A Scenario Assessment of Sustainable Electricity Strategies toward China's 2060 Carbon Neutrality Target

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ABSTRACT

This paper assesses the impacts of long-term electricity pathways to achieve China's carbon neutrality target for the period 2023-2060. For this purpose, three scenarios (BAU, CNCM, and CNIM) are developed to represent different levels of zero-carbon energy penetration. These scenarios are analyzed using the Low Emissions Analysis Platform (LEAP) model for the period 2023-2060 to assess their implications for China's electricity transition. The analyses revealed that a greater share of zero-carbon energy in electricity generation would bring various notable benefits, including greater diversification of the energy supply, reduced dependence on fossil fuel imports, decreased reliance on conventional energy sources, and cleaner electricity generation. Despite the considerable benefits, China's electricity transition would face several challenges, namely centralized infrastructure, land use conflicts, and workforce displacement risks. The Chinese government addresses these challenges through smart grid upgrades, energy storage investments, and market reforms to boost the private sector involvement in electricity generation. In addition, building on current policies, this paper proposes three complementary strategies to accelerate China's energy transition, including power grid modernization (digitalization and flexible infrastructure), land-use optimization (integrated spatial planning), and labor transition safeguards (reskilling programs, and regional economic diversification). A coordinated implementation of these strategies is critical for achieving a carbon-neutral energy system that balances technical feasibility and social equity.

Keywords-electricity sector; zero-carbon energy; LEAP model; sustainable transition

I. INTRODUCTION

Electricity is a necessity for the social and economic well-being, fostering economic and social growth. Being the most populous developing country, China had a total population of 1,409 billion by 2023, representing nearly one-fifth of the global population [1]. In addition, the country's GDP has been consistently growing at a rate of 5%-8% over the past few decades. Such a large population combined with the rapid economic expansion has resulted in high electricity consumption. This has made the country the world's largest electricity consumer. In 2023, China's total electricity consumption reached 9,220 TWh, accounting for 31.6% of the global consumption [2]. In terms of electricity generation, China has predominantly relied on coal, accounting for 60% of the total power production in 2023 [3]. As electricity becomes vital to China’s energy consumption, the power sector contributes nearly half of the country’s carbon emissions, emitting approximately 4.5 billion tonnes of CO_2 annually [4]. In response to the growing climate change concerns, China formally announced strengthened/its emission targets at the 75th UN General Assembly. The nation committed to have reduced carbon emissions by 2030 and have achieved carbon neutrality before 2060 [5]. To meet these targets, China has implemented comprehensive policies to accelerate wind and solar energy development as primary alternative energy sources. Considering the significant potential environmental implications in China, the impacts of renewable energy have been thoroughly examined across various dimensions including technological, economic, energy-related, and environmental aspects. For instance, the technical dimensions of renewable energy generation have been explored, including wind performance, energy storage system, heating systems, and power transmission line layout optimization [5-11]. The potential for carbon emission reduction in China's power sector has been evaluated from economic and social perspectives, considering factors, such as electricity market reform, social welfare, feed-in tariff, and carbon pricing mechanisms [12-20]. Although valuable insights into the impacts of renewable energy in China have been provided, the transition driven by technological changes and policy shifts necessitates new research to offer relevant suggestions and recommendations. The disruptive technological changes, for example, the advancement of solar and wind technologies, increased the capacity of stationaries and mobile energy storage devices, and the development of smarter electricity grids integrating digitalization, Artificial Intelligence (AI), and related innovations [21]. Considering such a disruption, this paper, therefore, assesses the implications of long-term electricity pathways to achieve China's carbon neutrality target for the period of 2023-2060. While the existing literature on China's power sector has examined carbon emission reduction in isolation, this paper provides a dual perspective by integrating energy security metrics (e.g., fuel diversification and import dependency) with environmental objectives (e.g., decarbonization). This assessment would help identifying a suitable electricity pathway to meet China’s future electricity needs. It also provides policy recommendations to tackle the rising challenges and seize new opportunities arising from the development of zero-carbon energy.

II. CHINA'S POLICY AND DEVELOPMENT OF ZERO-CARBON ENERGY

Energy has been a key driver of China’s economic expansion and societal advancement. As a cornerstone of China's energy infrastructure, the electricity sector has played a vital role in the nation's energy landscape. In 2023, electricity generation represented approximately 30% of China’s total energy consumption [22]. Furthermore, the electricity sector has experienced a consistent increase in energy consumption. In 2023, China's energy consumption for power generation reached about 2.75 billion tonnes of standard coal, representing 48% of the nation's total energy consumption [23]. Electricity generation in China primarily relies on coal, which is the main source of carbon dioxide emissions. As a result, the electricity sector has become one of the fastest-growing sources of carbon dioxide emissions.

