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Exploring Pathways toward the Development of High-Proportion Solar Photovoltaic Generation for Carbon Neutrality: The Example of China

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Abstract: Solar photovoltaic (PV) generation will play a crucial role in the global clean energy transition toward carbon neutrality. While the development of solar PV generation has been explored in depth, the development of high-proportion solar PV generation has yet to be discussed. Considering the back force of the constraint of achieving carbon neutrality within the specified timeframe, this paper establishes a unified, multi-dimensional, and achievable framework through which to perform a system analysis for exploring the potential risks and challenges involved in the development process of high-proportion solar PV generation and investigating possible pathways to fostering the development of high-proportion solar PV generation. The results show that the critical risks and challenges include a low conversion efficiency, poorer resource endowment, more limited land resources, a low use of rooftop resources, an increasing complexity of power system scheduling, and low public awareness. These challenges have emerged with the development of solar PV generation in China and the aim of developing high-proportion solar PV generation. Based on our findings, possible pathways toward developing high-proportion solar PV generation have been determined, including promoting the research and development of higher PV efficiency, determining the optimal development sequence of solar resources, tapping the potential of land resources, increasing the use of rooftop resources, improving the resilience of the power system, and enhancing the public awareness of deploying solar PV generation. Finally, recommendations are proposed to optimize policy formulation for stimulating the high-quality development of high-proportion solar PV generation for carbon neutrality in countries including China.

Keywords: carbon neutrality; high-proportion PV generation; process; high-quality development; unified analysis framework; potential pathways; system analysis

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1. Introduction

Climate change is increasingly affecting the entire world, with more frequent occurrences of extreme weather conditions, such as drought and heavy rain [1,2]. It is already having wide-ranging consequences for human health, the environment, and economies across the globe. Achieving carbon neutrality is a global vision for the mid-21st century [3]. Around the world, countries are working to achieve the carbon neutrality goal by the middle of the century. As the largest developing country, China declared at the general debate of the 75th session of the United Nations General Assembly in 2020 that it would peak carbon emissions before 2030 and achieve carbon neutrality before 2060 [4]. This commitment shows that China is a responsible world power that will play a leading role in global climate governance. In order to reach the carbon neutrality goal, the traditional energy system, dominated by high-carbon fossil fuel energy, must be transformed into a modern energy system, dominated by low-carbon and green energy, driving the traditional

socio-economic systems, characterized by extensive development, to transform into new socio-economic systems featuring green and low-carbon development [5–7].

Establishing a new system dominated by these new energies will play a vital role in the energy transition toward a carbon-neutral future. There is broad consensus that new energy, represented by solar photovoltaic (PV) power generation and wind power generation, will be the main components of the future energy system aimed at achieving carbon neutrality [8,9]. These main components will account for 60–80% of a new type of energy system toward a carbon-neutral future [4,10,11]. This means that the new energy system, with a high proportion of solar PV power, must be established urgently. Countries including the United States (USA), Germany, and China have aimed at fostering the development of solar PV generation to replace high-carbon energy [3,4]. The development of solar PV energy in the USA dates back to 1954, when a scientist at Bell Laboratories invented the solar PV cell. The government in the USA has issued solar PV development polices, dominated by acts such as The Energy Policy Act, highlighting an investment tax credit [12]. Owing to government policies, solar PV development in the USA has seen significant growth in recent years, and the USA is now the second leading consumer of solar PV energy worldwide, as of 2022 [13]. Solar PV use in the European Union (EU), represented by Germany, has achieved a massive expansion since it began in the wake of Germany's Renewable Energy Act in the year 2000 [14]. The EU has implemented development polices, dominated by acts and strategic targets, to promote the development of solar PV energy. In particular, with the EU Solar Energy Strategy in the REPowerEU Plan, the EU will achieve a new renewable energy target of 42.5% by 2030, up from the current 32% target, with the ambition to reach 45% [15]. In 2022, the cumulative solar PV capacity of the EU was 194.5 gigawatts, and Germany was the leading member of the EU in terms of highest cumulative solar PV capacity. As the leading country in the world for solar PV capacity share, China has issued a series of incentive policies to promote solar PV development since 2013 [16]. However, compared to the policies and practices related to solar PV energy in the USA and EU, more effort should be made to achieve stronger legislation and more specific strategic targets for the development of high-proportion solar PV generation, with the aim of reaching the carbon neutrality goal more effectively.

Along with the increasing focus on the energy transition toward carbon-neutral processes, there are increasing studies highlighting the research on new energy development and the deployment of high-proportion new energy. A plethora of studies concentrate on the deployment of new energies, from the perspective of analyzing the driving factors [17], challenges [18], and strategies [19] of new energy development, as well as the development of high-penetration new energy in terms of exploring the safety [20], dispatching [21], and optimization [22] of power systems, including those of high-penetration new energies. Concerns regarding the intent and the decision to adopt solar PV energy and other new energies have been addressed in the literature [21,23]. Several studies have highlighted the research on the development of high-proportion solar PV generation, but these studies usually focused on the access and consumption of high-penetration solar PV generation and the optimization of the power system for high-penetration solar PV generation [24–26]. However, few studies have focused on the development process of high-proportion solar PV generation, although some of the literature considers the impact of the construction of high-proportion solar PV generation on the achievement of the carbon neutrality goal [27,28]. More specifically, few attempts have been made to apply a unified analysis framework for exploring potential pathways to developing high-proportion solar PV generation to promote its high-quality development, considering the back force of the constraint of achieving carbon neutrality within the specified timeframe.

