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# Energy development in rural China toward a clean energy system: utilization status, co-benefit mechanism, and countermeasures

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In order to promote the construction of a clean, low-carbon, and diversified modern rural new energy system, this study examines the development, utilization, connection, and system construction of rural new energy in China. This is done through the classification, integration, and systematic analysis of official statistical data and materials from recent years. Utilizing descriptive statistical analysis, the study holds great theoretical and practical significance. The findings indicate the following: 1) overall, the development of new energy in China's rural areas is progressing well. However, there is an increasing contradiction between supply and consumption. 2) The new energy industry is experiencing overall growth, accompanied by increasing policy support. Despite this, the industry's driving effect is not substantial. 3) The development of new energy production equipment in rural areas is lagging, resulting in insufficient cleanliness of energy consumption. There is still a significant gap compared to the goal requirements of agricultural and rural modernization. 4) During the process of rural new energy connection and development, there exists a lack of strong connections between the various subjects of interest. The interest relationship is consequently unstable, necessitating the improvement of a closely-knit interest community. Taking the issue of rural new energy development as its starting point, this paper thoroughly explores the mechanisms driving rural new energy connection. It delves into the interest relationship between the different stakeholders and provides guidelines for optimizing rural new energy system construction. Ultimately, this research aims to contribute to rural revitalization, facilitate the realization of the "double carbon" goal, and establish a modern rural new energy system.

KEYWORDS

**rural clean energy, energy transformation, dual-carbon target, benefit linkage, energy system**

## 1 Introduction

The innovative development of the rural new energy industry is a crucial step toward establishing a green, low-carbon, and diversified rural energy system. It plays a significant role in achieving the dual-carbon goal, consolidating and expanding the achievements of poverty alleviation, promoting the common prosperity of farmers, and advancing agricultural and rural modernization. Additionally, it is an important measure to

comprehensively implement the strategy of rural revitalization (Zhou et al., 2022). With the completion of poverty alleviation and the development of rural revitalization, China's rural energy consumption shows an increasing trend, but because rural energy is mainly based on coal and other non-renewable fossil energy sources, and rural energy consumption has the characteristics of being extensive and dispersed, it has become one of the important sources of greenhouse gas emissions. Rural energy consumption accounted for approximately 15% of the country's total greenhouse gas emissions in 2021. According to the estimation of the Ministry of Agriculture and Rural Affairs, new energy in rural areas of China can obtain energy equivalent to 7.3 billion tons of standard coal every year, which is 12 times the current total energy in rural areas of China (Chen M. et al., 2022). On 15 March 2023, the National Energy Administration, the Ministry of Ecology and Environment, the Ministry of Agriculture and Rural Affairs, and the National Rural Revitalization Administration jointly issued the Rural Energy Revolution Pilot County Construction Program, which clearly pointed out that to promote rural energy revolution, rural clean energy construction should be increased so as to achieve the dual target of carbon peak and carbon neutrality. The promotion of rural industry upgradation not only drives the expansion of the industrial chain but also supports the development of livable, employment-oriented, and aesthetically pleasing rural areas (Han et al., 2022).

At present, scholars have carried out a lot of research on the exploitation and utilization of rural energy, industrial development, and related policies. Cong et al. (2017) analyzed the main problems and basic needs in China's rural energy development by discussing the current situation and basic characteristics of living and production energy in China's rural areas. Zhao et al. (2018), based on the rural energy-related data of 30 provinces and cities in China from 2000 to 2015, using Theil, ESDA, and the spatial Dubin model, analyzed the spatial–temporal changes and influencing factors of rural energy poverty in China, providing a reference for the formulation of China's rural energy policy. In view of the development status and development and utilization mode of rural energy in China, Sun et al. (2020) studied rural energy by the subdivision of east, central, west, and northeast provinces and pointed out that the local resource mode should be transformed into an economic and industrial advantage. Wu and Zheng (2022) made use of Chinese household energy consumption survey data, studied the income growth and household energy consumption ladder, and pointed out that efficiency should be strengthened to focus on the poor areas and low-income population. Yang and Li (2022), focusing on the rural energy transformation and development and rural revitalization strategy, put forward relevant suggestions on rural energy transformation and development. New energy has a broad development space in rural areas. In recent years, with the promotion of the double carbon goal and the rural revitalization strategy, the development of rural new energy has a new direction (Clausen and Rudolph, 2020).

With the development of the Chinese economy, the development and use of the new energy situation and supply consumption structure and industrial development patterns have all shown new characteristics and changes. The aforementioned studies are focused on China's rural energy system; however, China's new energy connection development mechanism problem is not explored. In order to adapt to the new characteristics and changes of its rural new energy development, China should promote the transformation and development of rural energy, strengthen the coordinated development of rural new energy interests, comprehensively promote the reform of rural new energy consumption patterns, build a pluralistic and clean rural new energy supply system, and constantly deepen the reform of the rural new energy system (Ma et al., 2022). By combining the official data on the development of rural new energy in recent years, through a descriptive statistical analysis method, this paper summarizes the status of development and utilization of new energy; puts forward the interest behavior and interest relation of the new energy connection mechanism, in view of the main problems in the construction of a rural new energy system; puts forward relevant suggestions; and provides guidance for the future policy formulation and implementation and the construction of a modern new energy system.

The rest of this paper is organized as follows. Section 2 presents the current situation of rural new energy development and utilization. Section 3 describes the development mechanism of rural new energy connection. Section 4 introduces the optimization of rural new energy system construction. Section 5 elaborates on the revelation and deficiency of the conclusion.

## 2 Current situation of rural new energy development and utilization

### 2.1 Rural new energy supply and consumption structure

Rural energy refers to the energy in rural areas. It includes energy development and utilization as well as supply consumption, namely, through the use of energy to ensure the livelihood of the rural population and the development of local industries and agriculture. In China, rural energy mainly includes non-renewable energy such as coal, crude oil, natural gas, oil shale, and nuclear energy (Wan et al., 2023) as well as new energy such as solar energy, wind energy, biogas energy, and biomass energy (Wu, 2020). With the construction of the new socialist countryside and the improvement of rural living standard, the demand for energy in rural areas is also increasing sharply, which also intensifies the contradiction between supply and demand of rural energy.