Given the concerns about the environmental pollution, promoting the development of alternative energy appears to be an effective strategy for the electricity industry to reduce carbon emissions and enhance energy security [24]. Therefore, the China's government has implemented various policies and measures to support alternative energy since 2001. The 14th Five-Year Plan for Renewable Energy Development released by the National Energy Administration (NEA) in June 2022, projects that by 2025, the annual electricity generation from renewable energy will have grown to approximately 3,300 TWh [25]. According to the Plan, the electricity generated from wind and solar power is expected to double, with renewable energy accounting for over 50% of the increase in primary energy consumption and representing around 33% of the total electricity generation. In addition, it is estimated that by 2025, the installed capacity of biomass power generation will have reached 40 GW, with a particular focus on the development of county-level municipal solid waste, incineration power generation, and biogas power generation [25]. The Guiding Opinions on Accelerating the Development of New-type Energy Storage plan was set out by the Chinese National Development and Reform Commission (NDRC) and NEA in July 2021 [26]. This plan seeks to have advanced the new energy storage technologies from early commercialization to large-scale deployment, with an installed capacity of over 30 million KW by 2025. By 2030, new energy storage technologies will have been fully commercialized, with their installed capacity fulfilling the demands of the modern power system. In 2022, the 14th Five-Year Plan for New-Type Energy Storage outlined various technological pathways, initiated demonstration projects for MW-scale flow batteries and sodium-ion batteries, and promoted the integration of energy storage and renewable energy development [26]. In August 2024, the Chinese government released the Opinions on Accelerating the Comprehensive Green Transformation of Economic and Social Development, highlighting the proactive, safe, and orderly advancement of nuclear power while ensuring a well-planned layout and steady construction progress [27]. By 2030, the proportion of non-fossil energy consumption is expected to have increased to about 25% [25].

To promote the development of alternative energy power generation, the Chinese government has implemented a series of measures, including planning guidance, financial subsidies, technological innovation, and power market reforms. For instance, the Renewable Energy Law was enacted to establish the legal status and development goals of renewable energy. Development plans have been formulated for wind, solar, nuclear, biomass, and new energy storage, aiming to establish efficient technical preparations and support. To foster the early development of the renewable energy sector, the government has introduced feed–in tariff subsidy policies for power generation from renewable sources.

Moreover, China has supported significant technological advancements across wind, solar, and nuclear energy, including the development of large-scale wind turbines, high-performance photovoltaic modules, and third-generation nuclear power systems. Efforts have been made to integrate renewable energy into power market transactions, improve green power trading mechanisms, and promote the Renewable Energy Certificate (REC) trading to encourage businesses and individuals to purchase green electricity. Furthermore, the construction of smart grids has been advanced to enhance the grid's capacity to accommodate renewable energy.

III. RESEARCH METHODOLOGY

A. *Methodological Framework and Research Scope*

This study adopts a scenario-based methodology combined with an energy model for assessing the impact of the increasing electricity production from non-fossil fuel sources on the power generation sector. A number of studies have adopted such an approach to assess the energy and environmental impacts of a high renewable energy penetration [28-33]. Regarding the energy modeling tools, several of them are widely utilized, including the EnergyPLAN, MARKet ALlocation

(MARKAL), The Integrated MARKAL-EFOM System (TIMES), Model for Analysis of Energy Demand (MAED), Model for Energy Supply Strategy Alternatives and their General Environmental impacts (MESSAGE), Simplified Approach for Estimating Impacts of Electricity Generation (SIMPACTS), Wien Automatic System Planning (WASP), and Low Emission Analysis Platform (LEAP). Authors in [34-35] have comprehensively reviewed computer tools for modeling energy and their impacts on electricity systems.

In this paper, the LEAP model is employed to examine the scenario impacts. LEAP is an integrated modeling tool that can track all energy flows in the economy and calculate greenhouse gas emissions based on these energy flows. In addition to energy, it can also model non-energy-related greenhouse gas impacts as well as air pollution beyond greenhouse gases. LEAP is particularly suitable for studying the co-benefits of reducing local air pollution and for building economic-environmental models [37]. LEAP offers several advantages, including minimal initial data requirements, visually intuitive processing results, and the automatic generation of standardized energy balance reports. Its widespread adoption has established it as a standard for integrated resource planning, Green House Gas (GHG) emission reduction assessments, and Low-Emission Development Strategies (LEDS), particularly in developing nations [36].

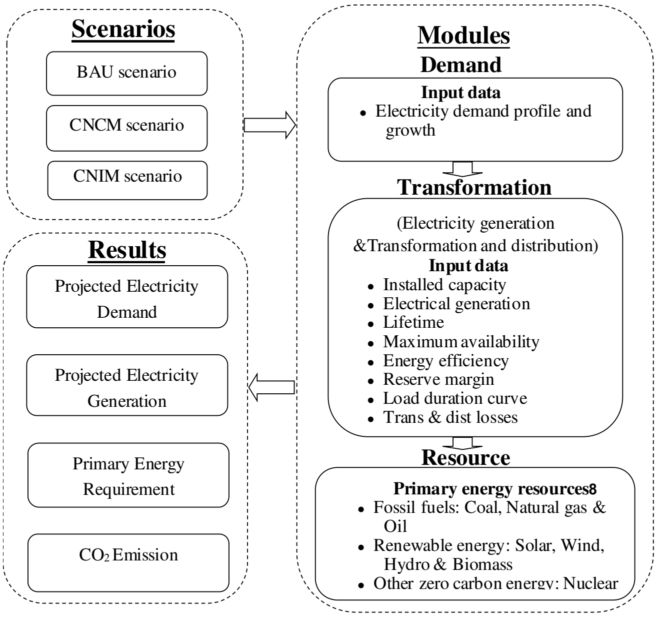

Fig. 1. Framework of the LEAP Model.