Compared to the published literature, this study may contribute to the research on fostering the development of high-proportion solar PV generation in the following three aspects: (1) A new research perspective: while the development of solar PV generation has been explored in depth, the development of high-proportion solar PV generation has yet to be discussed. Along with the development of solar PV generation, the increase in the use

of solar PV energy is becoming more important and more difficult. However, very little has been achieved in the study of possible pathways to developing high-proportion solar PV generation for promoting the achievement of high-proportion solar PV construction that aims to support the achievement of the carbon neutrality goal more precisely. This study will pioneer the investigation into the challenges of and pathways to developing high-proportion solar PV countries, like China, from the perspective of considering the impact of the need to achieve carbon neutrality within the specified timeframe, which provides a new perspective and a new research paradigm. (2) Establishing a unified analysis framework: precisely determining the potential risks and challenges of developing high-proportion solar PV generation is a complicated process. This process will play a crucial role in investigating the possible pathways to developing high-proportion solar PV generation more precisely. However, few attempts have been made to apply system thinking and back force mechanisms for exploring possible pathways to addressing the potential risks and challenges of developing high-proportion solar PV generation, considering the back force of the constraint of achieving carbon neutrality within the specified timeframe. This study will attempt to establish a unified analysis framework, based on system theory and the back force mechanism, for precisely determining the potential risks and challenges of developing high-proportion solar PV generation in a country like China. (3) Providing policy implications for promoting the high-quality development of high-proportion solar PV generation in countries including China more precisely: developing high-proportion solar PV generation to support the achievement of carbon neutrality within the specified timeframe is a dynamic process. This process is inseparable from the role of policy instruments. Issuing effective policies will help control the process more precisely. No literature was found on providing policy implications for developing high-proportion solar PV generation considering the constraint of achieving carbon neutrality within the specified timeframe with the aim of achieving the carbon neutrality goal more precisely. This study will attempt to provide policy recommendations based on system analysis to precisely stimulate the high-quality development of high-proportion solar PV generation with the aim of achieving carbon neutrality.

The established framework in this study intends to help policymakers and academics examine the critical challenges of developing high-proportion solar PV generation, explore the possible pathways to constructing high-proportion solar PV generation, and then investigate the potential policy measures with the aim of fostering the deployment of high-proportion solar PV generation. The established analysis framework in this article will be beneficial for a country like China to investigate the effective policy countermeasures from a new perspective by considering the back force mechanism. This is also helpful for countries similar to China in their efforts to foster the deployment of high-proportion solar PV generation that aims to achieve the carbon neutrality goal more precisely.

The rest of this article is organized as follows. Section 2 elaborates the current process of solar PV generation development in a country like China. Section 3 proposes a comprehensive analysis framework for investigating the possible pathways to promote the development of high-proportion solar PV generation considering the back force of the constraint of achieving carbon neutrality within the specified timeframe. In Section 4, the key challenges involved in the development process of high-proportion solar PV generation are presented. Section 5 introduces the possible pathways to developing high-proportion solar PV generation for more precisely promoting the high-quality development of high-proportion solar PV generation in countries like China with the aim of achieving the carbon neutrality goal based on considering the constraint of achieving carbon neutrality within the specified timeframe. Lastly, Section 6 concludes the study and proposes a few suggestions.

2. Current Process of Solar PV Generation Development in a Country like China

2.1. Issuing Incentive Policies to Promote the Development of Solar PV Generation

Compared to the traditional coal-fired power generation, solar PV generation reduces carbon dioxide and particulate matter $PM_{2.5}$ significantly, which means that it can yield

positive environmental externalities. In recent years, many countries like China have stepped up their efforts to promote the development of solar PV generation. Considering that the solar PV generation industry is in its initial stage, China has introduced various policies to stimulate the development of solar PV generation since 2013. These policies issued to promote the development of solar PV generation in China include development plans [29–31], action plans [32–34], implementation programs [35–37], administrative measures [38–40], guiding opinions [41–43], related matters [44–46], and other policies [47–49], as shown in Table 1. The implementation of these policies has favorably promoted the development of solar PV generation in China. And solar PV technology has achieved significant advances in both systems and materials. China has made remarkable achievements in the deployment of solar PV generation, with the largest installed power capacity in the world [50–52]. While the development policies for solar PV generation in China have been explored in depth, the types of government policies that could stimulate the deployment of high-share solar PV generation have yet to be explored.

Table 1. Summary of incentive policies for solar PV generation in China in recent years.

No.	Type	Representatives
1	Development planning	[29–31]
2	Action plans	[32–34]
3	Implementation programs	[35–37]
4	Administrative measures	[38–40]
5	Guiding opinions	[41–43]
6	Related matters	[44–46]
7	Other policies	[47–49]

2.2. Continuous Increase in the Proportion of Solar PV Generation Installed Capacity

In the past decade, the installed capacity of solar PV generation in China has experienced rapid growth. In 2022, China's cumulative installed capacity of solar PV generation reached about 393.5 million kilowatts (kW) [50,52] (as illustrated in Figure 1), with a 28.6% increase from 2021. The cumulative installed capacity of solar PV generation in China increased by 2380% in 2022 [52,53], with an average annual growth rate of 42.8% compared to that of solar PV generation in 2013. In 2022, the cumulative installed capacity of solar PV generation in China will account for 15.3% of the total installed power capacity, as shown in Figure 2. The cumulative installed capacity of solar PV generation related to the total installed power capacity has surpassed the share of hydropower, becoming the second largest cumulative installed capacity of the power supply. The cumulative installed capacity of wind power and biomass power generation accounted for 14.3% and 1.6% of the total installed power capacity, respectively [54–56]. Therefore, solar PV generation has become the largest installed new energy generation variety. Overall, the cumulative installed capacity of new energy generation in China reached about 799.5 million kW, accounting for 31.2% of the total installed power capacity. With the continuous advancement of the energy production revolution, clean and low-carbon energy represented by new energy generation has been positioned as a new resource to replace traditional high-carbon energy, and solar PV generation in China has rapidly advanced and developed in recent years.