As shown in Figure 1, the development and utilization of rural new energy in China includes two aspects (Naumann and Rudolph, 2020): one is the supply of new energy and the other is the consumption of new energy. The supply of new energy includes solar energy, wind energy, biomass energy, water energy, and geothermal energy. Biomass energy can be divided into traditional biomass energy and new biomass energy. Traditional biomass energy is generated by firewood and straw burning. New biomass energy is obtained by burning ethanol, biodiesel, molding fuel, etc. (Wang et al., 2023a). The consumption of new energy includes domestic energy, which includes cooking, heating, and lighting, and production energy, which includes planting, breeding, and primary processing of agricultural products. From the energy supply side, China's energy structure is found to be dominated by fossil fuels, of which coal accounts for 57 percent, according to the

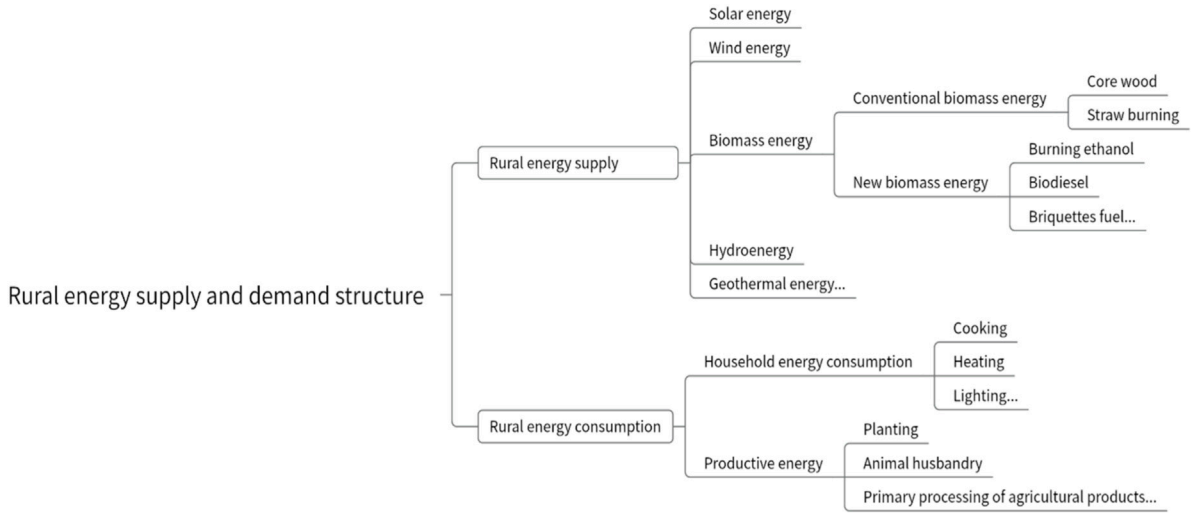


FIGURE 1
Supply and consumption structure of rural energy.

**TABLE 1 Output of the rural energy industry from 2011 to 2020 (10,000 tons of standard coal).**

| Year | Wind power generation | Hydropower generation | Photovoltaic power | | Biomass energy | | | Total |
|---|---|---|---|---|---|---|---|---|
| | | | Centralized photovoltaic | Distributed generation solar project | Biomass power generation | Marsh gas | Straw solid fuel | |
| 2011 | 864 | 2,154 | 7 | 0 | 418 | 1,194 | 183 | 4,820 |
| 2012 | 1,180 | 2,664 | 14 | 30 | 549 | 1,267 | 204 | 5,907 |
| 2013 | 1,735 | 2,739 | 51 | 52 | 606 | 1,277 | 255 | 6,715 |
| 2014 | 1,918 | 2,786 | 235 | 72 | 630 | 1,268 | 312 | 7,222 |
| 2015 | 2,283 | 2,884 | 392 | 89 | 648 | 1,278 | 255 | 7,829 |
| 2016 | 2,914 | 3,293 | 669 | 144 | 799 | 1,227 | 260 | 9,306 |
| 2017 | 3,653 | 3,040 | 1,060 | 393 | 977 | 1,071 | 302 | 10,495 |
| 2018 | 4,496 | 2,879 | 1,488 | 694 | 1,115 | 1,001 | 278 | 11,950 |
| 2019 | 4,981 | 3,109 | 1,851 | 900 | 1,365 | 917 | 336 | 13,460 |
| 2020 | 5,733 | 2,979 | 2,177 | 1,024 | 1,630 | 1,180 | 317 | 15,040 |

Data sources: National Bureau of Statistics, Agricultural Statistics of China, and National Energy Administration.

2021 National Statistical Yearbook. Although the proportion of non-fossil energy has increased rapidly in recent years, it is still less than 20%. From the energy consumption end, the consumption of rural energy continues to increase (Wang and Jiang, 2017).

On the whole, according to the official data of the National Bureau of Statistics of China, China Agricultural Statistics, and National Energy Administration, China's rural energy supply is increasing. As shown in Table 1, from 48.2 million tons of standard coal in 2011 to 150 million tons of standard coal in 2020, the average annual growth rate is approximately 15%. From 2015 to 2016, the energy output had the fastest growth of 18%. From 2012 to 2015, rural energy output grew at a slower rate, of 8%. At present, the energy output in rural areas is mainly concentrated in the installed power generation of wind energy, photovoltaic energy, and hydro energy, followed by biogas production from biomass through a biogas digester. The production scale of straw molding fuel is generally very small. The sum of the three items of biomass energy production accounts for 31.27 million tons of standard coal. According to the calculation of biomass energy, the amount of biomass resources in rural areas is approximately 570 million tons of standard coal, which only accounts for 6.4% of the theoretical exploitable amount, indicating that the utilization of biomass energy is very inadequate. In the future, the development processes of biomass energy should be increased to provide more room for growth in China's energy development.

