A Study on the Impact of Policies on the Development of Solar Energy Generation in Hunan Province of China

Yao Xiao

A Thesis Submitted in Partial Fulfillment of Requirements for

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January 2025

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ABSTRACT

Hunan province is heavily reliant on thermal power generation, with a significant dependency on imported energy. In recent years, the province has made considerable progress in developing solar energy, driven by supportive policies aimed at reducing reliance on fossil fuels and achieving carbon neutrality. The government has implemented various measures to boost solar power capacity, including financial incentives, infrastructure development, and regulatory support. This study utilizes the LEAP (Low Emissions Analysis Platform) model to analyze the development of solar power in Hunan province, examining the impacts of solar power and carbon neutrality policies on the power generation structure and environmental outcomes. The results demonstrate that increasing the share of renewable energy will transform Hunan's electricity generation mix, with solar power gradually replacing fossil fuels. This transition will significantly reduce the consumption of fossil fuels and lead to substantial reductions in CO_2, SO_2, and PM2.5 emissions. The study identifies several key challenges in the solar energy sector, such as high development costs, limited peak-shaving capacity, and the complexities of grid integration. To support the development of solar energy, the study suggests policy recommendations including strategic planning to better utilize local resources, the integration of wind, solar, and energy storage systems for grid stability, and the implementation of smart grid technologies to optimize efficiency and reduce waste. Furthermore, the study advocates for the acceleration of green electricity marketization and the establishment of efficient trading mechanisms to promote renewable energy adoption. This research offers valuable insights into the ongoing efforts to transform Hunan's energy sector and provides recommendations for overcoming the barriers to solar energy development, which will contribute to the province’s goal of achieving carbon neutrality while ensuring energy security and sustainability.

Keyword : Thermal Power Generation, Carbon Neutrality, Renewable Energy, LEAP Model, Fossil Fuel Reduction

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Chapter1 Introduction

As the global demand for clean energy becomes increasingly urgent, solar power, as an environmentally friendly and renewable energy form, is gradually emerging as a significant solution to address energy security and climate change issues. In China, Hunan province, characterized by rapid economic and energy development, also confronts the challenge of striking a balance between sustainable energy supply and environmental protection. Policies play a pivotal role in shaping the direction of energy development, fostering technological innovation, and promoting the utilization of renewable energy. Within this context, gaining an in-depth understanding of the impact of policies on the solar power generation industry in Hunan province is not only essential for grasping its current developmental status but also for envisioning potential trajectories for the future.

1.1 Background

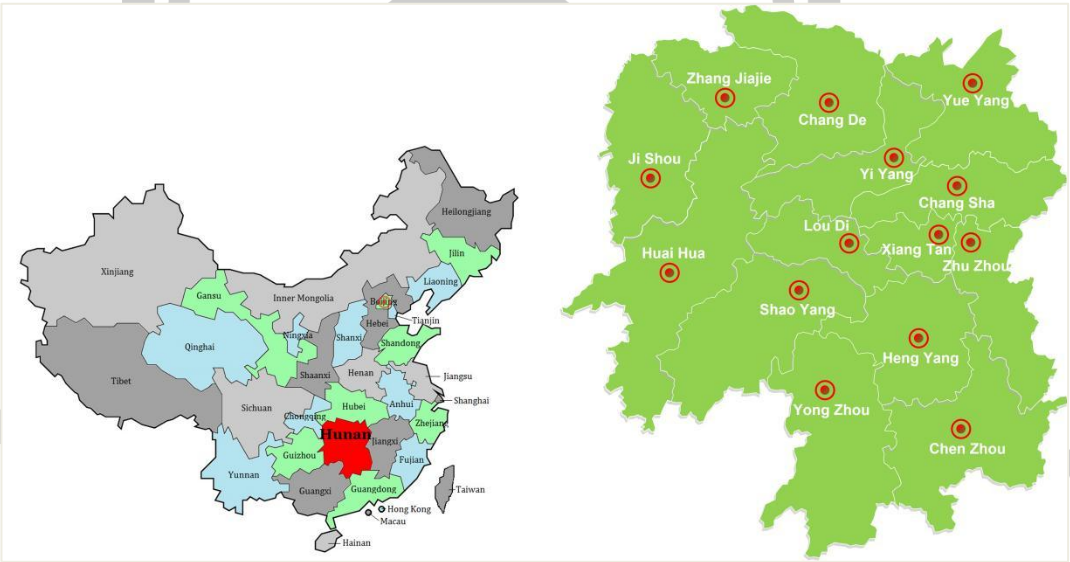


Figure 1. The map of Hunan province [1]

Hunan province is located in central China, with its capital situated in Changsha. It is positioned between 108°47' to 114°15' east longitude and 24°38' to 30°08' north latitude [1] . Its maximum east-west distance is 667 kilometers, while the longest north-south distance is 774 kilometers. Covering a total area of 211,800 square kilometers, it accounts for 2.2% of the national land area, ranking 10th among all provinces, autonomous regions, and municipalities and 1st in central China. The province administers 14 prefecture-level cities and 122 counties (cities, districts), as shown in figure 1.

Hunan is a populous province in China, with a permanent resident population of 66.22 million by the end of 2021. The rate of urbanization has been increasing year by year, reaching 59.71% in 2021 [2]. Simultaneously, the province is experiencing a deepening aging population trend, with people aged 60 and above accounting for 18.5% of the total.

As the largest province in central China, both in terms of population and economy, Hunan leads other provinces and cities in central China. The annual per capita disposable income of residents in the entire province was 31,993 yuan in 2021, an increase of 8.9% compared to the previous year [2].

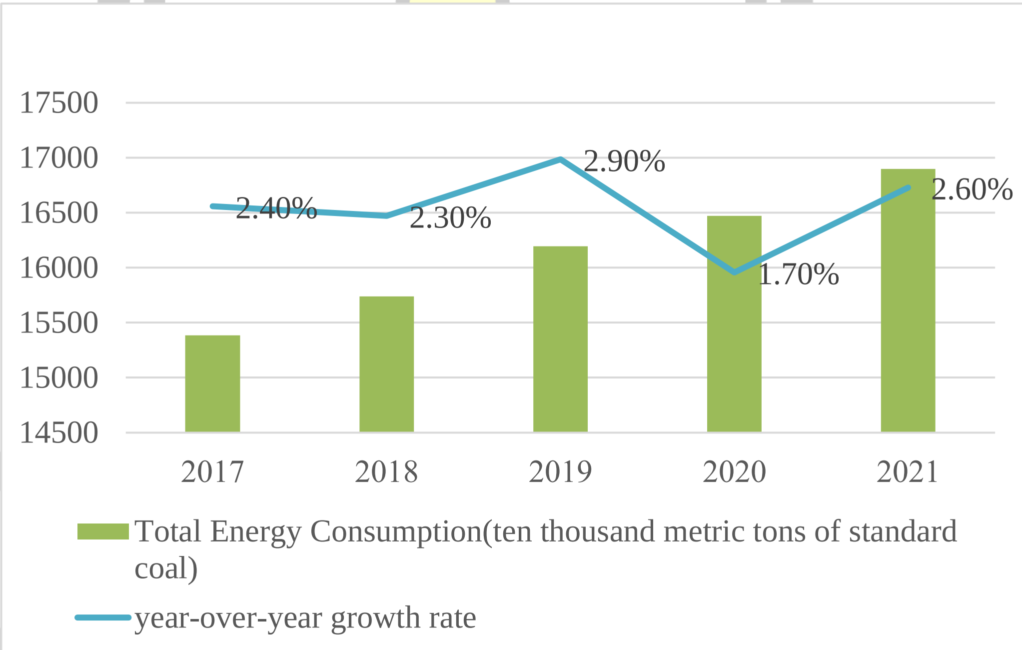


Figure 2. Total energy consumption in Hunan province from 2017 to 2021

With a large population, economic growth leads to substantial energy consumption. Figure 2 depicts the total energy consumption in Hunan Province from 2017 to 2021. As shown in Figure 2, the energy consumption in Hunan Province has been increasing over time, with the total energy consumption reaching around 167 million metric tons of standard coal in 2021, indicating a year-on-year growth rate of 2.6%.

With substantial resource consumption, its energy consumption structure for electricity is depicted in 2022 [1],as shown in Figure 3. The graph illustrates that the energy consumption for electricity generation in Hunan province is primarily sourced from coal, oil, natural gas, and wind， solar, and hydro-power etc. It's important to highlight that Hunan province's energy consumption is not entirely self-sustaining, as 9% of its energy needs are imported from other provinces. Furthermore, the consumption of fossil fuels is alarmingly high, accounting for as much as 53% of the total energy consumption. And the consumption of solar energy accounts for only 8%.

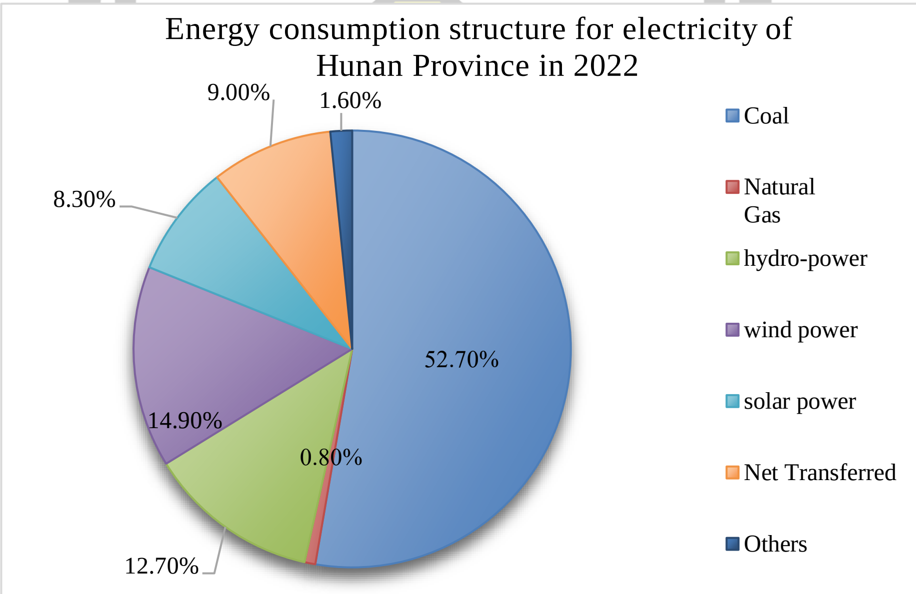


Figure 3. The energy consumption structure of Hunan province in 2022

Traditional fossil fuel energy sources have resulted in environmental and climate challenges, including haze and smog, climate change, coal mine accidents and so on. Therefore, shifting towards renewable energy sources such as solar power has become a crucial aspect of the national policy, aimed at reducing carbon emissions and environmental pollution.

Actually，Hunan province is rich in solar power resources. From a national perspective, China possesses abundant solar energy resources. China has a total land area of 9.6 million square kilometers, accounting for 7% of the world's total land area[3]. The total annual radiation ranges from 365-2,922kWh/m^2. In over two-thirds of the country's total area, the annual sunshine hours exceed 2,000 hours. The theoretical total solar energy potential is 147 × 108 gigawatt-hours per year. The distribution of China's solar energy resources is shown in Figure 4.

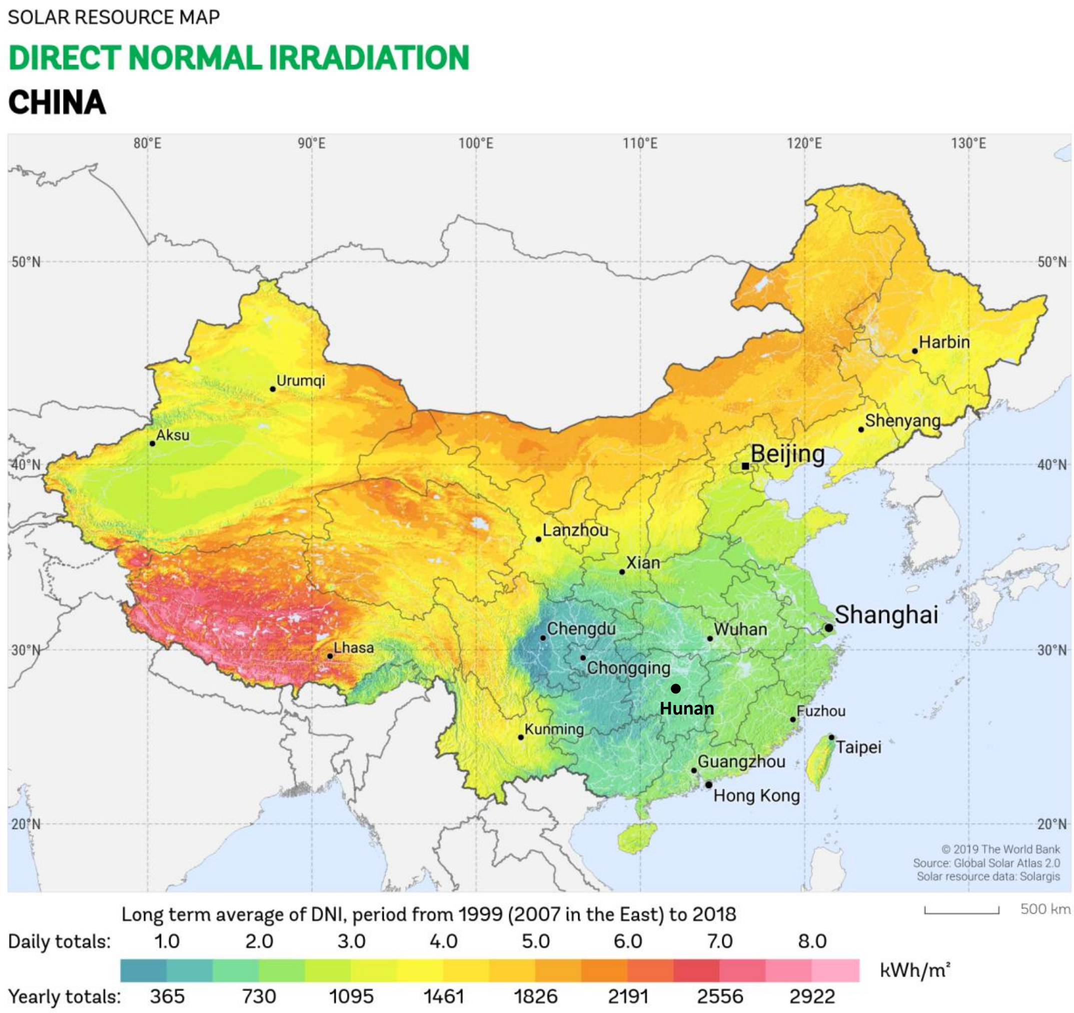


Figure 4. Solar energy resource distribution map of China [4]

According to the meteorological industry standard QX/T89-2008 "Method for Solar Resource Assessment," the classification of solar resource abundance levels is shown in Table 1 [3].

Table 1. Level of solar energy resource

Total Solar Radiation	Abundance Level of Resources	Resource Code
≥1750kWh/m^2	The most abundant resources	I
1400-1750kWh/m^2	Richer in resources	II
1050-1400kWh/ m^2	Rich in resources	III
<1050kWh/m^2	General	IV

Although from a nationwide perspective, solar energy resources in Hunan Province fall under Class III regions, when considering Hunan Province in isolation, just as mentioned in the "13th Five-Year Solar Development Plan for Hunan Province,"[5]meteorological observation data indicates that Hunan Province has abundant heat, strong radiation, and higher temperatures, with an annual average temperature ranging from 16°C to 18°C and annual sunshine hours between 1300h and 1800h. The Provincial Meteorological Bureau, utilizing historical meteorological data and solar radiation observation data, and based on the calculation methods outlined in the "Method for Solar Resource Assessment," has computed and depicted the distribution of annual (1981-2010), total solar radiation in Hunan Province, as shown in Figure 5. The annual total solar radiation in various counties (cities) of Hunan Province has an average range of 940-1,214kWh/ m^2 over many years showing an east-to-west spatial distribution pattern with higher values in the east and lower values in the west. Among them, the Dongting Lake area（including cities such as Yueyang, Changsha, Changde, Yiyang, and Zhuzhou, within Hunan province） is the most abundant region in terms of total solar radiation resources in the entire province.