2.3. Increasing Proportion of Solar PV Generation Accounting for Electricity Consumption

From 2013 to 2022, not only has China's solar PV generation made remarkable progress, but its proportion of the total power generation has also made important breakthroughs. In 2022, China's solar PV generation amounted to 427.3 billion kilowatt hours (kWh), up 31.1 percent year on year. In the past decade, China's solar PV generation has increased significantly from 9 billion kWh to 427.3 billion kWh by a factor of almost 46.5, with an average annual increase rate of 53.6%, as shown in Figure 3. In 2022, China's new energy generation accounted for 15.8% of the total power generation, an annual increase rate of 30.2%. Among them, wind power generation is the largest contributor to new energy

generation with a share of 8.8%, and solar PV generation is the second largest contributor to new energy generation with a share of 4.9%. Between 2013 and 2022, the share of new energy generation represented by wind and solar PV power of the total power generation in China increased by a factor of almost 8.4. In particular, the share of new energy generation represented by wind and solar PV power of China's total power generation in 2021 exceeded 10% for the first time since 2013, achieving important breakthroughs.

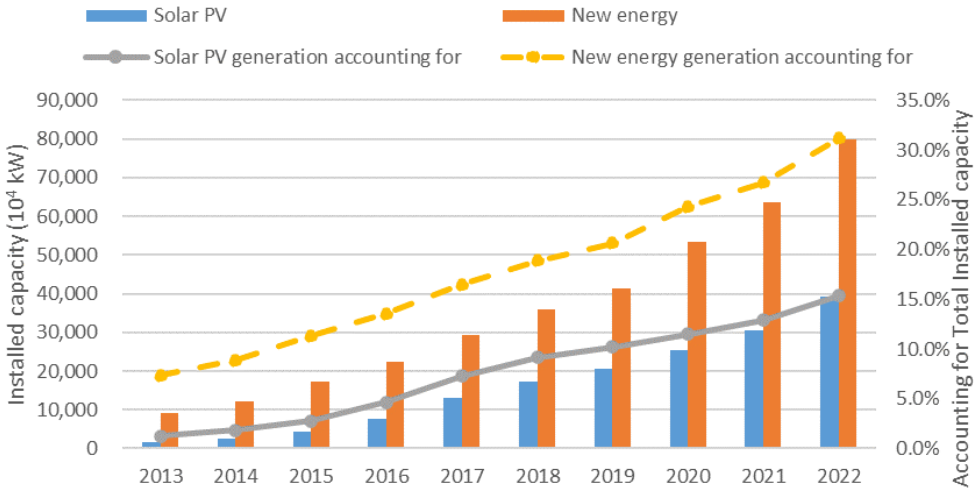


Figure 1. Increased proportion of the solar PV generation installed capacity in China in the past ten years.

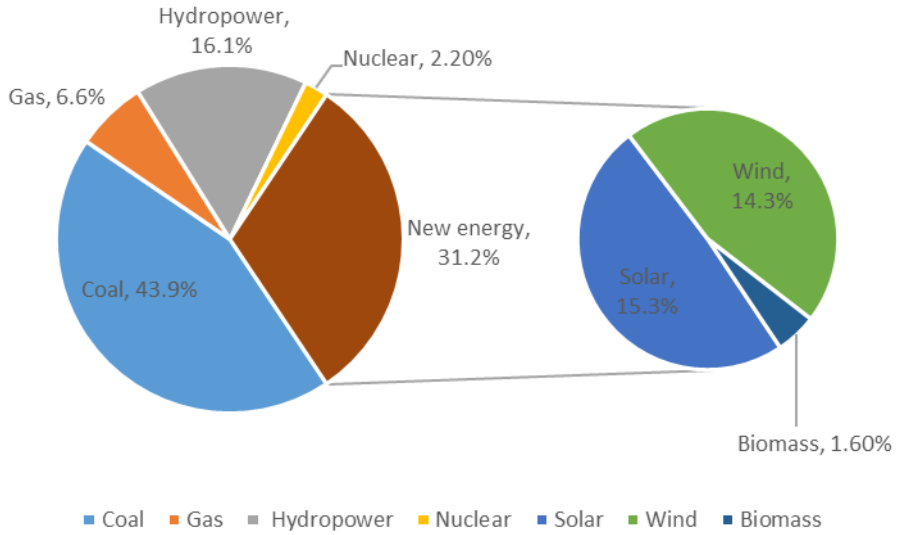


Figure 2. The proportion of the solar PV generation installed capacity in China in 2022.

With the development of solar PV generation in China, the power generation of new energy continues to increase. The contribution of new energy generation to provide a driving force for the economic and social development of China is also increasing significantly. The total social electricity consumption of China was 8637.2 billion kWh in 2022 [52], an increase of 62.3% over 2013, with an average annual growth rate of 5.5%, which means that a substantial increase in China's electricity consumption was achieved. China's new energy generation reached 1372.3 billion kWh in 2022, an increase of 39.6% over 2021. In 2022, China's new energy generation accounted for 15.9% of the total electricity consumption with an increase of 34.4% over 2021, and solar PV generation accounted for 4.9% of the total electricity consumption with an increase of 26.2% over 2021. Between 2013 and 2022, the proportion of new energy generation of the total electricity consumption increased by a

factor of almost 476.4, with an average annual growth rate of 21.5%, and the proportion of solar PV generation of the total electricity consumption increased by a factor of almost 2825.4, with an average annual growth rate of 45.3%. New energy generation in China accounted for 15.9% of the total electricity consumption in 2022. China was part of the second-tier countries, which include the United States, with a share of 13% [53]. The first-tier countries with an internationally advanced level of new energy development are represented by countries like Germany, with 36% of the total electricity consumption.

