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Impacts of Solar Energy Policies on the Electricity Generation in Hunan, China

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This paper analyzed the changes in electricity generation in Hunan province under different solar energy policies. Three scenarios, namely baseline scenario (BAS), current policy scenario (CPS), and future policy scenario (FPS), were developed to represent various levels of solar energy development from 2021 to 2035. Utilizing the Low Emissions Analysis Platform (LEAP) model, the study assessed the impacts of these scenarios on the electricity generation mix, fossil fuel consumption, and the emissions of CO_2, SO_2, and PM2.5 in Hunan province. The results indicate that with the increase in solar energy generation, the electricity generation mix becomes more diversified, and the consumption of fossil fuels significantly decreases, along with notable reductions in CO_2, SO_2, and PM2.5 emissions. The introduction of solar energy as a clean energy source plays a crucial role in reducing dependence on traditional energy sources, mitigating environmental issues, and enhancing sustainability. Nonetheless, the research also highlighted issues in Hunan province, such as the uneven distribution of solar energy resources and inadequate supervision of the power grid. Consequently, this article proposed a range of policy suggestions. These included establishing upgraded power system to enhance grid infrastructure stability, reinforcing regulatory frameworks to tackle non-compliance, and adjusting financial assistance for solar power generation. The objective is to propel Hunan province towards a future characterized by sustainability and cleaner energy.

Keywords: electricity generation, solar energy policies, environment and Hunan province.

Introduction

Confronted with the pressing challenge of climate change and the critical imperative to cut down carbon emissions, nations worldwide are progressively embracing renewable energy to meet their escalating energy demands. Being a significant contributor to global carbon emissions, China has systematically devised policies aimed at fostering the advancement and adoption of clean energy technologies. As the one of

prominent clean energy source, solar energy boasts numerous advantages including boundless renewable resources, emission-free operation, cost-effective maintenance, and extensive availability. Located in central China, Hunan province has been actively promoting solar power generation in recent years. Between 2016 and 2021, its installed capacity for solar power increased rapidly from 0.3GW to 4.5GW (CEC, 2022). The policies and development experience of Hunan province in solar power generation would serve as a model and guide for other provinces in central China.

Over the period 2017-2021, Hunan province witnessed a persistent and escalating trajectory in energy consumption, characterized by an average annual growth rate of 2.6% (NBS, 2021; NBS, 2022). As of 2021, the total energy consumption stood at roughly 167 million tonnes of standard coal, with approximately 36 million tonnes of standard coal allocated for power generation (NBS, 2022). Examining the energy consumption structure for electricity generation reveals that the consumption of fossil fuels was at a high level, accounting for 48% (CEC, 2022). Notably, 19% of electricity requirements were externally procured from other provinces. In contrast, the utilization of solar energy constituted a minimal 2% (CEC, 2022).

Hunan's electricity generation is expected to undergo significant changes. With the advancement of new energy policies, the province's energy structure will gradually shift from traditional fossil fuels to renewable sources such as solar and wind power. This transition will have several key implications. Firstly, it will help reduce dependence on high-carbon sources like coal, thereby lowering greenhouse gas emissions and air pollution, and improving environmental quality. Additionally, diversifying the energy supply will enhance energy security and reduce reliance on external energy sources. However, this process will require strengthening grid stability and flexibility to address the volatility of renewable energy generation. To successfully achieve this energy transition, supportive policies and regulatory frameworks are needed, including subsidy programs, market access mechanisms, and technical standards, to ensure a smooth shift from traditional to renewable energy sources.

Nevertheless, there remains considerable potential for the advancement of solar power generation in Hunan province. Just as mentioned in the "13th Five-Year Solar Development Plan for Hunan Province (Hunan PDRC, 2016)", with an average annual temperature ranging from about 17 to 19°C, the province is abundant in solar energy resources. The summer season extends for 4–5 months, with temperatures soaring to approximately 40°C (Hunan PBS, 2021). Over time, the average annual total solar radiation in counties and cities across Hunan province has consistently ranged between 940 and 1214 kWh/m^2 (Hunan PDRC, 2016). Furthermore, Hunan province has successively introduced policy plan such as the "13th Five-Year Solar Development Plan for Hunan Province," the "14th Five-Year Plan for Renewable Energy Development in Hunan Province (Hunan PDRC, 2022a)" and the "Hunan Province Electric Power Support Capability Enhancement Action Plan 2022–2025 (Hunan PDRC, 2022b)" to support solar power generation development.

