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Review

A Review on Renewable Energy Transition under China's Carbon Neutrality Target

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Abstract: To achieve their carbon peak and carbon neutrality target, China's energy transition is seen as the most important instrument. Despite the rapid growth of renewable energy in China, there are still many challenges. Based on the review of the contemporary literature, this paper seeks to present an updated depiction of renewable energy in the Chinese context. The potential, status quo, and related policy of China's renewable energy are thoroughly investigated. The challenges facing renewable energy development under the carbon neutrality target are analyzed, including enormous transition urgency and pressure, technology, and policy issues. Then, coping strategies are proposed to guide the direction of renewable energy development. Technology paths and policy recommendations are presented. This paper contributes to technology developing and policymaking by providing a comprehensive, thorough, and reliable review of renewable energy development in China.

Keywords: renewable; energy transition; policy incentive; technology path; power system

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1. Introduction

In recent years, climate change and energy issues have become the prominent global challenge and a major concern of China. In 2020, president Xi Jinping pledged to achieve carbon peak by 2030 and carbon neutrality by 2060 (referred to as the dual carbon target). China's energy sector, which heavily relies on fossil energy, especially coal, is the largest contributor to China's carbon emissions [1]. According to the International Energy Agency (IEA), China's energy consumption accounts for nearly 90% of China's total CO_2 emissions in 2020 [2]. The carbon neutrality target poses a huge challenge to China's energy system, causing energy transition to be the key to the overall decarbonization of China's economy and society.

Despite aggressive energy transition goals, China still faces many challenges in the energy sector. In terms of energy supply, fossil fuel still dominates with the problem of overcapacity to be addressed [1,3,4]. The supply and consumption of renewable energy resources in China are also highly mismatched, the center of renewable energy is in the northwest, and the electricity consumption center is in the east. In terms of energy consumption, the load profile of energy is becoming increasingly complex and the regional energy distribution is becoming more diversified, which demands a higher power system flexibility [5]. Moreover, China's economy is still growing at a considerable rate and renewable energy cannot independently meet the energy requirement of the economy's growth. Effective incentives for promoting renewable energy consumption are yet to be formulated [6].

In facing the above difficulties during the energy transition, renewable energy is recognized as the most important instrument and has attracted more and more attention. China has rich reserves of renewable energy. In recent years, the development of renewable energy has been impressively rapid. At present, renewable energy has accounted for nearly 30% of China’s electricity generation [7,8]. China has shown a great commitment to renewable energy. The target of renewable energy generation was set to taking up more than 50% of China’s total installed power generation by the end of the 14th Five-Year Plan [9]. It is estimated that by 2060, China will invest about RMB 122 trillion to build a new power system with clean energy as the main body [10].

There are many studies on the renewable energy transition in China. They can be classified into two groups. The first group of studies focus on quantitative analysis of the development of renewable energy. For example, Zhang et al. adopted the China TIMES model to analyze the required renewable energy supply and electrification rate in achieving carbon peak. The results showed that if emissions peak in 2025, the carbon neutrality goal demands a 45–62% electrification rate and 47–78% renewable energy in primary energy supply in 2050 [11]. Another study predicted that by 2050, renewable energy would account for 60% of the total energy consumption and 90% of the total power generation and the electrification rate would be close to 60% [12]. Liu et al. studied the latest hourly wind and solar data from 2007–2014 and provided the optimal wind/solar ratio for hybrid wind–solar energy systems [13]. Wen et al. presented an approach for the quantitative analysis of energy transition. They explained whether China’s cumulative carbon emissions can match the emission allowances under the global 2 °C target and provided directions for the low-carbon transition.

The other studies focus on qualitative analysis of China’s renewable energy policy. Yuan et al. presented a review of China’s energy Five-Year Plans before 2012, showing a pattern of increasing levels of attention from the Chinese government to energy efficiency improvement and renewable energy development [14]. He et al. analyzed the existing renewable energy regulatory system, pointed out that the main problems restricting the development of renewable energy are institutional mechanisms and market factors, and put forward policy suggestions for the development of the electricity market [15]. Junxia Liu conducted a research on the imbalance and inapplicability of China’s renewable energy laws and policies and provided recommendations for a renewable energy policy mix, such as streamlining renewable energy laws and policy, improving the practicability of renewable energy, and implementing market tools [16].

However, few studies integrate technological reviews with policy analysis and since the carbon neutrality target was announced, earlier related research had little relevance. In order to fill this gap, this study combines qualitative and quantitative analysis to provide an up-to-date status of China’s renewable energy development, as well as the major challenges facing renewable energy under the carbon neutrality target. Based on a systematic review of the current situation and an analysis of the challenges, suggested technology and a policy coping strategy are put forward.

2. Methods

The research framework of this paper is shown in Figure 1. This paper consists of four parts: the extensive literature collection, technology analysis of renewable energy, policy analysis, challenge identification, and coping strategies.

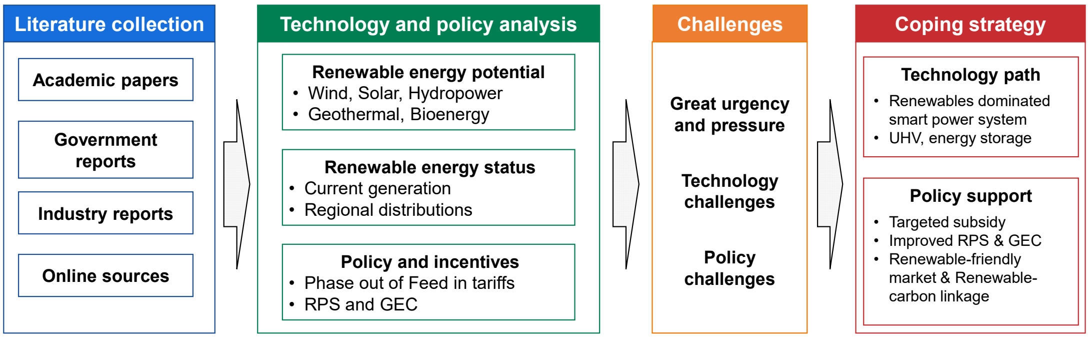


Figure 1. Research framework.

The study was carried out as follows. Firstly, this paper collected the literature from government, academic, and industry sources, the most important being the literature of the last 5 years. The key words searched on the website were mainly "China", "renewable energy", "subsidies", "renewable portfolio standard", "green power", "carbon neutrality", "renewable energy policy", etc. A total of about 200 papers and reports were collected, of which the 130 most relevant were selected. Then, a thorough analysis was conducted on all the relevant literature. Three thematic groupings were undertaken, i.e., renewable energy potential, status quo, and policy incentives. Secondly, based on the systematic literature review, the technology and policy challenges for renewable energy development under the carbon neutrality target were identified. In addition, to measure the difficulty and urgency of the renewable energy transition, predictions of the renewables' share in primary energy required to achieve carbon neutrality were collected and analyzed. The role of different renewable energy sources was compared. Finally, technology and a policy coping strategy are proposed. For technology strategies, the implementation paths of the key component in a renewable energy-dominated power system, such as energy storage, ultra-high voltage transmission, and intelligent dispatching, were put forward. For the policy support, four policy recommendations were proposed to ensure the transition from subsidy-driven development towards market-driven development.

3. Renewable Energy Potential and Status Quo in China

3.1. Renewable Energy Potential in China

China is endowed with abundant renewable energy resources that are currently underutilized and have significant potential for the development of renewable energy systems. Now, China has contributed remarkable achievements in renewable energy development, with the cumulative installed capacity and generation ranking first in the world. By the end of 2021, the cumulative installed capacity of renewable energy power generation in China exceeded 1 billion kW, reaching 1.06 billion kW [17]. Although the installed capacity has reached first place in the world, there is still substantial renewable energy to be developed. For example, the technical and economic exploitable installed wind power and photovoltaic (PV) power in China is estimated to be, respectively, 3.5×10^9 kW and 5×10^9 kW, which is much higher than what has been developed [18,19].

Hydropower resources are abundant in China. With a total installed capacity of 385 million kW, hydropower remains the second-largest conventional energy resource in China after coal [20]. China has 3886 rivers with theoretical hydropower reserves of more than 10 megawatts and more than 50,000 rivers with drainage areas of more than 100 square kilometers [19]. Hydropower was firstly developed in the early 20th century. In 2003, China completed the Three Gorges Hydropower Station with a total installed capacity of 22.5 GW, which is the largest hydropower station in the world [21]. In addition to power generation, hydropower can be used in many other areas such as flood control, irrigation, water supply, shipping, and tourism [22,23]. The total potential hydropower capacity is about 660 GW, of which 500 GW is technically and economically feasible [24].

Wind power plays an important role in the renewable energy supply of China. According to the meteorological department's assessment, the total potential capacity of China's land-based wind at 70 m height amounts to 5 billion kW [25]. It is far more than the installed wind power capacity. In terms of geographical distribution, China's wind energy resource varies greatly and presents a huge mismatch between supply and demand [26]. The southeastern coastal areas with large power demand have fewer wind power resources and the northern areas with huge wind power potential have fewer power demands. In terms of the temporal distribution, wind resources in the cold season (spring and winter, with a peak in April) are more than those in the warm season [27].

China is rich in solar energy, with 2/3 of China's areas having annual radiation levels above 5000 MJ per square meter [28]. In 2020, the average annual horizontal surface radiation on China's land was 1490.8 kWh/m^2 and the total land-based solar power potential is estimated to be 1.86 trillion kW [29]. However, similar to wind power, China's solar energy radiation also varies greatly among regions. Daily radiation ranges from less than 2 kWh/(m^2 day) to more than 9 kW h/(m^2 day). As shown in Figure 2, the most abundant area of solar energy in China is located in the southwest, while the middle and eastern coastal areas have lower solar exposure.