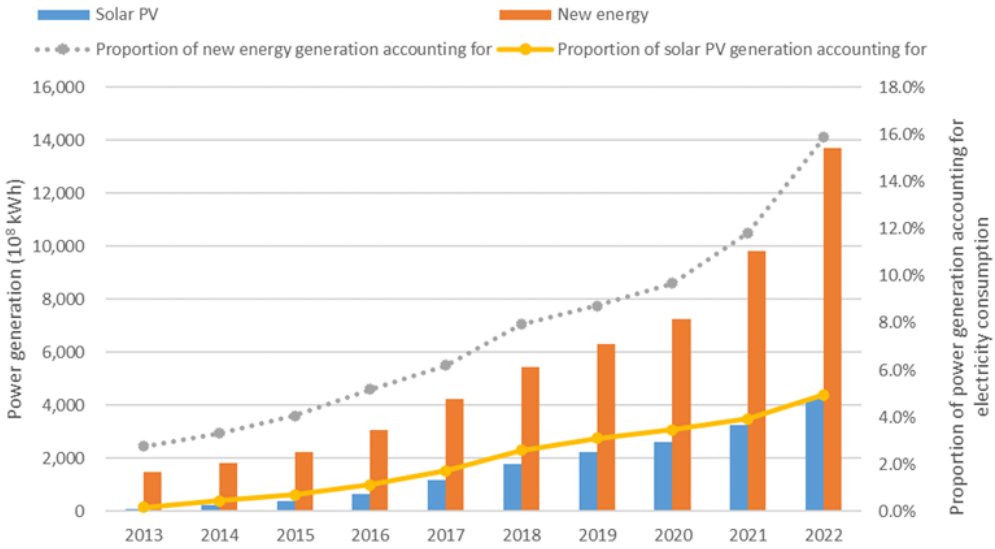


Figure 3. Proportion of the solar PV generation of China's total electricity consumption in 2013–2022.

3. An Analysis Framework for Exploring the Pathways toward Developing High-Proportion Solar PV Generation

After conducting an analysis of the development process and current status of solar PV generation in a country like China, this study develops an analysis framework for determining the potential risks and challenges and exploring the possible pathways toward constructing high-proportion solar PV generation in countries including China aimed at achieving the carbon neutrality goal based on considering the back force of the constraint of achieving carbon neutrality within the specified timeframe and exploring the policy recommendations to promote the high-quality development of high-proportion solar PV generation with the aim of helping countries like China achieve the carbon neutrality goal more precisely.

3.1. Developing a Unified Analysis Framework

Establishing a unified framework is critical for conducting a system analysis and drawing valuable conclusions about exploring the possible pathways to developing high-proportion solar PV generation. Based on an examination of the process and status of solar PV generation development in a country like China, this article proposes a unified, multi-dimensional, and achievable framework through which to conduct a system analysis to foster the deployment of high-proportion solar PV generation in China and other countries aimed at achieving the goal of carbon-neutrality (illustrated in Figure 4). Countries, including China, will have to achieve the carbon neutrality goal within the specified timeframe. This will pose a strong constraint on the development of the new energy system and high-proportion solar PV generation. If the construction target of high-proportion solar PV generation cannot be achieved, the carbon neutrality goal will be difficult to achieve within the targeted timeframe. Therefore, this established analysis framework attempts to consider the impact of the constraint of achieving carbon neutrality within the specified timeframe on the development process of high-proportion solar PV generation, which names a back force. This will help identify the pathways toward developing high-proportion solar PV

generation more precisely, which will contribute to achieving the construction target of high-proportion solar PV generation toward carbon neutrality more effectively.

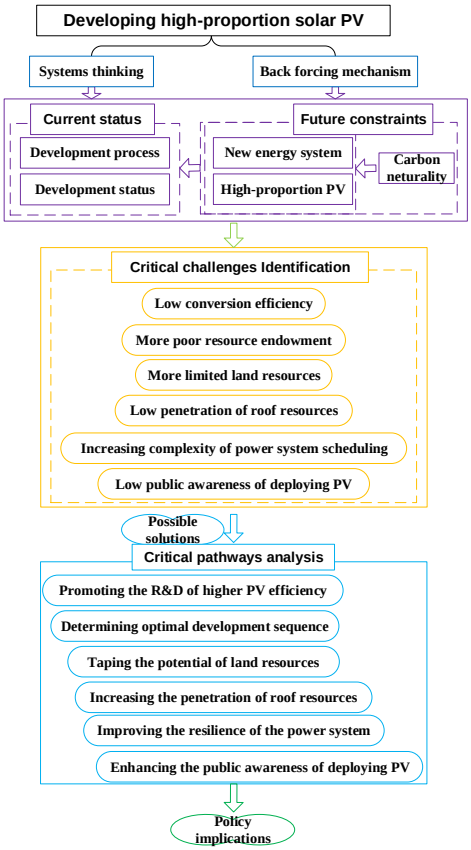


Figure 4. A framework for promoting the development of high-proportion PV generation.

From the perspective of systems thinking and considering the back-force mechanism, this study conducts a system analysis to explore the potential risks and challenges of the development process of high-proportion solar PV generation with the aim of achieving the carbon neutrality goal, based on considering the back force of the need to achieve carbon neutrality within the specified timeframe. This paper investigates the current status of solar PV generation development in a country like China. These findings will provide a crucial basis for the subsequent analysis aimed at investigating the critical risks and challenges that pose serious threats to the development process of high-proportion solar PV. Then, the work determines the possible pathways toward addressing these critical risks and challenges to promote the development of high-proportion solar PV generation toward carbon neutrality by considering the back force of the need to achieve carbon neutrality within the specified timeframe. Our findings will be helpful for obtaining policy implications aimed at fostering the development of high-proportion solar PV generation and for guiding the improvement of the formulation of government policies and related practices. After a challenge identification combined with subsequent pathway analysis, possible valuable ideas and suggestions for fostering the development of high-proportion solar PV with the aim of achieving the carbon neutrality goal are provided.