Extensive research on solar power generation in China, including studies by Sun et al. (2017), Zhao et al. (2013), Li and Huang (2020), Dong (2023), indicates that solar energy is in a rapid growth phase, currently representing a small proportion of the energy mix. By the end of 2018, global cumulative solar installed capacity accounted for about 30%. To further expand the application of solar energy, significant political and industrial efforts are required to address regional mismatches between solar generation and electricity demand, manage the variability of sunshine, and alleviate the financial burden of renewable energy subsidies. In grid planning, careful consideration must be given to generation and load characteristics, as well as the combined effects of photovoltaic and wind power on peak regulation capacity. Effective designs should include measures to manage voltage and harmonics while promoting the integration of energy storage systems to smooth load curves and enhance overall efficiency. Additionally, policy analyses by Liu et al. (2016), Zhang and He (2013), Wang and Li (2022) recognize the significant investment value and unique advantages of commercial photovoltaic systems in China, which the government has acknowledged in its commitment to fully utilize solar PV potential. However, challenges remain, such as electricity waste due to curtailment in some regions and the need to reduce financial pressures on solar projects. Furthermore, recent studies by Guo et al. (2023), Zhang (2019), Xu and Liu (2020) focus on technological progress and application prospects

in the field, categorizing technologies into three types: crystalline silicon, thin-film, and emerging solar cell technologies. Crystalline silicon technology, the most established, offers high efficiency and longevity but at a higher cost; thin-film technology is lightweight and cost-effective but has lower efficiency and a shorter lifespan. Emerging technologies are still under development, and the choice of technology should depend on specific application needs. Researchers predict that by 2023, the development cost of photovoltaic power generation systems will not exceed 0.6 yuan per kWh, reflecting ongoing advancements in the field.

Despite extensive studies on solar energy at the national level, research focused on Hunan Province remains limited, primarily addressing the feasibility and economic aspects of solar power generation, as seen in studies by Jiang et al. (2020), Chen et al. (2018), and Zhang (2015). Research indicates that Hunan's climate, particularly in areas like the Dongting Lake District, northern Hengyang, and southern Yongzhou, is highly suitable for photovoltaic power generation, with promising development trends. Additionally, less developed areas in southeast Hunan, including Yanling, Guidong, Rucheng, Chaling, and Zixing, show significant potential for future photovoltaic growth. Improvements in atmospheric conditions since the 1980s have expanded suitable areas for solar energy development, enhancing the province's photovoltaic climate. To capitalize on this potential, it is crucial to transform development modes, drive industrial growth, and align energy structures with national policies. Recommended strategies include simplifying examination and approval processes and providing electricity price subsidies, such as a 0.2 yuan per kWh subsidy for distributed photovoltaic projects over ten years. This approach will ensure policy sustainability and accelerate the photovoltaic industry in Hunan Province, especially given the stability of photovoltaic module prices and external market conditions. Thus, this article explores the impact of solar power generation policies on Hunan's power industry and offers key policy recommendations to promote sustainable development in the region.

Hunan province has numerous policies supporting solar power generation. This article primarily discusses the following three policies:

During the 13th Five-Year Plan period (2016–2020), "the Solar Development Plan for Hunan Province" aimed to achieve a total installed capacity of 2GW for solar power generation by the year 2020. The plan boosted distributed solar power generation, customized centralized projects to local conditions, and advanced the implementation of distributed solar on standard factory rooftops.

Moving to "the 14th Five-Year Plan (2021–2025) for Renewable Energy Development in Hunan Province", the installed capacity of solar power generation is to reach 13 GW by 2025. It additionally mentions that by the end of 2020, the installed capacity of solar power generation in Hunan province was projected to reach 3.91GW. The plan promotes large-scale development of solar power generation and establishes a national wind and solar power base projects.

Looking ahead to "the Hunan Province Electric Power Support Capability Enhancement Action Plan (2022–2025)", the goal is to achieve an installed capacity of over 25 GW for wind power and solar power generation by 2025, exceeding 40 GW by 2030. The plan actively explores the "PV (photovoltaic) +" model, tailoring construction of centralized solar facilities such as forest-solar complementary systems, aquaculture-solar complementary systems, and agriculture-solar complementary systems based on local conditions. The plan also supports on-site and nearby development and utilization of distributed PV, accelerating pilot projects in 12 counties (cities, districts) incorporated into the national pilot for whole-county rooftop distributed PV.