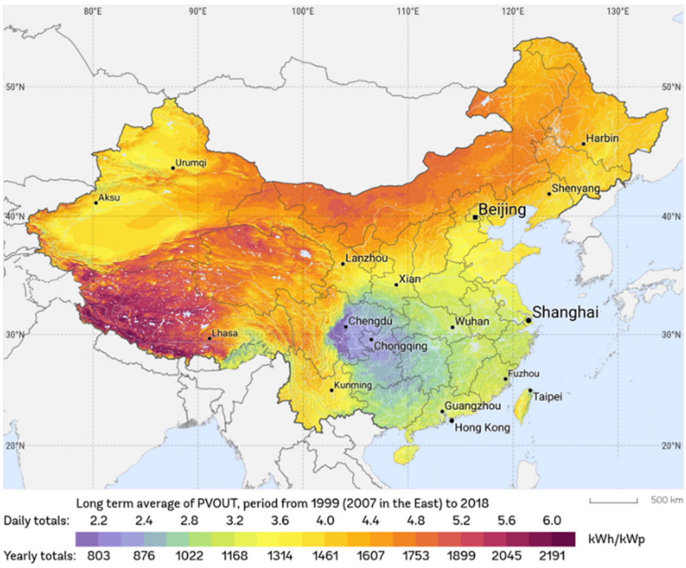
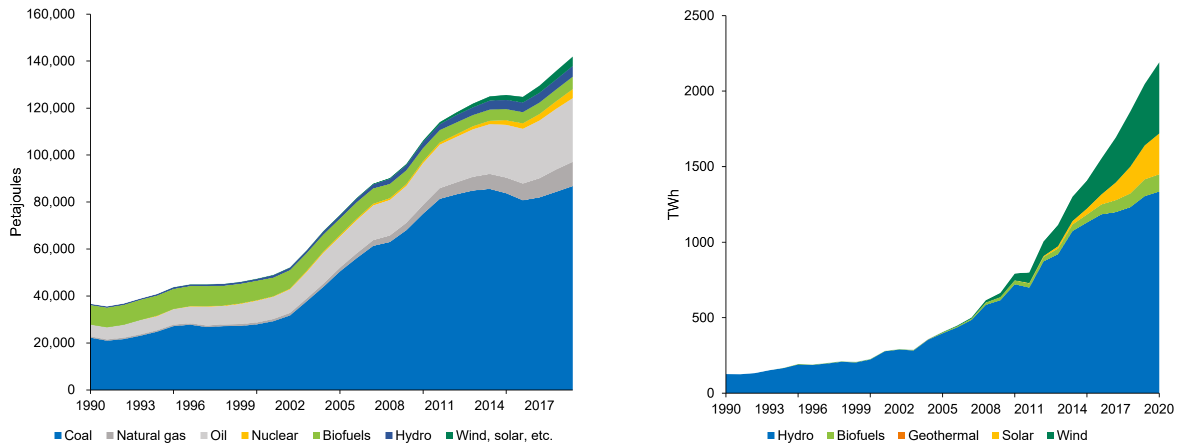


Figure 2. The solar energy potential of China [30].

Biomass energy utilization contributes a lot to the treatment of waste and environmental protection. Every year, China produces more than 900 million tons of agricultural and forestry wastes, equivalent to nearly 400 million tons of standard coal, but the current utilization rate of waste in China is still low, only 90 million tons per year are used for power generation [31]. Therefore, there is still much room for biomass power development in China. In addition, with the advancement of China's urbanization and industrialization, the domestic garbage volume and treatment rate maintain continuous growth, indicating a further increase in garbage power generation.

3.2. Renewable Energy Status Quo in China

According to data from China's National Energy Administration, China's primary energy heavily relies on fossil energy, especially coal. In 2021, the consumption of coal accounted for 56% of China's total energy consumption [32]. Although China's fossil energy supply is still rising, its share is declining with non-fossil fuels becoming an increasingly important role. Non-fossil energy mainly includes renewables and nuclear energy. According to IEA, as shown in Figure 3a, the proportion of non-fossil energy in the primary energy supply in China has increased from 9% in 2010 to 15.9% in 2020, maintaining a rapid growth rate. It is expected that by 2030, non-fossil energy will account for about 25% of primary energy consumption [6]. Among the non-fossil energy sources, the development of renewable energy is the most prominent. In 2021, China's total renewable energy use reached 750 million tons of standard coal, accounting for 14.2% of total primary energy consumption. The adoption of renewable energy reduced carbon dioxide emissions by about 1.95 billion tons, laying the foundation for achieving the "carbon neutrality" target.



(**a**) (**b**)

Figure 3. (**a**) Primary energy supply by the source of China, 1990–2019 [33]; (**b**) Renewable energy generation of China, 1990–2020 [33].

Considering renewable power generation only, as depicted in Figure 3b, China has seen rapid growth in renewable power generation over the past two decades, with hydropower accounting for the largest share and wind and solar PV as the fastest growing. The annual generation of renewable energy has increased tenfold in the past 20 years, The annual output of renewable energy has increased tenfold over the past 20 years, from 225 TWh to nearly 2000 TWh. The share of renewable energy in China's total generation also increased from 16.6% in 2000 to 28.2% in 2020.

Additionally, in 2021, China's renewable energy generation reaches 2.48 trillion kWh, accounting for 29.8% of the total generation. The shares of hydropower, wind power, solar PV, and biomass energy production are 16.1%, 7.9%, 3.9%, and 2%, respectively [33]. The growth of each type of renewable energy is as follows:

1. Hydropower generation remains the largest contributor to renewable energy in China, accounting for 54% in 2021. However, the share of hydropower is gradually declining as the cost advantage of wind and solar power becomes more prominent and the corresponding installed capacity surges.
2. Wind power generation has shown a steady growth rate during 2010–2020, contributing 27% of renewable energy generation in 2021.
3. Solar Photovoltaic power contributes 13% of renewable energy, with the highest compound annual growth rate of 81% among all renewables during 2010–2020.
4. Biomass generation is still in its infancy compared to solar generation, accounting for only 5% of the total renewable generation. However, it is growing at a high rate, nearly doubling from 2016–2017 to 2020–2021.

In the most recent five years, China's renewable energy development has been particularly remarkable. According to the national energy administration of China, as shown in Table 1, wind and solar PV have risen from 237 TWh and 67 TWh in 2016 to 471 TWh and 270 TWh in 2020, with growth rates of 98.7% and 305.6%. While the growth of hydropower is relatively steady, the hydropower generation from 2016 to 2020 has only increased by 12.7%. Although accounting for a small portion, biomass has also shown a great increase in recent years. The rapid development of renewable energy in China has significantly contributed to the transformation of the country's energy mix over the past few years and will play an ever-increasing role in the future.

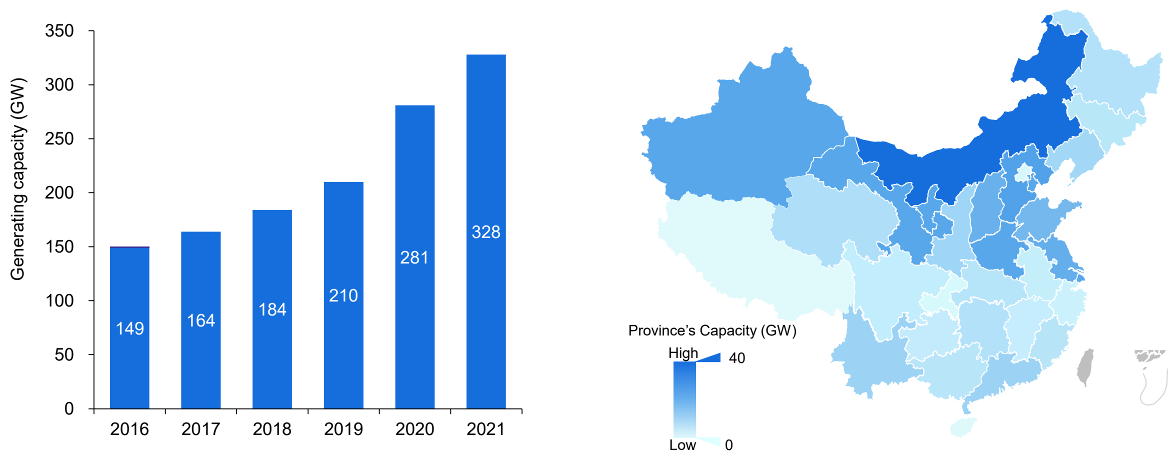
Table 1. Power generation by renewable energy of China (NEA [1]).

Renewables	2016–2017 (TWh)	2017–2018 (TWh)	2018–2019 (TWh)	2019–2020 (TWh)	2020–2021 (TWh)
Hydropower	1184	1198	1232	1304	1335
Wind	237	297	366	406	471
Solar PV	67	118	177	224	270
Bioenergy	65	79	91	111	114

[1] NEA means national energy administration.

3.2.1. Wind Power

Wind power plays a pivotal role in China's transition to a low-carbon energy system. As shown in Figure 4a, China's cumulative installed capacity of wind power reached 328 million kW by the end of 2021, indicating rapid growth [34]. China's installed capacity of wind power equaled 1.4 times that of the EU and 2.6 times that of the US by the end of 2020. China's wind power installed capacity has been leading the world for 12 years [35]. From 2010 to 2021, annual wind power generation increased from 44.6 TWh to 652.6 TWh [34]. In terms of installed plants, China currently has more than 4000 wind power plants. In 2021, 47.57 GW of new grid-connected wind power plants were installed nationwide, with the annual wind power generation increasing by 40.5% year on year. Onshore wind power dominates the total installed capacity, while distributed wind power accounts for less than 1% [34].