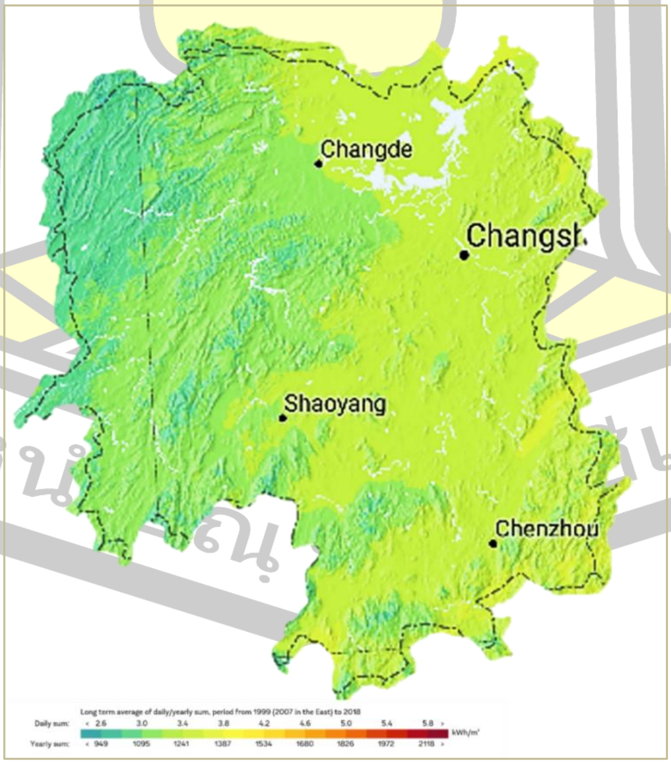


Figure 5. Solar annual total radiation distribution map of Hunan province [5]

The pivotal role of policies in energy development, particularly their impact in the field of solar energy generation. The Chinese government has consistently been promoting the development of renewable energy, particularly solar power generation. In 2005, China enacted the "Renewable Energy Law," [6] which explicitly designates solar power generation as a form of renewable energy. This law provides a legal framework for solar power projects, stipulating preferential policies and regulations related to grid access and other aspects. Moreover, China began implementing a fixed subsidy policy for solar photovoltaic (PV) projects in 2013 [7], providing subsidies based on factors such as project type, scale, and geographic location. Solar power generation projects can enjoy a certain proportion of electricity purchase subsidies, where the government provides fixed subsidy amount for solar power generation enterprises for electricity purchases, in order to reduce the operational costs of businesses. The government has launched photovoltaic poverty alleviation projects, integrating solar power generation with poverty-stricken areas to help improve local residents' income and living standards. For instance, this involves constructing photovoltaic power stations in impoverished regions, installing distributed photovoltaic power equipment in households, schools, hospitals, and other local facilities, establishing photovoltaic poverty alleviation bases, and creating demonstration villages. The government has established solar energy demonstration cities and pilot projects in certain regions, such as the Deyang Solar Energy Demonstration City, Wuxi Solar Energy Demonstration City, and Qinghai Yushu Photovoltaic Industry Park, aiming to promote innovation and dissemination of solar energy technologies. It is under the guidance of policies that China's solar energy technology continues to advance, its installed capacity keeps rising, and it maintains its leading position globally.

Hunan province, as one of the regions implementing national energy policies, actively responds to these policies and has introduced a series of measures to support the development of the solar energy industry. Hunan Province has successively introduced policy documents such as the "Implementation Opinions on Promoting the Development of Distributed Photovoltaic Power Generation [8]", the "13th Five-Year

Solar Development Plan for Hunan Province [5]," and the "14th Five-Year Plan for Renewable Energy Development in Hunan Province [9]," to support solar power generation development. These policy documents have transformed the solar power capacity planning from 4GW in 2030 to 13GW by 2025, with a combined wind and solar capacity of 40GW by 2030. To achieve these objectives, the government has put forward initiatives such as actively exploring the "PV+" model, advancing photovoltaic subsidy policies, and implementing pilot projects for whole-county rooftop distributed PV. This demonstrates that the government of Hunan Province is highly supportive of solar energy generation, and its outlook on the development prospects within the province is very optimistic. Under the impetus of these policies, the installed capacity of solar energy generation in Hunan Province has grown significantly, reaching 3.91GW in 2020.

Because of the significant consumption of fossil fuels in Hunan Province, the abundant availability of solar energy as a clean energy resource is notable. Moreover, Policy-driven initiatives are of paramount importance in propelling the development of solar energy generation. It makes researching development of solar energy in this context highly significant.

1.2 Research objective

Above this background, the primary objectives of this article are to analyze the impact of energy policies on solar power generation, with the aim of providing policy recommendations, reducing fossil fuel consumption, protecting the environment, and promoting the sustainable development of Hunan Province. This involves several specific aspects:

1.To obtain the current state of solar power generation, analyze the potential for solar energy generation, and evaluate the scale of solar power development provide a scientific basis for future project planning and development.

2. To analyze the impact of policies changes in solar power generation, aiming to assess the effects of increasing solar energy installed capacity on the power generation structure, reduction in carbon dioxide emissions, and decrease in fossil fuel usage.

3.To predict the impact of solar power development on Hunan's power generation industry under the carbon neutrality policy background.

4.To provide scientific evidence for government policies related to solar energy generation, promoting the rational development of the solar energy industry, and enhancing the proportion of renewable energy in the energy mix.

1.3 Scope of research

This study is focused on Hunan province. Hunan province is situated in central China and the middle reaches of the Yangtze River. It is named "Hunan" because the majority of its territory lies south of Dongting Lake.

Currently enacted policy plans regarding solar power generation only extend until the year 2030. Moreover, with the advancement of solar energy generation technology, solar power is expected to experience rapid growth in the future. Therefore, this research will make medium-term and long-term predictions. The forecast periods span from 2021 to 2035 and from 2022 to 2060.

1.4 Research significance

This research is essential for guiding Hunan province towards a more sustainable and resilient energy future, aligned with global efforts to address climate change and foster economic growth through solar power. The specific points are as follows:

- ✓ Energy Transition: Solar energy plays a crucial role in the transition towards renewable energy sources. Understanding how policies influence its development can guide the province towards a cleaner and more sustainable energy mix.
- ✓ Climate Commitments: Many regions, including Hunan Province, are committed to reducing carbon emissions to combat climate change. This study can provide insights into how solar energy policies contribute to achieving these commitments.
- ✓ Energy Security: Diversification of the energy mix through solar power can enhance energy security by reducing dependence on fossil fuels, contributing to a more resilient energy system.
- ✓ Environmental Benefits: Solar energy contributes to reduced air pollution and water usage compared to conventional energy sources. Understanding policy

effects helps assess environmental benefits.

- ✓ Policy Optimization: The research can provide recommendations for refining policies to better align with local energy goals, economic priorities, and environmental targets.
- ✓ Planning and Decision-making: Decision-makers can use research findings to make informed choices about policy adjustments and strategic planning for sustainable energy development.

1.5 Thesis organization

This research consists of six chapters. Chapter 2 is the literature review, which encompasses the current status of solar power generation, research progress in analysis of research methods and models for development forecasting, and advancements in analyzing energy demand, carbon dioxide emissions, and solar power generation using the LEAP model. By comparison, it discusses the innovative aspects of this research and identifies the methodological value from the reviewed literature.

Chapter 3 primarily introduces the method framework, establishment of the LEAP model, and data foundation.

Chapter 4 examines the changes in the power generation structure and fossil energy consumption, as well as the environmental impacts, under different solar power installation capacity policies in 2021-2035.

Chapter 5 analyzes the impact of increasing solar power installation capacity on Hunan's power generation industry from 2022 to 2060 under the framework of carbon neutrality policies.

Chapter 6 provides policy recommendations, such as further expanding the scale of solar energy generation, increasing research and development investments, and enhancing solar energy generation technology, among other suggestions. And it concludes the study, summarizing the work done in this research and extracting valuable information to offer recommendations for future research endeavors.

Chapter 2 Literature Review

As a central component of this study, the literature review will provide an in-depth understanding based on existing research and data, laying a solid foundation for the subsequent chapters' predictions and analyses. This chapter will explore the following aspects: Firstly, through comprehensive analysis of existing literature, it will comprehensively discuss the current status, development trends, and policy background of solar power generation in Hunan province. Secondly, we will delve into the existing methods and models for solar power generation forecasting in Hunan province, and through comparative analysis, select appropriate methods and models. Lastly, we will review existing research and application cases, analyzing the strengths and limitations of the LEAP model in the field of solar power generation.

2.1 The current status solar power generation in Hunan province

This section analyzed that the current status of solar power generation in Hunan Province can be approached from multiple perspectives, encompassing aspects such as solar energy resource potential, installed capacity, development trends, and policy support.

2.1.1 Solar energy resource potential

Hunan province boasts abundant solar energy resources, providing a solid foundation for the development of solar power generation. The temperature in Hunan province is relatively high. Especially in summer, which can last for 4-5 months, the highest temperature can reach around 40°C. The annual average temperature rank from around 17 -19°C [2], as shown in Figure 6 (data from "Hunan Statistical Yearbook"). The three cities with the highest average temperatures are Hengyang, Zhuzhou, and Yongzhou in 2019-2020. Among the major cities in Hunan Province, the city with the highest average temperature in the year 2020 was Hengyang, recording 19.5°C. This was 0.6°C higher than the second-place city, Yongzhou, which had an average temperature of 18.9°C. Furthermore, Hengyang's average temperature was 2.6°C higher than the city with the lowest average temperature, Jishou, which had an average temperature of 17.0°C. In addition, it's worth noting that the average temperatures for 8 major cities increased in the year 2020 compared to the previous year.

Situated in the subtropical zone, Human province enjoys ample sunshine, with an annual average of over 1,000 hours of sunlight [10], as shown in Figure 7 (data from "Hunan Statistical Yearbook"). In the year 2020, the top three cities in Hunan province with the highest number of sunshine hours were Xiangtan (1,485.9 hours), Yueyang (1,407.8 hours), and Hengyang (1,402.2 hours), all of which had sunshine hours exceeding 1,400 hours throughout the year. On the other hand, the cities with the least sunshine hours were Jishou, Huaihua, and Zhangjiajie, ranking at the bottom three positions. In 2020, their sunshine hours were 922.3 hours, 977.8 hours, and 993.3 hours, all falling below 1000 hours. This extended duration of sunlight enhances the collection of electric energy, rendering it favorable for solar power generation.

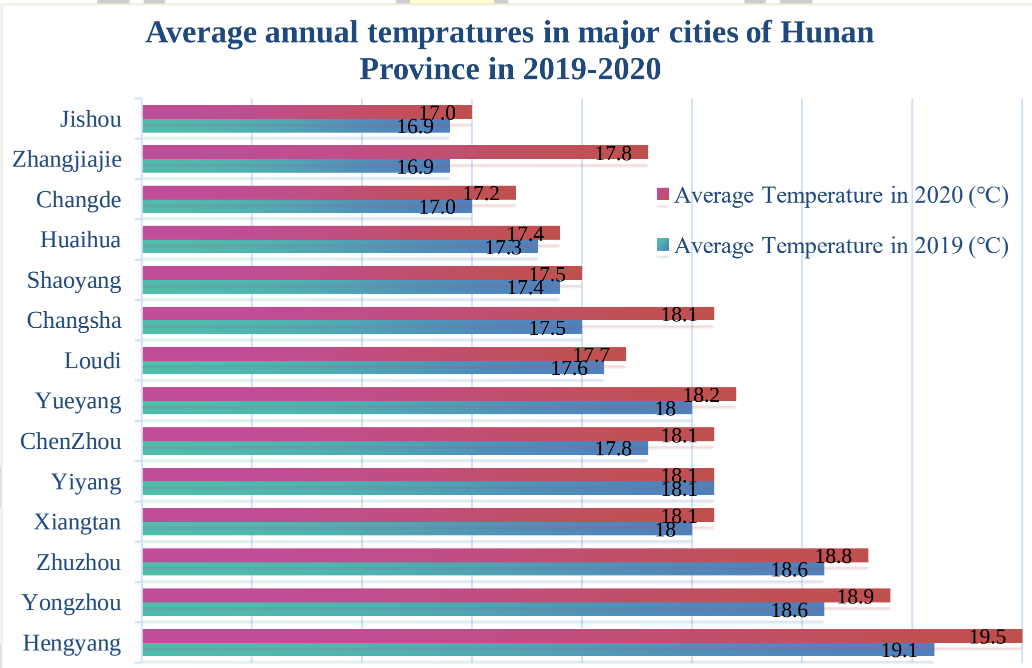


Figure 6. Average annual temperatures in major cities of Hunan Province in 2019-2022

Solar radiation, a pivotal factor in solar power generation, is notably influential in Hunan province. Dongsheng Du and others [11] conducted a study on the spatial and temporal distribution characteristics and assessment of solar energy resources in

Hunan province. This study utilized solar total radiation observation data from three radiation stations in Hunan province, as well as sunshine duration data from 97 ground meteorological stations. Through the study, it was found that the annual average solar total radiation in Hunan province ranges from 3,384.7 to 4,372.0 MJ/(m²·a), exhibiting an east-west spatial distribution pattern with more radiation in the eastern part and less in the western part. In terms of resource abundance, areas such as Dongting Lake and Changsha-Zhuzhou-Xiangtan exhibit rich solar energy resources, while most of the northwestern region of Hunan is categorized as having moderate resources, and other areas are considered to have relatively abundant resources. In terms of the value of resource utilization, a majority of the regions have more than 100 days of usable sunlight, with Dongting Lake area and Changsha-Zhuzhou-Xiangtan having the highest number of usable days. In regard to resource stability, the northern region of central Hunan and the southeastern part of Chenzhou are identified as relatively stable areas for solar resources, while other areas are considered unstable.

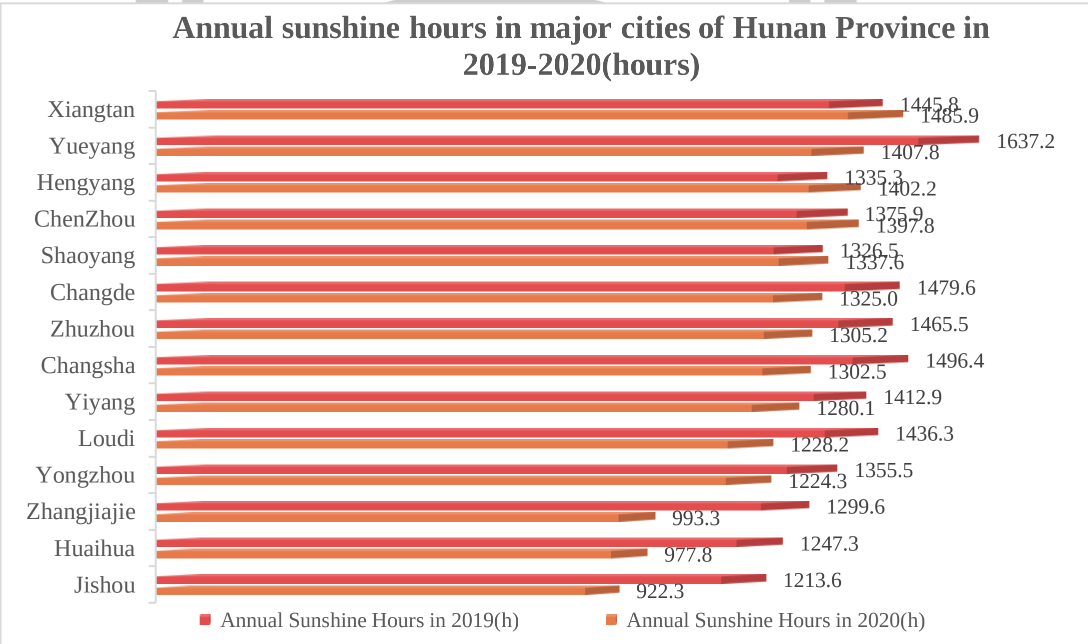


Figure 7. Annual sunshine hours in Major Cities of Hunan Province in 2019 - 2020

Jiang Difei et al. [3] conducted a study on the climatic suitability of photovoltaic power generation in Hunan province. They utilized data from 97 ground meteorological stations in Hunan province from 1985 to 2015, including sunshine percentage, sunshine hours, dusty days, and horizontal solar radiation at three radiation stations, to carry out zoning and evaluation of the climatic suitability for photovoltaic power generation in the province. Based on their research, they found that the total amount and distribution of solar radiation were consistent with the findings of Du Dongsheng et al. The regions that were more climatically suitable for photovoltaic power generation were Dongting Lake area, the northern part of Hengyang, and the southern part of Yongzhou. Furthermore, their results indicated that the climate conditions in the southeastern parts of Hunan (Yanling, Guidong, Rucheng, Chaling, Zixing), which have seen relatively limited development, were excellent. Additionally, they observed a significant decrease in annual dusty days in various counties and cities within the province from the 1980s and 1990s to the 2010s. This decrease was even more pronounced than the reduction in total solar radiation. The atmospheric environmental conditions for photovoltaic power generation have greatly improved as a result. From 1985 to 2015, there was a certain degree of increase in the area of suitable zones, indicating a significant improvement in the climatic conditions for photovoltaic power generation. This change has contributed to the favorable development and utilization of solar energy resources in Hunan province.

Moreover, Hunan province possesses vast rural and mountainous areas, which harbor considerable potential for the construction of distributed solar power stations. Hunan has diverse landform, mainly characterized by mountains and hills. Of the total land area, mountains account for 51.2%, hills for 19.9% [10].These areas hold promise for facilitating the development of decentralized solar energy projects.

Overall, Hunan province's rich solar energy resources, coupled with its advantageous geographic position, robust solar radiation levels, and potential for distributed solar installations in rural and mountainous regions, collectively contribute to its aptitude for fostering solar power generation initiatives.

2.1.2 Classification of Solar Power Generation

Solar power generation can be categorized based on different technologies, applications, and operating principles. It can be categorized into photovoltaic (PV) power generation and solar thermal power generation [12]. Photovoltaic power generation involves the direct conversion of solar energy into electricity using photovoltaic cells and is the most common method of solar power generation. Solar thermal power generation, on the other hand, concentrates sunlight using mirrors or lenses to generate high-temperature heat, which is then converted into electricity using a thermal power generator. As of now, there have been no widespread reports or records of large-scale solar thermal power stations in Hunan Province. Therefore, this article will only discuss photovoltaic power generation. PV generation can be classified into two main categories based on system scale and grid connection: distributed PV generation and centralized PV generation.