**TABLE 2 Total consumption of commodity energy and domestic energy in rural areas from 2000 to 2019 (tec).**

| Year | Coal | Petroleum | Natural gas | Liquefied petroleum gas | Electricity | Total | Total domestic energy consumption in rural areas |
|---|---|---|---|---|---|---|---|
| 2000 | 4,077.68 | 384.92 | - | 153.72 | 645.2 | 5,261.52 | 7,165.36 |
| 2001 | 3,960.16 | 401.85 | - | 151.49 | 753.46 | 5,266.96 | 7,399.359 |
| 2002 | 4,298.3 | 402.17 | - | 192.06 | 826.48 | 5,719.91 | 8,058.823 |
| 2003 | 4,865.08 | 494.98 | - | 246.07 | 959.44 | 6,565.57 | 9,145.269 |
| 2004 | 5,468.92 | 732.18 | 3.99 | 383.61 | 1,132.1 | 7,720.8 | 10,598.7 |
| 2005 | 5,709.96 | 836.95 | 3.99 | 450.35 | 1,340.08 | 8,341.33 | 11,554.32 |
| 2006 | 5,510.93 | 973.53 | 4.79 | 511.76 | 1,629.64 | 8,630.65 | 12,364.04 |
| 2007 | 5,208.42 | 1,165.64 | 6.03 | 595.55 | 2,053.47 | 9,029.11 | 13,298.256 |
| 2008 | 5,082.37 | 1,199.48 | 8.02 | 598.07 | 2,259.91 | 9,147.85 | 13,657.406 |
| 2009 | 4,967.01 | 1,299.79 | 8.03 | 604.05 | 2,507.36 | 9,386.24 | 14,201.228 |
| 2010 | 5,618.7 | 1,472.62 | 8.99 | 616.13 | 2,625.84 | 10,342.28 | 15,234.651 |
| 2011 | 6,061.48 | 1,732.14 | 9.89 | 653.1 | 2,971.8 | 11,428.41 | 16,702.173 |
| 2012 | 6,307.84 | 1,899.2 | 10.15 | 677.39 | 3,268.67 | 12,163.25 | 17,849.16 |
| 2013 | 6,048.09 | 2,255.69 | 12.18 | 760.37 | 3,845.97 | 12,922.3 | 19,351.664 |
| 2014 | 5,892.55 | 2,501.59 | 16.44 | 874.43 | 3,985.6 | 13,270.61 | 19,795.1 |
| 2015 | 6,246.56 | 2,871.66 | 18.58 | 1,030.79 | 4,253.9 | 14,421.49 | 21,012.544 |
| 2016 | 6,096.2 | 3,238.03 | 21.72 | 1,253.62 | 4,733.28 | 15,342.85 | 22,464.736 |
| 2017 | 6,066.41 | 3,444.13 | 35.17 | 1,377.07 | 5,050.89 | 15,973.67 | 23,213.556 |
| 2018 | 5,041.33 | 3,556.98 | 54.97 | 1,351.73 | 5,563.55 | 15,568.56 | 23,482.872 |
| 2019 | 5,745.61 | 2,353.63 | 4.92 | 739.22 | 5,851.44 | 14,694.82 | 23,346.408 |

Data source: China Energy Statistical Yearbook.

With the improvement of rural people's living standards, according to the China Energy Statistical Yearbook, as shown in Table 2, the total consumption of domestic energy in rural areas increased from 7,165.36 tons of standard coal in 2000 to 23,346.408 tons of standard coal in 2019, with a growth rate of 69.31%. The *per capita* living energy in rural areas has increased from 325 kg of standard coal to 434 kg of standard coal, and it is expected to reach 518 kg of standard coal by 2030. The consumption of energy in rural areas will continue to increase (Chen F. et al., 2022).

Coal, oil, and electricity are the main components of China's rural commodity energy. In the commodity energy mix, coal has been the main energy source for rural household consumption, with its consumption increasing from 40.78 million tons of standard coal in 2000 to 57.46 million tons of standard coal in 2019. Although coal consumption has been increasing, its share of total rural energy consumption has been declining. Both the total and the proportion of oil consumption have been increasing steadily, with its share in the total energy consumption increasing from 7.32% in 2000 to 17.25% in 2019 and reaching a peak of 22.85% in 2018. This is closely related to rural modernization. The popularization of automobiles has greatly increased the consumption of petroleum products in rural areas. Electricity consumption is an important index reflecting rural economic development and energy structure (Liu and Li, 2023). With the promotion of rural electrification, the total and the proportion of electricity consumption are increasing year by year. Electricity consumption peaked at 55.64 Mtce in 2018 and accounted for more than 35% of the total energy consumption for the first time, reaching 35.74%. In 2019, the proportion was 35.18%. The proportion of liquefied petroleum gas and natural gas in the rural energy consumption pattern is relatively small. On the whole, the total commodity energy consumption in rural China continues to expand, and the per capita energy consumption continues to increase (Ding et al., 2021). The total energy consumption of household commodities in rural areas increased by 5.14% annually, and the *per capita* energy consumption increased by 7.55% annually. According to the China Energy Statistical Yearbook, as can be seen in Figure 2, the total rural energy consumption experienced two periods of rapid growth, from 2000 to 2005 and from 2009 to 2018. Total energy consumption increased more slowly between 2005 and 2009. After peaking in 2018, the total consumption began to decline.

As shown in Figure 3, according to the "China Energy Statistical Yearbook" and "China Agricultural Statistics," rural production energy consumption is mainly dominated by coal, diesel, and electricity, with coal accounting for the largest proportion, followed by diesel and electricity. Coal and gasoline have been the main sources of rural production and consumption (Li W.

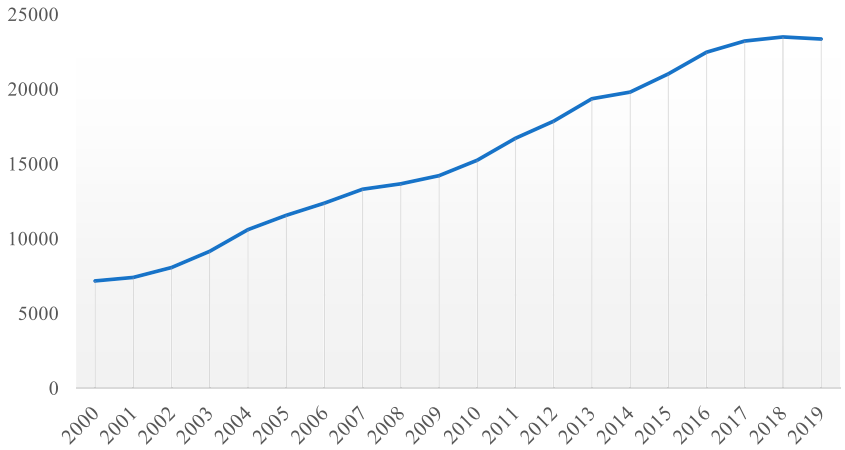


FIGURE 2
Total domestic energy consumption from 2000 to 2019 in rural China (tec).