(**a**) (**b**)

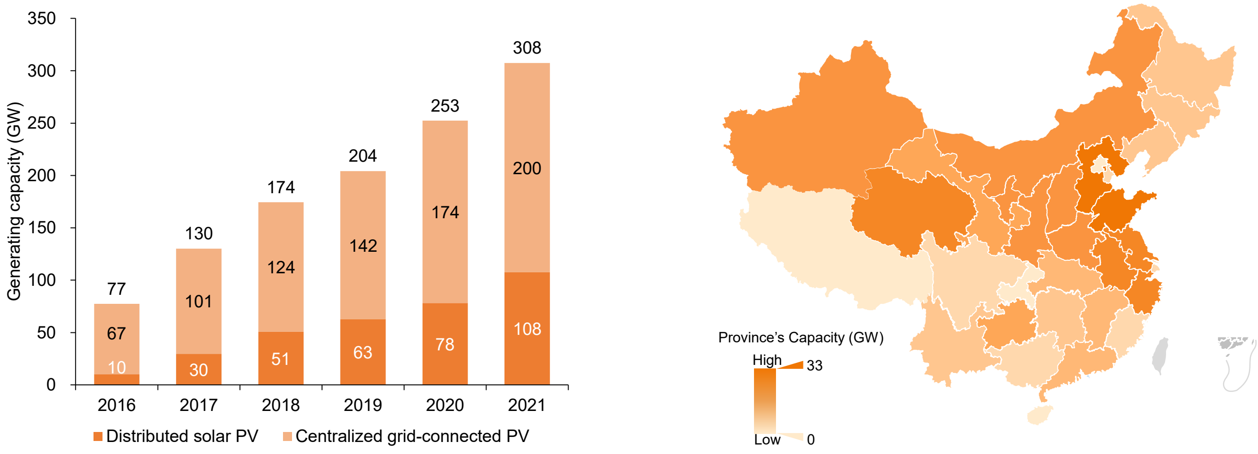
Figure 4. (**a**) 2016–2021 China cumulative installed wind power capacity; (**b**) 2021 China wind installed capacity by province [36–38].

As detailed in Figure 4b, China's onshore wind power capacity is mostly installed in the northern regions [39,40]. Inner Mongolia is the leading province with the largest installed wind power capacity of 39.9 GW. Although wind resources in Southwest China (mainly the Qinghai–Tibet plateau) are abundant, the installed wind power in this area is at the least level. It is difficult to build a wind power plant in Southwest China because of the low air density, high altitude, and fragile ecology. In addition, the rigorous intermittency and variability of wind power pose huge challenges to its consumption.

In addition to onshore wind, offshore wind is also playing an increasingly important role. In 2021, the newly installed capacity of offshore wind power reached 14.48 GW, a year-on-year growth rate of 276.7%. For China, the advantage of offshore wind sources is the wide range of environments in China's exclusive economic zone with water depths less than 60 m, which helps to significantly reduce the production costs of wind power [41].

3.2.2. Solar Power

Solar PV is the fastest-growing renewable energy source in China, playing an increasingly important role in China's energy supply. In 2021, China's solar power generation reached 325.9 billion kWh, with a year-on-year growth rate of 25.1% [34]. As detailed in Figure 5a, the annual installed capacity of solar PV reached 55 GW and the cumulative installed capacity reached 307.5 GW, with a compound growth rate of 32% from 2016 to 2021. Though the total capacity of solar PV is slightly less than that of wind, solar power is believed to be the backbone of China's renewable energy supply in the future due to its cost advantage and the popular adoption of distributed solar PV [42–45].



(**a**) (**b**)

Figure 5. (**a**) Cumulative generating capacity of China's solar PV; (**b**) 2021 China solar PV installed capacity by province [34,38].

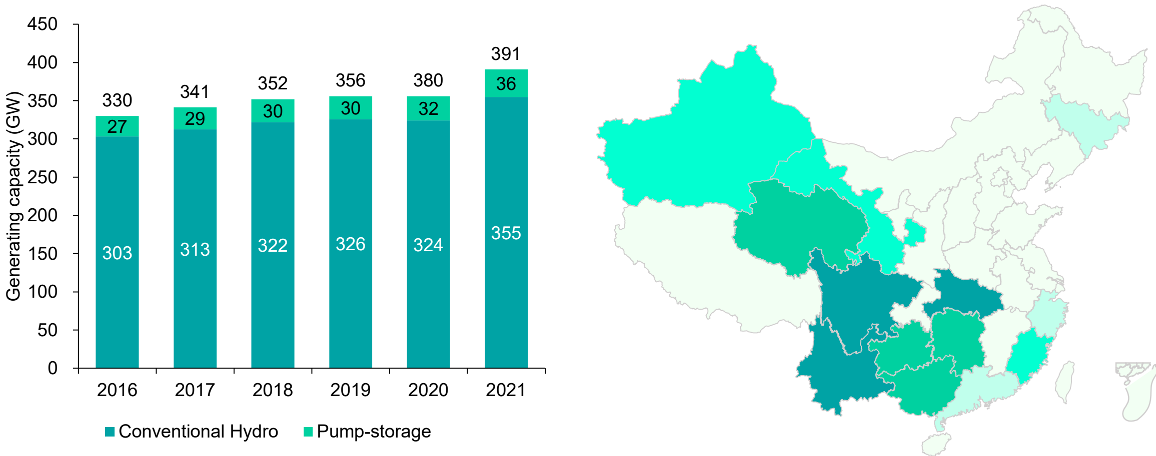
The centralized PV power station is usually a large-scale PV power station and its power generation is directly integrated into the public grid. Its installation scale is small and located closer to users. Compared with centralized solar PV, distributed solar PV has great advantages, such as unconstrained locations, high potential for nearby power utilization, and thus lower transmission costs and power losses. In recent years, distributed photovoltaics have dominated new photovoltaic installations in China. In 2021, distributed solar PV contributes to 55% of the newly installed solar PV capacity, which is the first time that distributed solar surpassed centralized solar power.

The geographical distribution of installed capacity is not balanced. As illustrated in Figure 5b, the regions with high installed capacity are North, East, and Central China, accounting for 39%, 19%, and 15% of the newly installed capacity in China, respectively. Shandong and Hebei rank first and second with cumulative installed capacities of 33.43 GW and 29.21 GW, respectively. Though solar resources in China are particularly abundant in the southwest and northwest of China [28,29], such as Tibet, Qinghai, Yunnan, Gansu, Shaanxi, and parts of Inner Mongolia, solar power generation in these areas is currently still minor. In terms of cumulative installed capacity, there is a huge imbalance between East and West China [46,47]. The proportion of East China's installed solar capacity is far more than that of Southwest and Northwest China. The installed capacity of Tibet is only 1.28 GW, indicating that it is still in the infancy of solar PV development.

3.2.3. Hydropower

Hydropower has long been the largest renewable power source in China [48]. Its generation and capacity continue to grow. Yet, considering resource constraints and environmental protection, the growth rate of hydropower in China is relatively slow.

There are 198 hydropower stations with more than 1000 MW capacity in the world, of which 60 are in China [49]. As detailed in Figure 6, by the end of 2021, China's cumulative installed capacity of hydropower has reached 391 GW, ranking first in the world. Its compound annual growth rate between 2016 and 2021 was only 3%, far lower than that of solar and wind power. Additionally, annual hydropower generation is 1339 billion kWh and contributes to 16% of China's total power generation in 2021, a 2 percentage-point decrease over 2020.



(**a**) (**b**)

Figure 6. (**a**) Cumulative capacity of China's hydropower; (**b**) 2021 China hydropower installed capacity by province [38,50].

Conventional stations and pumped storage are the two main types of hydropower. Pumped storage is considered the most suitable storage technology for highly variable renewable energy [22]. At present, China's installed pumped storage capacity is 36 GW (international hydropower), ranking first in the world (the world total is 160 GW). Nevertheless, pumped storage only accounts for 1.4% of China's total generation, which is still far behind developed countries in Europe and the United States [51]. It is expected to grow at a faster rate to 140 GW by 2050.

In terms of geographical distribution, China's hydropower is mainly distributed in the southwest, where hydropower generation accounts for about 60% of China's total. The Sichuan Province has the most installed hydropower at 89 GW. The primary reason for its geographical distribution is that hydropower stations have stricter environmental regulations. Southwest China is rich in hydraulic resources and its topography is suitable for the development of hydropower.

3.2.4. Others

Geothermal energy is a kind of renewable energy stored in the interior of the earth with great reliability and economy [52]. China is rich in geothermal energy, but the degree of development and utilization is relatively low. By the end of 2020, the total area of geothermal energy heating and cooling in China reached 1.39 billion square meters, reducing 108 million tons of carbon dioxide per year [53]. Due to difficulties in key technology improvement, however, its cost is higher compared with wind and solar power, resulting in slower growth [54]. The installed capacity of geothermal power in China is about 26 MW in 2019, which accounts for little in the total power system.

The growth of China's biomass energy is rapid. In 2020, the newly installed capacity of biomass power in China was 5.43 million kW, with a year-on-year increase of 22.6% [38,55]; there is now 29.52 million kW of cumulative installed biomass capacity in China. The generation of biomass power reached 132.6 billion kWh in 2020, which is 19.4% more than that of 2019. Its cumulative installed capacity and power generation accounted for 3.13% and 6.26% of total renewables, showing great room for growth. Currently, China is also promoting electricity and heat generation using waste. By applying CCS, waste can be converted into biomass, thus providing another pathway of negative emissions [56].