- Distributed PV generation: Distributed solar power systems involve installing solar photovoltaic systems at various decentralized locations, often near residential, commercial, industrial facilities, or other points of electricity consumption. These systems are generally smaller in scale and can cater to the energy needs of individual households, businesses, schools, etc. Distributed solar power systems directly inject electricity into local grids, reducing power transmission losses and potentially saving energy costs for users.
- Centralized PV generation: Centralized solar power systems refer to large-scale solar power plants that consolidate a significant number of solar panels in a single location to generate electricity on a larger scale. These power plants are typically located in regions with favorable solar resources, such as deserts or open areas. Centralized solar power plants transmit generated electricity to the grid via transformers and transmission lines, serving a broader range of electricity consumers.

Each of these power generation approaches has its own advantages and suitability for different scenarios. Distributed PV generation contributes to reducing power transmission losses, providing reliable distributed energy sources, and reducing users' electricity expenses. On the other hand, centralized PV generation is suitable for large-scale energy production, offering electricity to a wider range of users and potentially achieving higher energy efficiency under favorable conditions.

2.1.3 Solar power generation technology research progress

Since 2000, significant advancements in solar photovoltaic technology have been achieved in China, encompassing improvements in efficiency, reliability, and pollution control of photovoltaic power systems. PV power generation technology can be specifically divided into three categories. The first category is crystalline silicon solar cell technology, which boasts high photovoltaic conversion efficiency. It has a relatively wide range of applications and features the most mature technology. It has already entered the stage of industrial development. The second category is thin-film solar cell technology, which is developing rapidly, but its photovoltaic conversion efficiency is relatively low. It is currently in the promotion stage. The third category is emerging solar cell technology, which is still in its early stages [12], [13], [14].

1. Crystalline Silicon Solar Cell Technology

Monocrystalline silicon solar cells and polycrystalline silicon solar cells are the main types. According to available information, the photovoltaic conversion efficiency of monocrystalline silicon solar cells is about 17%, with laboratory efficiencies reaching as high as 24.8%. Currently, crystalline silicon solar cells can be mainly divided into monocrystalline silicon solar cells and polycrystalline silicon solar cells. These technologies have a high level of maturity and large industrial scale, making them mainstream products.

The lifespan of monocrystalline silicon solar cells is generally around 15 to 20 years. They have been applied in various architectural spaces and ground structures. In the case of polycrystalline silicon solar cells, their efficiency is comparatively lower than monocrystalline cells. The photovoltaic conversion efficiency of commercially produced polycrystalline silicon cells is around 16%, with laboratory efficiencies reaching as high as 20.4%. These types of crystalline silicon cells have lower application costs but shorter lifespans compared to monocrystalline cells.

2. Thin-Film Solar Cell Technology

Silicon-based thin-film and diversified compound thin-film solar cells are the main types of thin-film cells. This type of cell technology is currently in the trial stage of development, with the efficiency between 10% and 20% and lifespan typically around

10 years and development sector within the solar power industry and a more scattered industrial development scale. However, it offers several advantages. For example, the materials consumption for this type of cell structure is relatively low, leading to lower electricity consumption, lower costs, and lighter weight. This makes it conducive to large-scale production and suitable for power generation in areas with limited solar resources.

3. Concentrated Solar Cell Technology

Concentrated solar cell technology is similar to flat-panel cells, but with various concentration methods employed by operators to significantly increase the solar surface illuminance. This technology moves away from traditional, outdated power generation models. By using advanced optical systems, power generation personnel can achieve the intended power generation effects. While fully harnessing high photovoltaic conversion efficiency, a research institute in Germany has developed a triple-junction gallium arsenide concentrated solar cell structure using this technology, achieving a photovoltaic conversion efficiency of approximately 42.8%.

Table 2 is comparison of photovoltaic power generation technologies. From these comparisons, it can be observed that each photovoltaic power generation technology has its own set of advantages and disadvantages. The crystalline silicon technology offers higher efficiency and a longer lifespan but at a relatively higher cost. Thin-film technology excels in lightweight and cost-effective production but sacrifices some efficiency and lifespan. Concentrated solar cell technology provides significantly increased efficiency but requires complex optical systems and is limited in its applicability. The choice of technology depends on the specific needs and constraints of the intended application.

Furthermore, in terms of generation costs, due to the lack of significant attention from the national power generation regulatory authorities towards this development project, the construction costs of certain photovoltaic power stations have surged to as high as 1.26 to 2.00 yuan per kilowatt-hour (kWh), and for larger projects, the construction costs can only be reduced to 0.81 to 1.5 yuan per kWh [15]. According to relevant data, as of the year 2020, after photovoltaic power generation technology personnel learned operational modes from foreign photovoltaic power generation systems, the entire operational cost had been reduced to 0.61 to 0.81 yuan per kWh. Some research scholars, considering the current system's development trend, have predicted that by the year 2023, the development cost of photovoltaic power generation systems should not exceed 0.6 yuan per kWh.

Table 2. Comparison of Photovoltaic Power Generation Technologies [12], [13], [14]

Technology	Advantage	Disadvantage
Crystalline Silicon Solar Cell	- High efficiency: Efficiently converts solar energy into electricity, between 15% and 20%. - Mature technology: Developed manufacturing processes and techniques. - Long lifespan: Around 15 to 20 years	- Relatively higher cost: Manufacturing cost is relatively high. - Weight and material consumption: Heavier and requires more silicon material, limiting lightweight and thin-film applications.
Thin-Film Solar Cell	- Lightweight: Suitable for light load applications. - Lower cost: Relatively lower manufacturing costs. - Flexibility: Can adapt to curved or irregular surfaces.	- Lower efficiency: Requires a larger area for the same power output, the efficiency between 10% and 20%. - Short lifespan: Typically around 10 years.
Concentrated Solar Cell	- High efficiency: Significantly increases photovoltaic conversion efficiency approximately 42.8%. - Specific applications: Suitable for centralized solar power generation. - Increased power output: Allows greater power output within limited space.	- Complex optical systems: Requires intricate optical systems for light concentration. - Limited applicability: Primarily used in specific contexts such as large-scale solar power plants.

2.1.4 Installed capacity and development trends

Technological progress has led to reduced costs for photovoltaic cells and power systems, thereby expanding the application of photovoltaic technology [16].By the year 2019, China had developed into the world's largest solar photovoltaic market and the largest solar power generation manufacturer [17].

As shown in Figure 8, Jianglong Li and Jiashun Huang [18] summarized the installed capacity of solar energy generation by region in their article "The expansion of China's solar energy: Challenges and policy options." Due to the significant linear decrease in module and cell costs [19], the installation costs of solar power generation have markedly reduced. Solar installed capacity has been increasing year by year. According to their analysis, the solar installed capacity has been increasing year by year. By the end of 2018, it had accounted for approximately 30% of the global cumulative solar installed capacity. Given the relatively minor role of solar energy in China's energy structure at present, and considering the moderately per capita solar capacity, it is anticipated that solar energy in China will continue to experience rapid growth. Furthermore, in another aspect, China's solar power generation model is transitioning from centralized power plants to distributed generation.

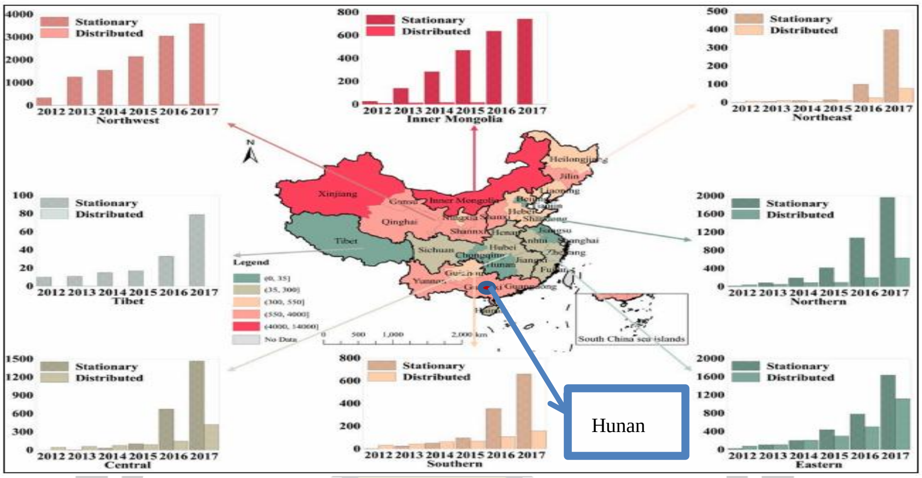


Figure 8. Historic solar capacities in China’s different regions [19]

Furthermore, due to the significant growth in solar photovoltaic (PV) generation capacity, capacity curtailment has hindered the development of China's solar PV industry. The high curtailment rates are attributed to supply-demand imbalances and the lack of transitional grids. Over 70% of China's large-scale solar projects have been installed in resource-rich northern regions. However, the electricity demand in these areas is notably lower than that in the more developed eastern regions of China. Distributed Solar Photovoltaic (DSPV) systems installed in high-demand regions are considered a promising technology for future sustainable energy systems due to their wide applicability, ease of local implementation, relatively lower peak demand, and reduced transmission issues[20]. Therefore, in another aspect, China's solar power generation model is transitioning from centralized power plants to distributed generation. Figure 9 also reveals that the growth of stationary solar installations in the northwest region has shown a decline since 2016. As a result, the solar curtailment rate in the northwest region decreased from 19.8% in 2016 to 14.1% in 2017.

Conversely, following 2015, there has been an accelerated growth of stationary solar generation capacity in the central, southern, and eastern regions. In particular, solar distribution in these regions has substantially increased, primarily during the period of 2015 to 2017. This pattern of change is crucial for the balanced development of solar energy in China, as it enables solar supply to meet the electricity demand within the spatial context.

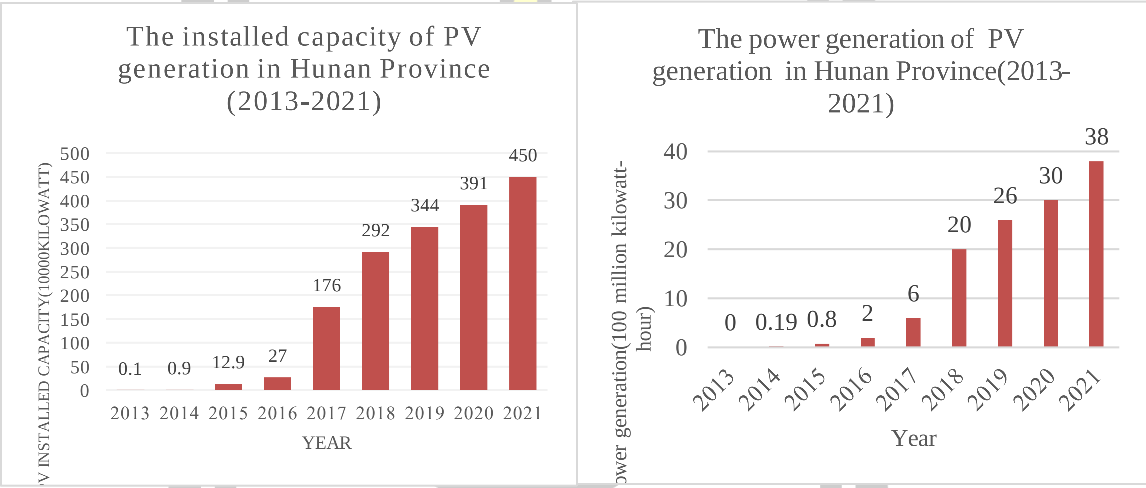


Figure 9. Photovoltaic Installed Capacity and Generation in Hunan Province from 2013 to 2021

From Figure 9, it can also be observed that Hunan province, located in central China, had a relatively late start in the field of solar photovoltaic power generation. Its vigorous development began in 2016.As shown in Figure 9, starting from 2016, the installed capacity of solar photovoltaic power generation in Hunan province began to experience significant growth [21]. In 2017, the solar installed capacity was approximately seven times that of 2016, reaching around 176（10,000 kilowatt）. Centralized solar photovoltaic development in Hunan, particularly in the areas of Yueyang, Changde, Yiyang, Hengyang, and Yongzhou, has shown rapid progress [22]. This signifies the gradual success of solar photovoltaic technology's introduction and application in Hunan Province. Over the subsequent years, the installed capacity exhibited steady growth, reaching 450（10,000 kilowatt） by 2021. This trend highlights the collaborative influence of governmental policy support and market demand in driving its development. With the increase in installed capacity, the solar power generation output in Hunan Province has been consistently rising year by year, reaching 38 (100 million kilowatt-hours) in 2021. This demonstrates that the maturity of technology and improvements in operational efficiency have led to a gradual increase in the contribution of solar photovoltaic power generation within the energy structure.

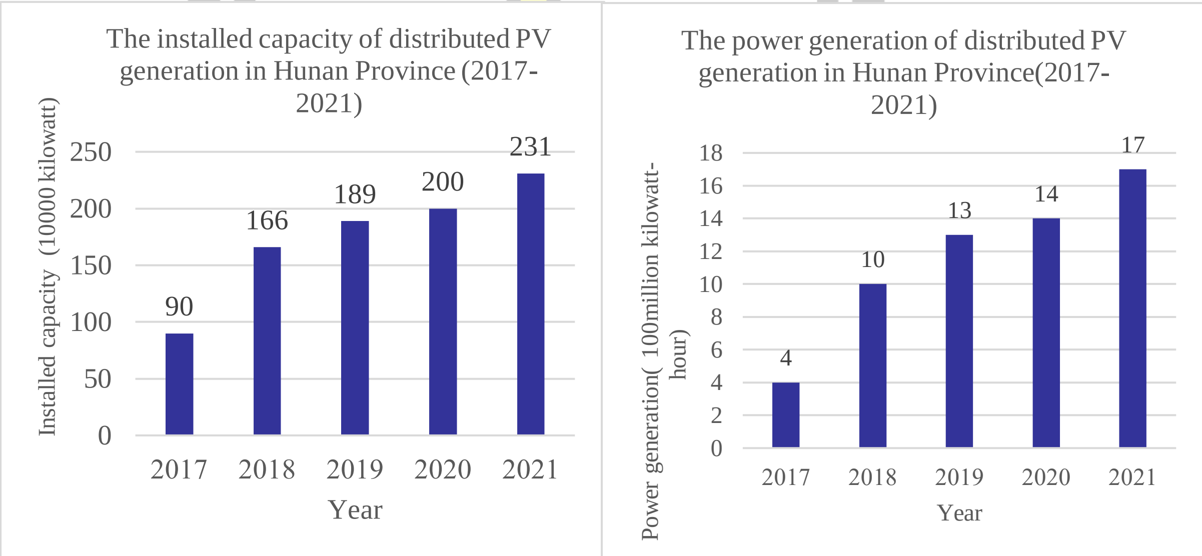


Figure 10. Distributed Photovoltaic Installed Capacity and Generation in Hunan Province from 2013 to 2021

From 2013 to 2016, the installed capacity of distributed solar photovoltaic power generation remained quite low [23]. However, starting in 2017, the growth rate accelerated noticeably (as shown in Figure 10). By the year 2021, the installed capacity of distributed solar photovoltaic reached 231(10000 kilowatt), accounting for over half of the total installed capacity. This indicates that distributed solar photovoltaic power generation in Hunan province has progressively garnered more attention and investment, achieving commendable progress. The growth of distributed solar photovoltaic power generation is not solely reflected in the installed capacity; the increase in power generation output is also noteworthy. From 2017 to 2021, the power generation output of distributed solar photovoltaic in Hunan province increased year by year, exhibiting a consistent upward trend. The advancements in technology and improvements in operational efficiency have led distributed solar photovoltaic power generation to play an increasingly crucial role in the energy supply.

2.2 Review of Relevant Policies

In Hunan Province, solar power generation policies are not only a significant guide in the energy sector but also a crucial means for achieving the substitution of traditional fossil fuels with clean energy sources. The government's supportive policies, industrial development plans, and the impetus for technological innovation have all laid a strong foundation for the flourishing growth of the solar power generation industry in Hunan. In this section, the main summarization revolves around policy in photovoltaic power generation installed capacity and distributed PV power generation.

2.2.1 Solar power generation installed capacity policy

At the national level, in the year 2021 alone, several policies were introduced concerning the scale of solar power generation construction in China. Specifically, they are as follows:

- In April 2021, the General Office of the Communist Party of China Central Committee and the General Office of the State Council jointly issued the "Several Opinions on Promoting the High-Quality Development of the Photovoltaic Industry." It proposed intensifying the promotion of areas such as photovoltaic poverty alleviation, photovoltaic + energy storage, and concentrated solar power generation. It emphasized enhancing technological innovation, establishing standards, optimizing policy environment, and striving to achieve a solar power generation installed capacity of over 300 GW by 2025.
- " In March 2021, the National Energy Administration released the "Notice on Printing and Issuing the 2021 Photovoltaic Power Generation Project Construction Plan." It stipulated that the construction scale of photovoltaic power generation projects in 2021 should be no less than 65 GW, with distributed photovoltaic capacity being no less than 35 GW, poverty alleviation photovoltaic capacity being no less than 10 GW, and poverty alleviation photovoltaic projects

accounting for no less than 15% of the total.

■ In February 2021, the National Development and Reform Commission issued the "Notice on Printing and Issuing the 2021 Renewable Energy Power Development Plan." It outlined that by 2025, China's renewable energy power generation capacity will reach 1.2 trillion kilowatt-hours, with the photovoltaic power generation installed capacity reaching 480 GW.