LEAP stands out both domestically and internationally for its comprehensiveness, ease of use, flexibility, extensive modeling methods, scenario analysis adaptability, diverse time spans, low data requirements, and wide applicability. In China, LEAP has been utilized for forecasting energy demand and carbon emissions at national, provincial, municipal, and industry levels [29-31, 38-43]. Figure 1 presents the modeling framework of the LEAP model used in this research. Electricity consumption across sectors is calculated based on historical load profiles and projected demand growth rates. Primary energy resources are obtained through transformation processes, taking into account installed capacity, specification of generation technologies, historical electricity generation, reserve margin load duration curve, and transmission and distribution losses. Additionally, primary energy requirement and transformation processes are employed to calculate CO_2 emissions.

B. Scenario Development

The scenario-developing approach typically involves creating multiple different perspectives based on an identified set of assumptions. These assumptions are formulated by taking into account several drivers that may impact potential future developments. The scenarios are quantitatively modeled to examine their impacts on energy and the environment. In this study, the development of scenarios takes into account the Chinese government's policies and plans regarding GHG emission mitigation. Since the Chinese government plans to have achieved carbon neutrality by 2060, it has introduced a series of new plans and strategies, while it has adopted a set of more effective policies and actions. The key policies focus on facilitating a substantial integration of renewable energy in the electricity industry, while also promoting greater use of nuclear energy, hydrogen, and energy storage. In response to these policies, the government has implemented various plans, such as the 14th Five-year Electricity Plan and 14th Five-year Renewable Energy Plan. According to the plan, renewable energy sources are projected to have accounted for over 50% of the total electricity production by 2025, with electricity generated from wind and solar sources being expected to double, relative to the production levels in 2025 [44]. Such a significant increase could be considered a potential target, given China's substantial renewable energy capacity. The projected wind power capacity potential is approximately 3,000 GW [45, 46], capable of generating 4,000-5,000 TWh annually. Solar power capacity has the potential to deliver between 4,000 GW and 39,300 GW, with generation potential ranging from 1,300 to 6,500 TWh per year. While nuclear power capacity is projected at 500 GW, biomass resources have a total generation capacity of 4,720 TWh. Since biomass power generation is similar to fossil fuel power generation, its potential limitation is mainly reflected in the total amount of resources rather than in the installed capacity, with the estimated potential for hydropower installed capacity development being 694 GW. For Energy Storage System (ESS), the installed capacity is expected to have exceeded 300 GW by 2060 [45-47].

Given the aforementioned policies, this research has developed three scenarios, namely Business-As-Usual (BAU), Carbon Neutrality Conservative Measure (CNCM), and Carbon Neutrality Ideal Measure (CNIM). The BAU scenario signifies the continuation of the existing generation shares by electricity-generating technologies and energy resources. In the CNCM scenario, the share of zero-carbon energy in total generating capacity is expected to have reached 76.2% by 2060. The CNIM scenario aims to have achieved a complete transition to non-fossil energy generation, reaching 100% by 2060. Additionally, under the CNIM scenario, solar and wind power are expected to have represented 85% of the total installed capacity. In this study, the growth in electricity demand and the total installed capacity for all three scenarios are based on the 14th Five Year Power Plan [48]. The electricity demand growth is divided into two different time periods, with a 2.3% growth rate from 2023 to 2035, followed by a 1.3% growth rate from 2036 to 2060, with the electricity generating capacity being expected to reach 9000 GW [31]. Table I presents additional details regarding the scenario descriptions.

TABLE I. KEY SCENARIO FEATURES AND ASSUMPTIONS

Scenarios	Scenario features and assumptions
BAU scenario	Illustrates the ongoing trend of the existing energy and technology mix in electricity production.
	Coal remains the dominant energy source for power generation, with the constant share of 40% for the entire period [22].
	Coal power plants including subcritical, supercritical, and ultra-supercritical continue to play a key role in electricity supply, accounting for 89% of the total installed capacity of the fossil fuel power generation.
	Solar and wind power in 2060 is projected to have represented 20.4% and 18.9% of the installed capacity respectively.
CNCM scenario	Decreasing the share of fossil fuels in electricity generating capacity, from 51% in 2023, to 24% in 2060.
	Wind and solar capacity will have increased to 76% of the total generating capacity in 2060 [23].
	By 2060, the generating capacity of solar, wind, nuclear, biomass, and ESS energy will have reached 3,000 GW, 2,500 GW, 360 GW, 180GW, and 120 GW, respectively [23-24].
	Due to the limited potential for further development of hydropower in China, the hydro capacity is expected to have peaked at 694 GW by 2045 and have remained constant at this level until 2060 [25].
CNIM scenario	Represents the carbon neutrality achievement by shifting to 100% zero carbon energy resources.
	Decreasing proportion of fossil fuels in power production, from 51% in 2023, to 0% in 2060.
	By 2060, the generating capacity of solar, wind, nuclear, biomass, and ESS energy will have reached 4,500 GW, 3,125 GW, 400 GW, 180GW, and 120 GW, respectively.
	The hydro power capacity follows the same assumption to the CNCM scenario.

C. Data Consideration

With an aim to assess the implications of electricity generation from various zero-carbon energy sources on energy and the environment, this study requires comprehensive data on the electricity, energy, environment, and economy. The framework developed in this study utilizes the LEAP model, a bottom-up approach that relies on a broad range of data. The essential data required for this model comprise power use for various economic sectors, electricity generation by energy resources types, installed capacities of power plants, electricity transmission and distribution losses, power generation technology efficiencies, electricity load duration curve and demand growth projections, and emission factors for key pollutants.