4. Policy and Incentives

In May 2021, China published the "1 + N" carbon neutral policy, of which "1" means the overall guidelines and "N" refers to the operating policy of key departments. The "1 + N" policy focuses on the transformation and carbon reduction in the 10 fields, of which the transformation of the energy structure is the most important [57]. There are many energy-related proposals, such as changing the energy structure, improving energy efficiency, and promoting clean energy technology innovation. The transformation of China's energy structure is confronted with great challenges. Policy and incentive measures are playing a crucial role in achieving the decarbonization goal. As shown in Table 2, from the beginning of the 21st century, China has begun to pay more attention to the development of renewable energy. In 2006, China issued the Renewable Energy Law, which formed the legal framework for renewable energy [58]. In 2007, the Medium- and Long-term Development Plan of Renewable Energy was formulated, promising to establish a perfect renewable energy technology and industry system by 2020 [58]. In 2008, renewable energy was formally incorporated into the Five-Year Plan, elevating renewable energy development to a national strategic status. In the following several years, plenty of policies on renewable energy subsidies were released and the subsidy-led development continued for about ten years [59].

Table 2. Major renewable energy policies in China over the past 20 years.

Year	Policy
2006	Renewable Energy Law of China
2007	Medium- and Long-Term Development Plan for Renewable Energy
2008	11^{th} Five-Year Plan for Renewable Energy Development
2009	Feed-in-tariff Policy for Wind Power Generation
2011	Feed-in-tariff Pricing Policy for Photovoltaic Power Generation
2015	Special Fund for Renewable Energy Development
2017	Implementation of Renewable Energy Green Power Certificate Issuance
2019	Notice on the Renewable Electricity Consumption Quota Mechanism
2021	14^{th} Five-Year Plan for Renewable Energy Development

In the past decade, China's FiTs have dominated the growth of renewable energy, especially wind and solar PV [60]. With the ever-increasing subsidy gap and the cost reduction in wind and PV, China's renewable energy has now shifted from the FiTs period to the grid-parity era, from a government-led pattern to a market-led one.

4.1. Feed-In Tariffs (FiTs)

The Chinese government's incentive policy is of paramount importance in promoting the growth of installed renewable energy. Renewable energy subsidies in China have gone through three stages: strong subsidies, subsidy phase-out, and grid parity [61]. As Figure 7 shows, as early as 2006, the Feed-in tariffs (FiTs) were established to subsidize grid-connected renewable energy projects [62]. The Ministry of Finance, the National Development and Reform Commission (NDRC), and the National Energy Administration (NEA) jointly formulated the benchmark FiTs system for renewable energy [63]. Among them, the Ministry of Finance will determine the total amount of subsidies for renewable energy projects; the NDRC and NEA allocate subsidies for various renewable energy generation projects. In 2009, the NDRC of China issued the "Notice on Improving the Policy of FiTs for Wind Power Generation" and decided to adjust FiTs for onshore wind power according to the region's resource level [64]. In 2013, the Ministry of Finance announced that distributed photovoltaic power generation projects would be subsidized according to the generation. Solar photovoltaic power generation also began to implement a similar subsidy system based on the level of resource zone [65]. China's solar and wind power resource areas are divided into three and four categories, respectively, according to the average annual utilization hours. The number of subsidies increases with the decrease in utilization hours. In 2015, the NDRC announced the reduction in the subsidy. Since 2015, the FiTs benchmark for onshore wind power and solar PV have been gradually decreasing with the increasing of scale. In 2016 and 2018, China's PV and wind FiTs were announced to be determined by tendering the further cut subsidies [66]. In January 2019, the NEA and NDRC jointly announced a plan to start subsidy-free wind and solar pilot projects in areas with superior wind or solar resources and high local energy consumption [67,68]. These projects do not receive subsidized electricity prices but can receive long-term contracts at prices equal to or lower than the local benchmark FiTs for coal plants. Unsubsidized renewable energy projects are on the rise. In 2020, 11.4 GW of wind projects and 33 GW of solar PV projects were subsidy-free. With the rapid increase in renewable energy installed capacity, the subsidy gap is surging. According to statistics from the Ministry of Finance, in 2020, the gap in national subsidies for wind and photovoltaic power is over 300 billion RMB [69,70].

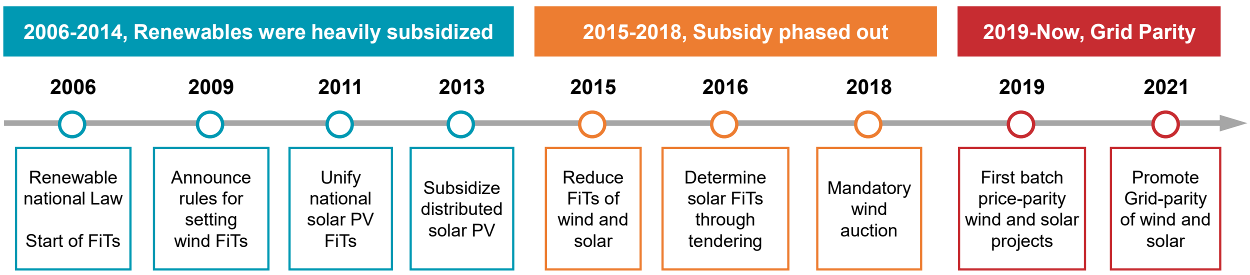


Figure 7. Timeline of renewable energy incentives in China, 2006–2021.

In June 2021, the NDRC announced that newly installed centralized PV, commercially distributed PV, and onshore wind energy would no longer be eligible for subsidies, meaning that grid parity would become mainstream. Reviewing the subsidies from 2016–2020 reveals that subsidies for both solar and wind power in China have decreased dramatically. As shown in Table 3, subsidies for centralized solar PV decreased from a maximum of 0.8–0.98 RMB/kWh in 2016 to 0.35–0.49 RMB/kWh in 2020 and for distributed solar PV from 0.42 RMB/kWh to 0.05–0.08 RMB/kWh. The decrease in onshore wind power is consistent with the declining trend of centralized photovoltaic energy, from 0.47–0.6 RMB/kWh in 2016 to 0.29–0.47 RMB/kWh. While the construction cost of offshore wind power is still hard to reduce because of the lack of key technology breakthroughs, its subsidy remains at 0.85 in 2016–2018 [71]. In 2020, it has slightly decreased to 0.8 RMB/kWh. For China's FiTs policy, 2019 is a key turning point. From 2019 onwards, state subsidies for solar and wind power have shifted from benchmark tariffs to guiding tariffs, causing FiTs to be determined by market competition. This mechanism provides better play to the role of the market and meanwhile reduces the financial pressure on the government.

Table 3. China's subsidies for wind and solar power in 2016–2020 (RMB/kWh) according to NEA.

Renewables		2016 (Benchmark)	2017 (Benchmark)	2018 (Benchmark)	2019 (Guiding)	2020 (Guiding)
Solar PV	Centralized	0.8–0.98	0.65–0.85	0.5–0.75	0.4–0.55	0.35–0.49
	Distributed	0.42	0.42	0.32–0.37	0.1–0.18	0.05–0.08
Wind	On-shore	0.47–0.6	0.47–0.6	0.4–0.57	0.34–0.52	0.29–0.47
	Off-shore	0.85	0.85	0.85	0.8	0.75

In addition, the cost of renewable energy is falling and now China has phased out subsidies for renewable energy. The newly installed onshore wind power and solar projects would no longer be subsidized by FiTs since the end of 2020 [72]. While household-distributed solar PV is still subsidized by 0.03 RMB/kWh. In 2022, the new energy subsidy budget of the Ministry of Finance is RMB 3.87 billion , of which RMB 1.55 billion for wind power, RMB 2.28 billion for solar, and RMB 38.24 million = for biomass [73,74]. The principle of subsidies is to prioritize national anti-poverty projects, projects with an installed capacity of 50 kW and below, public renewable energy independent system projects, etc. China's renewable energy has entered the era of grid parity. The key to achieving grid parity is the market-oriented system and the emission reduction benefits of renewable energy are reflected in value through the green certificates.

4.2. Renewable Portfolio Standards and Green Electricity Certificate

In May 2019, China's NDRC announced the notice on the renewable electricity consumption quota and related matters and started the renewable portfolio standards (RPS) for renewable consumption. The RPS refers to the target share of renewable energy power consumption in the total power consumption of different provinces. It consists of two assessment indicators: the total renewable energy consumption and the non-hydro renewable energy consumption. Considering the variations in renewable energy development between provinces, different provinces have varied renewable consumption obligations.

Given that non-hydro renewable energy has become the major development focus, non-hydro renewable obligations are more indicative. As Figure 8 shows, most provinces' non-water renewable energy consumption quotas are between 10 and 25% in 2021. Qinghai and Ningxia ranked in the top two with 24.5% and 22%, respectively. Tibet is excluded from renewable energy quotas due to the difficulty of them consuming renewable energy. In May 2021, the NEA issued a notice on the development and construction of wind power and photovoltaic power generation in 2021. It was mentioned that to strengthen the mechanism of the renewable electricity consumption quota, indicating that RPS will play a major role in developing renewable energy.

