000 TWh, fossil energy consumption declines to 2,503 KTOE, and CO_2 emissions decrease by 611.2 million tons compared with REF, demonstrating the deep decarbonization potential of Shanxi's power system.

The energy transition also demonstrates strong co-benefits for air quality. Compared with REF, the SO_2, NO_x and PM2.5 emissions under CNS decrease by 5,831.5 kt, 1,979.2 kt, and 132.4 kt, respectively, highlighting the positive effects of large-scale renewable energy deployment and coal reduction on air pollutant control.

Although the potential of renewable energy is substantial, Shanxi Province still faces many challenges: technically and resource-wise, it may be difficult to rapidly deploy wind power, solar power, and storage facilities; phased coal retirement will have immediate impacts on local GDP and employment; and environmental governance may continue to require substantial investments in controlling SO_2, NO_x and PM2.5 emissions.

To address these challenges, this study puts forward several policy recommendations, including accelerating energy diversification, promoting coordinated energy storage development, facilitating just transition and redeployment, strengthening environmental regulation and multi-pollutant control, promoting Carbon Capture, Utilization, and Storage (CCUS) and other negative emissions technologies, and improving policy coordination and regional planning.

In summary, this study establishes a comprehensive provincial-level framework for analyzing energy transition pathways, considering adjustments in generation structure, social equity, technological innovation, environmental protection, and carbon reduction. By promoting renewable energy deployment, gradually phasing out coal, and implementing coordinated policy and technological measures, Shanxi is expected to achieve carbon neutrality by 2060, while improving air quality, ensuring energy security, and supporting sustainable socioeconomic development. The approaches and findings presented in this study provide valuable guidance for other coal-dependent regions and demonstrate the effectiveness of using LEAP-based modeling for provincial carbon transition planning. Future work could extend the current LEAP framework by incorporating socio-economic policies, such as just transition strategies and CCUS deployment, to further enrich the policy relevance of the analysis.

ACKNOWLEDGEMENTS

This research project was financially supported by Mahasarakham University. The authors sincerely thank the College of Electrical Engineering, Hunan Mechanical and Electrical Polytechnic, and the Electrical and Computer Engineering Research Unit, Faculty of Engineering, Mahasarakham University, for their generous support and guidance throughout this study.

DATASET AVAILABILITY STATEMENT

All data used in this study are publicly available from official government statistics and energy planning reports, including the National Bureau of Statistics "China Energy Statistical Yearbook", the Shanxi Provincial Government's "Shanxi Statistical Yearbook", and the China Electricity Council's "China Electric Power Statistical Yearbook". Data were obtained from official websites in Excel or PDF format and were processed through unit conversion, classification, aggregation, and supplementation of missing years to ensure usability and consistency. Processed datasets generated during this study are available from the corresponding author upon reasonable request, to facilitate replication of the results.

REFERENCES

[1] W. Jiang and Y. Sun, "Which is the more important factor of carbon emission, coal consumption or industrial structure?," *Energy Policy*, vol. 176, May 2023, Art. no. 113508, https://doi.org/10.1016/j.enpol.2023.113508.

[2] NBS, *China Energy Statistical Yearbook 2021*. Beijing, China: China Statistical Publishing House, 2022.

[3] C. Zhao, S. Ju, Y. Xue, T. Ren, Y. Ji, and X. Chen, "China's energy transitions for carbon neutrality: challenges and opportunities," *Carbon Neutrality*, vol. 1, no. 1, Apr. 2022, Art. no. 7, https://doi.org/10.1007/s43979-022-00010-y.

[4] F. Zhao, F. Bai, X. Liu, and Z. Liu, "A Review on Renewable Energy Transition under China's Carbon Neutrality Target," *Sustainability*, vol. 14, no. 22, Nov. 2022, Art. no. 15006, https://doi.org/10.3390/su142215006.

[5] Y. Hu, R. Zhang, X. Qie, and X. Zhang, "Research on coal demand forecast and carbon emission reduction in Shanxi Province under the vision of carbon peak," *Frontiers in Environmental Science*, vol. 10, Nov. 2022, Art. no. 923670, https://doi.org/10.3389/fenvs.2022.923670.

[6] Xinhua. "China's Shanxi sees over half of coal produced by intelligent mining." The People's Republic of China's official portal. https://english.www.gov.cn/news/202410/15/content_WS670da7d7c6d0868f4e8ebe04.html.

[7] CEC, *China Electric Power Statistical Yearbook 2022*. Beijing, China: China Statistical Publishing House, 2023.

[8] "Emission Inventories for 30 Provinces 2022." Carbon Emission Accounts and Datasets. https://www.ceads.net.cn/data/province/.

[9] "China CO2 Emissions." Worldometer. https://www.worldometers.info/co2-emissions/china-co2-emissions/.