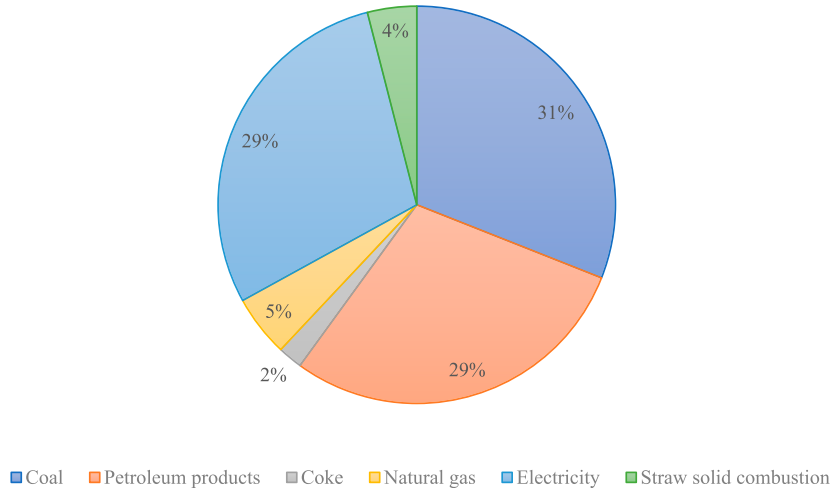


FIGURE 3
Proportion of major components of rural energy use in 2019. Data source: Ministry of Agriculture and Rural Affairs of China.

et al., 2023). Rural coal consumption shows an overall growth trend, as shown in Table 3. By 2019, rural coal production and consumption had reached 28 million tons of standard coal. The proportion of coal products in total rural production and consumption has been declining, from 47% in 2009 to 32% in 2019, a decrease of 15 percentage points. Diesel and coal have the same trend of change. The total amount of diesel has been increasing, but the proportion of energy consumption in rural production shows a slow decline. The consumption of diesel had increased from 17.28 million tons of standard coal in 2009 to 21.81 million tons of standard coal in 2019. From 2009 to 2014, although electricity consumption showed an increasing trend, its proportion in rural production energy consumption showed a decreasing trend. After 2014, with the promotion of rural electrification construction, the total amount and proportion of electricity consumption increased year by year. As shown in Figure 3, in 2019, the electricity consumption reached 26 million tons of standard coal and accounted for 29% of total energy consumption. In the future, cleanliness and intelligence will be a direction of rural reform (Choudhury et al., 2019), and the proportion of electricity in rural production and consumption needs to be further increased.

In rural energy consumption, in addition to coal, gasoline, diesel, electricity, etc., there are also coke, natural gas, kerosene, and fuel oil, which account for a very small proportion. In addition, although the current output of straw solid fuel is less than that of other commodity energy sources, only 3.36 million tons of standard coal in 2019, in recent years, the consumption scale of straw solid fuel has been increasing, and its proportion in rural energy production has been increasing. In the future, with the demand for rural clean reform and the utilization of clean biomass energy, the proportion of straw solid fuel consumption in rural production and consumption will be further increased. On the whole, the consumption of commodity energy in China's rural areas showed

**TABLE 3 Energy consumption of commodities produced in rural areas from 2009 to 2019 (10,000 tons of standard coal).**

| Year | Coal | Petroleum products | | | | Coke | Natural gas | Electricity | Straw solid combustion | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Gas | Kerosene | Diesel | Fuel oil | | | | | |
| 2009 | 3,484 | 296 | 1.4 | 1,728 | 19.61 | 60 | 9 | 1,634 | 40 | 7,271 |
| 2010 | 3,624 | 306 | 2.1 | 1,841 | 15.61 | 60 | 18 | 1,722 | 96 | 7,685 |
| 2011 | 3,668 | 322 | 2.6 | 1,925 | 11.02 | 66 | 22 | 1,824 | 183 | 8,024 |
| 2012 | 3,619 | 329 | 1.9 | 2,020 | 9.5 | 67 | 30 | 1,891 | 204 | 8,172 |
| 2013 | 4,042 | 341 | 2 | 2,175 | 8.79 | 77 | 38 | 1,968 | 255 | 8,907 |
| 2014 | 3,825 | 363 | 1.4 | 2,246 | 5.77 | 44 | 50 | 1,998 | 312 | 8,845 |
| 2015 | 3,731 | 382 | 2.4 | 2,245 | 3.88 | 185 | 88 | 2,066 | 255 | 8,959 |
| 2016 | 3,819 | 365 | 3.8 | 2,241 | 4.5 | 191 | 146 | 2,168 | 260 | 9,197 |
| 2017 | 3,681 | 364 | 2.5 | 2,307 | 5.07 | 171 | 241 | 2,325 | 302 | 9,335 |
| 2018 | 3,023 | 372 | 7.6 | 2,176 | 3.67 | 233 | 297 | 2,466 | 278 | 8,858 |
| 2019 | 2,800 | 383 | 16.2 | 2,181 | 3.86 | 180 | 436 | 2,622 | 336 | 8,958 |

Data sources: China Energy Statistical Yearbook and China Agricultural Statistical Data.

an increasing trend and reached a peak in 2017, when the energy production of commodity energy in rural areas reached 93.35 million tons of standard coal. In 2018, there was a decline for the first time compared to the past years. In 2019, rural commodity energy consumption increased slightly, and rural commodity energy consumption amounted to 89.58 million tons of standard coal.

According to the 2022 China Rural Energy Development Report, different regions in China are classified based on their potential for rural energy development. Shandong, Henan, and Anhui are among the top three provinces in the country in terms of potential for rural energy and resource development, among which Shandong with its rural main resources and energy development potential ranks first in the country, reaching 87.43 million tons of standard coal. Heilongjiang, Sichuan, Yunnan, Guangxi, and Hunan provinces also have high resource exploitation potential. At present, for Tibet and Qinghai, the development potential of rural main energy is relatively weak. In the future, if the development and utilization of major rural resources can be made according to local conditions, the balanced utilization of resources will be promoted in all provinces, and the development of provinces will be more environmentally friendly and coordinated, thus playing an important role in realizing the dual-carbon goal (Zhang et al., 2022).