Table 3. Hunan Province Solar Energy Development Policy

Year	Policies	Installation Capacity Plan	Action Plan
2016-2020	13th Five-Year Solar Development Plan for Hunan Province	By the year 2020, the total installed capacity of photovoltaic power generation in the province will reach 2GW, with distributed photovoltaic power station installed capacity exceeding 1.5 GW. By the year 2030, the province aims to strive for a photovoltaic power generation installed capacity of over 4 GW.	● The emphasis will be on developing the area around Dongting Lake, encouraging the construction of fishery-photovoltaic and agriculture-photovoltaic complementary projects. In the central region of Hunan, it is encouraged to construct large-scale distributed photovoltaic power systems in industrial parks with stable loads and abundant rooftop resources. In the southern region of Hunan, combining distributed photovoltaic power generation with agricultural facilities is encouraged, and effectively utilizing barren hills and slopes for constructing centralized ground-mounted photovoltaic power stations. ● Promote the vigorous development of distributed photovoltaic power generation; tailor the construction of centralized photovoltaic power projects to local conditions; advance the implementation of distributed photovoltaic power generation on standard factory rooftops. ● Strive for significant breakthroughs in the conversion efficiency of crystalline silicon solar cells during the "13th Five-Year" period. Starting from strengthening key technology research and development and enhancing production process levels, make efforts to reduce the cost of photovoltaic power generation.
2021-2025	14th five-year plan for renewable energy development in Hunan province	By 2025, the installed capacity of renewable energy power generation is projected to reach around 44.5 GW, with photovoltaic power generation contributing 13 GW.	● By the end of 2020, the installed capacity of renewable energy power generation reached 28.55 GW, accounting for 57.3% of the province's total installed power capacity, including 3.91 GW from photovoltaic power generation. ● Adhere to a combined approach of centralized and distributed development, promote the large-scale development of photovoltaic power generation, and establish one national large-scale wind and solar power base project. ● During the "14th Five-Year" period, the total investment in renewable energy in the province is estimated to be about 130 billion yuan, with hydropower investment of 34 billion yuan (including

			pumped storage) and photovoltaic power generation investment of 36 billion yuan.
2022-2025	Hunan Province Electric Power Support Capability Enhancement Action Plan[19]	By 2025, the installed capacity of wind power and PV generation will reach over 25 GW, and by 2030, it will exceed 40 GW.	● In regions with abundant wind and solar resources and favorable construction conditions, explore the establishment of several integrated clean energy bases featuring multi-complementary capabilities. Following the approach of "reserving, maturing, and advancing," drive the scaling and sustainable development of wind power within the province. Actively explore the "PV+" model, and tailor the construction of centralized photovoltaic facilities such as forest-solar complementary systems, aquaculture-solar complementary systems, and agriculture-solar complementary systems based on local conditions. ● Support the on-site and nearby development and utilization of distributed PV. Accelerate the implementation of pilot projects in 12 counties (cities, districts) that have been incorporated into the national pilot for whole-county rooftop distributed PV. Actively promote the development of incremental distributed PV and rooftop photovoltaic installations in industrial parks, public institutions, shopping malls, and other areas. Encourage the integration of distributed PV with transportation, construction, and new infrastructure development.

The development targets for solar power installed capacity in Hunan province have consistently been set higher. As part of the 13th Five-Year Plan [5], the established target is to reach an installed capacity of 4.0 GW by 2030.However, by the actual year 2020, Hunan province had already achieved an installed capacity of 3.91GW. Moving into the 14th Five-Year Plan [9], the target for 2025's installed capacity is an ambitious 13 GW. In line with the requirements of the Electric Power Support Capability Enhancement Action Plan [24], the installed capacity of wind power and photovoltaic generation is expected to surpass 40 GW by 2030. These policy documents have adjusted the solar power installed capacity and action plan as shown in Table 3. This also indicates that solar power generation in Hunan province holds promising prospects for extensive development.

2.2.2 Distributed PV power generation policy

In September 2014, the National Energy Administration issued the "Notice on Further Implementing Relevant Policies for Distributed Photovoltaic Power Generation," [25]encouraging the appropriate use of abandoned land, barren hills and deserts, agricultural greenhouses, tidal flats, fish ponds, lakes, and other locations for constructing on-site distributed photovoltaic power stations. For photovoltaic power station projects connected to the grid with a voltage of 35 kV or below, individual project capacity not exceeding 20,000 kW, and primarily consuming the generated electricity in the substation area of the grid connection point, these projects were incorporated into the management of distributed photovoltaic power generation scale indicators.

Considering the resource conditions, total land availability, grid infrastructure, and national policies in Hunan Province, it is advisable to prioritize distributed photovoltaic (PV) power generation. The focus should be on areas with concentrated industrial parks, commercial zones, and public facilities, especially in regions with high electricity prices. By utilizing building rooftops and adjacent spaces, a cluster of on-site distributed PV projects can be developed to locally accommodate power generation. These projects primarily connect to the electricity grid with voltage levels up to 10 kV, operating under two modes: "self-consumption with surplus power fed into the grid" or "full-grid-feeding." [26]

In January 2015, Hunan Province issued the "Implementation Opinions on Promoting the Development of Distributed Photovoltaic Power Generation" [8]with reference number Xiang Zheng Ban Fa [2014] No. 118, aiming to encourage the development of distributed photovoltaic power generation. The document primarily encompasses the following aspects:

Strive to achieve, by the end of 2017, a newly added installed capacity of distributed photovoltaic power generation in Hunan Province exceeding 1 million kilowatts, with a cumulative total surpassing 1.45 GW or more.

Industrial Promotion: To drive and support the development of the local photovoltaic industry, including photovoltaic inverters, battery components and packaging, design consultation, system integration services, construction and installation, and other related sectors.

The policy suggests that electricity price subsidies will be provided for distributed photovoltaic power generation projects using domestically produced photovoltaic components and meeting acceptance criteria, without having received central fiscal subsidies. For residents who utilize their own rooftops to construct distributed photovoltaic power generation projects for self-consumption, the electricity generated for personal use will not be subject to the tiered electricity pricing structure.

In 2021, the National Energy Administration issued the "Notice on Publishing the List of Pilot Units for Whole County (City, District) Rooftop Distributed Photovoltaic Development" [27], with 12 counties (cities, districts) in Hunan being selected as national pilot promotion units. These 12 counties (cities, districts) are as follows: Liling City, Yuexi District, Xiangyin County, Wuling District, Lianyuan City, Qiyang City, Miluo City, Shuangfeng County, Nan County, Longhui County, Lengshuitan District, and Shaoyang County.

In July 2022, the Development and Reform Commission of Hunan Province issued a letter of consent regarding the development and construction of the first batch of centralized photovoltaic power projects during the "14th Five-Year Plan" period[28]. The document generally approved the construction of a total of 236 centralized photovoltaic power projects across various cities in Hunan Province, with a combined capacity of 24.49 million kilowatts. Furthermore, the document also mandated that each region adhere to the requirements set by the National Energy Administration, uphold a dual-track approach of both centralized and distributed photovoltaic development, actively promote the development and construction of whole-county distributed rooftop photovoltaic projects in the 12 counties (cities, districts) included in the national pilot program. The focus was placed on advancing the utilization of rooftop photovoltaic projects in 144 industrial parks across the province, aiming to significantly increase the coverage of building rooftop distributed photovoltaic systems. This directive aims to enhance the comprehensive utilization of distributed photovoltaic energy and contribute to the balanced development of both centralized and distributed photovoltaic projects in Hunan province.

2.3 Energy forecasting research methods and selection

The main research methods for predicting the development of energy generation under the policy background have been summarized in this research, along with their approaches, advantages, limitations, and relevant literature, as presented in Table 4 below:

According to Table 4, policy analysis is limited to the policies themselves and overlooks other potential factors influencing development. Data-driven models typically fail to consider the impact of policies on development, thus making them less suitable for scenarios with frequent policy changes and the need for long-term predictions. Conversely, scenario analysis provides policymakers with various options and the ability to anticipate the effects of policy changes. Energy model simulations can comprehensively consider multiple influencing factors, offering comprehensive insights for policy formulation. Therefore, aligned with the research objectives of this research, an examination of the development of solar energy generation in Hunan Province was conducted. Different policy contexts, such as installation capacity variation policies and advancements in generation technology, were considered, culminating in policy recommendations. As presented in table 4, a combination of energy modeling simulation and scenario analysis methods can be employed. Various scenarios, such as increased installation capacity or enhanced generation efficiency, can be established, factoring in energy demand, generation structure, and policy backdrop. By integrating these elements, models can be developed to simulate the developmental trajectories, future roles, and contributions of solar energy generation under diverse scenarios.

Table 4. Energy forecasting under the policy background research methods

Method	Approach	Advantages	Limitations	Relevant Literature
Policy Analysis	Analyzing policy texts to understand their mechanisms.	Understanding long-term policy impacts; revealing policy objectives.	Neglecting other influencing factors; requiring comprehensive data.	[29]
Data-Driven Models	Analyzing development trends based on historical data.	Supported by actual data; good predictive ability.	Not considering policy impacts; not suitable for long-term forecasts.	[30]
Scenario Analysis	Simulating different policy scenarios to forecast development trends.	Providing multiple policy choices; predicting policy impacts.	Scenario assumptions influencing results; difficulty in scenario selection	[31]
Energy Model Simulation	Establishing a simulation model based on the energy system, Considering the	Considering the interaction of multiple factors;	Complex model; high data requirements.	[32], [33]

	interplay of system elements for comprehensive forecasting.	providing comprehensive forecasts.		

2.4 Energy Model Analysis and Selection

An energy model is used to express the interrelationships between complex energy systems and other socio-economic systems through mathematical methods. Due to the flexible parameter settings of energy models, they can be used for qualitative and quantitative analysis of energy systems. Currently, there are many well-developed energy models internationally, covering various fields such as technology, economics, environment, and security. These models share similarities in structure, functionality, and methods, but there has not yet been a unified classification method established.

Based on the modeling approach, energy models can generally be categorized into three main types: top-down, bottom-up, and hybrid energy models.

2.4.1 Top-down energy models

Top-down energy models, originating from economic models, primarily use economic indicators such as energy prices and economic elasticity to reflect their relationships with energy consumption and production. Representative models include macroeconomic models (MACRO) [34] based on nonlinear macroeconomics, computable general equilibrium models (CGE) [35] based on general equilibrium theory, and modular capabilities like the GEM-E3 [36] general equilibrium model. These models are more suitable for macroeconomic simulation analysis of energy policy planning in situations where market systems are well-established. Moreover, these predictive models are based on existing development trends and lack foresight into factors such as technological advancements and policy changes. As a result, they are not sufficiently capable of accurately assessing the impacts of policy shifts and changes in economic structure in medium- to long-term predictions.

2.4.2 Integrated models

Integrated models are a simulation and emulation of the entire energy system, encompassing both top-down macroeconomic models and bottom-up energy supply and demand models. They constitute a complex mega-system. Given the extensive range of technologies and fields these models involve, a considerable number of specialized researchers and ample research time are required to accomplish this intricate system engineering. Representative examples of integrated energy models include the National Energy Modeling System (NEMS) for regional energy economies [37], the Integrated Energy-Economy-Environment model IIASA-WECE3[38]]and Comprehensive Evaluation Model of China's Energy Policies IPAC.

2.4.3 Bottom-up models

Bottom-up models, represented by Market Allocation (MARKAL) model [39], Asia-Pacific Integrated Model (AIM)[40], and Low Emissions Analysis Platform System (LEAP) [41], enable us to describe energy supply, usage, and conversion technologies by modeling specific technical and economic parameters. These models suggest that, compared to structural adjustments, technological advancements are the primary driving force for energy efficiency and emission reductions. In contrast to top-down models, bottom-up models allow us to describe energy supply, energy use, and energy conversion technologies in a detailed manner by constructing concrete technical and economic parameters. They comprehensively capture the technological and environmental-economic effects associated with energy substitution. Bottom-up models offer a more comprehensive depiction of energy substitution-related technologies and their impacts on the environment and the economy. Specifically, the MARKAL model focuses on market analysis, while the AIM model concentrates on the selection of energy technologies.

Top-down models, integrated models, and bottom-up models each have their own advantages and disadvantages (as shown in Table 5); their suitability should be assessed based on specific circumstances, particularly considering the research objectives.

Table 5. Comparison of Energy Models

Model Types	Typical Representations	Advantages	Disadvantages
Top-down models	MACRO CGE GEM-E3	Applicable to macroeconomic analysis and energy policy planning research	Lacks information about the impacts of energy substitution and technological changes
Integrated models	NEMS IIASA-WECE3	both thoroughly considers the cost of technological	The structure is complex, representing a sophisticated

	IPAC	choices and takes into account price elasticity, providing a simulation and analysis of the entire energy system	system for simulation and emulation, and obtaining data for it is quite challenging.
Bottom-up models	MARKAL AIM LEAP	provides a detailed description of technologies and can reflect the impact of technologies on the energy system.	The difficulty of collecting detailed data related to energy technologies

From the table 5, it is evident that Top-down models prioritize macroeconomics, Integrated models are highly complex, and Bottom-up models are better suited for this study. Specifically, we will choose typical representatives from each category for analyzing energy policies and then proceed with a comparison.

2.4.4 Model Comparison and Selection

1. CGE Model

The Computable General Equilibrium (CGE) model is currently the most widely used policy simulation model, also known as a computable general equilibrium model. It was founded by Johansen in 1960. The CGE model is a macroeconomic closed policy analysis tool that has evolved over several decades, gradually becoming refined in functionality, widely applied, and even forming a branch of applied economics. The core of the CGE model involves scenario design and policy simulation, and it is commonly used for studying changes in areas such as taxation, public expenditure, industrial restructuring, trade policies, environmental policies, climate policies, energy policies, and income distribution systems. Its main approach involves establishing connections between different sectors and then studying how changes in economic activities in one sector affect other parts.

So far, numerous scholars have applied the CGE model for policy simulation analysis. For instance, Mustafa [42] used this model to study carbon emissions issues in Europe, indicating that distributing the costs of carbon reduction among different sectors would lead to a dispersed reduction task. Wan Min [43] utilized the CGE model to analyze the impact of two emission reduction policies, carbon tax and carbon trading, on energy consumption and carbon emissions in China's power industry.

It can be observed that the use of the CGE model for research primarily focuses on the economic impacts of carbon reduction policies. Furthermore, due to the inherent characteristics of CGE models, a common feature among these studies is the significant requirement for specific data. In some cases, this data demand is even more complex than what input-output methods necessitate. Acquiring such data can often be exceedingly challenging.

2. IPAC mode

The IPAC model, also known as the Integrated Policy Assessment for China model, is often referred to as the Comprehensive Evaluation Model of China's Energy Policies. In the 1990s, China's energy research sector collaborated with international energy research organizations to jointly develop the IPAC model tailored for China. The IPAC model consists of three distinct parts with different characteristics and policy analysis functionalities: the Energy and Emission Model section, the Environment Model section, and the Impact Model section.

The core component of the IPAC model is the Energy and Emission Model, which encompasses various sub-models of different types. The Environment Model is composed of a climate model and an atmospheric pollutant dispersion model. Finally, the Impact Model mainly focuses on health impacts. The model takes the output data from the Energy and Emission Model and inputs it into the Environment Model to calculate the atmospheric pollution, carbon emissions, and their impacts on health resulting from energy activities.

Furthermore, the IPAC model has undergone a series of improvements, such as IPAC-SGM, IPAC-e, IPAC-Material, and IPAC-Air, to simulate and analyze the impacts of energy-environment policies on the economy. While the IPAC model conducts policy simulations, similar to the CGE model, it considers the interdependencies among various economic activities. It assesses the economic impacts of energy-environment policies rather than focusing on the effects of these policies on energy consumption and climate change themselves.

3. LEAP model

LEAP model combines analysis of energy, economy, and environment, functioning as a mathematical computation, policy simulation, and optimization model. It incorporates a Technology and Environment Database (TED), providing technical characteristics, costs, and environmental impacts of a range of environmental technologies. Furthermore, due to its characteristics of low initial data requirements, versatility, ease of mastery, and application, 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.

In terms of energy consumption and demand, using the LEAP model, PengWang et al. [44] analyzed energy consumption in Hunan Province. They set up five scenarios: 1) benchmark scenario, 2) scale effect (GDP growth rate), 3) structure effect adjustment, 4) efficiency effect adjustment, and 5) Comprehensive Scenario. They analyzed total energy consumption and drew the following conclusions: 1) The combined structure effect and efficiency effect will have an inhibitory impact on total energy consumption growth, with the inhibitory impact of the structure effect increasing over the years. 2) The GDP growth rate will be the most crucial factor in determining future total energy consumption. Huang Jian [45] utilized the LEAP model, using the year 2010 as the base year, to conduct a scenario analysis of China's electricity demand for the next forty years. Building upon this scenario analysis, probability distributions were constructed for the main parameters, and uncertainty analysis was carried out using the Monte Carlo simulation method. The analysis revealed that the uncertainties in the baseline scenario primarily stem from factors such as the internal structure of industries, residential lifestyles, energy utilization in the service sector, and adjustments in industrial composition. J.A. Nieves and others [46] studied energy demand in Colombia's industrial, residential, transportation, and tertiary sectors, finding that the transportation sector consumes the most energy. Based on scenario analysis in China, Chi Chunjie [47] demonstrated that enhanced energy-saving measures can effectively reduce terminal energy demand. Yang Shunshun's [48] calculation of carbon emissions in the eastern, central, and western regions of the Yangtze River Economic Belt showed that by 2030, the central region's carbon emission share will surpass that of the eastern region. Qiu Shuo [49] taking Shaanxi province as an example, proposed that improving terminal energy efficiency and adjusting industrial structures can significantly reduce emissions. Similarly, a study on an industrial park in Changsha found that transitioning the economic growth model has a positive impact on emission reduction [50].