The information on electricity demand growth across various economic sectors can be collected from the China Statistical Yearbook, the National Bureau of Statistics (NBS) [49]. To develop the electricity scenario, this study employs scenario assumptions from a number of energy plans and reports. For example, the 14th Five-Year Plan for Renewable Energy Development and 14th Five-Year Plan for New Energy and Energy Storage Development Implementation Plan can be obtained from the NDRC [25, 26]. China Nuclear Energy Yearbook 2023 is available from the China Nuclear Energy Association (CNEA) [50], while the Action Plan to Reach Carbon Emission Peak before 2030 can be taken from the State Council [51]. The information on technology-specific information, including the lifetime of the power plants, maximum availability, capacity credit, electricity reserve margin, electricity load duration curve, efficiency of the generation technologies, and transmission and distribution system losses, can be achieved from the NBS and relevant literature [38, 52, 56]. The historical data on the primary energy consumption for electricity generation including coal, natural gas, oil, solar, wind, hydro, biomass, and nuclear energy can be taken from the NBS [1]. The emission factors for calculating environmental pollutants, such as CO_2 emissions, are available at the Intergovernmental Panel on Climate Change (IPCC) [57, 58].

IV. EMPIRICAL RESULTS AND DISCUSSIONS

This paper explores the long-term electricity pathways and their implications for achieving China's carbon neutrality goal between 2023 and 2060. To analyze the implications of each scenario, this paper employs four attributes: electricity generation projections, primary energy requirements, diversification of the primary energy supply, and CO_2 emissions.

A. Projected Electricity Generation

In order to meet the rising electricity demand, electricity generation is projected to have increased across all scenarios from 2023 to 2060. As shown in Figure 2, electricity generation will have increased substantially, from 8,970 TWh in 2023 to 18,127 TWh by 2060, representing a greater than a two-fold growth in electricity production. Figure 2 demonstrates that the electricity production and generation mix follow a similar trend over the period 2023-2030. This is attributed to the government's reduction policy target in 2030, which will result in the same installed capacity and annual growth rates of power generation across all three scenarios during this period. In view of the power generation from sources, the electricity production mix across the three scenarios will vary significantly. For the coal power generation between 2023 and 2060, the BAU scenario will result in a 104% increase in generation from coal power plants consisting of sub-critical, super-critical, and ultra-supercritical technologies. In contrast, the CNCM and CNIM scenarios will contribute to a decline of 1% and 49%, respectively. By 2060, electricity produced from coal is expected to have reached 10,485 TWh under the BAU scenario and 5,056 TWh under the CNCM scenario, while in the CNIM scenario, it is expected to have dropped to 0 TWh. Similarly, by 2060, the natural gas power production is expected to have increased to 1,664 TWh under the BAU scenario and 1,962 TWh under the CNCM scenario. In contrast, under the CNIM scenario, it will have dropped to 0 TWh. The power generation from non-fossil fuel resources appears to increase noticeably. For example, the power produced by solar energy is expected to have risen by about 6 times in the BAU scenario, 12 times in the CNCM scenario, and 23 times in the CNIM scenario by 2060 compared to 2023. Moreover, the electricity generation from wind in the CNCM and CNIM scenarios in 2060 will be, respectively, 222% and 276% of the generation in the BAU scenario. Electricity generated from nuclear energy is expected to have increased to 1,177 TWh in the CNCM and 1,660 TWh in the CNIM by 2060, that is, more than a three-fold increase compared to 2023. The electricity production from biomass in the case of the BAU, CNCM, and CNIM scenarios is estimated to have risen by 48%, 213%, and 297%, respectively, by 2060. With a limited potential for further hydropower development in China, hydro capacity is projected to have reach a peak of 694 GW by 2045 and have remained steady at this level until 2060 for CNCM and CNIM scenarios [46]. For ESS, the electricity from ESS is expected to have increased to 207 TWh in the CNCM and 263 TWh in the CNIM by 2060 – representing an over five-fold increase compared to 2023.

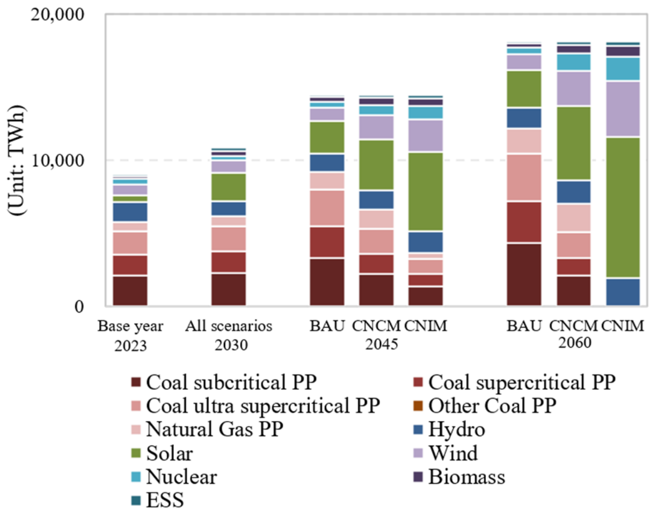

Fig. 2. Electricity generation by technology.