## 2.2 Current situation of the rural new energy industry

Promoting rural economy and social development is an important measure to vigorously develop rural new energy. To build a new power system with new energy as the main body, the development of photovoltaic power generation, wind power, and other projects needs space resources most, and rural areas have particular advantages in this field (Shen et al., 2022). Figure 4 shows the current development and utilization model of the Chinese rural new energy industry. According to reliable research, greenhouse gas emissions from China's agricultural and rural sectors will total 1.7 billion tons of carbon dioxide equivalent in 2022, accounting for approximately 15% of the country's total emissions. Agricultural waste resources in China are approximately 400 million tons, converted into approximately 200 million tons of standard coals. The amount of forestry waste resources is approximately 350 million tons, which is converted into approximately 200 million tons of standard coal. The accumulated grid-connected installed capacity of agricultural and forestry biomass power generation is 13.3 million kW, and the biomass heating uses approximately 20 million tons of solid formed fuel annually, which is mainly used for urban heating and industrial and commercial heating. A total of 16 commercial bio-natural gas projects have been put into operation nationwide, with an annual output of 149.5 million cubic meters of gas and 4 million tons of liquid bio-fuel, comprising 3 million tons of ethanol and 1 million tons of biodiesel.

Biomass resources such as straw are abundant (Cui et al., 2021), mainly including agricultural waste, forestry waste, and livestock and poultry manure. The total amount of energy utilizable resources is equivalent to approximately 460 million tons of standard coal every year. The development of new energy in rural areas and the conversion of biomass such as crop straw and livestock manure to produce biological gas, molding fuel, and electricity can offset the emissions of fossil energy used in production and living and improve the ability of agricultural production to adapt to climate change and help carbon peak and carbon neutrality (Sun et al., 2021).

### 2.2.1 Industry scale

1) Rural solar energy

China is territorially broad and has abundant solar energy resources. It is estimated that the annual solar radiation received by the Chinese land surface is approximately 50 × 1018 kJ. The total solar radiation amounts to 335–837 kJ/cm$^2$·a, and the median is 586 kJ/cm$^2$·a. As shown in Figure 5, according to the National Bureau of Statistics, China's solar energy capacity increased from

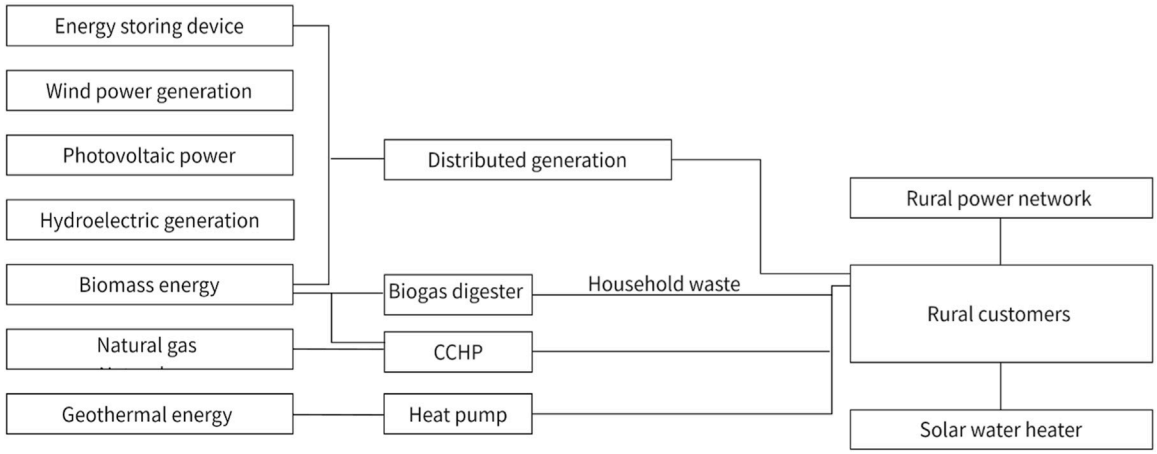


FIGURE 4
Development and utilization mode of rural new energy.

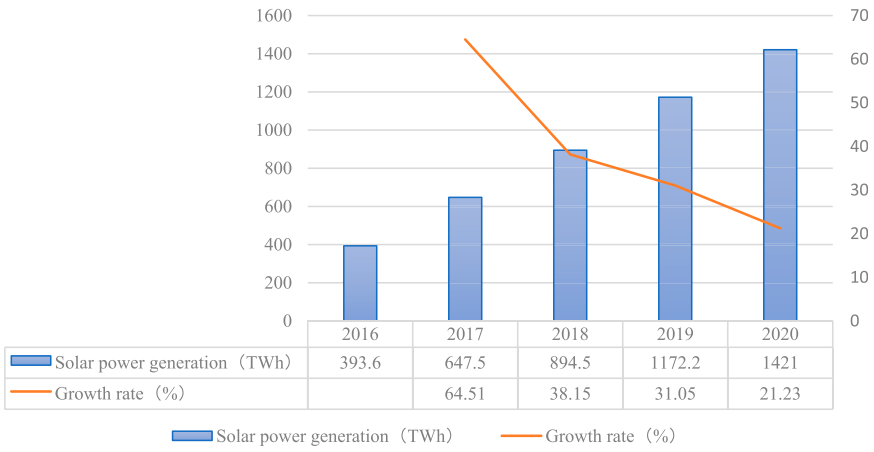


FIGURE 5
China's solar energy capacity, 2016–2020. Data source: National Bureau of Statistics of China.

2016 to 2020. In 2020, China's solar energy capacity reached 142.1 billion KWH, an increase of 24.88 billion KWH compared with 2019.

By the end of 2020, China had 228,134 solar houses covering 18.223 million square meters; 46,733,400 solar water heater units, 84,207,500 square meters; and 1,706,244 solar stoves. Table 4 shows the development and utilization of solar energy in China from 2013 to 2020.

As a human life resource, solar energy plays an increasingly important role in the development of rural areas (Liu et al., 2023). Figure 6 shows the top 10 provinces with grid-connected PV capacity in 2020. As can be seen in the figure, Shandong, Jiangsu, Qinghai, Zhejiang, and other regions have a higher grid-connected capacity, followed by Anhui, Hebei, Shanxi, Xinjiang, Ningxia, and Henan.

At present, with the rise of photovoltaic agriculture in China and photovoltaic agriculture as an innovative agricultural development model (Zhao et al., 2023), the organic combination of agriculture and new energy in rural areas provides double benefits. It not only promotes the development of new energy and reduces the dependence on traditional energy but also promotes the improvement of agricultural production efficiency and the development of rural economy (Wang et al., 2023b). However, in the process of promoting and applying photovoltaic agriculture, factors such as land use, environmental protection, and socio-economic feasibility need to be considered, and corresponding policies and measures need to be taken to achieve sustainable development of photovoltaic agriculture (Hu et al., 2023).