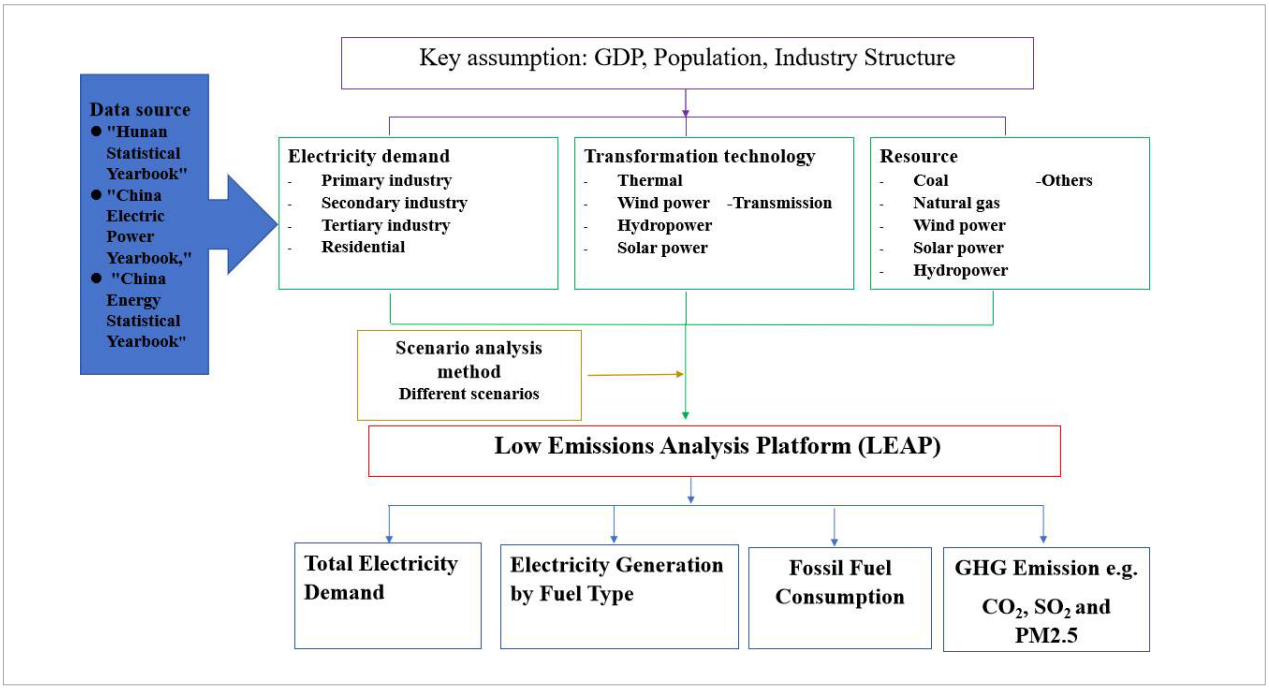
Methods

Low Emissions Analysis Platform (LEAP) model

To assess the implication of the stated policy on solar energy generation in Hunan province, this study employs the Low Emissions Analysis Platform (LEAP) model for analysis. The LEAP model has been widely employed in various policy simulations and technological transformation analyses across sectors of the national economy, such as steel, transportation, and electricity. For example, Wang et al. (2017) analyzed energy consumption in Hunan province. Huang (2012) conducted a scenario analysis of China's electricity demand for the next forty years. Wattana and Aungyut (2022) analyzed the impacts of solar electricity generation on the Thai electricity industry. Wu and Zu (2015) studied carbon reduction policy scenarios in the electric power industry.

This study established a LEAP model for power generation forecasting in Hunan province, as shown in *Fig.1*. The modules predominantly comprise four components: key assumption, demand, transformation and resource. The key assumption is principally dedicated to GDP (gross domestic product), population, and industrial structure. Considering the industrial composition of Hunan province, energy demand is categorized into primary industry (agriculture), secondary industry (industrial sector), tertiary industry (service sector), and residential sectors. Transformation technology primarily encompasses factors such as line loss rate, thermal power generation, wind power generation, hydropower generation, solar power generation, and supercritical technology. Among these, Hunan province exclusively relies on coal and natural gas for thermal power generation. Ultimately, under different scenarios, the study primarily considers outcomes such as electricity generation by fuel type, greenhouse gas (GHG) emissions, and so forth.