In terms of the generation share based on the fuel type, it will vary across the three scenarios, as shown in Figure 3. Under the BAU scenario, coal maintains a major share similar to the 2023 levels, whereas both CMCM and CNIM scenarios show substantial reductions in the share of coal in power production. By 2060, the proportion of coal will have dropped significantly to 28.2% under the CNCM scenario and to 0% under the CNIM scenario in comparison to 57.4% in 2023. This decline is primarily driven by the Chinese government's policies promoting the transition to cleaner energy sources. For zero carbon energy, renewable energy, particularly solar and wind power, will experience an increased share for the CNCM and CNIM scenarios. By 2060, wind power's share is expected to have risen to 13.6% and 21.7% in the CMCM and CMIN scenarios, respectively. The solar power generation will experience a substantial growth, reaching 28.3% and 54.1% under the CMCM and CMIN scenarios, respectively. The reduction in coal consumption is largely substituted by penetration of renewable energy sources. Nuclear power will also experience a moderate increase under the CNCM and CNIM scenarios, rising from 4.7% in 2023 to 6.6% and 9.3% in 2060. This increase is attributed to China's leadership in nuclear power capacity and its advancements in safety and environmental benefits, which have led to its inclusion in the national green energy development strategy [60]. The share of biomass generation will increase slightly from 2.1% in 2023, to 3.3% in the CNCM scenario and 4.2% in the CNIM scenario.

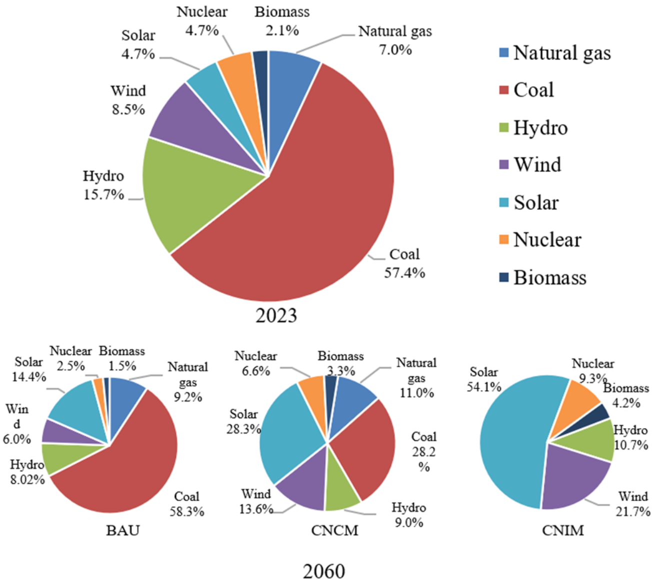

Fig. 3. Electricity generation share by fuel type in 2023 and 2060.

B. *Primary Energy Requirements and Energy Diversity*

In this section, primary energy requirements are employed to represent how the growing share of zero-carbon energy in electricity production could contribute to a decrease in the primary energy supply and especially, to a greater diversification of the energy sources. This study uses the Herfindahl-Hirschman Index (HHI) as an indicator to analyze the diversification of the energy supply. The HHI assesses THE energy diversity by summing the squares of each energy source's market share in a country's energy mix [61]. A lower HHI indicates a more diverse energy portfolio, while a higher value reflects reliance on a few energy sources. Table II shows that between 2023-2060, the primary energy needed for electricity generation will increase at different levels across all three scenarios. The BAU scenario represents a substantial rise in the primary energy demand – from 1,609 MTOE in 2023 to 3,221 MTOE in 2060, that is, an increase of 1,612 MTOE, highlighting a continued reliance on conventional energy sources. The CNCM and CNIM scenarios are projected to have risen primary energy requirements by 1,044 MTOE and 333 MTOE, respectively, compared to the 2023 levels. Table II further indicates that boosting the share of zero-carbon energy in power production will lead to a substantial reduction in the primary energy needed for producing electricity. For instance, in 2060, the primary energy requirement will drop to 2,653 MTOE under the CNCM scenario and 1,942 MTOE under the CNIM scenario – representing reductions of 18% and 40% compared to the BAU scenario. The coal demand for power generation, in the CNCM scenario, declines to 42% of the total demand for primary energy, whereas the CNIM scenario achieves full decarbonization, reducing coal utilization to zero. As China transitions to carbon neutrality, zero-carbon energy will play an ever more critical role in the nation's primary energy supply. For instance, the share of solar power is projected to have increased considerably from just 2% in 2023 to 17% in the CNCM scenario and 44% in CNIM scenario by 2060. The wind power proportion will have grown to 8% in the CNCM scenario and 17% in the CNIM scenario by 2060. In addition, the share of nuclear and biomass power in the primary energy mix is also projected to have increased. By 2060, the proportion of nuclear energy in the primary energy mix is expected to have reached 10% in the CNCM scenario and 19% in the CNIM scenario, while biomass's share is projected to have grown to 6% and 11%, respectively, representing an increase of approximately two to four times. With the rising share of diverse zero-carbon energy sources, the HHI in the CNCM and CNIM scenarios is expected to have decreased from 0.52 in 2023 to 0.24 and 0.28 by 2060, respectively, indicating a significant improvement in the diversification of energy supply. However, the CNCM scenario exhibits lower energy diversity compared to the CNIM scenario. This could be due to greater distributed energy sources in CNCM compared to CNIM, as displayed in Table II.