The launch of RPS indicates that China's renewable energy development is transitioning from fiscal incentives to market direction, i.e., from FiTs to RPS and renewable certificates. There are two ways of completing the consumption obligation as follows. (1) The market players that bear the obligation of RPS consume renewable energy power to complete the target, which is the major way. (2) As a compensatory measure for completing the target, duty-bearers can purchase renewable-related certificates from the regional power grid enterprises to complete the quota targets.

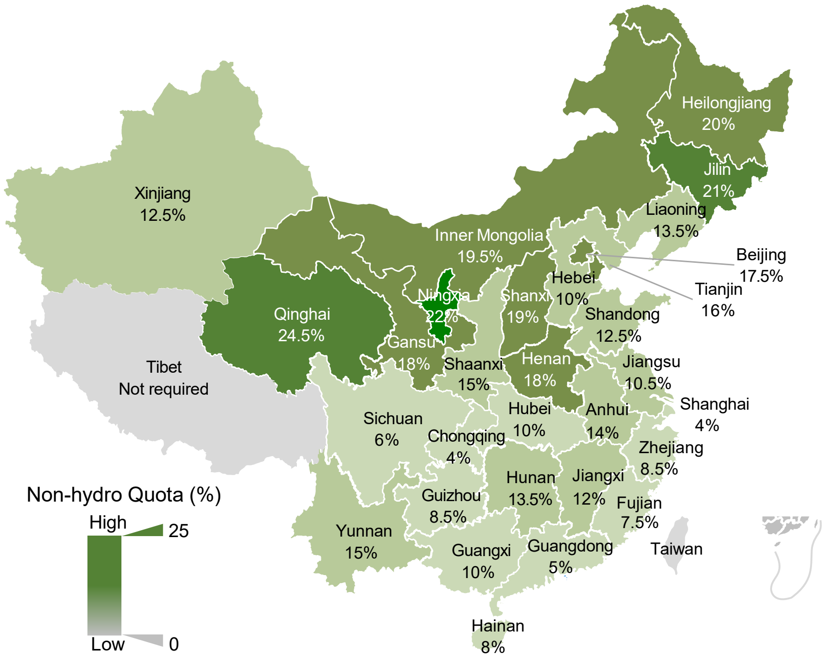


Figure 8. Provincial non-hydro renewable obligations for 2021 [75].

In conjunction with the RPS mechanism, China's green electricity certificate (GEC) system is becoming increasingly important. In 2017, China announced the trial implementation of renewable energy green power certificate issuance and the voluntary trading system. The green electricity certificate refers to an electronic certificate with unique code identification issued by the state to power generation enterprises according to their renewable power generation. Each green certificate corresponds to 1 MW of settlement power and each certificate has a unique code, reflecting the basic situation of the project. The green electricity certificate is proof of green electricity consumption. The holder of GECs and the demander of GECs, who undertakes the specified quota obligation, monetize the GEC through market trade. The price of GECs is determined by the market. However, GECs are not the only way to meet the quota target. Electricity consumers can also complete the obligation by developing and constructing self-generating renewable energy projects. By setting the green electricity certificate, green electricity can be circulated among different entities and the business model based on green electricity can be constantly evolved. All in all, it can provide information identification and policy guarantees for green consumption, so that the green value of clean energy can be smoothly reflected into the market value and keep a sustained development.

The green electricity certificate is divided into two types, subsidized certificate, and unsubsidized certificate. The price of a subsidized green card is higher, while GECs of grid parity projects (unsubsidized) are cheaper, costing about RMB 50 per certificate. At the beginning of 2020, China announced Several Opinions of the Ministry of Finance, the MDRC, and the NEA on Promoting the Healthy Development of the Power Generation of Non-water Renewable Energy, making it clear that the GEC mechanism will be fully implemented and enterprises will obtain income from GEC trading to replace former FiTs. As of January 10 2022, about 38.07 million green certificates had been issued and 619,198 had been subscribed, of which 540,426 were unsubsidized green certificates, accounting for 88% of the total subscription number [76]. China's current RPS + GEC mechanism serves as a substitute for the subsidy policy (FiTs). In the era of renewable power grid parity, it is a more suitable system that can ensure the achievement of China's mid- and long-term energy development goals in a market-oriented manner and address the challenges caused by the withdrawal of incentives.

RPS and GEC are two main policy tools that complement each other. Through market-based methods such as green electricity trading and the voluntary purchase of green electricity certificates, incentives are provided to market players to balance the consumption differences of renewable energy nationwide and achieve RPS's effectiveness, to establish a long-term mechanism for ensuring the consumption of renewable energy electricity. As one of the significant policy tools, the GEC is aimed at supporting the completion of RPS. RPS and GEC can reduce the burden of financial subsidies and encourage the market-driven growth of renewable energy.

5. Challenges to Renewable Energy Transition under the Carbon Neutrality Target

5.1. Great Transition Urgency and Pressure

The energy transition is key to achieving carbon neutrality. Since nearly 90% of China's greenhouse gas emissions come from its energy sector [2], the mitigation task for the energy sector is especially heavy. Before the carbon peak and carbon neutral targets were proposed, the targets for renewable energy development were relatively modest. As proposed in the 13th Five-Year Plan in 2016, the targets for the share of non-fossil energy consumption were set at 15% in 2020 and 20% in 2030 [77]. However, in October 2021, the "Carbon Peaking Action Plan before 2030" was issued by the State Council of China [78]. It proposed that the proportion of non-fossil energy must reach more than 20% in 2025. Now the 2030 target proposed in 13th Five-Year Plan has been brought forward to 2025. The target share of wind and solar power generation in total power generation was set at 20.14%, an increase of 10.60 percentage points over 2020 [78]. During the 14th Five-Year Plan period, wind and solar power generation are supposed to exceed the sum of the 10 years from 2010 to 2020, indicating a more aggressive growth than before. The energy sector must realize a structural transformation to achieve carbon neutrality. It means that the energy structure will shift from fossil-based to renewable-based [79]. A renewable-dominated power sector is generally viewed as the foundation and the most important technological tool in achieving the carbon neutrality target.

Under the carbon neutral scenario, most institutions and scholars predicted that the proportion of renewable energy in primary energy would increase from about 10% in 2020 to about 70% in 2060. Figure 9 shows the prediction of different scholars. Zhang et al. predicted that renewable energy will account for more than 65% in China's 2060 primary consumption [80]. Zhang et al. calculated that under the 2030 carbon peak scenario, China's renewable energy will account for more than 68% of primary energy in 2050 [11]; the China National Petroleum Corporation (CNPC) predicts that by 2030 and 2060, China's renewable energy will account for 23.87% and 70.44%, respectively [81]. In this paper, we calculate the average of prediction data from these institutions and scholars. The results show that by 2030 and 2060, the proportion of renewable energy in the primary energy in China will reach 20% and 66%, respectively. To achieve a carbon peak, the share of China's renewable energy in primary energy needs to achieve a 10% growth in 10 years, which means a 1 percentage increase per year. Compared with the task of peaking carbon, it is more difficult and urgent to achieve carbon neutrality. The share of renewable energy needed to achieve carbon neutrality will increase by 60% over 40 years, which is a 1.5 percentage increase per year. This implies faster and more aggressive growth between 2030 and 2060 than between 2020 and 2030. In addition, such a high share of variable energy will pose serious challenges to China's relevant infrastructure, such as power transmission, power distribution, and energy storage.

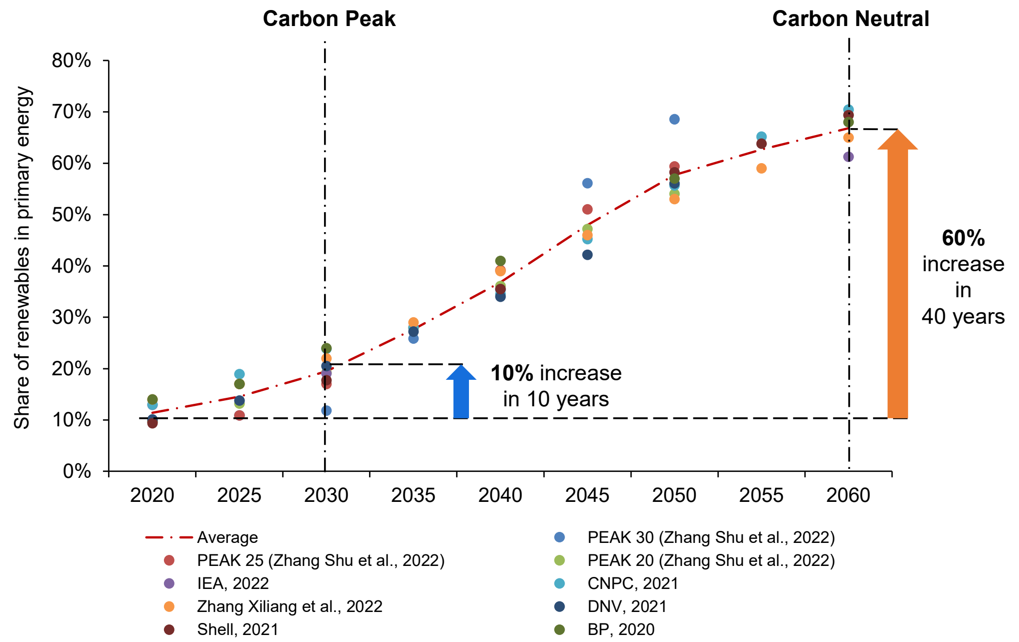
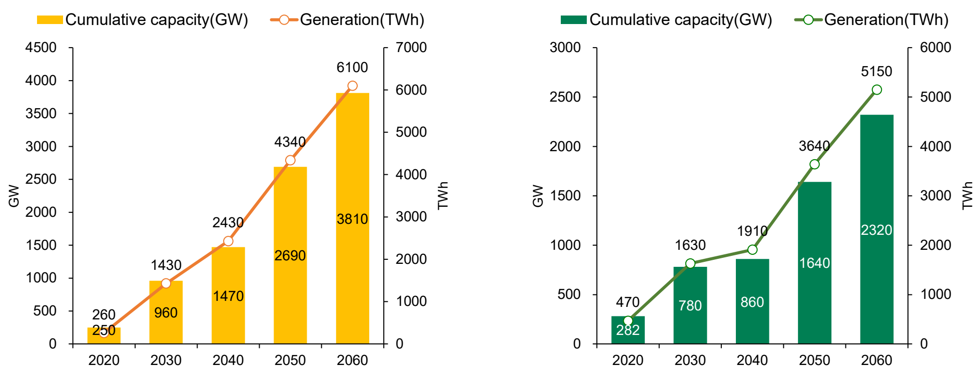
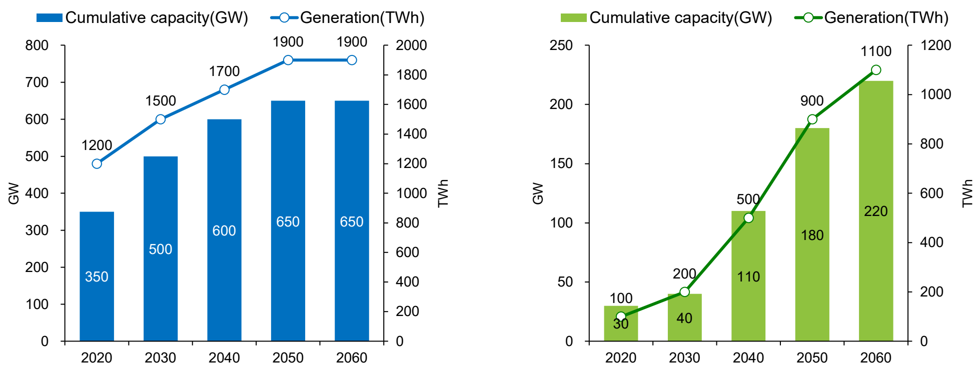