Fig. 1. *LEAP Model for solar power generation forecasting in Hunan province*



Data considerations

In the LEAP model, because of the delay in data updates, 2021 is the base year, and 2022 is the start of simulations. Although the current policy framework for solar power generation is outlined only until 2030, the rapid advancement of solar power technology suggests a significant growth trajectory in the future. Therefore, 2035 is chosen as the endpoint. According to the historical data of sourced from "The Hunan Statistical Yearbook 2017-2021 (Hunan PBS, 2021)", with the industrial structure undergoing adjustments, the growth rate of electricity demand in the secondary industry stands at 2.25%, while the growth rates for the primary and tertiary industries are 4.3% and 4.63%, respectively. The line loss rate, process efficiency, maximum availability and installed capacities of fuel types for power generation are available from "The China Electric Power Statistical Yearbook 2017–2021 (CEC, 2018, 2019, 2020, 2021, 2022)," and "The China Energy Statistical Yearbook 2017–2021 (NBS, 2018, 2019, 2020, 2021, 2022)," published by the China Statistical Publishing House. The emission factors for CO_2 and SO_2 are based on IPCC standards. And according to the technical document "Guidelines for Compilation of Emission Inventory of Atmospheric Fine Particulate Matter (PM2.5) Sources (Trial)"(Ministry of Ecology and Environment of China, 2014) issued by the Ministry of

Ecology and Environment of China, the PM2.5 emission factor for raw coal used in power generation is 12 g/kg.

Scenarios development

This article establishes three scenarios in total. The baseline scenario (BAS) is set based on historical trends, while the current policy scenario (CPS) is configured in accordance with the "14th Five-Year Plan for Renewable Energy Development in Hunan Province," and the "Hunan Province Electric Power Support Capability Enhancement Action Plan" policies. Because the actual installed capacity of solar energy in 2020 was almost twice that of the Thirteenth Five-Year Plan for Solar Energy, this paper assumes a future policy scenario (FPS) in which the actual installed capacity far exceeds the target of the Fourteenth Five-Year Plan, reaching 20 GW by 2025, as shown specifically in *Table 1*.

Table 1. *Key features of three scenarios*

Scenario	Scenario features
Baseline scenario (BAS)	• Continue the current development trend and leverage existing power generation technologies. • By the year 2035, the installed solar power capacity would reach 12 GW.
Current policy scenario (CPS)	• By 2025, the installed capacity for solar power generation is projected to reach 13 GW, and this figure is expected to further increase to 27.4 GW by 2035.
Future policy scenario (FPS)	• By 2025, the installed capacity for solar power generation is set to reach 20 GW, with further growth projected to 40 GW by 2035.

Notably, the installed capacity of wind energy in Hunan Province experienced rapid growth during its early stages. However, it transitioned to a phase of steady growth in 2021 and 2022. Consequently, in all three scenarios, the installed capacity of wind power generation for 2025 and 2035 is forecasted based on historical data, as shown in *Table 2*.

According to the principle of a single variable, in both CPS and FPS scenarios, keep the installed capacity of wind power the same as in the baseline scenario. Only adjust the installed capacities of solar power and thermal power based on policy changes. It is important to note that thermal power generation operates with higher efficiency than solar power generation. To ensure consistency in the final power generation across each scenario, the total installed capacity in the FPS scenario is slightly higher than in the CPS scenario, with the CPS scenario exceeding the BAS scenario. Therefore, the proportion of wind power, hydropower, and the installed capacity of input electricity has decreased in both the CPS and FPS scenarios. The specific installed capacity ratios of different fuel types for each scenario are outlined in *Table 3*. Because of the almost complete development of hydroelectric power in Hunan province, this paper assumes that the installed capacity of hydroelectric power remains constant. Consequently, as the total installed capacity increases year by year, the hydro-power's ratio declines from 27% in 2021 to 17% in BAS. Based on historical data, the proportion of installed capacity for wind power generation and imported electricity is expected to continue increasing compared to 2021.Solar power undergoes a significant rise in FPS to 35%, emphasizing its importance in efforts. As a result of the increased proportion of clean energy, thermal power generation has decreased in all scenarios, dropping to 27% in the FPS.

Table 3. *Installed capacity ratios of different fuel type for three scenarios*

Fuel type	2021	2037		
	Base Year	BAS	CPS	FPS
Hydro-power	27%	17%	15%	14%
Thermal	42%	41%	33%	27%
Wind	13%	17%	15%	14%
Solar	8%	13%	26%	35%
Import electricity	10%	12%	11%	10%

Table 2. *The installed capacity of wind power generation*

Year	2017	2018	2019	2020	2021	2022	2025	2035
Capacity (GW)	2.63	3.48	4.27	6.69	8.03	9.00	10.90	15.90

Empirical Results and Discussions

This paper analyzes the changes in the power generation mix, fossil fuel consumption, and emissions of CO_2, SO_2 and PM2.5 in Hunan province from 2021 to 2035 under various solar energy policy scenarios.