TABLE II. PRIMARY ENERGY REQUIREMENTS AND ENERGY DIVERSITY

	2023	2060		
		BAU	**CNCM**	**CNIM**
Primary energy requirement (MTOE)	1,609	3,221	2,653	1,942
Coal (%)	70.8%	72.4%	42.2%	0.0%
Natural gas (%)	5.4%	7.2%	10.1%	0.0%
Hydro (%)	7.5%	3.9%	5.2%	8.4%
Wind (%)	4.1%	2.9%	7.9%	17.2%
Solar (%)	2.4%	7.3%	17.1%	44.0%
Nuclear (%)	5.9%	3.2%	10.0%	19.4%
Biomass (%)	3.3%	2.5%	6.4%	11.0%
HHI	0.52	0.54	0.24	0.28

C. CO_2 Emission

To mitigate CO_2 emissions in the electricity sector, the Chinese government's decarbonization policy emphasizes increasing the adoption of zero-carbon energy. The results from Figure 4 show that the CO_2 emissions are projected to nearly have doubled, increasing from 4,625 million tonnes in 2023 to 9,591 million tonnes by 2060. This represents a net rise of 4,966 million tonnes – equivalent to an average annual growth rate of 1.97% over the period. In contrast, increasing more zero-carbon energy sources would result in a substantial reduction in the CO_2 emissions. For example, the CO_2 emissions under the CNCM scenario are projected to have increase slightly by 346 million tonnes – representing only a 7% increased over 2023 levels. Under the CNCM scenario, the CO_2 emissions decline steadily, reaching net zero by 2060 and achieving the carbon neutrality target.

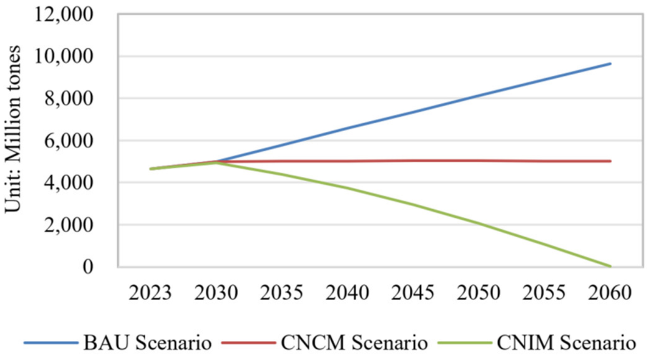

Fig. 4. CO_2 emission from electricity generation.

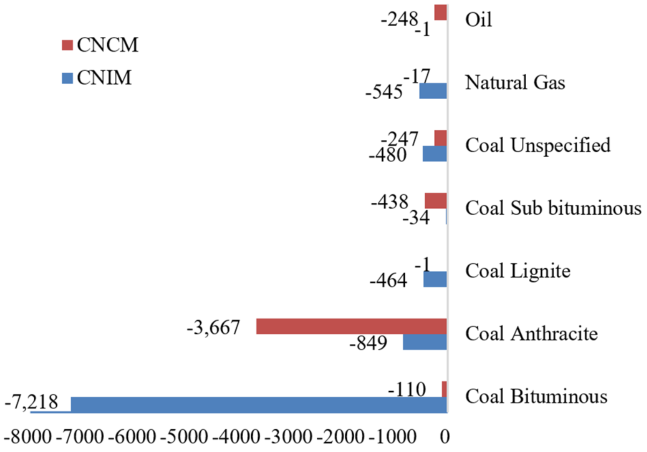

Fig. 5. Changes in CO_2 emissions.

Figure 5 presents the changes in CO_2 emissions under the CNCM and CNIM scenarios in 2060 compared with the BAU scenario. It is further observed from Figure 5 that the largest reductions in the CO_2 emissions under both the CNCM and CNIM scenarios would stem from bituminous and anthracite coal, accounting for over 80% of the total decrease. In the case of the CNIM scenario, the decrease in bituminous coal consumption will result in the highest CO_2 savings – amounting to 7,218 million tonnes in 2060 in comparison with the BAU scenario. For the CNCM scenario, the decline in anthracite coal use, however, contributes the most to emission reductions, with CO_2 savings totaling 3,667 million tonnes.

V. POLICY IMPLICATIONS

Aiming to develop sustainable long-term electricity strategies for China, this study analyses the implications of various carbon neutrality measures from 2023 to 2060. It examines the implications of each scenario in terms of the projected electricity generation, primary energy requirements, energy diversity, and CO_2 emissions.

A significant integration of zero-carbon energy in China's electricity production sector would bring various benefits. For example, an increase in the share of renewable energy in the electricity sector would significantly contribute to enhancing China's energy security, while it would significantly reduce the role of fossil fuels in electricity production. China has been ranked as the world's largest coal importer – accounting for nearly 30% of global coal imports [62]. China also became the leading natural gas importer in 2023, representing nearly 20% of the global imports [62]. The decrease in the fossil fuel shares would lead to reduced demand for coal and natural gas, and hence a decline in the fossil fuel imports. In addition, a greater share of renewable energy in the primary energy supply would help enhance the diversification of energy sources for electricity production. The enhancement in energy diversity combined with a reduced reliance on the energy imports, therefore, will help strengthen the country's energy security. In view of an environmental perspective, an increase in the share of renewable energy in electricity production would lead to a significant drop in the CO_2 emissions, promoting a more sustainable and eco-friendly power development. This is important for achieving the carbon neutrality goal.