[10] Shanxi Provincial Government. "Notice of the Shanxi Provincial People's Government on Issuing the Implementation Plan for Carbon Peaking in Shanxi Province." Shanxi Provincial People's Government Portal. https://www.shanxi.gov.cn/zfxxgk/zfcbw/zfgb2/2023nzfgb/d2q_76595/szfwj_77832/202301/t20230119_7825853.shtml.

[11] Shanxi Provincial Development and Reform Commission, Shanxi Provincial Energy Bureau. "Notice on Issuing the '14th Five-Year Plan for the Development of Renewable Energy in Shanxi Province." Shanxi Provincial People's Government Portal. https://nyj.shanxi.gov.cn/zfxxgk/fdzdgknr/ghjh/202302/t20230201_7903550.shtml.

[12] Y. Wang *et al.*, "Carbon peak and carbon neutrality in China: Goals, implementation path and prospects," *China Geology*, vol. 4, no. 4, pp. 720–746, Dec. 2021, https://doi.org/10.31035/cg2021083.

[13] R. Dong, C. Fu, Y. Liu, Y. Xu, and K. Li, "Modeling China's carbon emission reduction trajectory and peak path using a system dynamic approach," *Ecological Modelling*, vol. 505, June 2025, Art. no. 111104, https://doi.org/10.1016/j.ecolmodel.2025.111104.

[14] X. Wang, F. Fan, C. Liu, Y. Han, Q. Liu, and A. Wang, "Regional differences and driving factors analysis of carbon emissions from power

sector in China," *Ecological Indicators*, vol. 142, Sept. 2022, Art. no. 109297, https://doi.org/10.1016/j.ecolind.2022.109297.

[15] M. Yang, Y. Liu, J. Tian, F. Cheng, and P. Song, "Dynamic Evolution and Regional Disparity in Carbon Emission Intensity in China," *Sustainability*, vol. 14, no. 7, Apr. 2022, Art. no. 4052, https://doi.org/10.3390/su14074052.

[16] X. Zou, R. Wang, G. Hu, Z. Rong, and J. Li, "CO2 Emissions Forecast and Emissions Peak Analysis in Shanxi Province, China: An Application of the LEAP Model," *Sustainability*, vol. 14, no. 2, Jan. 2022, Art. no. 637, https://doi.org/10.3390/su14020637.

[17] M. Li, Y. Zhang, and H. Liu, "Carbon Neutrality in Shanxi Province: Scenario Simulation Based on LEAP and CA-Markov Models," *Sustainability*, vol. 14, no. 21, Nov. 2022, Art. no. 13808, https://doi.org/10.3390/su142113808.

[18] L. Wang *et al.*, "Carbon emission scenario simulation and policy regulation in resource-based provinces based on system dynamics modeling," *Journal of Cleaner Production*, vol. 460, July 2024, Art. no. 142619, https://doi.org/10.1016/j.jclepro.2024.142619.

[19] Y. Han and T. Masui, "Economic Impacts of Decarbonization in Power Sector from the Perspective of Carbon Neutrality: A Case Study of Shanxi Province," *Chemical Engineering Transactions*, vol. 106, pp. 349–354, Dec. 2023, https://doi.org/10.3303/CET23106059.

[20] Q. Wu and C. Peng, "Scenario Analysis of Carbon Emissions of China's Electric Power Industry Up to 2030," *Energies*, vol. 9, no. 12, Dec. 2016, Art. no. 988, https://doi.org/10.3390/en9120988.

[21] X. Xie, Y. Li, H. Zhang, Z. Chang, and Y. Zhan, "Pathway Simulation and Evaluation of Carbon Neutrality in the Sichuan-Chongqing Region Based on the LEAP Model," *Sustainability*, vol. 17, no. 7, Apr. 2025, Art. no. 3233, https://doi.org/10.3390/su17073233.

[22] Y. Xiao, C. Yang, T. Chen, M. Lei, and B. Wattana, "Analysis of Wind-Solar Power Development and Policy Strategies for Carbon Neutrality in Hunan Province," *Engineering, Technology & Applied Science Research*, vol. 15, no. 2, pp. 21326–21334, Apr. 2025, https://doi.org/10.48084/etasr.10023.

[23] Shanxi Provincial Government. "Notice on Issuing the Outline of the 14th Five-Year Plan for National Economic and Social Development and the Long-Range Objectives through the Year 2035 of Shanxi Province." Shanxi Provincial People's Government Portal. http://www.xiaoyi.gov.cn/xxgk/fdzdgknr/jhgh/202210/t20221025_1704869.shtml.

[24] Shanxi PBS. "Shanxi Statistical Yearbook 2011-2020." Shanxi Provincial People's Government Portal. https://tjj.shanxi.gov.cn/tjsj/tjnj/.

[25] CEC, *China Electric Power Statistical Yearbook 2011-2020*. Beijing, China: China Statistical Publishing House, 2021.

[26] MEE. "Guidelines for Compilation of Emission Inventory of Atmospheric Fine Particulate Matter (PM2.5) Sources (Trial)." Environmental Protection Technical Documents. https://www.mee.gov.cn/gkml/hbb/bgth/201401/W020140124409250653376.pdf.