Diversification of electricity generation

In the BAS, CPS, and FPS scenarios, the power generation mix in Hunan province from 2021 to 2035 is illustrated in *Fig.2*. It is evident from the figure that, across all three scenarios, the electricity production in Hunan province is projected to increase from 174 TWh in 2021 to 253 TWh by 2035. According to the BAS, CPS, and FPS scenarios, the electricity generation from natural gas is expected to increase from 1.3 TWh to 2.4, 2.1, and 2.0 TWh. Similarly, coal-based electricity generation is anticipated to rise from 85.5 TWh to 156.8, 141.1, and 128.1 TWh in the BAS, CPS, and FPS scenarios, respectively. The fluctuations in coal and natural gas-based power generation are primarily influenced by the changes in solar power generation. Notably, in the year 2035, in the three scenarios, the electricity generation from wind power remains at 32.4 TWh. However, the BAS scenario forecasts solar power generation at 12.5 TWh. In the CPS and FPS scenarios, there is a relative decrease in coal and natural gas-based power generation, accompanied by a significant increase in solar power generation, reaching 28.4 TWh and 41.5 TWh. This represents 2–3 times the BAS scenario at 2035 and approximately a tenfold increase compared to 2021.

Fig. 2. *Electricity generation by fuel type*

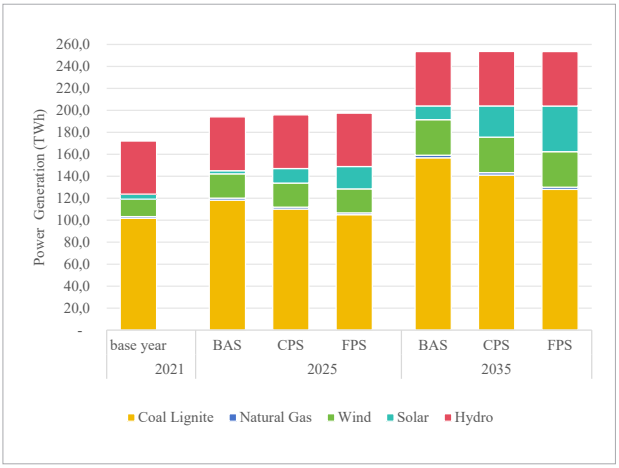


Table 4. *Electricity generation share for fuel type*

Fuel type	2021	2037		
	Base Year	BAS	CPS	FPS
Natural Gas	0.9%	0.9%	0.8%	0.8%
Coal Lignite	59.1%	61.5%	55.6%	50.5%
Wind	9.3%	12.7%	12.7%	12.7%
Solar	2.7%	5.4%	11.2%	16.5%
Hydro	28%	19.5%	19.5%	19.5%

Based on the percentage share of electricity generation for each fuel type in *Table 4*, notable observations can be made when comparing with the BAS scenario. In the CPS and FPS scenarios, the share of coal lignite in electricity generation decreases by 5.9% and 10%. This shift is attributed to Hunan province's historical reliance on coal and hydroelectric power generation. In recent years, the development of hydropower has been nearly exhausted, leading to a continuous decline in its proportion of the total electricity generation. During the "13th Five-Year Plan" period (2015–2020), the Hunan provincial government vigorously promoted wind and solar power generation, resulting in an increasing total electricity generation while the proportion of thermal power generation remained at around 57% (CEC, 2021). During the "14th Five-Year Plan" period (2021–2025), the government continues to actively promote the development of renewable energy, particularly solar power. In the CPS scenario, the share of solar power generation is projected to increase from 2.7% in 2021 to 11.2%. In the FPS scenario, assuming the over achievement of solar power generation capacity targets by 2035, the share of solar power generation may even reach 16.5%. This underscores the ongoing transition of Hunan province's energy structure towards a cleaner and diversified direction.

Fossil fuel consumption

Under different scenarios (BAS, CPS, FPS), Hunan province exhibits varying trends in fossil fuel consumption from 2021 to 2035, as presented in *Table 5*. In the BAS scenario, the consumption of fossil fuels significantly increases from 8,882.9 thousand tonnes of oil equivalent (KTOE) in 2021 to 13,687.4 KTOE in 2035. In 2025, compared to the BAS scenario, the CPS and FPS scenarios witness reductions of 4.6% and 9% in fossil fuel consumption. By 2035, the CPS and FPS scenarios exhibit reductions of 10% and 18.3%, respectively.