The promotion of zero-carbon energy policies appears to be beneficial for China. However, the adoption of renewable energy sources and the shifts in the power consumption patterns driven by renewable energy would inevitably disrupt the existing electricity structure. The traditional structure was defined by a centralized, unidirectional power system reliant on fossil fuels, involving only a limited number of participants. Such a structure was not originally designed to handle the intermittent nature of renewables or the active and dynamic participation of demand in the power system operation. This could pose multidimensional challenges for China's energy transition.

A major issue is the centralized nature of the electricity system. Traditional electricity grids are based on large-scale power generation facilities, with electricity transmitted and distributed to end users through expansive and complex network infrastructures. This infrastructure is incompatible with distributed generation systems, which are characterized by smaller installed capacities, low-voltage grid connections, and simple electricity structure. Distributed generation predominantly utilizes renewable energy sources, such as wind and solar power generation. To transition from the traditional power system to a modernized grid that effectively integrates renewable energy sources, it is imperative to enhance the flexibility across all components of the power system. This approach includes creating a diversified and supplementary energy supply, adopting flexible demand-side management strategies, integrating energy storage systems to enhance grid stability, and upgrading the grid infrastructure with advanced smart management technologies.

Another key challenge involves the land use constraints causing technical, economic, and ecosystem concerns. To achieve carbon neutrality by 2060, transitioning to zero-carbon energy sources—particularly solar and wind—is essential for the Chinese electricity sector. Deploying terawatt-scale solar and wind power capacity depends on the availability of adequate land resources for large-scale system installation. Large-scale solar and wind energy facilities typically require nearly ten times the land area compared to traditional coal or natural gas power plants with the same generation capacity [63]. Therefore, China's solar and wind expansion might face challenges due to the varying geographical conditions and resource availability across different regions. For example, in eastern and southern China, where electricity demand is high, the government focuses on developing nearby generation capacity to reduce transmission distances and improve reliability. However, these regions also encompass a significant proportion of the country's agricultural land (excluding large forested areas), presenting additional land-use challenges. The installation of large-scale solar and wind power generation systems in these areas requires an integrated planning to address the competing demands for agriculture, ecosystem protection, and energy infrastructure under the existing regulations. In addition, wind and solar resources are mainly concentrated in northwest and northeast China.

The significant expansion of renewable energy generation in these regions requires investments in transmission infrastructure to ensure the reliable delivery of sufficient electricity. Despite operating the world's most extensive Ultra-High Voltage (UHV) grid, China's existing transmission capacity remains inadequate to support the significant expansion of renewable energy generation from China's peripheral regions, particularly the wind-rich northeast and solar-abundant northwest. While renewable energy plays a crucial role in decarbonization, large-scale wind and solar installations have the potential to impact local microclimates and ecosystems. Wind power generation could cause local temperature changes and affect the wind direction, and may also pose risks to bird populations [64]. Large-scale solar installations may alter the local ecosystems through vegetation clearance and habitat fragmentation, potentially disrupting the native wildlife populations.

The issues of employment insecurity are also important. The reduced reliance on coal for power production would inevitably result in job losses in coal-related industries. In 2023, China's power sector employed approximately 3.61 million workers, representing a reduction of 140,000 jobs compared to the 2022 levels [65]. Moreover, a study by the United Nations Development Programme (UNDP) revealed that 52% of Chinese's coal industry jobs are projected to have been lost by 2030, escalating to 90-94% by 2050 [66]. These projections indicate a reduction of approximately 1.3 million coal industry jobs within the next decade, cumulating to 2.35 million job losses over a 30-year period. In spite of the job losses in coal-related industries, renewable energy expansion is projected to create new jobs to yield a net increase in power industry employment. According to UNDP, the shift to renewable energy is expected to significantly boost employment, with jobs created in wind industry projected to double and employment generated in solar industry to triple over the next 50 years [66]. While the power industry is expected to experience net job growth, a further analysis of the occupational shifts and regional impacts is vital. The major obstacle lies in labor market inflexibility, particularly regarding workforce relocation and retraining. Workers may face barriers to sectoral transition, such as insufficient skills for new roles and physical distance from emerging job opportunities [67]. Workforce analysis reveals limited educational attainment and skill development among the coal industry employees, with advanced competencies predominantly found in large-scale enterprises. The renewable energy sector, including wind and solar energy, requires advanced technical skills that most coal industry workers currently lack, posing significant barriers to the direct workforce transition. Smart grid development emerges as another transitional obstacle, potentially disrupting traditional employment patterns in electricity system operations. Smart grid systems employ advanced automation through digital technologies, AI-driven analytics, and IoT – enabled remote monitoring, significantly diminishing reliance on manual operation and maintenance compared to conventional grid infrastructure.

This suggests that achieving decarbonization through large scale deployment of renewable energy could raise interconnected technical, economic, and social transition challenges. These include infrastructural centralization in energy systems, geographical land use conflicts, and socioeconomic employment instability. To address these challenges, this study proposes the following strategies:

The primary strategy is to implement multiple measures simultaneously to systematically address the power system infrastructure challenges. The electricity system might face significant operational challenges in integrating high shares of zero-carbon energy (particularly wind and solar), requiring technical, economic, and institutional solutions. Expediting smart grid deployment would significantly enhance the grid stability amidst high-penetration renewable energy integration, particularly for variable wind and solar power generation. The implementation of advanced digital infrastructure, including IoT, 5G communications, and cloud computing would enable the development of intelligent grid management platforms capable of dynamic, precision-controlled power system operations. In addition, to maintain grid balance and enhance renewable energy reliability, a strategic investment in diversified storage technologies, including battery energy storage, pumped hydro storage, and compressed air storage, should be prioritized. Additionally, developing Vehicle-to-Grid (V2G) systems to enable bidirectional energy flow between electric vehicles and power networks could enhance grid peak-shaving capabilities through distributed energy storage aggregation. From a policy and market perspective, the Chinese government should establish regulatory frameworks that incentivize renewable energy adoption by: (1) offering feed-in tariffs with guaranteed grid access, (2) implementing tiered subsidy structures, and (3) introducing market mechanisms to ensure fair pricing – each aimed at encouraging private sector and individual investment in renewable projects.