3.2. Systems Thinking for Sustainable Processes of High-proportion PV toward Carbon Neutrality

Due to the global climate change threats, developing high-proportion solar PV generation can fulfil many expectations for achieving a cleaner energy transformation and provide a more sustainable solution for reaching the carbon neutrality goal given its nature. In order to increase the sustainable supply of cleaner energy, efforts to stimulate the deployment of high-proportion solar PV generation aimed at reaching carbon neu-

trality have been made by many countries including China, Germany, and the USA. As the development process of high-proportion solar PV generation is an entire system of its own, with complex and dynamic features, sustainability considerations should be adopted with the aim of achieving high-quality development to achieve the carbon neutrality goal more precisely [35,57,58]. This will provide a unique opportunity to support government policies and management practices to align the deployment of high-proportion solar PV generation with the sustainable development goals (SDGs) proposed by the United Nations (UN) [59,60].

With the continuous evolution and dynamic development of systems thinking, there are an increasing number of academics and policymakers taking the systems approach to addressing sustainability challenges [61,62]. Given the complex and dynamic features accompanying the development process of solar PV generation, system analysis is applied to the fields of the optimization of policy solution formulation and management practices. This article adopts the systems approach to determine the potential risks and challenges and to explore the possible solutions for developing high-proportion solar PV generation in China, which is a typical country committed to the deployment of solar PV generation aimed at establishing a new energy system toward a carbon-neutral process. These will enable a systematic investigation of the possible risks and challenges and determine the suitable pathways toward developing high-proportion solar PV generation in a country like China.

The development process of high-proportion solar PV generation is influenced by the achievement of the goal of carbon neutrality. That is, identifying the potential risks and challenges of developing high-proportion solar PV generation and exploring the possible solutions to promoting the development of high-proportion solar PV generation should consider the impact of the need to achieve carbon neutrality within the specified timeframe. This study adopts the back force mechanism to identify the critical risks and challenges of developing high-proportion solar PV generation in countries like China and to explore the possible solutions to promote the high-quality development of high-proportion solar PV generation considering the back force of the need to achieve carbon neutrality within the required timeframe [63]. These will help investigate the potential risks and challenges and determine the suitable pathways to developing high-proportion solar PV generation with the aim of promoting the development of high-proportion solar PV generation more comprehensively.

4. Challenges in the Development Process of High-Proportion Solar PV Generation

Solar PV generation will play a vital role in the development of new energy generation and the establishment of new power system in a country like China. However, challenges emerge with the process of developing high-proportion solar PV generation considering the impact of the need to achieve carbon neutrality within the specified timeframe. These will be not helpful for constructing high-proportion solar PV generation considering the new situation. Considering the impact of the constraint of achieving carbon neutrality within the specified timeframe aimed at achieving the carbon neutrality goal more precisely, this paper attempts to perform a systematic investigation of the potential risks and challenges, which may pose serious threats to the achievement of the construction target of developing high-proportion solar PV generation in a country like China.

4.1. Low Conversion Efficiency of Solar PV Cells

The conversion efficiency is a vital parameter of solar PV power cells, which has a significant impact on the power generation capacity of solar PV generation. Currently, the highest conversion efficiency of the most widely used solar PV cells in China is about 26% [53,64]. The current conversion efficiency of solar PV generation systems generally remains at a low level. The lower the conversion efficiency of solar PV cells is, the less electricity is emitted from the area of solar PV cells absorbing light. Most of the solar energy resources have been wasted due to the low conversion efficiency of solar PV cells. This will

not only increase the installed capacity of solar PV generation due to the need for more solar PV cells, but it will also increase the consumption of various resources, thus increasing costs. In order to achieve the carbon neutrality goal, if countries like China want to develop high-proportion solar PV generation, the impact of the low conversion efficiency of solar PV cells on the deployment of solar PV generation will be increasingly significant. The low conversion efficiency of solar PV cells may pose a threat to the process of developing high-proportion solar PV generation in China.

4.2. Poorer Resource Endowment of Solar Energy

As a type of renewable, clean, and low-carbon energy, the new energy generation represented by solar PV generation is the most important part of the future power system. In order to reach the goal of carbon neutrality, countries need to speed up the construction of solar PV generation. This means that achieving carbon neutrality within the specified timeframe will create strong pressure on the development of solar PV generation, especially on the need to develop high-proportion solar PV generation. For instance, China is increasing its efforts to develop new energy power generation represented by solar PV generation, and it has made some achievements. However, the proportion of new energy generation of the total power generation and the proportion of new energy generation of the total electricity consumption are 15.8% and 15.9% respectively, which are at a relatively low level. This is far from the expected high proportion (60-80%) of the construction requirements. More effort should be made to develop more solar energy resources for constructing more solar PV generation projects. Although solar energy resources are very rich, the distribution is extremely uneven [65]. With the gradual development of solar PV generation projects, most of the high-quality solar energy resources will be developed. With the development of solar PV generation, the solar energy resources will become increasingly poor. Poorer endowment of solar energy resources, higher development costs, and a more chaotic development process will increase the difficulty of the follow-up construction of solar PV generation. Therefore, the follow-up development of a high proportion of solar PV generation will face serious problems.

4.3. More Limited Land Resources

The development of concentrated solar PV generation requires a large amount of land. Although China is a large country, it has the second largest population in the world. Therefore, its land resources are very limited. Most of the land is used for fulfilling certain human needs. According to the third national land resource survey [66], the land use types in China include eight categories, as shown in Figure 5. The situation of land use is very tense, and the land resources that can be used to develop economic industries are limited. China's available land resources are also very limited, but many economic industries need to be developed. The development of solar PV generation will face increasingly fierce competition. New energy projects represented by solar PV generation projects generally cover a large area and involve complex land types as well as involve diverse land purposes, which brings corresponding risks to the construction of solar PV generation projects, as well as the protection of the ecological environment [67,68]. Ensuring the land demand for solar PV generation development and realizing the coordinated development of solar PV generation and the ecological environment will increase the difficulty of the large-scale and high-proportion development of solar PV generation in a country like China in the future.