2) Rural wind energy

Wind energy resources are rich and widely distributed in China. With the breakthrough of low wind speed technology, most areas of China, especially the low wind speed resource areas in the middle and southeast of China, have been equipped with the development conditions (Wang, 2023), and the potential resources available for

**TABLE 4 Development and utilization of solar energy nationwide from 2013 to 2020.**

| Year | Solar house | | Solar cooker | Solar water heater | |
|---|---|---|---|---|---|
| | Quantity (place) | Area (10,000 square meters) | Quantity (units) | Quantity (10,000 units) | Area (10,000 square meters) |
| 2013 | 269,304 | 2,445.55 | 2,264,356 | 4,099.65 | 7,294.57 |
| 2014 | 286,744 | 2,527.59 | 2,299,635 | 4,345.71 | 7,782.85 |
| 2015 | 290,448 | 2,549.37 | 2,327,106 | 4,571.24 | 8,232.98 |
| 2016 | 292,676 | 2,564.60 | 2,279,387 | 4,770.84 | 8,623.69 |
| 2017 | 291,144 | 2,540.98 | 2,222,666 | 4,792.64 | 8,723.50 |
| 2018 | 291,848 | 2,529.76 | 2,135,756 | 4,835.56 | 8,805.43 |
| 2019 | 256,933 | 2,529.76 | 2,135,756 | 4,835.56 | 8,805.43 |
| 2020 | 228,134 | 1,882.30 | 1,706,244 | 4,676.34 | 8,420.75 |

Data source: Agricultural Resources, Environmental Protection, and Rural Energy Development Report.

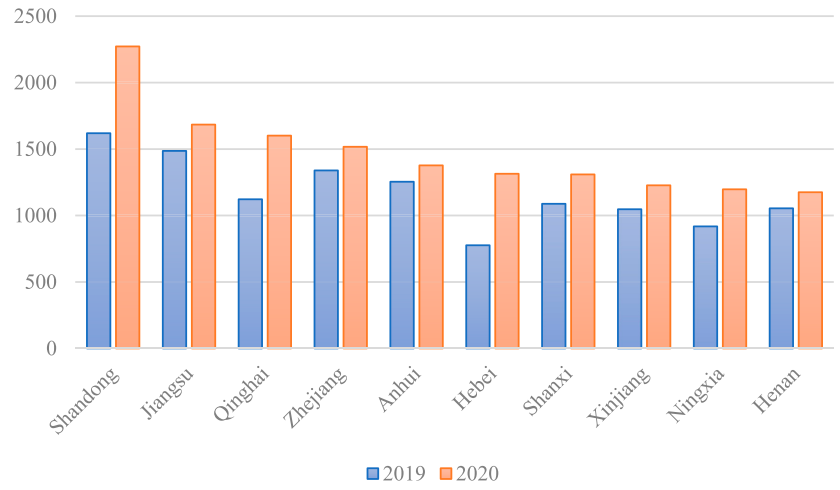


FIGURE 6
China's top 10 provinces in terms of grid-connected PV capacity in 2020 (unit: 10 MW). Data source: National Bureau of Statistics of China.

development are more than 1 billion kW. A large number of scattered unused land resources in rural areas also provide the resource base for wind power development and utilization. Figure 7. In 2022, 11,098 newly installed machines with a capacity of 49.83 million kW were installed in China (excluding Hong Kong, Macao, and Taiwan). The installed capacity of onshore wind power increased by 44.672 million kW, and that of offshore wind power increased by 5.157 million kW. By the end of 2022, China had installed more than 180,000 units, with a capacity of over 39 million kW, of which 36 million kW had been installed on land and 30.51 million kW had been installed on sea.

As shown in Figure 8, in 2021, wind power was mainly installed in North China, Northwest China, and East China, and the installed wind power capacity in North China accounted for 26.9%. Northwest China followed with 22.8 percent. East China installed 64.4 million kW of wind power, accounting for 19.6 percent. Central China, Northeast China, Southwest China, and South China had less installed wind power, accounting for 10.3%, 7.9%, 6.6%, and 6.0%, respectively.

In the current development scenario of rural wind power in China, although the income of rural decentralized wind power at this stage is not as concentrated as the project, if we increase the investment in technology optimization, model innovation, and other aspects, the future rural decentralized wind power will have very good development prospects. On the one hand, decentralized projects have the natural advantage of being close to the power load side, especially with the continuous improvement of rural electrification. From the perspective of overall energy production and utilization efficiency, the rural decentralized wind power market has broad prospects. The self-balance of energy in a certain region is also the trend and direction of future power grid development. On the other hand, combined with the current situation of the development of new energy in China's rural areas, especially in the central and eastern regions, the large-scale development of centralized contiguity is facing increasing challenges in terms of land, forest, grass, and environmental protection. At these levels, decentralized projects are more flexible.

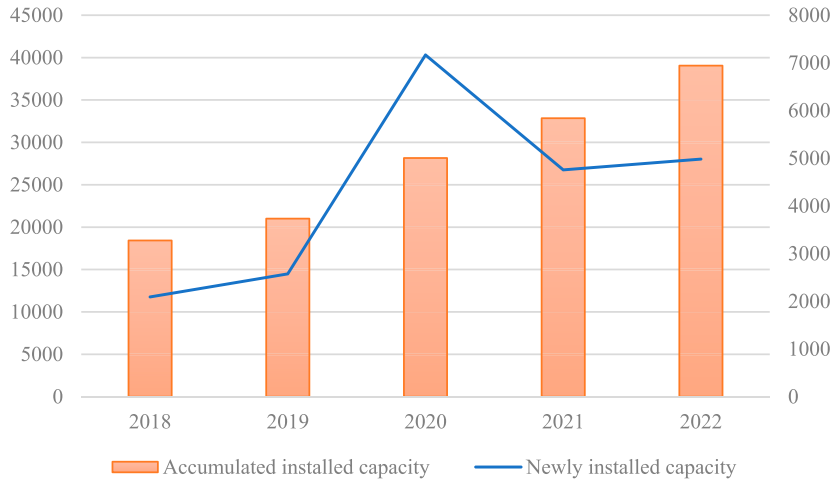


FIGURE 7
China's accumulated installed capacity and new capacity of wind power generation from 2018 to 2022 (10 MW). Data source: China Wind Power Market Current Situation In-depth Research and Future Prospects Analysis Report (2023–2030).