Figure 9. The predicted share of renewable energy in primary energy supply [2,11,80–84].

Among all renewables, the large-scale development of wind and solar PV are the two most important contributors to achieving carbon neutrality. According to data from the CNPC, as detailed in Figure 10, between 2030 and 2060, the average annual increase in installed solar PV and wind power is expected to be 95 GW and 51 GW, respectively, with most of them being built in the resource-rich regions, e.g., North and West China [81]. The installed solar PV and wind capacity are expected to reach 3810 GW and 2320 GW in 2060, 15 and 8 times more than in 2020, respectively. It is expected that the total wind and solar power generation will reach 11.2 trillion kWh in 2060, accounting for 60.7% of total power generation. Since wind and solar PV are both strongly volatile energy sources. Such rapid growth rates and large expansions in wind and solar energy would place a higher demand on the flexibility of energy systems, the improvement of grid regulation capabilities, and the evolution of power markets.



(**a**) (**b**)



(**c**) (**d**)

Figure 10. Predicted capacity and generation of China's renewables: (**a**) solar PV; (**b**) wind; (**c**) hydropower; (**d**) bio-energy [81].

Compared with wind and solar PV, the growth of hydropower is supposed to be relatively stable and slow. Its proportion of total electricity generation will gradually decrease in the future, from 16% in 2020 to 10% in 2060. For hydropower, major attention will be paid to energy storage and peak shaving to support the construction of a smart power system.

Biomass power generation has a special but important role. It can replace industrial coal-fired boilers and rural bulk coal combustion, which will be the main scenario for biomass energy to facilitate decarbonization. From 2030, in combination with carbon capture, utilization, and storage (CCUS) technology, biomass will serve as a negative emission source for the energy system [85]. It is expected that power generation from biomass energy will reach 1100 TWh by 2050, achieving emission reductions of over 2000 Mt CO_2e in an optimistic scenario.

It can be seen from the above that to achieve carbon neutrality, renewable energy bears great transition urgency and pressure. A comprehensive technology strategy and policy support are the foundation for achieving these goals. However, at this stage, it is difficult for China's renewable energy to support the transformation goal in terms of technology and policy system. There are still many challenges and difficulties in the technology foundation and policy mechanism. Technically, it faces difficulties in consumption, instability in the industrial chain, high costs, and demanding natural conditions. In terms of policy, due to the current transition from subsidy-driven to market-driven, there is still a lack of corresponding market mechanisms and appropriate incentives.

5.2. Consumption Challenges and Technology Flaws

The first and most important technology challenge facing China's renewables is to promote renewable energy consumption. It has attached great attention from the Chinese government and industry. In March 2021, the State Grid Corporation of China released the "carbon peak, carbon neutral" action plan, improving the consumption of renewable energy was said to be a crucial task [86]. On 1 June 2022, the NDRC issued the 14th Five-year plan for renewable energy development. The Plan set a target of 18% of non-hydro RPS in 2025, compared with 11.4% in 2020 [9]. The challenges in consumption mainly come from two aspects. On the one hand, the volatility and intermittency of renewable energy cause it to be difficult to connect to the grid and result in a low utilization rate [87]. Therefore, energy storage is required to reduce the abandonment of wind and solar energy. The current generation cost of photovoltaic and wind power has already become remarkably competitive, but its utilization cost is still high, mainly due to curtailment and additional costs. In 2020, wind power curtailment and solar power curtailment reached 16.61 billion KWh and 5.26 billion kW, respectively. The curtailment rate of renewable energy in Xinjiang, Qinghai, Tibet, Gansu, and other western regions even exceeds 10%

[36]. Part of the renewables is either abandoned or stored in the energy storage system, while the energy storage system can increase the cost of renewables by 30–60% on average and even double for projects with high construction costs [88–90]. On the other hand, China's renewable energy-rich area is in the west, while the load center is in the east. Therefore, energy storage and UHV transmission are needed to balance the uneven distribution of energy. For example, in the first half of 2022, the newly installed renewable capacity in Northern and Western China accounted for 72.5% [91], but the power consumption center lies in the coastal Eastern China [92,93]. The curtailment of renewable in Southwest China is the most serious due to insufficient local consumption and limited grid dispatch capacity [94]. For example, the curtailment rate of Tibet remains at nearly 20%, ranking first in China [95]. This demands an enhanced transmission network to balance energy supply and demand between the east and west of China, which can further promote the consumption of renewable energy. Thus far, whether the power system has sufficient "storage and adjustment" capacity is a key factor determining the consumption of renewable energy [96].

The second technology challenge comes from the industrial supply chain. The rapid development of renewable energy has greatly increased the long-term demand for critical materials. Unlike traditional fossil energy power generation, photovoltaics and wind turbines require more lithium, nickel, cobalt, manganese, and other metal materials [97]. China relies heavily on imports for these materials, which brings huge impact and uncertainty to the industrial chain under the current international upheaval and epidemic [98,99]. The scale-up of renewable energy and rapid technological iteration put forward higher requirements for parts and components process and raw material attributes [100]. In the future, technological innovation will be more difficult to bring down renewable energy costs than in the past.

The third one is renewables' low land-use efficiency and higher natural condition requirements. Wind energy and solar energy are energy forms with low energy density. To replace fossil energy, more land areas need to be occupied or affected. Taking a common 4 × 600 MW thermal power plant as an example, according to national standards, its maximum required area is about 330 hectares, while the construction area of a wind farm of the same scale is about 50 times that. A hydropower station normally has a more complex structure and occupies a larger area relative to wind and solar stations, it has higher requirements for natural conditions [101]. Recent climate change has threatened the reliability of the water supply, posing huge challenges to the hydropower project [102]. Additionally, the developed hydropower resource in China already accounts for 57% of the total exploitable value [101,103–105]. Further development is hindered by many problems such as demanding transportation, difficult construction, and huge capital investment. So, improving efficiency and fully utilizing renewables' value has become more and more important in the future.

5.3. Policy Challenges

In the past 10 years, China's policies and incentives have dominated the development of renewable energy and have achieved remarkable results in reducing curtailment rates and increasing installed capacity [106,107]. The national wind curtailment rate has been reduced from more than 15% in 2017 to less than 5% in 2020 [108]. By the end of 2021, the total installed capacity of wind power and PV connected to the grid totaled 670 million kW, nearly 90 times that of 2012. However, the Chinese government is under enormous fiscal pressure for this. It is estimated that by the end of 2021, the accumulated arrears of renewable energy power generation subsidies will be around RMB 400 billion [109].

China's policy-driven renewable development needs to be transformed into market-driven development, which will pose severe challenges to its growth. A well-structured policy mix plays a crucial role in promoting new installations of renewable energy and mitigating the curtailment of renewable energy generation. While China's current policy infrastructure on the development of renewable energy is still well suited for the transformation.

First of all, the value of renewable energy in the electricity market has not been fully reflected. China's current electricity market is immature for adopting variable renewable energy. It is composed of medium- and long-term electricity trading, a badly framed spot electricity market, and an imperfect auxiliary service market [110]. Under such an electricity market system, nearly all power suppliers' revenue comes from electric energy trading. This not only makes power suppliers unwilling to improve the peak regulating capacity and build peak regulating power units but also discourages power suppliers with strong peak regulating capacity to provide full play to peak shaving ability.