In terms of policy analysis, Buncha Wattana[51] used the LEAP model to analyze the impacts of solar electricity generation on the Thai electricity industry. Based on Thailand's solar electricity generation planning policies for the years 2015 and 2018, Buncha established three scenarios: a baseline scenario, a 2015 scenario, and a 2018 scenario. They evaluated the impacts under these three scenarios in terms of diversification of electricity generation, fossil fuel requirements, and emissions of CO_2 and SO_2 from 2019 to 2037. In conclusion, a greater role of solar energy in electricity generation would yield positive effects for the Thai electricity industry. These benefits include enhancing the diversification of primary energy sources for electricity generation, reducing fossil fuel consumption for power production, decreasing dependence on fossil fuel sources, and promoting environmentally friendly electricity generation. Wu Qunli et al[52] utilized the LEAP model to study carbon reduction policy scenarios in the electric power industry. This study designed three scenarios: 1) a benchmark scenario, 2) Energy-saving Policy Scenarios (such as the adoption of energy-efficient light bulbs by residents), and 3) Climate Policy Scenarios involving CCS Technology (Carbon Capture and Storage Technology). The analysis encompassed the Energy Consumption Situation, CO_2 emissions, and Contribution Rate of Emission Reduction Policies. The conclusion drawn is that, considering both energy conservation and carbon dioxide reduction perspectives for the future, energy-saving policies are fundamental and the most effective in China.

In terms of energy forecasting, utilizing the LEAP model, a study by He jiaxin [53]was conducted regarding the Forecast of Biomass Power Generation Prospects in China. This research primarily focused on the installed capacity proportions of waste-to-energy, agroforestry biomass power generation, and biogas power generation from 2016 to 2030 under a carbon dioxide constraint scenario. Additionally, policy recommendations were provided. Gao Hu and others [54]applied the LEAP model, based on historical data of energy consumption in our country, to study the future prospects of China's energy development through reasonable and scientific scenario simulation and forecasting. Nnaemeka Vincent Emodi's [55]research in Nigeria demonstrated that clean energy and energy-saving policies can effectively reduce greenhouse gas emissions. Nayyar Hussain Mirjat and colleagues [56] set multiple power supply scenarios in Pakistan, finding that the energy efficiency and conservation (EEC) scenario has the lowest investment cost and is more aligned with sustainable development paths. Deng Mingxiang [57] proposed suggestions for energy structure optimization in Yunnan Province's supply-side reforms.

From the aforementioned study, it is evident that the LEAP model has a wide scope of application. It can be employed at both the national and provincial levels, enabling analysis of electricity demand as well as energy consumption and CO_2 emissions. Moreover, it facilitates the prediction of the impact of policies on the power sector and forecasts future installed capacity proportions.

In summary, top-down models (such as the GEC model) primarily emphasize economic research, while hybrid models (like IPAC) are notably complex and also tend to focus on economic impacts. On the other hand, in bottom-up models, the LEAP model concentrates on the influence of policies and also allows for predictions, making it highly suitable for this study.

The integration of the LEAP model with scenario analysis method can be used to predict medium to long-term energy supply, energy transition, energy end-use demand, and emissions of pollutants (such as greenhouse gas CO_2) under different developmental conditions. It comprehensively considers the impacts of factors such as population, economic development, transportation turnover, technology, and prices on energy-environment development.

Chapter 3 Research Methodology

This research will introduce the research methodology employed in the context of Hunan Province, utilizing the LEAP model for solar power generation forecasting. Through this approach, our aim is to predict the solar power installed capacity, changes in power generation structure, and the associated energy and environmental impacts in the upcoming years. With thorough data collection, model parameter setup, and scenario establishment, we will utilize the LEAP model to construct and analyze potential development trends of solar power generation under different policy scenarios.

In the subsequent sections, this research will progressively outline the process of data collection, principles and applications of the LEAP model, model parameter configuration, establishment of various scenarios, and the execution of the model. Through the methodology presented in this chapter, our aspiration is to provide in-depth insights and scientific basis for solar power generation forecasts, benefiting not only Hunan Province but also similar regions in their energy planning and policy formulation.

3.1 Methodology framework

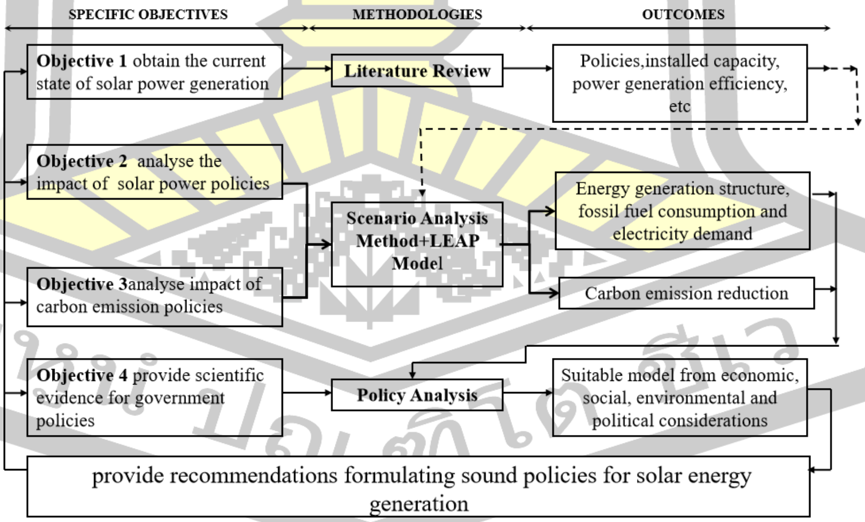


Figure 11. Methodology framework

Based on the descriptions in the preceding two chapters, this thesis primarily employs scenario analysis and the LEAP model, aiming to analyze the impacts of policies on the development of solar energy generation in Hunan province. By simulating various scenarios and policy settings, this study intends to predict changes in solar energy generation capacity in solar energy generation on energy consumption, generation structure, carbon dioxide emissions, and related aspects. The ultimate objective is to provide policy makers and decision-makers with essential insights to optimize policies and expedite the transition to clean energy. Additionally, this research endeavors to address the research gap concerning the influence of policies on the development of solar energy generation. It offers reference and guidance for similar regions in formulating clean energy policies and promoting sustainable energy practices. The specific methodological framework is depicted in Figure 11.

3.2 Introduction to Scenario Analysis Method and LEAP Model

3.2.1 Scenario analysis method

Scenario analysis method can be understood as an approach to address "what if" questions. Scenarios are used to describe potential future situations that may arise over time. It can also be referred to as foresight analysis or scripting method. Scenario analysis method is a qualitative and intuitive simulation and prediction technique. It is employed to simulate the social and economic impacts resulting from assuming that the present state, conditions, or specific factors persist until a certain point in time, based on the analysis of historical data. Scenario analysis method is a tool that combines qualitative and quantitative analysis, recognizing multiple potential futures and diverse approaches to achieving those possibilities. General scenario development includes a baseline scenario and a policy scenario. The predicted data from the baseline scenario is extrapolated from historical data, whereas the policy scenario is defined from the perspective of different policy focuses. The policy scenario includes specific variables contained in the baseline scenario, but the data for these variables changes based on differing policies.

Scenario analysis method is an effective tool commonly used for medium- to long-term global climate issue analysis. The LEAP model is precisely a modeling tool designed around the concept of scenario analysis. LEAP model is a bottom-up approach, forming the basis of our scenario analysis. Within this, scenario analysis examines how the energy system evolves and the environmental impacts it brings about with changes in time and policy. Policy simulation analysis within the LEAP model can be achieved through scenario setting and alternative options, comparing factors such as energy demand, consumption, environmental impact, costs, and benefits among different scenarios to showcase policy effects. These scenarios can be edited and calculated in various forms and combinations or can be edited and calculated as individual scenarios. Scenario analysis can help assess the policy effects of individual policies and analyze the interplay among various policies within a policy mix. The purpose of scenario analysis is not just to obtain predictive results, but also to compare and analyze the predictive results of different scenarios, providing decision support for policy formulation. Scenario development is the focus and challenge of the entire research process.

3.2.2 Introduction to the LEAP model

The LEAP model, also known as the Long-term Energy Alternative Planning System model, is an energy-environment-economic scenario analysis model. The LEAP model was co-developed by the Stockholm Environment Institute (SEI) and the Tellus Institute in Boston, USA. It is a bottom-up analytical technique widely used for energy policy analysis, climate and environmental assessments, and computational software tools [58].

The LEAP model establishes a comprehensive energy and environmental analysis system. It has relatively low data requirements and can be applied to study energy demand and greenhouse gas emissions reduction across various sectors of the national economy. Furthermore, it can be applied at the urban, provincial, and even global levels for energy and environmental analysis. The model analyzes energy demand, conversion, transmission and distribution, end-use, and energy-environmental impacts of various sectors through three modules: energy demand, energy conversion, and energy resources. Using model data, the LEAP model can analyze energy demand, energy consumption, and greenhouse gas emissions, such as carbon dioxide, under different policy-defined scenarios. By comparing results across different scenarios, the model can derive policy or technological effects. Additionally, it can be employed for predicting energy demand, analyzing energy consumption, and assessing the environmental impacts of energy across various sectors.

Due to its powerful capabilities and flexible and user-friendly characteristics, the LEAP model has found widespread applications. As of now, LEAP has been adopted by thousands of organizations in over 190 countries and regions for environmental climate assessments and policy simulation analyses. Its user base primarily includes government agencies, academic groups, non-governmental organizations, energy units, and consulting companies.

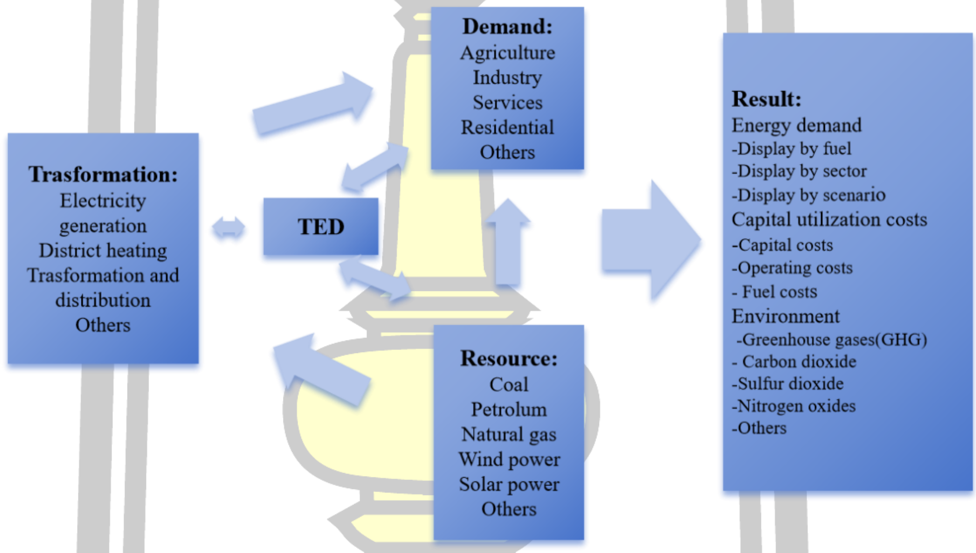


Figure 12.Structure Diagram of the LEAP Model

The first step involves inputting relevant data on end-use energy technologies that are currently available or may be used in simulation processes. Subsequently, based on historical data, estimations are made regarding economic and societal developments. Following this, policy measures, technological levels, and scenario analysis content are input, and upon this foundation, corresponding data models are established. Relevant data is input, ultimately leading to the derivation of relevant predictive results.

From the analysis structure diagram and the model's operational interface of the LEAP model, it is evident that the model primarily consists of several modules: the Energy Analysis Module (including Energy Resources, Energy Demand, and Energy

Conversion), Energy and Environmental Forecast Module, Energy Charts Module, Energy Balance Module, Overview and Summary Module, Technology and Environment Database, and Annotation Module, as shown in figure 12. Among these, the key modules are the Energy Analysis Module, Energy and Environmental Forecast Module, and the Technology and Environment Database. The specific functions of each module are described as follows:

1. Energy Analysis Module

The Energy Resources module includes both primary and secondary energy sources. The Energy Demand module represents the demand for various energy types from sectors like residential, industrial, and commercial. The Energy Conversion module pertains to the process of transforming primary energy into secondary energy, involving processes such as processing, conversion, storage, and distribution. The Energy Demand module utilizes an end-use driven approach.

2. Energy and Environmental Forecast Module

This module is primarily designed to analyze the outcomes of energy demand, energy resource utilization, costs, and environmental impacts under different scenarios. Energy demand results can be presented in terms of fuels, sectors, and scenarios. Costs include capital costs, operational costs, and fuel costs, while environmental impacts encompass greenhouse gases and air pollutants. The Energy and Environmental Forecast Module primarily displays the results calculated by the Energy Analysis Module.

3. Technology and Environment Database

The Technology and Environment Database (TED) is an open database that researchers can use, edit, and supplement with various energy, technology, cost, and environmental data. It contains a range of data on technology characteristics, costs, greenhouse gas emissions, and pollutant emission standards for a variety of energy end-use devices and environmental technologies. This database includes hundreds of technology types. Additionally, the Technology and Environment Database includes qualitative data, such as information about technology applicability and cost-effectiveness. Automatic retrieval of technology data requires establishing links between various energy use devices and the Technology and Environment Database.

In summary, the LEAP model comprises several interconnected modules, each serving specific functions related to energy analysis, forecasting, and technology and environment data management.

3.3 Module Design

This study established a LEAP model for power generation forecasting in Hunan province, as shown in Figure 13. The data sources included the "Hunan Provincial Statistical Yearbook," "China Electric Power Statistical Yearbook," and "China Energy Statistical Yearbook." The input modules mainly consist of four components: Key Assumption, Demand, Transformation, and Resource. The Key Assumption module is primarily focused on setting the conditions for economic and social development, as well as key factors influencing the energy environment. This includes factors such as domestic gross domestic product (GDP), population, and industrial structure. Primary Industry, Secondary Industry, and Tertiary Industry are the three main sectors of economic activity. The primary industry focuses on activities directly related to natural resources, such as agriculture, forestry, animal husbandry, and fisheries. The secondary industry involves processing and manufacturing products from the primary sector, including industries like manufacturing, mining, power generation, and construction. The tertiary industry centers on providing services and commercial activities, such as transportation, finance, education, healthcare, tourism, and IT services. The Transformation technology refers to the process of converting primary energy into secondary energy. The main technologies for thermal power generation in Hunan province are supercritical technology and CCGT (Combined Cycle Gas Turbine). The electricity generation module covers various methods including thermal power generation, wind power, hydroelectric power, solar power generation and supercritical technology. The Resource component mainly includes the resources involved in the model, such as coal, petroleum, and solar power. Finally, under different scenarios, the study primarily considers results like Total Electricity Demand, Electricity Generation by Technology Type, GHG Emissions, and so on.

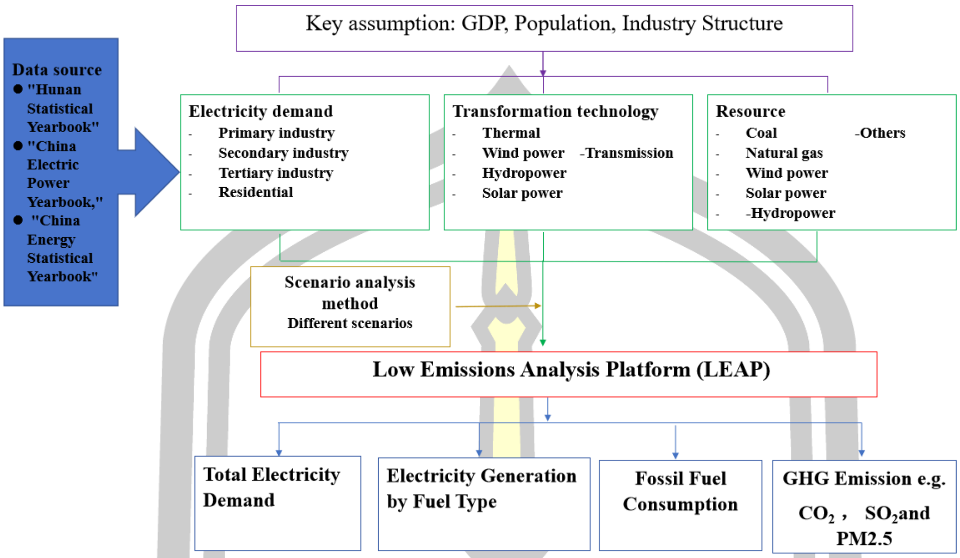


Figure 13. LEAP Model for Hunan Province.

3.4 Relevant historical data in the model

The development of solar energy is influenced by various complex factors, including economic, technological, policy, and societal changes. Therefore, to forecast future scenarios, it is necessary to make assumptions based on existing data and knowledge.

1. Population size

Relevant studies indicate that the growth in total population imposes pressure on resources and the environment. With the continuous expansion of population size, the consumption of electricity will also increase. The rise in electricity demand will inevitably drive an increase in supply, consequently leading to elevated emissions of greenhouse gases such as carbon dioxide. In recent years, due to factors such as population aging and changing perceptions towards childbirth, Hunan province experienced a negative growth in population in 2021 and 2022, where the mortality rate surpassed the birth rate, as illustrated in Table 6.