Table 5. *Fossil fuels consumption for electricity generation*

Year	BAS (KTOE)	CPS	FPS
2021	8,882.9		
2025	10,079.9	(-4.6%)	(-9%)
2035	13,687.4	(-10%)	(-18.3%)

Notes: The number in brackets indicates the changes in fossil fuels consumption from the BAS scenario.

Fig. 3. *The fossil fuel consumption by fuel types (KTOE) in 2035*

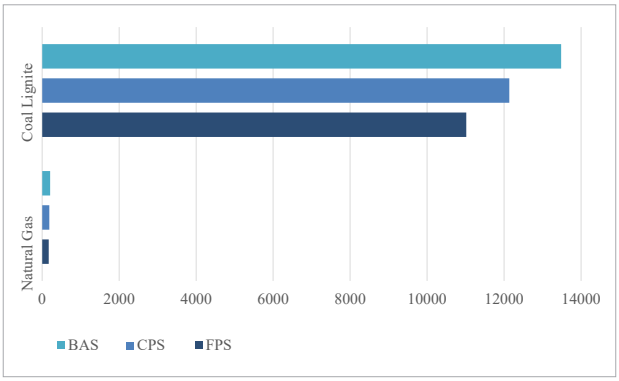


Fig.3 provides the fossil fuel consumption by fuel types in 2035 for the CPS and FPS scenarios relative to the BAS scenario. Overall, fossil fuel consumption for power generation in Hunan province is predominantly coal-based, constituting approximately 99%. In the BAS scenario, the coal consumption for power generation in 2035 is projected to be 13,482.1 KTOE. In the CPS and FPS scenarios, the projected fossil fuel consumption in 2037 is 12,134.6 KTOE and 11,014.8 KTOE, respectively, indicating reductions of 1,347.5 KTOE and 2467.3 KTOE compared to the BAS scenario. However, Hunan province heavily relies on importing coal from other provinces. According to statistics (NBS, 2022), the total coal consumption in Hunan province in 2021 amounted to 94,051.3 thousand tonnes, while its domestic production was only 7,267.7 thousand tonnes. Over 90% of the coal is sourced through imports from other provinces. With a decrease in demand for coal lignite, this is expected to contribute to a reduction in the dependence on imported fossil fuels for electricity generation. Therefore, the increase in solar energy generation would reduce reliance on coal, enhance energy security, and foster a more sustainable development of energy resources.

CO_2 emissions

From the perspective of CO_2 emissions, *Table 6* illustrates the trend of CO_2 emissions in different scenarios (BAS, CPS, FPS) in Hunan province. Compared to the 83.5 million tonnes in 2021, it is projected that by 2025, CO_2 emissions under the BAS scenario would increase to 94.8 million tonnes, while under the CPS and FPS scenarios, they would be 90.5 and 61.7 million tonnes. By 2035, the expected CO_2 emissions in the BAS, CPS, and FPS scenarios would reach 128.7, 105.1, and 104.9 million tonnes. Overall, CO_2 emissions show a decreasing trend in different scenarios, especially in the CPS and FPS scenarios. Compared to the BAS scenario, in 2035, CO_2 emissions under the CPS and FPS scenarios are reduced by 10% and 18.3%, respectively. This is due to the increased efficiency of solar power generation, leading to a reduced utilization of fossil fuels. This would contribute to the improvement of air quality in Hunan province and facilitate sustainable development.

Table 6. *CO_2 emissions from electricity production over the period 2021–2035*

Year	BAS (million tonnes)	CPS (million tonnes)	FPS (million tonnes)
2021	83.5		
2025	94.8	(–4.3)	(–8.5)
2035	128.7	(–12.9)	(–23.6)

Notes: The number in brackets indicates the changes in CO_2 emissions from the BAS scenario.

SO_2 emissions

Table 7 illustrates the variations in SO_2 emissions in Hunan province from 2021 to 2035 under different scenarios. In the BAS scenario, SO_2 emissions in Hunan province were 789.9 thousand tonnes in 2021 and are projected to increase to 1217.1 thousand tonnes by 2035. Under the CPS and FPS scenarios, compared to the BAS scenario, by 2035, there are respective decrease of 121.1 thousand tonnes (10%), and 227.7 thousand tonnes (18.3%). It is noteworthy that the reduction ratio of SO_2 is consistent with that of CO_2. This is attributed to the fact that the fossil energy consumption for electricity generation in Hunan province is predominantly from coal. Moreover, reducing SO_2 emissions would contribute to protecting ecosystems,

maintaining respiratory system health, preventing acid rain formation, and more.