The development of integrated spatial planning frameworks could serve as an effective strategy to optimize land allocation and mitigate renewable energy siting conflicts with agricultural/ecological priorities. The growth of wind and solar energy infrastructure is constrained by the overlapping territorial demands from ecological conservation zones and agricultural protection areas. Addressing land-use conflicts requires integrated solutions across three dimensions: (1) strategic spatial planning, (2) efficient land resource utilization, and (3) disruptive technology applications. First, strategic spatial planning should prioritize the deployment of utility-scale solar and wind projects in China's northwestern desert, Gobi, and arid regions to optimize land use and resource potential. These regions offer abundant wind and solar resources with minimal interference to ecological reserves and high-quality farmland, offering optimal conditions for large-scale development with manageable environmental impact. Second, implementing hybrid land-use models that combine energy generation with agricultural, ecological, or industrial activities could help achieve synergistic resource utilization. For example, Agricultural Photovoltaics (APV) represents an innovative dual-use solution, enabling simultaneous electricity generation through elevated solar panels and uninterrupted crop cultivation beneath the array, thereby addressing both energy and food security priorities.

Offshore renewable energy development should adopt integrated marine spatial planning, combining wind/solar installations with aquaculture operations to optimize the multidimensional use of marine resources while maintaining an ecological balance. Also, a dual-track development strategy should be implemented to optimize land use by: (1) deploying centralized utility-scale projects in the northwestern deserts, such as Gobi, and offshore zones; and (2) expanding the distributed renewable systems in land-scarce central and eastern regions by utilizing rooftops, village edges, and degraded lands. Third, the wind and solar companies should prioritize compact system innovations, like Floating Photovoltaics (FPV) – a rapidly emerging global solution that minimizes land requirements while maintaining generation efficiency. FPV systems integrate solar panels with water surfaces, like reservoirs and oceans, reducing land use competition while providing extra synergistic benefits. Advancing photovoltaic conversion efficiencies directly reduces land area requirements per unit energy output.

Silicon-based solar cells, including both single-crystal and multi-crystal varieties, currently dominate the global market; however, their theoretical maximum efficiency has reached a limit of around 29%. Next-generation photovoltaic technologies, like Perovskite solar cells, could potentially overcome these existing limitations. While silicon solar cells face about 29% efficiency limit, perovskite technologies could reach to 33% (single-junction) and even more than 40% (multi-junction) efficiencies [68]. In addition, Perovskite solar cells exhibit superior performance under low-light conditions, maintaining high efficiency even during cloudy weather or at dawn/dusk. This feature effectively boosts their electricity generation potential.

To address employment insecurity issues, strengthening the current workforce policy frameworks may provide more robust support for vulnerable workers. The restructuring of power systems has created labor market pressures for more medium- and high-skilled workers. To support displaced workers, local governments should take a leading role in establishing provincial job placement centers, monitoring affected employees, offering proactive career services, and expanding upskilling initiatives. To encourage entrepreneurship among the unemployed, governments should offer exemptions from company registration fees and other related administrative costs. Furthermore, those facing long-term unemployment should be given a priority access to specially designed community service positions that match their skills and circumstances. Flexibly-employed job seekers should be eligible for adaptable social security terms, including deferred contributions, partial waivers, and subsidies, to help them maintain coverage while rebuilding their livelihoods.

VI. CONCLUSIONS

This paper assesses the impacts of long-term electricity pathways to achieve China's carbon neutrality target for the period 2023-2060. The results show that integrating zero-carbon energy into China's electricity sector may deliver various benefits, including greater diversification of energy supply, reduced fossil fuel import dependency, decreased reliance on conventional energy, and cleaner electricity generation. However, scaling zero-carbon energy requires balancing trade-offs: while solar/wind expansion aids decarbonization, over-reliance may threaten energy security by reducing fuel diversity and grid resilience—a critical consideration for China's 2060 targets. In addition, the zero-carbon transition may raise interconnected challenges across technical, economic, and social dimensions. These include increased infrastructure centralization, geographical constraints on land availability for renewable projects, and potential socioeconomic disruptions in traditional energy employment sectors. Policymakers need to address the trilemma of the challenges emerging from decarbonization: technical barriers in grid infrastructure, spatial limitations for renewable deployment, and fair transition considerations for the affected workers. To tackle these challenges, the Chinese government has introduced a range of policies, for example, smart grid development, storage technology advancement, and market reforms encouraging private sector participation in power generation. In addition to the existing policies, this paper proposes three integrated policy strategies, including modernizing power system infrastructure, optimizing land use through spatial planning and innovation, and safeguarding employment through proactive labor measures. The coordinated action across these three strategies is important to achieve a decarbonized energy system that is both technically viable and socially equitable. By tackling these interconnected barriers holistically, decision-makers can maximize zero-carbon energy adoption while mitigating transition risks.

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