Since the peak shaving capability of the power system is a key capability for the connection of renewables to the grid. The inadequate market could reduce the space for renewable energy consumption in the grid. In addition, if the scale of renewable energy increases exponentially, the current peak-shaving cost sharing may lead to a severe loss of coal-fired power units and force them to suspend. This will further weaken the stability of the power supply. In addition, green power supply is mainly concentrated in Northwestern China, while the major power demand is in the eastern coastal region. Due to the space mismatch, it is very difficult to translocate green power across provinces and regions, which makes it difficult for enterprises to meet their green power needs or pay high costs. Moreover, the uncertain transaction timing, complicated process, complicated contract, and lack of willingness to power delivery by the sending province affected by the assessment of the responsibility of renewable energy electricity consumption have brought challenges to the inter-provincial green power transaction. Regarding the GEC, the original goal of adopting GEC in China was to partially replace the subsidy scheme. However, for a GEC transaction, the associated subsidy is deducted from its market price. This would reduce energy suppliers' desire to apply and sell GEC [111]. Renewable energy suppliers strive to bring the GEC price as close as possible to the subsidy, resulting in an overall high price for GEC in China, which is also difficult for purchasers to accept.

In addition, the green certificate market has failed to form a price that fully reflects renewable energy's environmental benefits. It cannot have a significant impact on electricity market prices. The penalties for market participants who do not meet the renewable energy consumption target are not strong. Another drawback is that GEC is not connected to the emission trading system (ETS) [112]. China's national carbon emission trading market was officially launched in July 2021. At present, the power generation industry has been included in the implementation cycle of the national carbon emission market. China also requires key emitters in the petrochemical, chemical, building materials, steel, nonferrous metals, papermaking, and civil aviation industries to verify and submit their greenhouse gas emissions [111,113]. However, in the current national accounting guidelines for these eight industries, there is no clear regulation on how to reduce carbon emissions from the use of green power [114]. Consequently, the emission reduction through the consumption of renewable energy cannot be reflected in the accounting of greenhouse gas emissions. Due to the lack of a direct connection between the GEC market and the carbon emission market, green power consumption cannot accurately reflect the company's efforts to reduce carbon emissions. It is challenging for green power usage to become the preferred solution for companies. The majority of companies that purchase green certificates do so to increase their influence and brand's social standing. The intrinsic desire to actively engage in green certificate trades is insufficient. These flaws lead to the weak market liquidity of GECs. For GEC buyers, the purchase of green certificates is voluntary and does not provide substantial benefits to the business.

6. Coping Strategy

Through the above analysis, it can be seen that to achieve carbon neutrality in the energy sector, the development of China's renewable energy requires joint institutional and technological reforms. Figure 11 illustrates the technology path and policy support for renewable energy development to achieve carbon neutrality goals. As for the technological path, the major focus is to promote the installation and consumption of renewable energy, so it is necessary to establish a new intelligent power system, which will have four characteristics of extensive connectivity, flexibility, intelligent interaction, and safety. In terms of policy, it is necessary to establish a balanced market mechanism and fully tap the value of renewable energy. The synergistic effect of policy mechanisms and technology can ensure the stable transition of renewable energy from policy-driven to market-driven in this critical period.

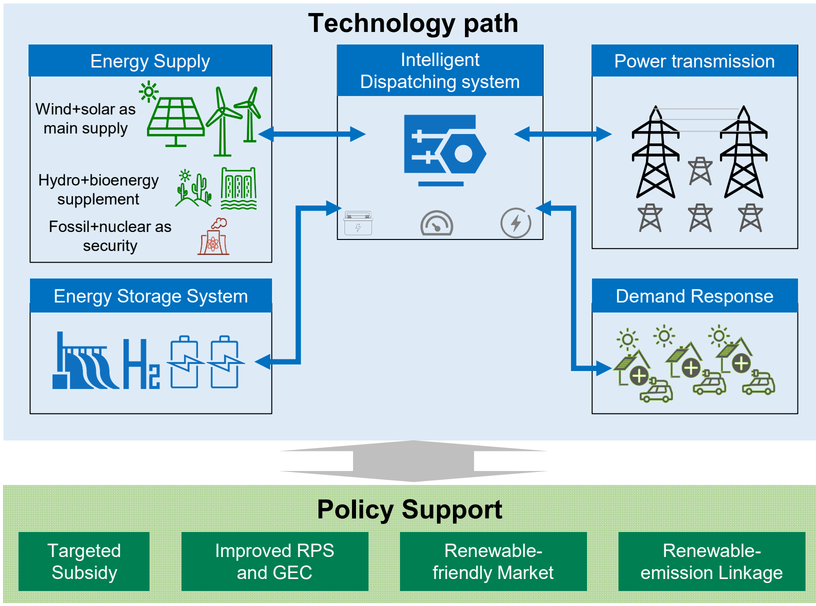


Figure 11. Coping strategy for renewable energy development.

6.1. Technology Path

To achieve China's renewable energy transition, it is essential to build a renewable-dominated and intelligent power system [115]. With variable renewable energy becoming the main body of the energy supply in the future, the power system needs a more advanced management system and a higher load-balancing capacity [116,117]. Some high technologies such as AI and big data can be used to empower the management system [118]. To accommodate a high penetration of renewable energy sources, the renewable-dominated power system should have the following features in terms of energy supply, power transmission, dispatch, demand side, and energy storage.

- Power supply: As shown in Figure 11, the renewable-dominated power system will form a paradigm of wind–solar–hydro–thermal–storage complementarity. Renewable energy especially wind and solar PV need to become the main power generation supply, while thermal power, nuclear power, and energy storage will play the role of security guarantee. This combination can ensure a high-quality power supply and increase the power reliability. For different forms of renewables, as resources such as land required for centralized renewables become more and more scarce, distributed renewable energy must play an increasingly important role. Centralized and distributed power present a simultaneous development.
- Power transmission: Ultra-high voltage (UHV) transmission needs to be the major contributor to China's "West-to-East Power Transmission" due to the huge east–west imbalance [119,120]. The construction of UHV transmission network needs scientific and comprehensive planning. Before 2025, the construction of UHV delivery channels for renewables in Western China and UHV alternating current (AC) backbone networks in the east and west should be prioritized. Before 2035, the construction of two UHV AC synchronous power grids in the east and the west needs to be completed so the scale of west–east power transmission will be expanded. Renewable

energy will dominate electricity transmission by 2025. Before 2050, China's interconnected energy internet will be fully completed. The energy transmission efficiency between the east and the west will be significantly improved, bringing about a fundamental change in energy development. In addition to UHV transmission, the intelligent microgrid is an important tool to promote the consumption of distributed renewable energy. Microgrids can operate either connected to or off the larger grid, providing a more flexible form of renewable energy consumption. At present, the main problems of microgrids are the low yield and profitability. It is thus necessary to adopt incentives for microgrids to encourage them to participate in market transactions as independent auxiliary service providers.

- Intelligent dispatching system: To address problems caused by the high penetration of variable renewable energy, a more responsive and robust dispatching system must be established. Relying on advanced information technology, big data, the Internet of Things, 5G, artificial intelligence, etc., the new dispatching system can comprehensively cover all aspects of the power generation side, grid side, power consumption side, and energy storage side. It has the ability of high-speed, intelligent, and agile perception of the power grid system. Based on the external information and prediction of the power grid, the intelligent and precise self-control of the power grid can be realized through real-time system monitoring and advanced strategies. The dispatch center also has the function of accident prediction and protection, which can minimize the loss of system accidents. An intelligent dispatching system will serve as a core to realize the optimal adjustment of all parties with a quick response and strong robustness.
- Demand side: To promote the consumption of renewable energy, the regulation service of demand response (DR) should be fully utilized. Demand response is an effective way to control demand-side resources through information and communication technologies to provide regulation services for smart grids [121]. Through demand response, power consumption at the demand side is guided and changed so that the energy consumption is aligned as much as possible with the output of renewable energy. It can shift the peak load, causing the grid to be more reliable and efficient with lower costs. The implementation of DR is a complex system-level project that requires the cooperation of power grids, distributors, and users [122]. By establishing corresponding incentives or price agreements between retailers and users, users can change their consumption behavior, thereby providing regulation services. For the better application of demand response, cluster analysis based on big data and artificial intelligence should be conducted to accurately grasp the law between load change and user's behavior. For areas with high load and abundant renewable energy, demand response pilot projects should be promoted. In addition, the combination of demand response and energy storage systems will exert synergistic effects to further optimize the energy consumption of smart grids. Among all energy users, the development of electric vehicles will produce the greatest contribution. Compared with other demand-side resources, electric vehicles promise a more flexible and cheaper demand response service [123]. China is the world's largest electric vehicle market and is uniquely positioned for electric vehicle-grid interaction. It is predicted that China's V2G implementation could reduce total power system costs by 2% by 2030 [124]. Through reasonable guidance and scientific market mechanisms, a win–win situation can be achieved for both EV owners and the grid side [125,126].
- Energy storage: As mentioned above, the difficulty of renewable energy consumption has become a major factor restricting its development. Renewable energy with high variability needs a powerful storage system to mitigate the curtailment. In the future, China should adopt efforts to develop flexible energy and realize the integration of different renewables and energy storage systems. There are three main types of renewable energy storage: (1) Mechanical energy storage, such as pumped storage. (2) Electrochemical storage, e.g., energy storage batteries. (3) Electro-fuels (e-fuels),

which are hydrogen produced through renewable electricity and other electric fuels derived from hydrogen [127].