[27] G. He and D. M. Kammen, "Where, when and how much wind is available? A provincial-scale wind resource assessment for China," *Energy Policy*, vol. 74, pp. 116–122, Nov. 2014, https://doi.org/10.1016/j.enpol.2014.07.003.

[28] "Shanxi's renewable energy installed capacity will surpass 83 GW by 2025." Azure International. https://www.azure-international.com/shanxis-renewable-energy-installed-capacity-will-surpass-83gw-by-2025/.

[29] "China wind and solar power generation potential assessment 2024." China Academy of Environmental Planning (CAEP). https://www.caep.org.cn/sy/tdftzhyjzx/zxdt/202406/W020240614475295022348.pdf.

[30] J. Yan, D. Zhang, W. An, Y. Liu, J. Wu, and P. Yang, "Distribution Characteristics and Assessment of Solar Energy Resource in Shanxi," *Journal of Arid Meteorology*, vol. 32, no. 5, pp. 712–718, Oct. 2014, https://doi.org/10.11755/j.issn.1006-7639(2014)-05-0712.

[31] L. Cui, J. Zhang, Y. Su, and S. Li, "A GIS-Based Multidimensional Evaluation Method for Solar Energy Potential in Shanxi Province, China," *Energies*, vol. 16, no. 3, Feb. 2023, Art. no. 1305, https://doi.org/10.3390/en16031305.

[32] C. Zhou, G. Huang, and J. Chen, "A Multi-Objective Energy and Environmental Systems Planning Model: Management of Uncertainties and Risks for Shanxi Province, China," *Energies*, vol. 11, no. 10, Oct. 2018, Art. no. 2723, https://doi.org/10.3390/en11102723.

[33] J. Yuan *et al.*, "The social impacts on China's vulnerable cities in the transition away from coal power," *iScience*, vol. 28, no. 11, Nov. 2025, Art. no. 113643, https://doi.org/10.1016/j.isci.2025.113643.

[34] W. Ge *et al.*, "Impacts of coal use phase-out in China on the atmospheric environment: (1) emissions, surface concentrations and exceedance of air quality standards," *Atmospheric Environment*, vol. 315, Dec. 2023, Art. no. 120163, https://doi.org/10.1016/j.atmosenv.2023.120163.

[35] Y. Xu, J. Hu, Q. Ying, H. Hao, D. Wang, and H. Zhang, "Current and future emissions of primary pollutants from coal-fired power plants in Shaanxi, China," *Science of The Total Environment*, vol. 595, pp. 505–514, Oct. 2017, https://doi.org/10.1016/j.scitotenv.2017.03.267.

[36] J. Lou, S. Yu, R. Y. Cui, A. Miller, and N. Hultman, "A provincial analysis on wind and solar investment needs towards China's carbon neutrality," *Applied Energy*, vol. 378, no. A, Jan. 2025, Art. no. 124841, https://doi.org/10.1016/j.apenergy.2024.124841.

[37] Y. Xiao, C. Yang, T. Chen, M. Lei, S. Wattana, and B. Wattana, "Strategies of a Wind–Solar–Storage System in Jiangxi Province Using the LEAP–NEMO Framework for Achieving Carbon Peaking Goals," *Energies*, vol. 18, no. 5, Mar. 2025, Art. no. 1135, https://doi.org/10.3390/en18051135.

[38] S. Nemdili, I. C. Ngaru, and M. Kerfa, "Solar-Wind Hybrid Power Generation System Optimization Using Superconducting Magnetic Energy Storage (SMES)," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9515–9522, Dec. 2022, https://doi.org/10.48084/etasr.5236.

[39] Z. Zhi, Z. Ming, Y. Bo, G. Zun, W. Zhaoyuan, and L. Gengyin, "Multipath retrofit planning approach for coal-fired power plants in low-carbon power system transitions: Shanxi Province case in China," *Energy*, vol. 275, July 2023, Art. no. 127502, https://doi.org/10.1016/j.energy.2023.127502.

[40] K. Jiang, P. Ashworth, S. Zhang, X. Liang, Y. Sun, and D. Angus, "China's carbon capture, utilization and storage (CCUS) policy: A critical review," *Renewable and Sustainable Energy Reviews*, vol. 119, Mar. 2020, Art. no. 109601, https://doi.org/10.1016/j.rser.2019.109601.

[41] W. Zhou, L. Pan, and X. Mao, "Optimization and Comparative Analysis of Different CCUS Systems in China: The Case of Shanxi Province," *Sustainability*, vol. 15, no. 18, Sept. 2023, Art. no. 13455, https://doi.org/10.3390/su151813455.

[42] D. Song, T. Jiang, and C. Rao, "Review of Policy Framework for the Development of Carbon Capture, Utilization and Storage in China," *International Journal of Environmental Research and Public Health*, vol. 19, no. 24, Jan. 2022, Art. no. 16853, https://doi.org/10.3390/ijerph192416853.