Table 6. Population Figures for Hunan Province from 2010 to 2022 (in millions)

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Population (million)	65.7	65.8	65.9	66	66.11	66.15	66.25	66.33	66.36	66.4	66.45	66.22	66.04

2. GDP

Hunan province's industrial structure is categorized according to the national industrial classification as follows: 1) Primary industry: This sector includes agriculture, forestry, fishing, and mining. Despite its diminishing contribution to the overall economic output of Hunan Province, it still plays a crucial role in providing raw materials for industries and supporting rural livelihoods. 2) Secondary industry: The secondary sector comprises manufacturing and construction industries. Manufacturing has been a primary driver of economic growth in Hunan Province, with a focus on areas such as electronics, machinery, textiles, and automotive manufacturing. Due to its substantial manufacturing capacity, Hunan is often referred to as the "world's factory." 3) Tertiary industry: Also known as the services sector, this segment encompasses services like retail, finance, healthcare, education, entertainment, and tourism. The rapid growth of the tertiary sector in Hunan Province reflects the transition towards a more consumption-driven economy.

Table 7. GDP of Hunan province from 2012 to 2022

Year	GDP（100 million yuan）	GDP growth rate(%)	The proportion of the primary industry（%）	The proportion of the secondary industry(%)	The proportion of the tertiary industry(%)
2012	21207.23	12.1	12.1	46.8	41.1
2013	23545.24	11	11	46.4	42.6
2014	25881.28	9.9	10.3	45.7	44
2015	28538.6	10.2	9.6	44.4	46
2016	30853.45	8.1	9.4	42	48.6
2017	33828.11	9.6	8.9	39.8	51.3
2018	36329.68	7.4	8.5	38.3	53.2
2019	39894.14	9.8	9.1	38.6	52.3
2020	41542.57	4.1	10.2	38.4	51.4
2021	46063.09	9.8	9.4	39.3	51.3
2022	48700	5.7	9.4	39.4	51.2

Table 7 provides information about the Gross Domestic Product (GDP), GDP growth rate, and the proportions of different industrial sectors (primary, secondary, and tertiary industries) in the economy for a series of years. The table illustrates that from 2012 to 2019, the GDP growth rate fluctuated across different years but overall exhibited a relatively stable trend. Notably, in 2020 and 2022, the GDP growth rate was lower due to the impact of the COVID-19 pandemic. Excluding these two years, the average GDP growth rate was around 9%.

In 2012, the proportion of the primary industry was 12.1%, gradually declining and reaching 9.1% by 2019. This trend suggests a gradual shift in the economic structure towards industry and the service sector, indicating a relative weakening of the importance of the primary industry. The proportion of the secondary industry, including manufacturing and construction, decreased over this period, going from 46.8% in 2012 to 38.6% in 2019. This decline possibly signifies a deceleration in the growth rate of the manufacturing industry.

Conversely, the tertiary industry involving services, finance, education, healthcare, and other fields, saw a gradual increase in its proportion from 41.1% in 2012 to 52.3% in 2019. This trend reflects the ongoing development of the service sector, emerging as a vital pillar of the economy.

In conclusion, from these data, it is evident that there has been a shift in the economic structure over these years, with a reduced share of the primary industry, a slower pace of growth in manufacturing, and a strengthening service sector, which has become a primary driver of economic growth. This transformation is primarily influenced by factors such as technological advancements, industrial upgrading, and changes in consumer patterns.

3. Electricity consumption

Table 8 presents electricity consumption data for Hunan province from 2016 to 2022, along with the electricity consumption growth rates across various sectors and industries. Through analysis, it is observed that from 2016 to 2022, the overall societal electricity consumption consistently increased from 149.6 billion kilowatt-hours to 223.6 billion kilowatt-hours. The average growth rate is approximately 6.9%. The electricity consumption in the primary industry exhibited fluctuations but displayed an overall upward trend. There was a slight decline from 2016 to 2018, followed by rapid growth in the subsequent years, particularly in 2021 and 2022, with an average growth rate of about 12.4%. The electricity consumption in the secondary industry also experienced fluctuations but demonstrated an overall increasing trend. The growth between 2017 and 2020 was relatively stable, with an average growth rate of approximately 4.3%. The electricity consumption in the tertiary industry exhibited steady growth during this period. From 2016 to 2022, electricity consumption rose from 24.3 billion kilowatt-hours to 44.4 billion kilowatt-hours. The average growth rate is approximately 10.4%. Residential electricity consumption has also maintained continuous growth. From 2016 to 2022, electricity consumption increased from 38.7billion kilowatt-hours to 64.1 billion kilowatt-hours. The average growth rate is around 10.44%.

Table 8.The electricity consumption from 2016 to 2022 (100 million kilowatt-hours)

Year		2016	2017	2018	2019	2020	2021	2022
Whole society	**Electricity consumption**	1,495.6	1,581.5	1,745.2	1,864.3	1,929.2	2,154.5	2,235.5
	Growth rate(%)	3.3	5.7	10.4	6.8	3.5	11.7	3.8
Primary industry	**Electricity consumption**	18.2	19.3	15.1	16.6	17.5	21.5	26.6
	Growth rate(%)	6.4	6.5	13.5	10.0	5.7	22.9	23.9
Secondary industry	**Electricity consumption**	847.7	886.7	955.9	987.5	1030.3	1136.8	1123.2
	Growth rate(%)	-4.4	4.6	8.0	3.3	4.3	10.3	-1.2
Tertiary industry	**Electricity consumption**	242.5	266.4	315.3	350.6	348.9	419.8	444.2
	Growth rate(%)	12.6	9.9	15.2	11.2	-0.5	20.3	5.8
Residential	**Electricity consumption**	387.1	408.9	458.8	509.5	532.4	576.3	641.3
	Growth rate(%)	17.8	5.6	12.2	11.0	4.5	8.2	11.3

4. Line loss rate

According to the “China Electric Power Statistical Yearbook”, the line loss rate during electricity transmission in Hunan Province from 2017 to 2021 is shown in Table 9.

Table 9. Line loss rate of Hunan province from 2017 to 2021

Year	2017	2018	2019	2020	2021
line loss rate (%)	8.47	8.16	7.96	7.98	7.94

5. Electricity import

Currently, the electric power production capacity in Hunan province is insufficient to meet the demand, requiring the import of electricity to make up for the supply deficit. The formula for calculating the imported electricity quantity is as follows:

Import = Consumption - (Generation - Loss) = Consumption - (1 - Loss Rate) × Generation. (1)

According to the formula, the specific imported quantity is shown in Table 12.It can be observed that from 2017 to 2022, Hunan province required an annual electricity import ranging between 300 and 600（100 million kilowatt-hours）, accounting for over twenty percent of the total electricity consumption. If solar energy could be developed, it has the potential to significantly reduce the need for electricity imports.

Table 10. The electricity imports from 2017 to 2022(100 million kilowatt-hours)

Year	Consumption	Generation	Loss Rate (%)	Import
2017	1,581.5	1,340.0	8.47	355.0
2018	1,745.2	1,432.0	8.16	430.1
2019	1,864.3	1,551.0	7.96	436.7
2020	1,929.2	1,552.0	7.98	501.1
2021	2,154.5	1,749.0	7.94	544.4
2022	2,234.7	1,968.0	7.92	422.2

6. Installed capacity

Table 11. The installed capacity of Hunan province from 2017 to 2022 (10000 kilowatt)

Year		2017	2018	2019	2020	2021	2022
Hydro-power	Capacity	1,570	1,598	1,612	1,581	1,578	1,592
	Growth rate(%)	1.1	1.7	0.9	-1.9	-0.2	0.9
Thermal power	Capacity	2,267	2,284	2,280	2,269	2,502	2,591
	Growth rate(%)	-2.3	0.7	-0.2	-0.5	10.3	3.5
Wind power	Capacity	263	348	427	669	803	900
	Growth rate(%)	21.6	32.0	22.7	56.7	20.0	12.0
Solar power	Capacity	176	292	343	391	450	640
	Growth rate(%)	567.2	84.4	13.8	5.8	15.5	42.0

Table 11 presents the installed capacity data for different types of power generation in Hunan Province from 2017 to 2022. Excluding data points representing individual anomalies, it is observed that the installed capacity of hydro-power generation remains relatively stable, with growth rates ranging from -1.9% to 1.7%. Thermal power generation also exhibits minor fluctuations, with growth rates ranging from -2.3% to 0.7%. Notably, wind power generation shows a significant increase in installed capacity, with growth rates spanning from 21.6% to 56.7%. In particular, the growth rate stabilizes at around 20% in 2021. When considering solar power generation, both centralized and distributed solar power are examined in detail. It is evident that, aside from rapid growth in 2017 and 2018, solar power generation experiences steady growth rates between 5% and 25% in other years.

7. Maximum availability

Table 12. The availability of power generation types in Hunan province from 2017 to 2021(%)

Year		2017	2018	2019	2020	2021	2022
Hydro-power	Time(hours)	3,245	2,785	3,421	3,754	3,398	3,262
	Availability(%)	37.0	31.8	39.1	42.8	38.8	37.2
Thermal power	Time(hours)	3,564	4,048	3,978	3,761	4,391	4,278
	Availability(%)	40.7	46.2	45.4	42.9	50.1	48.8
Wind power	Time(hours)	2,097	2,051	1,960	2,028	2,080	2,045
	Availability(%)	23.9	23.4	22.4	23.1	23.7	23.3
Solar power	Time(hours)	512	933	905	902	1,040	1,032
	Availability(%)	5.8	10.6	10.3	10.3	11.9	11.8

The term "Availability" refers to the proportion of the maximum potential usable time for a system or device. The maximum utilization time of power generation is influenced by various factors, which can be summarized as follows: Firstly, power generation equipment requires regular maintenance and upkeep to ensure normal operation and longevity. During maintenance periods, the equipment may experience temporary shutdowns, affecting the utilization time. Secondly, different power generation technologies exhibit distinct characteristics and limitations. For instance, solar and wind power generation are influenced by factors like sunlight and wind strength, while methods like coal-fired and nuclear power generation can provide a more stable electricity supply. Thirdly, in the case of renewable energy sources such as solar, wind, and hydroelectric power, their availability is dependent on the availability of resources. For instance, solar power generation is only feasible during daylight hours with sufficient sunlight.

The maximum utilization time divided by the total hours in a year (365 * 24 hours) can yield the maximum availability. From the “China Electric Power Statistics Yearbook”, the maximum utilization time for each type of power generation can be obtained, and then the maximum availability can be calculated, as shown in Table 12.

8. Generation efficiency

In Hunan province, thermal power generation is primarily dominated by coal and oil-based power generation. Traditional thermal power plants, such as those using coal or oil, typically have thermal efficiencies ranging from 30% to 40%. With the widespread adoption of supercritical technology, the efficiency of thermal power generation can be increased to around 41%.

China's wind power efficiency ranges from 20% to 40%, and the wind power efficiency in Hunan province is similar to that of China as a whole. The wind energy resources in Hunan province vary due to geographical location and climate. Different regions have varying wind speeds and wind energy resource abundance. Generally, areas with higher elevations or more open terrain may experience higher average wind speeds, thereby favoring higher wind power efficiency.

Generally, the efficiency of traditional water turbine-based hydroelectric power generation ranges from 70% to 90%, meaning the proportion of energy extracted from the water flow and converted into electricity falls within this range. Located in central-southern China, Hunan province is abundant in water resources and has a well-established history of hydroelectric power development.

Table 13. Generation efficiency

Generation Type	Efficiency
Thermal power	around 41%
Wind power	20%-40%
Hydro-power	70%-90%
Solar power	15%-18%

In terms of solar power generation, Hunan province currently employs the widely used Crystalline Silicon Solar Cell technology in China. The power generation efficiency ranges from 15% to 20%. Additionally, due to specialized maintenance, optimized resource utilization, and other reasons, centralized solar power generation has a slightly higher efficiency of about 2% compared to distributed solar power generation. The generation efficiency of thermal power, wind, power, hydro-power, solar power can be summarized in Table 13.

9. Emission factors

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)"[59] issued by the Ministry of Ecology and Environment of China, the PM2.5 emission factor for raw coal used in power generation is 12g/kg.

Chapter 4 Impacts of Solar Energy Policies

4.1 Scenario Settings

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 ," 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.

In this section, three distinct scenarios are established. 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 research 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 Table14.

Table 14. 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.

Due to the significant import of electricity in Hunan province, this article takes into account the imported electricity. The specific installed capacity ratios of different power generation technology type for each scenario are outlined in Table 15. Notably, because of the almost complete development of hydroelectric power in Hunan province, this research 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. For wind power generation and import electricity, based on historical data, the installed capacity is expected to continuously increase. 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 15. Installed capacity ratios of different power generation technology type for three scenarios

Technology type	**2021**	**2035**		
		Different scenarios		
	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%

4.2 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.14. 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, 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.

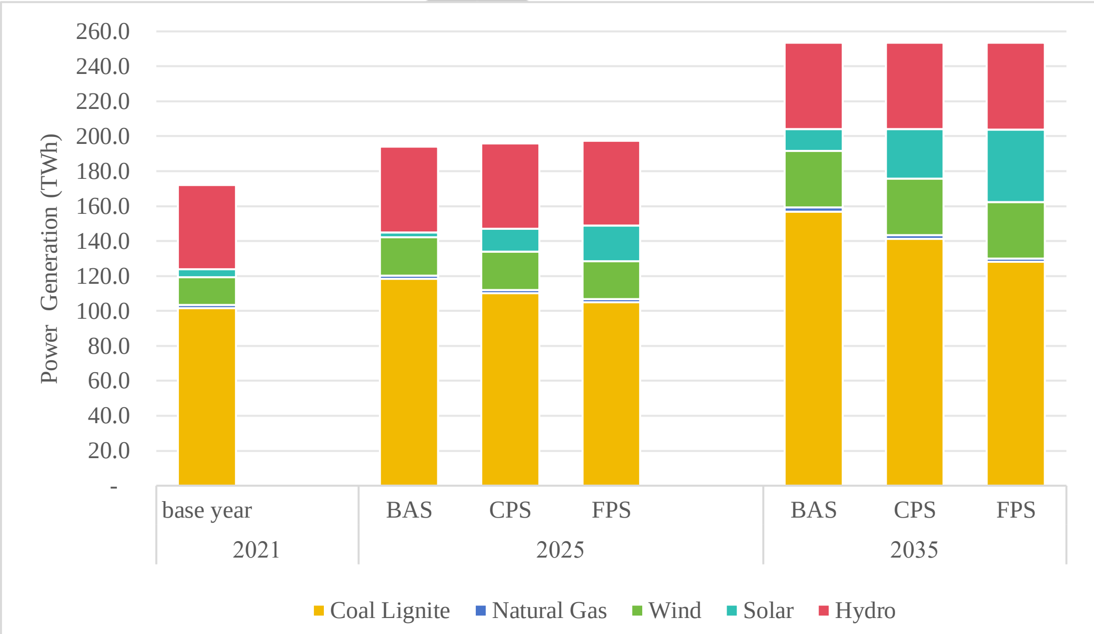


Figure 14. Electricity generation by fuel type

Based on the percentage share of electricity generation for each fuel type in Table 16, 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% [60]. 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.

Table 16. Electricity generation share for fuel type

Fuel type	2021	2035		
		Different scenarios		
	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%

4.2 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 17. 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 17. Fossil fuels consumption for electricity generation from 2022 to 2035

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.15 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 2,467.3 KTOE compared to the BAS scenario. However, Hunan province heavily relies on importing coal from other provinces. According to statistics, the total coal consumption in Hunan province in 2021 amounted to 94,051.3 thousand tonnes [61], 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.

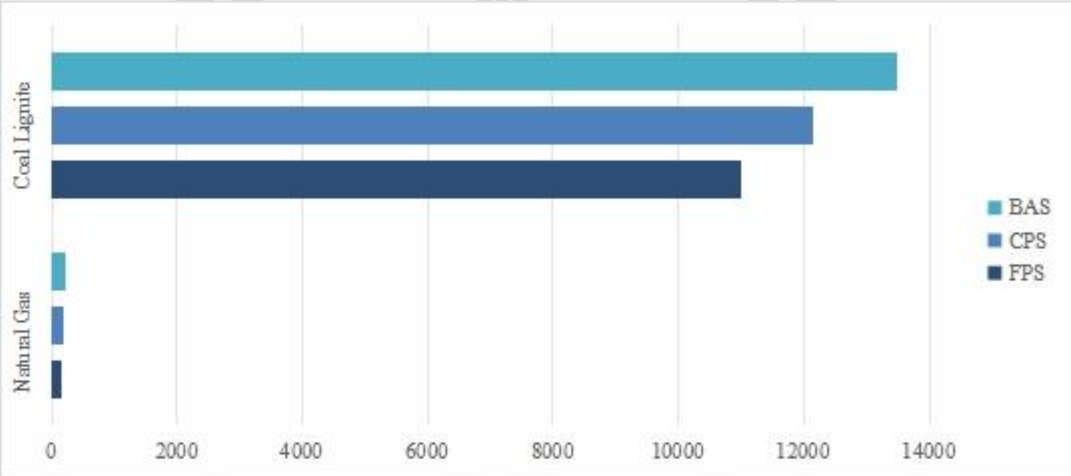


Figure 15. The fossil fuel consumption by fuel types (KTOE) in 2035

4.3 CO_2 emissions

From the perspective of CO_2 emissions, Table 18 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 18. CO_2emissions 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.

4.4 SO_2 emissions

The Table 19 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 19. SO_2emissions 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 SO_2 emissions from the BAS scenario.