a. Pumped storage can be divided into two stages. First, when the power generation power is greater than the load, the excess power is used to pump water into the upstream reservoir, and then generate electricity using the energy of water flowing downstream when the power generation power is less than the load. Pumped storage has many functions such as peak shaving, valley filling, frequency regulation, energy storage, and emergency standby. It is one of the most mature storages with great efficiency and promising large-scale development [128]. However, it has high requirements for site selection and construction. At present, 36 GW of pumped storage capacity has been put into production in China. The Chinese government proposes that by 2025, the total scale of the pumped storage capacity will be doubled compared with the 13th Five-Year Plan, reaching more than 62 GW [129]. By 2030, the total scale of pumped storage will be doubled compared with the 14th Five-year plan, reaching about 120 GW [130].
b. Besides pumped storage, battery energy storage has attracted notable attention. It can absorb power through electrochemical reactions in a lithium-ion battery, sodium–sulfur battery, and others. Because of its geographical independence, it is widely used on the power supply side, grid, and user side. Its main features are low-power, short-period, and distributed energy storage [131,132]. In addition, the development of the vehicle-to-grid (V2G) causes electric vehicles to become major mobile battery storers in China in the future [125,133,134]. By 2060, the stock of light electric vehicles in China will reach 350 million units and their electrochemical energy storage capacity will be about 25 TWh [135].
c. With the increasing variability of renewable energy generation, it is necessary to store a large amount of power over days, weeks, or even months [136]. Hydrogen has obvious advantages in large-scale, long-term energy storage scenarios and is considered the most desirable way. It stores renewable energy by electrolyzing hydrogen with renewable electricity. It can be transmitted through the form of compressed gas, liquefied, metal hydride storage, or hydrogen-based fuels over long distances. It is believed that large-scale energy storage using hydrogen is an order of magnitude cheaper than batteries. For China, hydrogen is a particularly important energy carrier because it can transmit energy from areas with ample renewable energy to areas with high power demand, which addresses the mismatch of the energy supply center and demand center.

The new power system could achieve three key value potentials: to fully support new energy consumption, to have a robust and intelligent power system, and to realize the value sharing of economy, people, and companies.

6.2. Policy Support

Achieving the transition to renewable energy requires a comprehensive socio-political effort to stimulate public demand for renewable energy sources. China's policy incentives of the past decades have contributed a lot to renewable energy development, especially wind and solar PV. However, the current policy mix does not fit the challenging carbon peak and carbon neutrality target. It needs to be improved to ensure the market-based development of renewable energy. Figure 12 illustrates China's four primary policy coping mechanisms: to set more targeted subsidies, to enhance the current RPS and GEC, to create a pricing mechanism and be market-friendly to renewable energy, and to link the renewable energy and carbon emission trading system (ETS). Through these policy measures, the value of renewable energy can be fully achieved and market-driven development can be promoted.

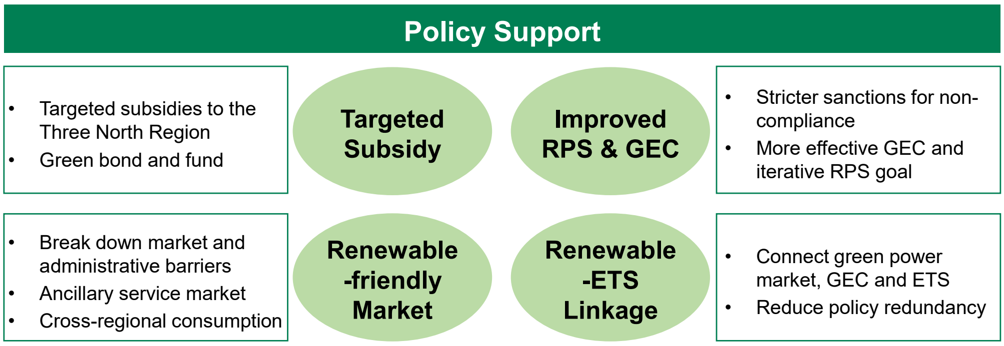


Figure 12. Policy support for renewables' market-based development.

- Improve the current subsidy system to fully exploit Western China's enormous renewable energy potential. Now, there is still a lot of renewable energy to be developed, particularly in Southwestern China. However, the cost and curtailment rate of renewable energy in the western region is still high and renewable energy power generation is still in its infancy due to poor infrastructure, lower local consumption, and difficulty in power transmission. As a result, Tibet is not included in RPS [137]. This sets up a vicious cycle whereby the absence of policy regulations causes renewable energy growth in these areas to lag even further. Facing the huge renewable energy development pressure brought by carbon neutrality, the great renewable energy resource endowment and lower land cost in the western region cause it to be necessary to develop renewable energy there. In the future, China should implement targeted incentives to encourage the growth of renewable energy in the west, including funding, developing infrastructure, and promoting the pilot project. Some market-based instruments, such as green credit and green bond pilots, should also be promoted. Since the capital investment in renewable energy projects is particularly high, the payback period is long, and the profitability is poor. The government's support for the underdeveloped region is especially important.
- Enhance the RPS allocation system. First, a scientific and appropriate RPS system should be designed to focus on the development of various forms of renewable energy. Currently, RPS implementation is still in its infancy and the target is only separated into renewable energy generation and non-hydro renewable energy generation, which does not reflect the diversity of renewable energy. RPS targets should include precise targets for each type of renewable energy source. Within an implementation cycle, the RPS target should be constantly revised based on the actual completion of each province and each renewable energy source. To accommodate the rapid expansion of renewable energy, the verification cycle should be gradually shifted from annual to half-annual/monthly. RPS should also take into account the perspectives of local power grid firms and implement a feedback mechanism between power grid enterprises, province energy departments, and the National Energy Administration to thus accomplish a balanced and complete development. In addition, a sound quota obligation assessment mechanism and severe punishment measures should be implemented. Third-party regulators should be involved in monitoring transaction pricing, checking compliance with quota commitments, and penalizing infractions. Increasingly severe punishments should be established for provinces that do not achieve the RPS target. The green certificate market can only completely fulfill its role and have a certain impact on the electricity market under a robust RPS regulating mechanism and mandatory punishment.
- To effectively take advantage of the environmental benefit of renewable energy, the renewable energy market, and emission trading system should be linked. China currently has coexisting power, emission trading, and GEC markets. Demand for electricity, carbon emission quotas, and the RPS are all crucial factors that influence renewable consumption. Renewable energy, GEC, and other environmental rights

products can play a certain role in promoting carbon emission reduction. It is essential to rationalize the pricing relationship between carbon emissions and renewable energy. Therefore, the carbon emissions reduced by the consumption of green electricity should be considered in the company's carbon emissions accounting. The closer relationship between the emission trading system and the renewable energy market will enhance the company's enthusiasm to consume green electricity. Moreover, the additional social cost brought about by the consumption of renewable energy should be shared with all stakeholders in the whole society through ETS, GEC, and RPS. In this way, energy consumers can be pushed to optimize their manner of energy consumption and lead the transformation of energy consumption. The GEC and RPS can also be paired with other financial tools such as green bonds. However, it should be highlighted that the overlap of different policy instruments should be avoided. To promote the growth of both the supply and demand sides of renewable energy, market and policy standards should be harmonized to minimize redundancy and imbalance.

- Build a renewable energy-friendly electricity market. The price mechanism maximizing the consumption of renewable energy should be adopted to increase the transactions of renewable energy in the electricity market. Market and administrative impediments should be eliminated to build a reasonable market mechanism. A level playing field for renewable energy should be provided. For renewable energy consumers, the long-term renewable power purchase agreement should be encouraged. In addition, the power market should be enhanced to incorporate auxiliary power services and represent the value of flexible regulating resources, such as peak shaving and energy storage. To increase cross-regional renewable energy consumption, the flexibility of the trading system should be optimized to encourage a larger share of power to participate in inter-provincial spot trading. Specific measures include expanding the share of market-oriented power trading and reducing non-market electricity, such as national power transmission plans. The transmission pricing should be modified to reduce the barrier effect of transmission cost on the inter-provincial consumption of renewable energy. A perfect market mechanism should be provided to maximize the consumption of renewable energy.

7. Conclusions

Based on a systematic review of the extensive literature, this paper draws the following conclusions about the development of renewable energy in the context of China's dual carbon target.

(1) China's renewable energy reserves are quite rich. Wind power and photovoltaic have the greatest potential for development. They are expected to overtake hydropower soon to become the major renewable energy. In terms of geographical distribution, most of China's renewable energy sources show a huge imbalance. Western China, with rich renewable resources, is supposed to be the center of supply, yet Eastern China accounts for most of the energy consumption.

(2) China's renewable energy development has contributed significant achievements, with it having the world's largest installed capacity and power generation. In the past, China's policy incentives have led to the growth of renewable energy. However, most renewable energy projects in China are currently no longer subsidized. It is at a critical stage of transition from policy-driven development to market-driven development. RPS and GEC are replacing FiTs as the new policy mix to support renewable energy development.

(3) In the context of carbon neutrality, China's renewable energy development is facing serious challenges. First, the proposed goal of carbon neutrality poses a huge challenge to China's energy transformation. It requires increasing installed renewable energy at a faster rate over the next 40 years. Second, there are issues with energy

storage, the instability of industrial chain change, and the poor utilization rate. Third, the transition period from policy-led to market-led requires stronger policy support. The current competitiveness of renewable energy in the power market needs to be enhanced.

(4) To achieve the energy transition required by the carbon neutrality target, China should establish a power system dominated by renewable energy and comprehensively assist the development and consumption of renewable energy in energy storage, smart grid, demand side, and dispatching. In terms of policy, we should improve the existing incentive and punishment system, refine the RPS and GEC mechanism, build a renewable energy-friendly market mechanism, link the renewable energy market and carbon emissions trading system.

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