4.4. Low Use of Rooftop Resources

In view of the significant advantages of distributed solar PV generation, many countries, including China, emphasize the development of distributed power generation represented by distributed solar PV generation, positioning distributed solar PV generation as equally important to centralized solar PV generation by adapting to the local conditions. China now has the second largest population in the world, with many buildings and rich rooftop resources. Regarding the rooftop resources of rural buildings in China, according

to the cooperative investigation and calculation of Tsinghua University and the former Satellite Information Institute of the Ministry of Land and Resources [69], the capacity of solar PV devices including various types that can be installed on these rural roofs is about 2 billion kW, and the annual power generation can be close to 3 trillion kWh, accounting for 36.1% of the total electricity consumption in 2022. In the future, with the continuous advancement of the urbanization process, China's rural population may further decline, but the scale of rural buildings and rooftop resources may not change much, and the scale of the capacity of distributed solar PV generation that can be installed will basically stabilize at this level. Regarding the urban rooftop resources in China, according to the estimation of the Land Satellite Remote Sensing Application Center of the Ministry of Natural Resources [70], the rooftop area of urban buildings is about 14000 square kilometers, about 1540 million kW of solar PV devices can be installed, and the annual power generation can reach 2310 billion kWh, accounting for 26.7% of the total electricity consumption in China in 2022. In 2022, China's installed capacity of distributed solar PV generation amounted to 157.6 million kW, which was far lower than the potential installed capacity. It is obvious that there has been limited development of the rooftop resources of buildings. The use rate of the rooftop resources for the deployment of solar PV generation is very low.

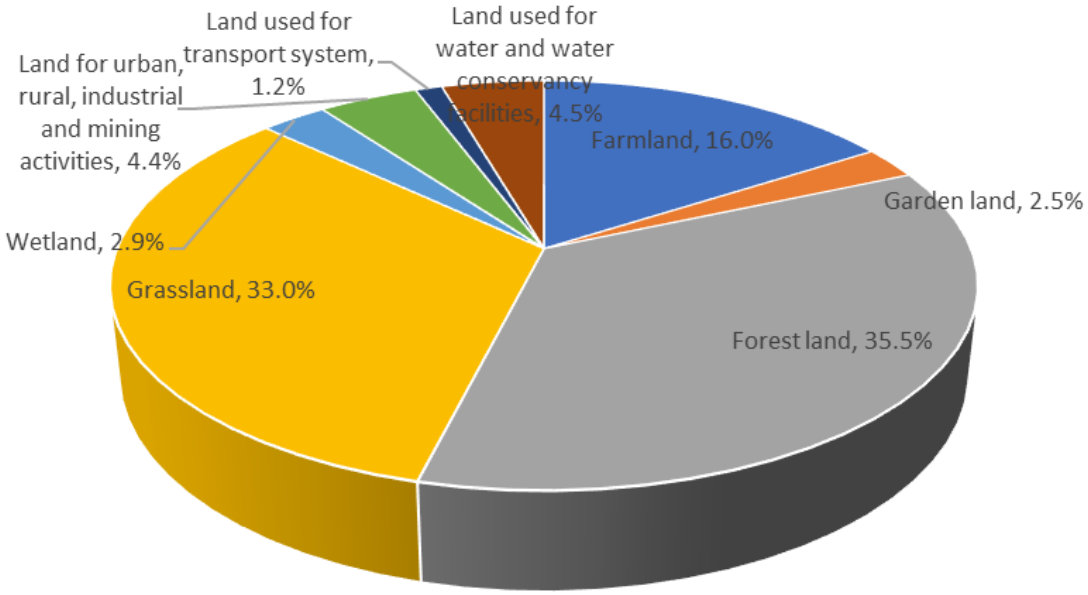


Figure 5. Typical types of land use in China.

4.5. An Increasing Complexity of Power System Scheduling

The new energy generation represented by solar PV generation is clean, low-carbon, and renewable. And there are rich solar energy resources for the deployment of PV generation. But the defects of new energy power generation are also very obvious; in particular, the power system faces many challenges due to the grid-connection of a large share of solar PV generation. The new energy generation represented by solar PV generation has significant intermittency, volatility, and uncertainty, which pose great challenges to the stability and peaking capacity of the power grid and power system [71]. With the increasing proportion of new energy generation represented by solar PV generation in the power system, the power supply structure of the power system will gradually undergo great changes. Owing to the high permeability of solar PV generation, the randomness, volatility, and uncertainty of the output of solar PV generation will gradually impact the stability and peak regulation of the power grid and power system. In particular, in the future, China will develop large-scale and high-proportion solar PV generation, which will greatly challenge the stability of the power grid and power system and dramatically

increase the complexity of the dispatch of the power system with a high proportion of solar PV generation [72].

4.6. Low Public Awareness of Deploying Solar PV Generation

Distributed solar PV generation is a burgeoning industry. Public acceptance and the implementation of the national new strategy will be established based on recognition and understanding. According to the survey on the use of distributed solar PV generation for rural households in 31 provinces [73], the generalizability of the national strategy and related policies of distributed solar PV generation in rural areas is still low, and the effect of the publicity and science popularization implemented by village committees is not ideal. Based on the sample surveys, the analysis found that 60% of residents had insufficient understanding of the significance of the construction of rooftop distributed solar PV generation projects and were "confused" about the complex process of deploying rooftop distributed solar PV generation projects. If the public lacks awareness of the significance, specific process, and rights and interests of the construction of rooftop distributed solar PV generation, the large-scale promotion of rooftop distributed solar PV generation will be hindered. In this study, when we investigated the situation of the installation of distributed solar PV generation in industrial and commercial industries in China, we found that there was an unexpected factor that became the key factor affecting the installation of distributed solar PV generation, namely, "the installation of distributed solar PV generation will make the roof of the workshop leak". Such misconceptions will significantly hinder the development of distributed solar PV generation. Therefore, it is urgent to further enhance public awareness and public acceptance of the strategy and the policy of developing solar PV generation and other types of new energy power generation in the future.