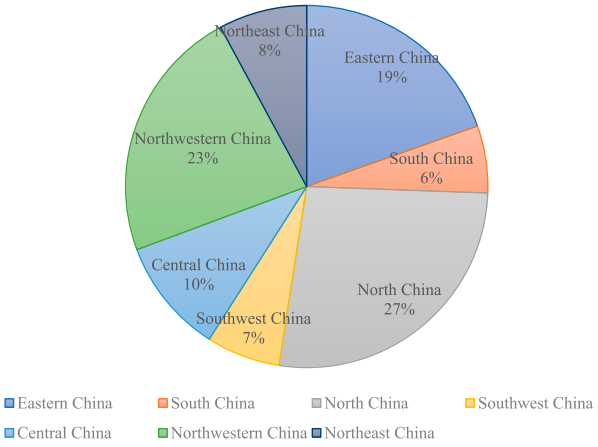


FIGURE 8
2021 China wind power industry regional market share. Data source: China Wind Power Market Current Situation In-depth Research and Future Prospects Analysis Report (2023–2030).

3) Rural biogas energy

Rural biogas digestion is mainly carried out through the use of poultry manure through natural fermentation, thus producing large amounts of biogas, biogas slurry, and other energy. A 6-cubic small biogas digester can alone maintain the energy consumption for a year for a family of five people. Biogas technology is one of the biomass energy technologies (Chen et al., 2023). At present, our household biogas technology is basically mature, and increasingly perfect, with its popularity rate rapidly. As shown in Figure 9, in 2022, the accumulated installed capacity of biogas power generation in China reached 1.22 million kW, with an annual output of 3.95 billion KWH, an on-grid electricity of 3.32 billion KWH, and an annual utilization hour of 3,233 h.

By the end of 2020, China had 30.7771 million methane users, 11% less than that in the previous year. There were 93,480 biogas projects of all kinds, 8.9% less than that from the previous year. The biogas project has a total pool capacity of 21,793,500 cubic meters, a gas supply of 1,701,000 households, and an installed power generating capacity of 350,000 KWH. The quantity of household biogas and biogas projects showed a decreasing trend year by year. The details are shown in Table 5. The operation of biogas projects has effectively controlled pollution, improved the rural environment, and improved the quality of life of farmers, which is an inevitable trend of constructing ecological homes and realizing a virtuous cycle of agricultural economy.

4) Rural biomass energy

With the rapid growth of biomass power generation, the proportion of biomass power generation in our country's new energy has been steadily increasing year by year. China's rural areas are carrying out a revolution from traditional energy to biomass energy and other new energy transformations, which, once successful, can not only improve the rural ecological environment but also promote the construction of a beautiful livable countryside. In addition, it can make full use of rural idle resources, solve the problem of energy shortage in China's rural areas, and promote the development of green agriculture. China's installed capacity of biomass power generation has been the highest worldwide for 3 consecutive years. In recent years, China's biomass energy generation has maintained a steady growth, with a year-on-year growth of 19.35%. The details are shown in Figure 10. By the end of 2022, the cumulative installed capacity of agricultural and forestry biomass power generation was 16.23 million kW, with an annual generating capacity of 51.6 billion KWH and an on-grid power capacity of 44.2 billion KWH, with an annual utilization of only 3,199 h. Since 2018, the utilization hours of agricultural and forestry biomass power generation projects have been declining year by year. The main reason is that subsidies from the National

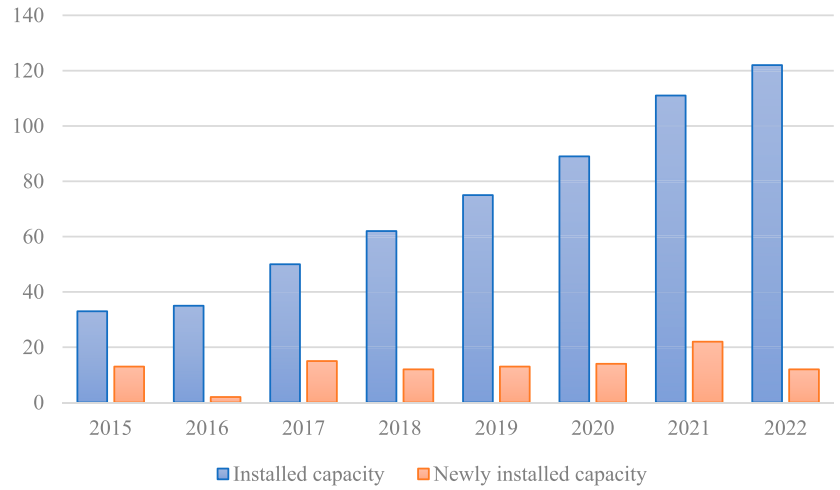


FIGURE 9
Installed capacity and new capacity of biogas power generation from 2015 to 2023 (10 MW). Data source: China Biomass Energy Industry Development Yearbook (2023).

**TABLE 5 Development of biogas in rural areas of China from 2013 to 2020 (accumulated at the end of the year).**

| Year | Household biogas (ten thousand households) | Biogas project | | | |
|---|---|---|---|---|---|
| | | Total | Mini-type | Medium | Large (including extra-large) |
| 2013 | 4,150.37 | 99,957 | 83,512 | 10,285 | 6,160 |
| 2014 | 4,183.12 | 103,036 | 86,236 | 10,087 | 6,713 |
| 2015 | 4,193.30 | 110,975 | 93,355 | 10,543 | 7,077 |
| 2016 | 4,161.14 | 113,440 | 95,185 | 10,734 | 7,523 |
| 2017 | 4,057.71 | 109,974 | 91,585 | 10,514 | 7,875 |
| 2018 | 3,907.67 | 108,059 | 89,761 | 10,332 | 7,966 |
| 2019 | 3,380.27 | 102,650 | 94,913 | 94,913 | 7,737 |
| 2020 | 3,007.71 | 93,481 | 86,086 | 86,086 | 7,395 |

Data source: Agricultural Resources, Environmental Protection, and Rural Energy Development Report.

Renewable Energy Development Fund cannot be issued in a timely manner, and the funding chain of some agricultural and forestry biomass power generation projects has been broken.

As shown in Table 6, by the end of 2020, there were 183 straw pyrolysis gasification projects in China, with 14,000 households supplying gas. There were 2,664 straw curing molding fuel production plants, with an annual output of 12.797 million tons, and 102 straw carbonization projects, with an annual output of 462,000 tons. In 2020, there were 238 straw baling central heating projects, providing heating space for 106,000 households and 8.15 million square meters. In 2020, the country carried out the whole village pilot application of biomass clean stoves in Heilongjiang and other places.