Table 7. *SO_2 emissions from electricity production over the period 2021–2035*

Year	BAS (thousand tonnes)	CPS (thousand tonnes)	FPS (thousand tonnes)
2021	789.9		
2025	896.3	(–41)	(–80.7)
2035	1,217.1	(–121.1)	(–227.7)

Notes: The number in brackets indicates the changes in S02 emissions from the BAS scenario.

PM2.5 emission

The changes in PM2.5 emissions in Hunan province under different scenarios from 2021 to 2035 are depicted in *Table 8*. Similarly, the variations in PM2.5 in the other scenarios compared to BAS are consistent with those of CO_2 and SO_2. Within the BAS scenario, PM2.5 emissions amounted to 1450 tonnes in 2021, with projections indicating an increase to 2,311.2 tonnes by 2035. In the CPS and FPS scenarios, the emissions are estimated to decrease by 230.9 tonnes and decrease by 940.1 tonnes, respectively, compared to the BAS scenario by 2035. Particularly, the reduction in the FPS scenario is most significant. The decrease in PM2.5 emissions would contribute to reducing haze occurrence and improving air quality in Hunan province.

Table 8. *PM2.5 emissions from electricity production over the period 2021–2035*

Year	BAS (thousand tonnes)	CPS (thousand tonnes)	FPS (thousand tonnes)
2021	789.9		
2025	896.3	(–41)	(–80.7)
2035	1,217.1	(–121.1)	(–227.7)

Notes: The number in brackets indicates the changes in PM2.5 emissions from the BAS scenario.

Policy implications

Through the analysis above, it is evident that integrating solar energy as a clean energy source not only reduces reliance on finite fossil fuels but also mitigates environmental issues. Moving forward, this paper would propose some policy recommendations to address obstacles in the development of solar energy in Hunan province, aiming to propel the province towards a cleaner and more sustainable energy future.

Due to the numerous benefits of solar power generation, the Chinese government has been actively promoting the development of the PV industry and has introduced a series of policies and measures to support and encourage the construction of PV projects. For example, the government provides tax incentives, subsidies, and reduces land use costs for PV projects. Nonetheless, the investment required for centralized PV power plants is quite substantial, while government subsidies are progressively diminishing (Zhang, 2020). Moreover, investors must take into account the durability of power stations, as they are exposed to outdoor conditions throughout the year. Consequently, in recent years, the government of Hunan province has increasingly favored the promotion of distributed photovoltaic power generation. In rural areas, proactive efforts are underway to establish PV poverty alleviation stations and advocate for "household PV + energy storage" systems to support farmers' self-sufficiency. Surplus electricity is seamlessly integrated into the grid. Additionally, farmers are encouraged to install rooftop PV systems and integrate PVs with fisheries (Hunan PDRC, 2023).

However, the comprehensive promotion of PV power generation in Hunan province still faces significant challenges. Initially, the annual solar radiation across each county (city) in Hunan province displays an east-west spatial distribution pattern, showcasing higher levels in the east and lower levels in the west (Du et al., 2015). Owing to seasonal fluctuations and regional discrepancies, the distribution of solar energy resources within Hunan province is notably uneven, exerting a discernible influence on solar power generation development. Furthermore, the insufficient capacity for grid regulation has become one of the primary obstacles hindering the development of distributed PV power generation. Renewable energy generation itself has intermittency and instability, which presents significant challenges for the grid in managing load fluctuations. To ensure grid stability, effective peak shaving measures are needed to balance electricity supply and demand. Distributed PV systems typically participate in power dispatching with a "self-use and surplus electricity to the grid" approach. While this unstable power supply is

comparatively modest, its continuous injection into the "main power grid" would exert considerable pressure on the seamless operation of the system, consequently impacting the stability of local voltage within the distribution network and the grid frequency. In addition, in 2022, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) released the "Guidance on Accelerating the Construction of a National Unified Electricity Market System" (NDRC and NEA, 2022). It proposed that by 2030, the country would essentially establish a unified power market system, with full participation of new energy sources in market transactions. However, due to the inherent drawbacks of randomness, intermittency, and volatility in solar power generation, the operation and balance of the power grid become more complex. After entering the power market transaction stage, these deficiencies would all be converted into operating costs, posing significant challenges to the development of solar power generation in Hunan province. Finally, the widespread promotion of distributed PV power generation in recent years has led to various irregularities. Public reports (Huaxia Energy Network, 2023) indicated that certain industrial and commercial PV power stations adopted the strategy of 'breaking them into parts,' masquerading as individual household solar projects, thereby seizing distribution network access resources. Such PV projects were more dispersed and exhibited greater uncertainty, further impacting the stability of the power grid.