5. Pathways toward Developing High-Proportion Solar PV Generation

Based on the above findings, suitable solutions for precisely promoting the high-quality development of high-proportion solar PV generation in a country like China aimed at achieving the carbon neutrality goal will be obtained. This work attempts to conduct a systemic analysis for determining the possible pathways toward developing high-proportion solar PV generation in many countries like China from the perspective of promoting the research and development (R&D) of higher efficiency, determining the optimal development sequence of solar resources, tapping the potential of land resources, increasing the use of roof resources, improving the resilience of the power system, and enhancing the public awareness of deploying solar PV generation. It will provide guidance on the optimization of policy formulation and management practices on the practical actions of developing high-proportion solar PV generation toward carbon neutrality.

5.1. Continuously Promoting R&D for Higher Efficiency

Continuing to strengthen the R&D for solar PV technology to further break through the efficiency limits of solar PV cells will play a vital role in promoting the development of high-proportion solar PV generation in China. The higher the conversion efficiency of solar PV cells is, the higher the generation of electricity from the same area of a solar PV cell with the same light. In the future, it is necessary to further improve the power generation efficiency through R&D to increase the solar PV electricity generation and reduce the development costs, so as to increase the income and improve the economic efficiency, to promote more solar energy resources to be developed, and to build more solar PV generation projects. For instance, if the conversion efficiency of solar PV cells increases a percentage point in 2022, the solar PV electricity generation in China will increase 17.1 billion kWh, the installed capacity of solar PV generation will reduce 151.3 million kW, and the investment will reduce by CNY 625.1 million, under the same conditions. Therefore, more efforts should be made to continuously promote the R&D of highly efficient solar PV cells. For example, laminated crystalline silicon–perovskite cells are a vital option for increasing conversion efficiency in the future, because their theoretical efficiency limit can reach 43% [74].

5.2. Determining the Optimal Development Sequence of Solar Energy Resources

With the goal of carbon neutrality, the future energy system will be dominated by a high proportion of new energy power generation represented by solar PV generation. In order to build a new system dominated by solar PV generation, countries like China need to develop a large number of solar energy resources. However, given the characteristics of the resource endowment of solar energy, the future development of solar PV generation in these countries will gradually become difficult. Moreover, with the advancement of the development process of high-proportion solar PV generation, the resource endowment will become worse, and how to develop solar energy resources more efficiently will be critically important. To this end, countries like China can formulate a sequence for solar PV development to optimize the development process of solar PV generation, deeply tap the potential of solar energy resources, and develop as many solar energy sources as possible. Considering the resource endowment, technological progress, policy conditions, and economic benefits, a solar PV development sequence aimed at developing high-proportion solar PV generation can be formulated. Constructing a comprehensive evaluation model from the perspective of the technical dimension, economic dimension, and environmental dimension considering the resource endowment, technological progress, policy conditions, economic benefits, and other factors, will be helpful to formulate a specific sequence of solar PV development, to optimize the development process of high-proportion solar PV generation, and to efficiently develop solar energy resources and other new energies in a country like China.

5.3. Continuously Tapping the Potential of Land Resources

Land resources are a crucial factor limiting the deployment of new energy generation, represented by solar PV generation. In the construction process of a high proportion of solar PV generation, the limiting effect of land resources will become increasingly obvious. China must find ways to tap the potential of land resources and to break through the bottleneck for promoting the development of a high proportion of solar PV generation. In order to promote the development of high-proportion solar PV generation, China can try to make breakthroughs by following new paths. Firstly, the development of both centralized solar PV generation and distributed solar PV generation should be promoted, breaking through the restrictions of land resources according to the local conditions. In order to promote the development of centralized solar PV generation, increasing attention should be paid to make full use of fragmented land resources including waste land resources such as abandoned mines, marginal land resources such as highway roadsides, as well as inhospitable land resources such as saline–alkali land, for further increasing the installed capacity of solar PV generation. In order to promote the deployment of distributed solar PV generation, more efforts should be made to take full advantage of distributed solar PV generation, using the least land resources to build as many solar PV generation projects as possible. Secondly, the development of distributed solar PV generation plus others is an innovative development pattern for solar PV generation. The innovation of development patterns through distributed solar PV generation plus tourism, distributed solar PV generation plus fishery, distributed solar PV generation plus agriculture, and other models is a viable option to improve the efficiency of land resource utilization and to further increase the installed capacity and proportion of distributed solar PV generation.

5.4. Increasing the Use of Roof Resources

The previous analysis found that both the current installed capacity of solar PV generation in a country like China and the proportion of solar PV electricity generation of the total electricity generation are still relatively low. However, roof resources of buildings, which can be used to develop distributed solar PV generation, are very rich, and the future development of distributed solar PV generation has great potential. In the future, China needs to take innovative ideas and multiple measures to improve the use rate of the roof resources for distributed solar PV generation. First is to further identify the number of

roof resources for distributed solar PV generation. Currently, the number of roof resources that can be used to develop distributed solar PV generation in China is unclear, and the only available data were obtained from the results of one study, without a large-scale survey. China needs to carry out large-scale background surveys in the provinces, cities, and counties to determine the number of roof resources for distributed solar PV generation. Second is to introduce targeted policies and measures to effectively improve the use rate of distributed solar PV rooftop resources. China needs to introduce targeted policies and measures to promote the construction of distributed solar PV generation considering the type of building roofs and the potential for developing distributed solar PV generation projects, effectively improving the use rate of distributed solar PV roof resources and ensuring suitable building roofs are used for the development of distributed solar PV generation projects.