4.5 PM2.5 emission

The changes in PM2.5 emissions in Hunan province under different scenarios from 2021 to 2035 are depicted in Table 20. 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 20. PM2.5 emissions from electricity production in 2021 – 2035

Year	BAS (tonnes)	CPS (tonnes)	FPS (tonnes)
2021	1,450		

2025	1,702.1	(-77.9)	(-153.2)
2035	2,311.2	(-230.9)	(-940.1)

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

4.6 Summary

This chapter 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 show that with the increase in solar power capacity, by 2035, under the EPS scenario, the share of solar power generation will reach 16.5%, while thermal power generation will decrease to around 51%. Fossil fuel consumption will also drop by 18.3 KTOE compared to the BAS scenario. Pollutant emissions will decrease by 18.3% compared to the BAS scenario. It indicates 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.

Chapter 5 Effects of Solar Power Development under Carbon Neutrality Policy

5.1 Scenario development and data consideration

In this study, due to data update delays, 2022 was selected as the base year, with 2023 as the first simulation year and 2060 as the final year. It is projected that Hunan province's population will decline, reaching approximately 64.85 million by 2030 and around 53.3 million by 2060. At the same time, GDP is expected to grow at a rate of 5%. As the industrial structure evolves, the share of the secondary industry will gradually decrease, while the tertiary industry's share will increase. Residential electricity consumption was estimated using linear regression analysis based on historical data. Considering the advancements in energy-saving technology, the growth rate of residential electricity consumption is expected to slow down between 2030 and 2060. The electricity consumption from 2023 to 2026 is shown in Table 21. By 2060, the total electricity demand of Hunan province is estimated to be approximately 828.9 TWh.

Table 20.Electricity consumption forecast for Hunan province from 2022 to 2060 (TWh)

	The primary industry	**The secondary industry**	**The tertiary industry**	**Residential**	**Total**
2022	2.7	112.3	44.4	64.1	223.4
2030	3.5	148.4	71.3	110.2	333.5
2040	6.1	187.2	124.6	130.2	447.8
2050	11.3	223.8	221.5	150.2	606.8
2060	20.6	244.9	393.1	170.2	828.9

Three scenarios are established in this section. The Historical Trend-Based Scenario (BAS) assumes all energy types grow at the 2016－2022 trend under current technological conditions. Under the framework of carbon neutrality, a Policy Support Scenario（PSS） and a Deep Emission Reduction Scenario（DES） are developed. The PSS, based on Hunan's 2023 Development Plan for the New Power System [62], prioritizes wind and solar energy. It reduces thermal power and sets a 20% planning reserve margin to address renewable energy variability. The DES focuses on transforming the power system toward low-carbon development, limiting thermal power to peak shaving and minimizing carbon emissions. Details are in Table 22.

Table 21. Key strategies of three scenarios

Scenario	Scenario features
Baseline scenario (BAS)	◆ Thermal power generation will increase to meet demand, while hydro power, solar, wind, biomass power generation, and energy storage capacity will grow according to historical data trends. The installed capacity of pumped storage will remain unchanged. ◆ the planning reserve margin will gradually increase to **15%**.
Policy support scenario (PSS)	◆ By **2025**, the installed capacity of wind power and solar power generation will reach a total of **25 GW**, with hydropower, biomass power generation, pumped storage power generation, and energy storage capacity reaching **16.59 GW**, **1.5 GW**, **1.55 GW**, and **3 GW**, respectively. By **2030,** the installed capacity of wind power and photovoltaic power generation will reach a total of **40 GW**, with hydro power, biomass power generation, pumped storage power generation, and energy storage capacity reaching **17 GW, 2 GW**, **10.4 GW,** and **4.5 GW**, respectively. ◆ The planning reserve margin will gradually increase to **20%**.
Deep emission reduction scenario (DES)	◆ By **2030**, the installed capacity of thermal power generation will reach its **peak** and remain unchanged thereafter. The installed capacity of solar and wind power generation will be adjusted to ensure that thermal power generation accounts for **10% of** the total power generation by **2060**. Other settings will remain the same as in the PSS. ◆ The planning reserve margin will gradually increase to **25%.** ◆ Technologies such as carbon capture and storage are expected to make significant advancements.

The installed capacity data under three scenarios is presented in Table 22. Renewable energy capacity grows significantly across all scenarios. Notably, in the DES scenario, solar power capacity increases from 6.4 GW in 2022 to 200 GW by 2060, while wind power remains capped at 51 GW due to its development limit. In the PSS scenario, wind and solar capacities are balanced in 2025, but solar capacity grows faster thereafter. Thermal power capacity increases in the BAS and PSS scenarios but remains stable in the DES scenario after peaking at 27.8 GW in 2030, indicating a gradual phase-out of fossil fuels. In the BAS scenario, Hunan’s thermal generation is over 98% coal-based. The PSS and DES scenarios predict a coal-to-gas power ratio shift to 9:1 by 2060, supporting energy diversification. Hydropower grows steadily, while biomass energy remains limited by resource availability and economic constraints. Pumped hydropower and energy storage expand rapidly in the PSS and DES scenarios, addressing renewable energy intermittency. Regional power interconnection projects, like the Jingmen-Changsha 1,000 kV UHV line and Turpan-

Hunan UHV project [62], strengthen connections, increasing electricity imports in the PSS and DES scenarios compared to the BAS scenario.

Table 22. Installed capacity of different power generation technology type type for three scenarios (GW)

Fuel Type	Base year	BAS			PSS			DES		
	2022	**2025**	**2030**	**2060**	**2025**	**2030**	**2060**	**2025**	**2030**	**2060**
Thermal	25.9	29.0	35.0	108.0	27.9	31.5	66.1	26.2	27.8	27.8
Hydro-power	15.9	16.5	17.0	20.0	16.5	17.0	20.0	16.5	17.0	20.0
Wind	9.0	12.8	20.0	51.0	12.5	18.0	51.0	12.5	18.0	51.0
Solar	**6.4**	**9.2**	**20.0**	**55.0**	**12.5**	**22.0**	**79.0**	**12.5**	**25.0**	**200.0**
Biomass	0.7	0.8	1.1	3.7	1.5	2.0	5.0	1.5	2.0	5.0
Pumped	1.2	1.2	1.2	1.2	1.6	10.4	64.2	1.6	10.4	64.2
Storage	0	0.2	0.3	0.3	0.2	0.5	3.5	0.2	0.5	3.5
Import	4.6	6.4	7.3	16.9	6.4	7.9	27.9	6.4	7.9	27.9

In Figure 16, the share of installed capacity is depicted for the BAS, PSS, and DES scenarios. Under the BAS scenario, traditional thermal energy (blue) remains the dominant source throughout the time period, though its share gradually decreases. Meanwhile, renewable energy sources such as solar energy (yellow) and wind energy (green) experience a slow but steady increase, with minimal changes observed in the proportions of energy storage and imported electricity. In the PSS scenario, driven by policy initiatives, the share of thermal energy declines significantly, while solar and pumped hydro energy storage expand markedly. Pumped hydro energy storage technology (pink) emerges as a crucial component for enhancing the flexibility of the power system, while wind and biomass energy maintains a relatively stable proportion. In the DES scenario, thermal energy is almost entirely phased out, and solar energy take on a dominant role. The shares of energy storage and pumped hydro energy storage align closely with those in the PSS scenario, while the proportion of imported electricity remains consistent at a certain level.

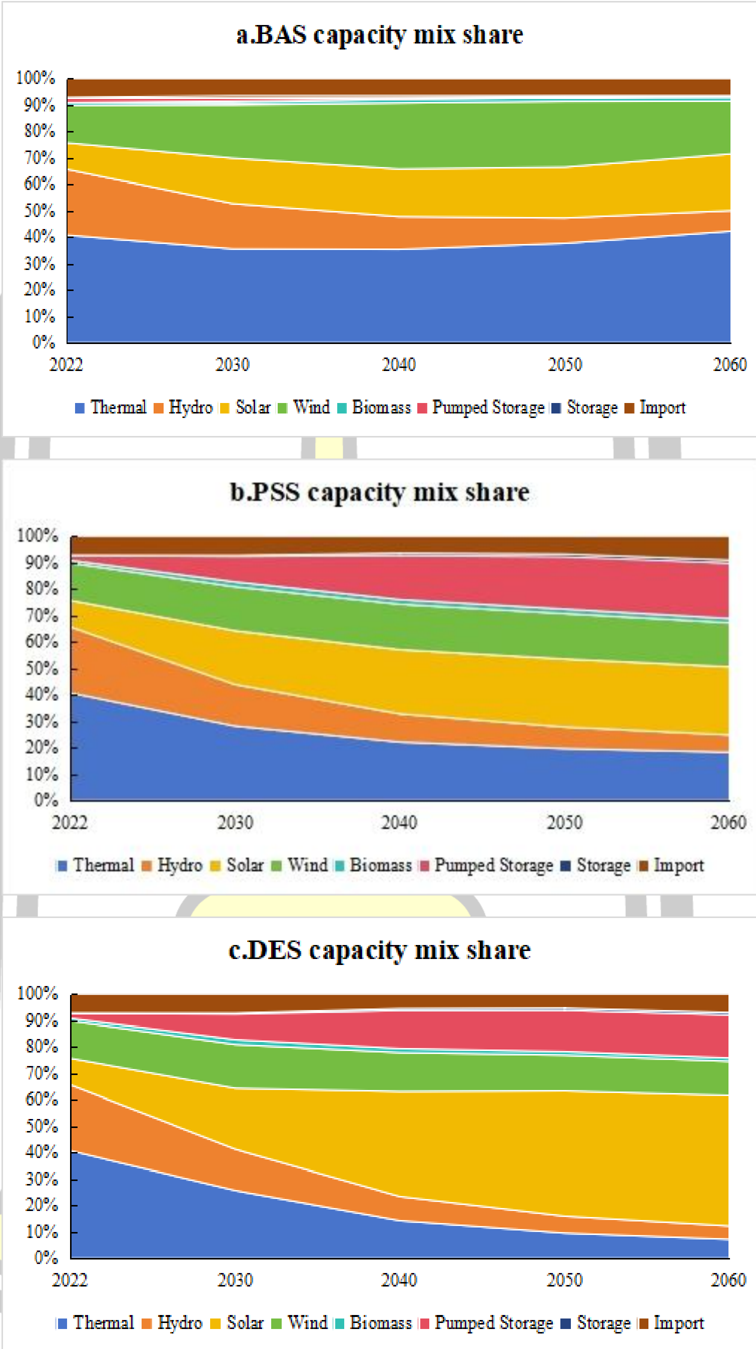


Figure 16. Capacity mix share in 2022-2060

5.2 Electricity generation structure

From 2022 to 2060, the power generation capacity across different scenarios is depicted in Figure 16. Hunan Province's total power generation is projected to rise from 224 TWh in 2022 to 829 TWh in 2060, aligning precisely with the electricity demand of that year. Specifically, under BAS, PSS, and DES, coal power generation is expected to increase from 100 TWh to 426 TWh, 204 TWh, and 83 TWh, respectively. However, in the DES scenario, coal power generation peaks at 109 TWh in 2030 before gradually declining. Meanwhile, by 2060, wind power generation is anticipated to reach 110 TWh, while solar power generation rises to 60 TWh, 86 TWh, and 212 TWh under the BAS, PSS, and DES scenarios, respectively, thus making solar power the primary replacement for coal power. In addition, in the PSS and DES scenarios, pumped storage power generation grows substantially to 72 TWh by 2060, thereby significantly enhancing the system's flexibility and stability.

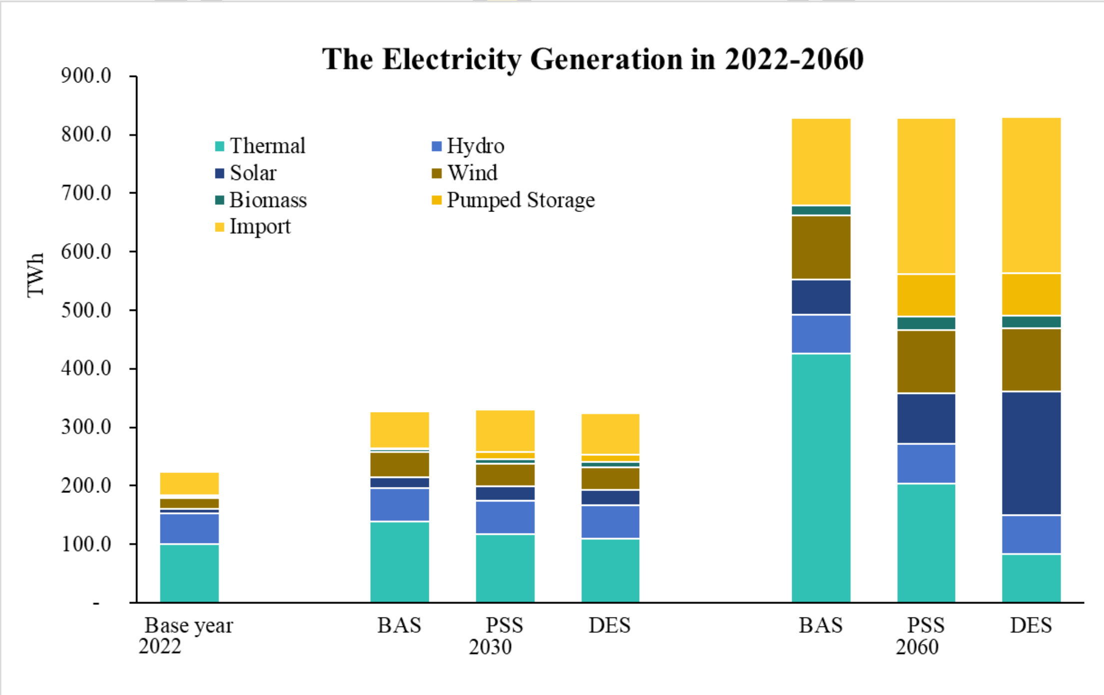


Figure 17. Electricity generation structure for power generation technology type from 2022 to 2060

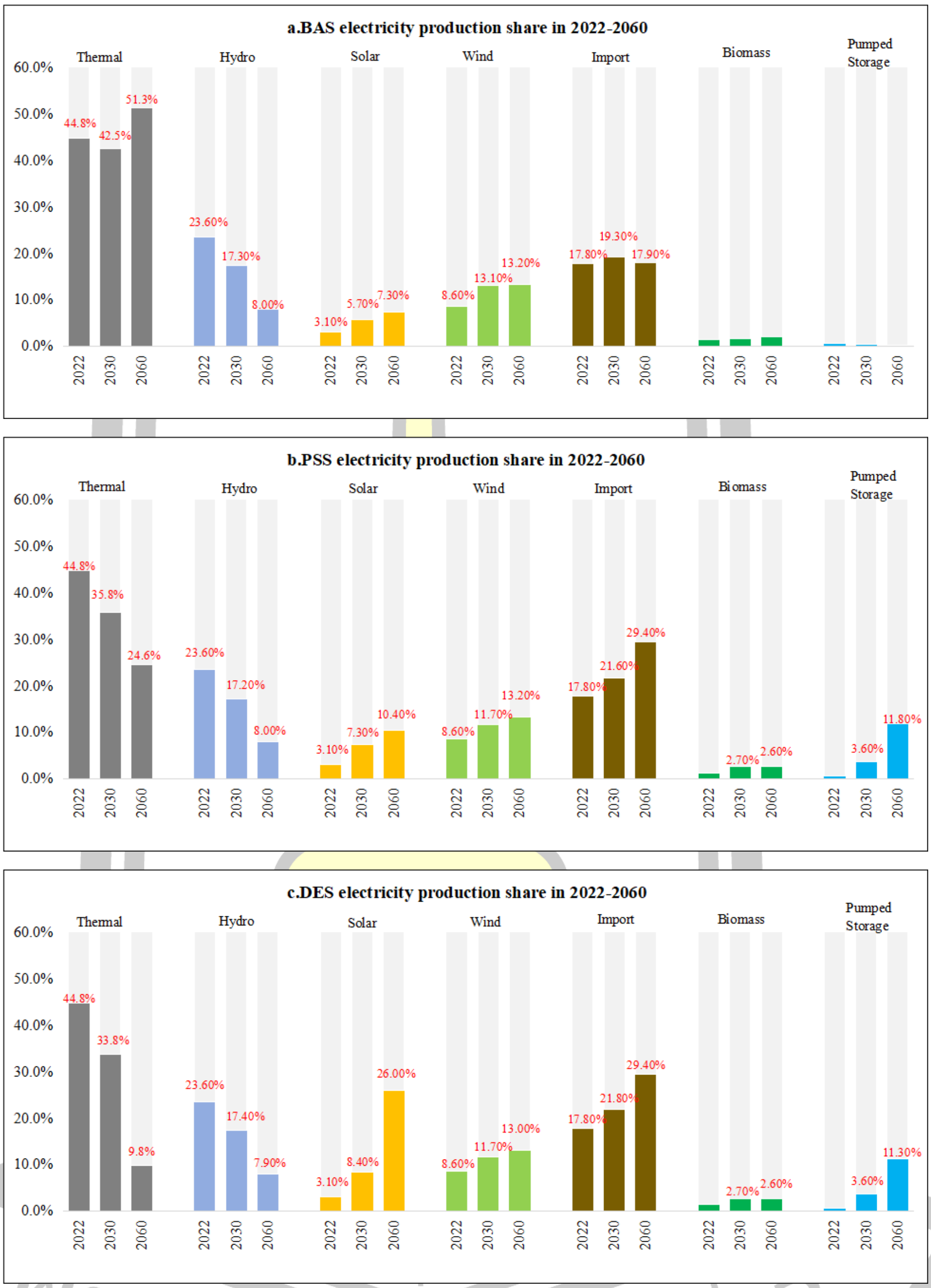


Figure 18. Electricity generation share for power generation technology type from 2022 to 2060

The changes in the electricity production share of Hunan province from 2022 to 2060 under the BAS, PSS, and DES scenarios are illustrated in Figure 17. In the BAS scenario, the share of coal power initially decreases from 44.8% in 2022 to 42.5%, before gradually rising back to 51.3%. This shift is primarily driven by the rapid growth of wind power, which experienced an approximately fourfold increase in generation from 2016 to 2021[63]. Consequently, the proportion of wind power is expected to rise from 8.6% in 2022 to 13.1% by 2030. However, due to the finite development potential of wind resources, its share is projected to stabilize by 2060. Simultaneously, the share of solar power is expected to steadily increase from 3.1% to 7.3%. As hydropower reaches its development ceiling, its share gradually declines, while the proportions of other energy sources remain relatively stable. In the PSS scenario, coal power's share declines sharply to 24.6%, with solar power rising to 10.4%. Compared to the BAS scenario, the shares of externally imported power, pumped storage, and energy storage see significant increases, reaching 28.6%, 8.8%, and 3.6%, respectively. Under the DES scenario, the share of thermal power drops drastically to 9.8%, primarily used for balancing peak loads, while solar power generation is fully utilized, with its share increasing to 26%. Overall, Hunan province is on track to transition to a low-carbon, green energy production model in the coming decades, promoting the sustainable development of renewable energy.