In light of the aforementioned issues, this paper proposes the following policy recommendations:

- Significantly Increasing the Proportion of Solar Power Generation: On July 29, 2022, the Hunan Provincial Development and Reform Commission issued the "Reply on Approving the Development and Construction of the First Batch of Concentrated Photovoltaic Power Generation Projects for the 14th Five-Year Plan,"which announced the first batch of 236 concentrated photovoltaic projects with a total installed capacity of 24.49 GW (Hunan PDRC, 2022c). To further increase the proportion of solar power generation, based on the analysis in this article, it is recommended to set a target of achieving an installed solar capacity of 40 GW by 2035. In this process, priority should be given to adding at least 40 new concentrated photovoltaic power generation projects annually in regions with abundant sunlight, such as Changde and Hengyang. Additionally, it is encouraged to install rooftop photovoltaic systems on industrial factories, commercial buildings, municipal facilities, and other public buildings. In line with the requirements of the Hunan Provincial Development and Reform Commission (Hunan PDRC, 2021), this article recommends that the proportion of photovoltaic power installations on government building roofs should reach 50% or more; on roofs of schools, hospitals, and village committees, it should reach 40% or more; and on roofs of industrial and commercial factories, it should reach 30% or more. Additionally, the proportion of rooftop photovoltaic power generation for rural residents should be increased from 20% to 30% or higher.
- Addressing key technical issues with the utilization of innovative technologies: Accelerate the construction of "virtual power plants" to enhance the stability and balance of the power grid, preparing for the marketization of new energy generation. At present, solely hydroelectric stations within Hunan province have been linked to "virtual power plants" (Liu, 2022). Given the swift progression of solar power generation, this article advocates for the swift aggregation of distributed power sources, controllable loads, and energy storage equipment across diverse locations, enabling hierarchical management. Unified dispatching facilitated by digital technologies facilitates the exchange of power grid data. On the other hand, employing advanced technologies is also crucial in the process of solar power generation. For instance, currently, the efficiency of solar power generation is 15-20%. Adopting concentrated solar cell technology can elevate solar energy conversion efficiency to 42.8% (Guo et al., 2023).
- Strengthen regulatory oversight: Based on the PV power generation consumption responsibilities assigned by the national government to Hunan province, the construction plans of photovoltaic projects would undergo approval and filing after evaluating their impact on the distribution network in various regions. To ensure uniformity, the development process and relevant standards would be standardized through online publication of the review and filing procedures. Furthermore, unauthorized PV power generation initiatives should be halted, accompanied by appropriate penalties. Rigorous scrutiny of the qualifications of companies involved in the photovoltaic business would be conducted, along with supervision of the transaction process.
- Refine the financial subsidy strategy: Prior to 2030, systematically decrease electricity price subsidies for

solar power generation to expedite adaptation to market regulations. Concurrently, amplify subsidies for solar power station installation and maintenance, as well as energy storage system installation, fostering continued advancement.

These policy recommendations aim to address the challenges faced by the comprehensive development of PV power generation in Hunan province and foster a more sustainable and efficient energy future.

Conclusions

In summary, this paper analyzed the impact of solar power generation on the electricity generation mix, fossil energy consumption, and emissions of CO_2, SO_2, and PM2.5 in Hunan province from 2021 to 2035 under different policy scenarios. The results indicate that solar energy, as a clean and renewable energy source, plays a crucial role in diversifying the energy mix, reducing dependence on traditional energy sources, and mitigating environmental issues.

However, the comprehensive promotion of solar power in Hunan faces significant challenges, including uneven distribution of solar resources, inadequate regulation, and insufficient grid adjustment capabilities, which constrain its development. Taking into account these challenges and opportunities, the paper proposes a comprehensive set of policy recommendations. These include reforms in regulatory frameworks, enhancement of grid infrastructure, and adjusted financial incentives. These policy suggestions aim to create a more sustainable and efficient energy landscape in Hunan province, ensuring that solar energy plays a central role in steering the province towards a cleaner and more diversified energy future.

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