5.5. Improving the Resilience of the Power System

New energy generation, represented by solar PV generation, not only has the natural advantages of being clean and low-carbon but also has the natural defects of volatility, intermittence, and uncertainty. For achieving the goal of carbon neutrality, many countries like China urgently need to build a new power system dominated by solar PV generation. In order to develop a high proportion of solar PV generation, these countries have to overcome these natural defects of solar PV. Specifically, China should find a breakthrough path to enhancing the resilience of the power system from the following aspects. First is to actively develop new energy microgrids for multi-energy complementary. The development of a micro-grid composed of wind power, solar PV, natural gas power, and other energy supplies, with the participation of power suppliers and consumers, can help achieve a basic balance between local energy production and energy consumption load through energy storage and optimal configuration, achieve full consumption of new energy, and improve the comprehensive utilization efficiency of energy. This will be helpful to build a smart local area network for comprehensive energy utilization and to smooth the impact of solar PV generation on the power system. Second is to vigorously develop energy storage. The impact of a high proportion of solar PV generation will bring great challenges to the dispatching of the power system. The future power system needs to build a flexible power supply that includes various forms of energy storage to optimize the power scheduling, to cut peaks and to fill valleys, and to ensure the safe and stable operation of the power system.

5.6. Enhancing Public Awareness of Deploying Solar PV Generation

Combining the field investigation of this study with the existing research [72], the public's cognition of solar PV generation has a profound impact on the construction of solar PV generation. Improving the public's awareness and acceptance of solar PV generation will be conducive to the development of solar PV generation projects with the aim of developing high-proportion solar PV generation. Taking distributed solar PV generation as an example, countries like China need to introduce policies and measures to improve the public awareness of distributed PV generation projects in the future. Firstly, they need to strengthen publicity, education, and knowledge to enhance public awareness. Through publicity, education, and the popularization of scientific knowledge, the public will understand solar PV generation, including the significance, the development process, economic benefits, rights, and interests of building distributed solar PV generation projects. This will help improve public awareness and then increase the penetration rate of residential distributed solar PV generation and industrial and commercial distributed solar PV generation. Secondly, they need to take a multi-pronged approach to increasing the public willingness to develop distributed solar PV generation projects. Government departments, universities, and enterprises can work together to improve the public willingness to develop distributed solar PV generation projects through training courses for solar PV generation, museum visits for solar PV generation, and site visits for solar PV generation station, thereby increasingly improving the penetration rate of distributed solar PV generation.

6. Conclusions

Aimed at achieving carbon neutrality, countries, including China, emphasize the development of solar PV generation, which is positioned as a strategic part of the future power system. Considering the back force mechanism, this study conducts a system analysis to explore the potential risks and challenges of the development process of high-proportion solar PV generation in a country like China toward carbon neutrality based on considering the back force of the need to achieve carbon neutrality within the specified timeframe. The results show that the critical risks and challenges include a low conversion efficiency, poorer resource endowment, more limited land resources, a low penetration of roof resources, an increasing complexity of power system scheduling, and low public awareness. These challenges have emerged with the large-scale deployment of solar PV generation in a country like China aimed at developing high-proportion solar PV generation. After challenge identification, possible pathways toward developing high-proportion solar PV generation have been determined, including promoting the research and development of high-efficiency PV cells, determining the optimal development sequence of solar resources, tapping the potential of land resources, increasing the penetration of roof resources, improving the resilience of the power system, and enhancing public awareness of deploying solar PV generation.

Based on these findings, recommendations for government policies are proposed for fostering the deployment of high-proportion solar PV generation in a country like China. Specific policy countermeasures proposed are as follows: (a) promoting the research and development of PV cell technology with higher PV efficiency aimed at producing higher efficiency solar PV cell products, differentiated policies for multiple technology paths toward improving solar PV cells should be considered; (b) motivating the establishment of the optimal development sequence of solar energy resources, highlighting the development of the remaining solar energy resources as efficiently as possible to achieve the goal of constructing high-proportion solar PV generation; (c) establishing an incentive mechanism for tapping the potential of land resources for centralized solar PV generation and for exploring innovative development forms of distributed solar PV generation and finding more land resources to develop more solar PV generation projects; (d) putting greater effort into further identifying the number of roof resources and introducing targeted policies and measures to effectively improve the use rate of distributed solar PV rooftop resources; (e) stimulating the establishment of new energy microgrids that can complement each other with multiple energy sources, motivating the deployment of energy storage aimed at reducing the impact of high-proportion solar PV generation on the power system; and (f) formulating policy measures to strengthen publicity, education, and knowledge to enhance public awareness of deploying solar PV generation and to take a multi-pronged approach to increase the public's willingness to develop distributed PV generation projects.

System analysis in this article will help decision makers to examine the critical risks and challenges involved in the development process of high-proportion solar PV generation in countries, including China, and to explore valuable policy measures for fostering the deployment of high-proportion solar PV generation toward carbon neutrality. We anticipate that these findings will provide valuable resources for decision makers in a country like China aiming to develop solar PV generation to construct high-proportion solar PV generation to achieve the carbon neutrality goal. The recommendations for government policies presented in this study will also be helpful for decision makers to implement suitable approaches for the optimization of the process of developing solar PV generation. Moreover, the findings in this article will provide guidance for future researchers for identifying the possible risks and challenges which may affect the development process of constructing high-proportion solar PV generation and to determine effective government policies for promoting the high-quality development of high-proportion solar PV generation for carbon neutrality.

The established framework in this study focuses on a qualitative analysis for determining the possible risks and challenges involved in the developing process of high-proportion

solar PV generation in countries including China. Based on this analysis, policy recommendations are proposed to promote the high-quality development of high-proportion solar PV generation. In this established framework, it is difficult to measure the relationship between the construction of high-proportion solar PV generation and the achievement of the carbon neutrality goal in terms of examining the critical risks and challenges and evaluating the impact of policy measures on the deployment of high-proportion solar PV generation. Our future work will focus on a quantitative modeling framework to examine the potential challenges of the development process of high-proportion solar PV generation more precisely. It will attempt to perform an in-depth analysis by establishing a risk evaluation model based on more original data. And a quantitative analysis will be conducted to investigate the impact of policy measures on the deployment of high-proportion solar PV generation. Based on the in-depth analysis, more valuable policy suggestions may be provided to foster the deployment of high-proportion solar PV generation in the world considering the quantitative impact of a carbon-neutral vision.

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