5.3 Consumption of traditional energy sources

According to the "Hunan province Energy Development Report for 2021," [64]in Hunan province in 2021 was approximately 167 million tonnes of standard coal, including 11.8 million tonnes of coal and 3.758 million tonnes of coal used for power generation. Only 7.2677 million tonnes were locally produced [61], with over 90% of the coal sourced from imports from other provinces. Reducing the consumption of fossil fuels will decrease dependence on imported energy, enhancing energy independence and security. Table 23 illustrates the consumption of fossil fuels for electricity production in 2022, 2030, and 2060 under the BAS, PSS, and DES scenarios. In the BAS scenario, fossil fuel consumption rises from 21,068.9 KTOE in 2022 to 29,162.4 KTOE in 2030, and further increases to 89,321.2 KTOE by 2060. This growth reflects the ongoing increase in electricity demand, which leads to a greater reliance on fossil fuels. In contrast, the PSS scenario shows a decrease in fossil fuel consumption, with reductions of 15.2% by 2030 and 21.2% by 2035 compared to the BAS scenario. This decline is primarily attributed to the implementation of policies promoting the development of renewable energy and reducing fossil fuel dependence. The DES scenario sees the most significant reduction in fossil fuel consumption, dropping by 52% by 2030 and 80.5% to 15,643 KTOE by 2060. This shift highlights Hunan Province's active efforts to transform its energy structure and reduce reliance on fossil fuels in pursuit of its carbon neutrality goals.

Table 23. Fossil fuels consumption for electricity generation in 2022-2060

Year	**BAS (KTOE)**	**PSS (%)**	**DES (%)**
2022	21,068.9		
2030	29,162.4	(-15.2)	(-52.0)
2060	89,321.2	(-21.2)	(-80.5)

Figure 19 illustrates the consumption of different fossil fuel types in 2060 (KTOE). Under the BAS scenario, Coal Lignite exhibits the highest consumption at approximately 87,982 KTOE. In the PSS scenario, lignite consumption significantly decreases to around 38,559 KTOE and drops further to approximately 15,643 KTOE in the DES scenario, marking a reduction of nearly 60,000 KTOE compared to the BAS scenario. This trend highlights the significant reduction in lignite consumption driven by policy measures and technological advancements. Natural Gas consumption is relatively low under the BAS scenario, at about 1,340 KTOE. However, with the assumption that natural gas will account for 10% of installed capacity in the PSS and DES scenarios by 2060, its consumption increases compared to the BAS scenario. In the PSS scenario, natural gas consumption rises to approximately 4,284 KTOE, while in the DES scenario, the share of thermal power generation declines significantly, with its consumption further restricted, dropping to around 1,738 KTOE. This indicates that natural gas serves as a transitional energy source, playing a crucial role in the policy-driven energy transformation. In summary, as the energy transition progresses, the overall consumption of fossil fuels decreases substantially, particularly the use of lignite. The energy structure is shifting toward a more low-carbon and diversified model, which not only enhances Hunan Province's energy security but also effectively reduces its reliance on external energy sources.

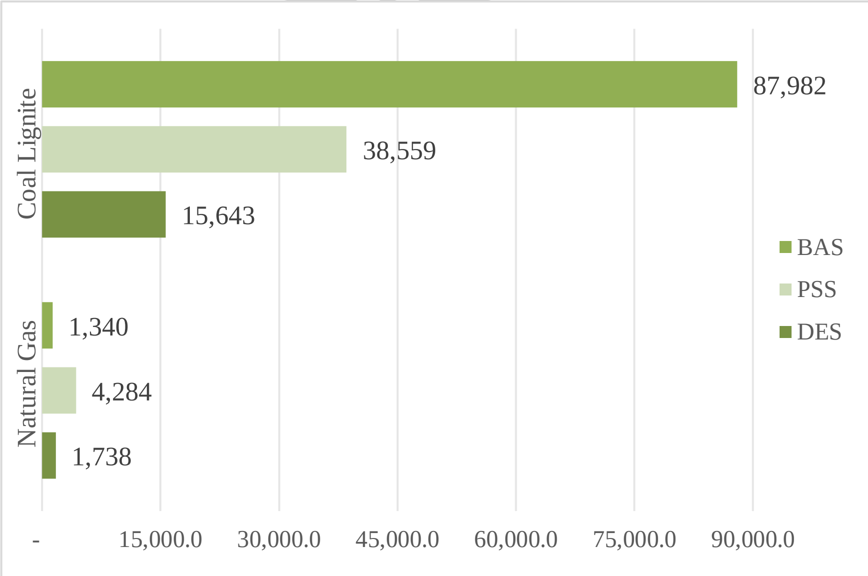
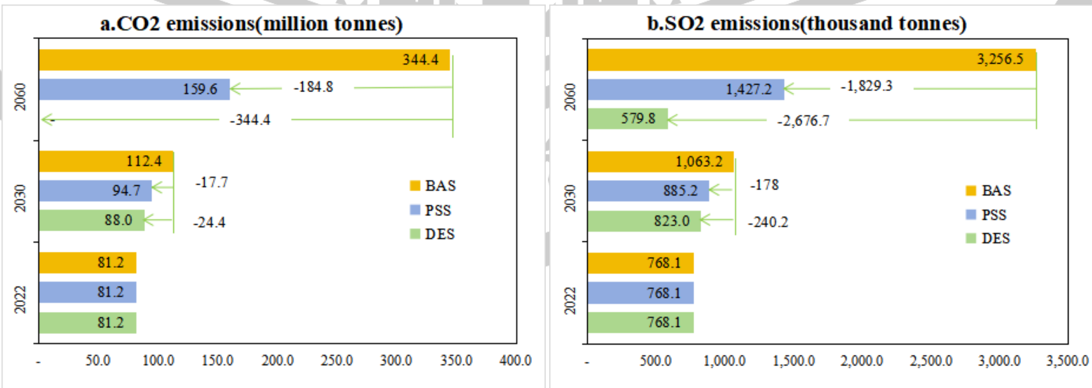


Figure 19. The fossil fuel consumption by fuel types (KTOE) in 2060

5.3 Pollutant emissions

Reducing the use of fossil fuels can significantly lower emissions of greenhouse gases and pollutants, improving air quality. As shown in Figure 4, by 2060, under the BAS scenario, emissions of CO_2, SO_2, NO_2, and PM2.5 will reach 344.4 million tons, 3,256.5 thousand tons, 1,368.1 thousand tons, and 1,569.7 thousand tons, respectively, marking an approximate threefold increase compared to 2022. This surge is due to the lack of technical and policy support, leading to increased fossil energy consumption.



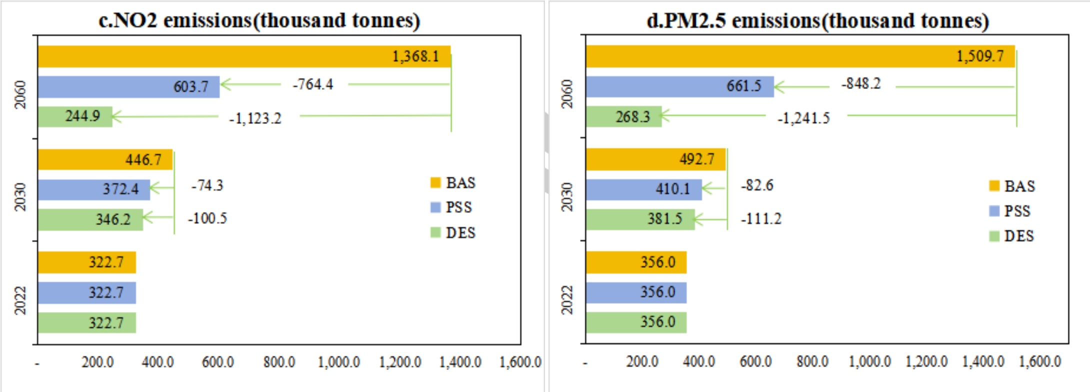


Figure 20. Pollutant emission forecast from 2022 to 2060

However, under the PSS and DES scenarios, emissions of these pollutants will decrease by about 21% and 80%, respectively, compared to BAS, in line with the reduction in fossil energy use. In the PSS scenario, due to the limited scale of wind and solar power generation, coal power remains a significant source of electricity, causing emissions of these pollutants to still double compared to 2022. CO_2 emissions will reach 159.6 million tons, with SO_2, NO_2, and PM2.5 reduced to 1,421.2 kilotons, 603.7 kilotons, and 661.5 kilotons, respectively. With the improvement of carbon capture and storage technologies, in the DES scenario, CO_2 emissions will peak in 2030 and then drop to zero, with SO_2, NO_2, and PM2.5 falling to 579.8 thousand tons, 244.9 thousand tons, and 288.3 thousand tons, respectively. Emissions by 2060 will be significantly reduced from 2022 levels, with the low-carbon goal largely achieved. This highlights the significant challenges Hunan's power industry will face in the coming decades. Therefore, the government must halt new fossil energy projects, set mandatory renewable energy consumption targets, and accelerate Hunan's transition to meet its carbon peak and carbon neutrality goals.

5.4 Summary

This chapter previously analyzed the power structure, fossil energy consumption, and environmental impacts in Hunan province under the BAS, PSS, and DES scenarios. Under the PSS scenario, by 2060, thermal power generation in Hunan province still accounts for 24.6%, with fossil energy consumption reaching approximately 43,000 KTOE. Carbon dioxide emissions will continue to rise from 2022, reaching 160 million tons by 2060, failing to peak by 2030. In contrast, the DES scenario results align more closely with low-carbon development expectations. Carbon dioxide emissions peak at 88 million tons in 2030 and then gradually decline. In the absence of carbon capture, carbon storage, and other technologies, by 2060, emissions decrease to approximately 65 million tons, representing 80% reduction compared to BAS scenario, essentially achieving the low-carbon target. To achieve the goal of carbon neutrality in power production by 2060, Hunan province needs to increase installed capacity, particularly for solar power. What's more, according to the Hunan Regulatory Office of the National Energy Administration, as of May 2024, Hunan Province’s installed capacity for new energy has reached 24.61 GW, including 10.06 GW of wind power and 14.55 GW of solar power, already surpassing the planned targets[65]. This data further validates the reasonableness of the installed capacity settings in the DES scenario. The continuous growth in solar power capacity provides important support for optimizing Hunan Province's energy structure and driving its low-carbon transition.

Chapter 6 Policy Implications and Conclusions

6.1 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 research 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.

The Hunan Provincial Government has introduced various policies to support the development of solar power. These policies include setting capacity targets for photovoltaic (PV) power, actively promoting the construction of key wind and centralized PV power projects, and exploring "PV+" models[65][24][9].Nevertheless, Hunan province faces numerous challenges in the development of wind and solar power. Firstly, the average annual utilization hours for solar power in the province are merely 900 hours, indicating relatively limited solar resources. Additionally, the focus on mountainous composite photovoltaic systems (such as agriculture-PV and forest-PV) within the province presents significant development difficulties. Furthermore, in areas like southern Hunan, wind, solar, and water resources overlap, exacerbating resource conflicts. The contradiction between solar power development and ecological conservation is particularly pronounced. Hunan has canceled 31 solar power projects, with a total installed capacity of 1.48 GW, due to issues involving ecological reserves and military land[66]. The inherent instability and intermittency of solar power, as well as insufficient peak-shaving capabilities, are also major obstacles to their development in Hunan. Reports indicate that the province's peak-to-valley load difference rate has reached nearly 60%, the highest in the State Grid system. Although solar power capacity has increased 3.2 times since 2020, during winter electricity demand peaks, PV output accounted for only 5% of the total supply, with the province relying heavily on external power transfers and local coal power for support. Finally, as the construction of new power systems accelerates, grid systems are becoming increasingly complex. The distribution network has yet to fully adapt to the flexible integration of distributed wind and PV energy, raising concerns about power system security. Additionally, the pressure of absorbing high-capacity installations and a high proportion of renewable energy, along with the need to ensure system safety and reliability, will significantly increase construction costs. This may, in turn, impact electricity prices in Hunan.

In light of these numerous challenges, this research puts forward the following recommendations to address them effectively and drive sustainable development：

- ✓ Promote the high-quality development of solar power. When approving wind and solar power projects, it is essential to comprehensively consider resource endowments, ecological requirements, and spatial carrying capacity. Following the principle of simultaneous development of distributed and centralized systems, distributed wind power projects should be scientifically promoted in areas with limited land resources and constrained development conditions. Additionally, rooftop photovoltaic projects should be encouraged by utilizing privately owned building rooftops.
- ✓ Establish an integrated development model for wind, solar, pumped hydro storage and energy storage. This model involves combining wind power, solar power, and various energy storage technologies, such as pumped hydro storage and electrochemical storage, to form a new, cohesive energy supply system[67]. According to the PSS and DES scenarios analyzed in this study, with planned installed capacities, pumped hydro storage and energy storage will reach 64.4 GW and 3.5 GW, respectively, by 2060. By leveraging the daily complementarity of wind and solar energy, strategically deploying storage facilities and pumped hydro storage systems will stabilize hydropower output and mitigate the adverse impacts of integrating independent wind and solar systems into the grid. Based on the distribution of new energy sources in Hunan and the siting conditions for pumped hydro storage and advanced energy storage technologies, areas suitable for integrated wind, solar, and storage development primarily include the regions around Dongting Lake, central Hunan, and southern Hunan.
- ✓ Advancing the Intelligence of the Power System. In June 2024, the Xiangjiang

New Area's "Virtual Power Plant" became the first successful entity-based virtual project in Hunan Province. This project integrates advanced control technology, IoT, and information communication technology to aggregate and optimize distributed power sources, energy storage, and adjustable loads, achieving regulation capabilities comparable to traditional power plants[68]. During the peak summer period, this virtual power plant is expected to adjust its capacity in real-time by 50,000 to 100,000 kilowatts. Building on this technology, Hunan can promote the development of "Smart Photovoltaics" by combining solar energy development with ecological restoration and energy storage technologies, creating an integrated platform that covers all aspects of power station operation, maintenance, and management. Additionally, "Smart Wind Power" initiatives can be pursued through predictive maintenance, accurate power forecasting, wind farm predictive operations, and cluster efficiency enhancements, ensuring the efficient and stable intelligent management of wind farms.

✓ Facilitating the Marketization of Solar Power. Currently, in Hunan, the cost of centralized solar photovoltaic development is approximately 3.3 yuan per watt, while the cost of distributed development is around 2.9 yuan per watt, indicating that solar and wind energy have reached grid parity. According to the "National Unified Electricity Market Development Blueprint," by 2029, a fully integrated national electricity market will be established[69]. Therefore, Hunan province should accelerate the commercialization of solar and wind power, establishing a comprehensive green electricity trading mechanism. For example, priority should be given to organizing wind and solar companies with expiring subsidies or grid parity projects to participate in trading their electricity; carbon offset rules should consider the decarbonization properties of green electricity; and the trading price of green electricity should be determined through market-driven mechanisms.

6.2 Conclusion

This study, utilizing the LEAP model, conducted an in-depth analysis of the development of solar power in Hunan province under solar power policies and carbon neutrality policy, focusing on its impact on the power generation industry structure and the environment. The results show that increasing renewable energy shares will transform Hunan's power structure, with solar power gradually replacing fossil fuels. The consumption of fossil fuels significantly decreases, along with notable reductions in CO_2, SO_2, and PM2.5 emission. To facilitate the development of solar energy, the study identified challenges such as high development costs, limited peak-shaving capacity, and integration difficulties. Policy recommendations include strategic project planning to leverage local resources, integrating wind, solar, and energy storage for stability, and implementing smart grids to optimize efficiency and reduce waste. Additionally, accelerating green electricity marketization and establishing effective trading mechanisms are suggested. Future research should focus on further refining the power transition model by considering variations in industrial structure adjustments across different scenarios and incorporating advanced technologies such as IGCC (Integrated Gasification Combined Cycle). Furthermore, it is essential to account for economic costs, social impacts, and other multifaceted factors. This study provides valuable policy insights for Hunan province to achieve its renewable energy and low-carbon power generation objectives. It is recommended to leverage local resources to gradually transition from coal-fired power to renewable energy and advanced energy storage technologies, ultimately establishing a more efficient, low-carbon, and sustainable power generation industry system.

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