### 2.2.2 Industrial policy

Since entering the new era, the development of China's rural energy policy has experienced three stages. The first was the shortage period (1979–1995), when rural areas lacked basic commodity energy services and mainly relied on non-commodity energy sources such as fueling wood and straw (Shi et al., 2023), which led to serious energy poverty (Wu and Han, 2022). The second is the period of security demand (1996–2006), during which China's rural energy policy focused on serving national energy security and promoting the diversification of energy supply. Last but not least was the phase of coping with climate change (2007–present). In 2007, the Chinese government had issued China's National Program on Climate Change, which assigns new tasks to rural energy to improve and mitigate the impact of climate change. In addition, in 2020, the country announced the goal to actively yet prudently promote carbon peak carbon neutrality. An energy revolution in rural areas can help achieve the goal of reaching peak carbon neutrality. From 2019 to 2023, the state has repeatedly promulgated a series of policies in the field of rural new energy (Guo and Li, 2023) (see Table 7).

As can be seen from Table 7, from the situation of policy promulgation, the number of policies is on the rise. The issuing

**TABLE 6 National biomass energy development from 2013 to 2020 (accumulated at the end of the year).**

| Year | Centralized gas supply by straw pyrolysis and gasification | Centralized gas supply of straw biogas | Straw curing molding fuel generation plant | Straw carbonization engineering | Straw baling central heating project |
|---|---|---|---|---|---|
| 2013 | 906 | 434 | 1,060 | 105 | - |
| 2014 | 821 | 458 | 1,147 | 103 | - |
| 2015 | 795 | 458 | 1,190 | 106 | - |
| 2016 | 766 | 454 | 1,362 | 106 | - |
| 2017 | 674 | 431 | 1,616 | 105 | - |
| 2018 | 559 | 386 | 2,331 | 82 | - |
| 2019 | 376 | - | 2,360 | 91 | 178 |
| 2020 | 183 | - | 2,664 | 102 | 238 |

Data source: Agricultural Resources, Environmental Protection, and Rural Energy Development Report.

departments have changed from a single subject to multiple subjects, and the degree of joint decision-making has increased. The contents of the document are mostly related to rural revitalization strategy, economic and social development, and the dual-carbon target. According to the policy mechanism, there is still some imbalance in the new energy policy of rural areas (Wu, 2020), more inclined to direct financial allocation, increase technical support and scientific and technological research and development, strengthen publicity and guidance, and create demonstration, while ignoring the incentive of other economic measures, the construction of technical personnel, and the construction of supporting infrastructure; from the perspective of policy implementation purposes, the scope of our rural new energy policy has been gradually refined; from the perspective of the overall energy structure, the scope of our rural new energy policy has been gradually refined to a certain field, from the initial focus on the overall rural electricity security, improving coal clean transformation efficiency, energy comprehensive construction to focus on new energy utilization, double carbon goals, rural energy revolution, and rural revitalization (Li et al., 2021).

China's new energy policy system is multi-level, all-round, and diversified, which is mainly divided into three categories: development policies. For example, the 2019 photovoltaic power generation project construction work plan issued by the National Energy Administration in May 2019 strictly regulates the competitive allocation of subsidy projects and optimizes the construction investment and business environment, starting from the development of new energy sources. Energy-saving policies, such as the work plan for comprehensive supervision of clean energy consumption issued by the National Energy Administration in March 2021, promote the effective implementation of new energy consumption policies and ensure the efficient use of new energy in rural areas (Luo et al., 2022). Traditional energy transformation policies, such as the opinions on improving the system mechanisms, policies, and measures for green and low-carbon energy transformation issued by the National Development and Reform Commission and the National Energy Administration in February 2022, are conducive to promoting the high-quality development of rural new energy and the comprehensive green transformation of economic and social development (Song et al., 2023). It will provide a guarantee for the scientific and orderly promotion of the goal of carbon peaking and carbon neutrality on schedule and the construction of a modern economic system.

# 3 Development mechanism of rural new energy connection

## 3.1 Interest behavior of rural new energy connection development

Rural new energy connection development includes three stages: development, production, and utilization of new energy. The interest behavior of rural new energy connection development is as follows.

### 3.1.1 Development stage of rural new energy resources

1) Benefit target of new energy resource development. In the development of rural energy resources, the goal is, on the one hand, to develop biomass resources, rural straw, and other biomass resources for centralized collection and large-scale development, forming an industrial scale and on the other hand to develop clean energy such as wind and other clean distributed units of site selection.
2) Interest behavior of new energy resource development. Based on the key business, in the industrial resource development stage, the main cooperative subjects are social subjects, agricultural users, logistics enterprises, and distributed unit location research institutions. Recycling straw and other biomass resources from the hands of agricultural users; relying on the logistics enterprises to improve the logistics system, transport, to achieve the large-scale development of rural straw and other biomass resources; cooperating with research institutes of distributed unit siting to study distributed unit siting layout; and realizing the development of clean energy resources such as landscape; social subjects are mainly reflected in reaching investment cooperation alliances with investors and builders, investing funds, and participating in the whole process of resource development.

**TABLE 7 China's major new energy policy from 2019 to 2023.**

| Number | Date | Publishing department | Document | Content |
|---|---|---|---|---|
| 1 | 2019.4.28 | National Energy Administration | Notice on improving the on-grid pricing mechanism for photovoltaic power generation | The benchmark feed-in price of centralized photovoltaic power stations will be changed to the guiding price under market bidding, and the guiding price for class I to III resources will be 0.40 yuan, 0.45 yuan, and 0.55 yuan per kilowatt-hour, respectively. It is stipulated that the feed-in price of new centralized photovoltaic power stations shall be determined in principle through market competition and shall not exceed the guiding price of the resource zone |
| 2 | 2019.5.10 | National Development and Reform Commission National Energy Administration | Notice on establishing and improving the guarantee mechanism for the consumption of renewable energy electricity | The competent energy department of The State Council shall monitor and evaluate the completion of the consumption responsibility weight of renewable energy in each provincial administrative region and link the consumption of renewable energy with the dual control assessment of the total amount and intensity of national energy consumption |
| 3 | 2019.5.30 | National Energy Administration | Work plan for photovoltaic power generation project construction in 2019 | It calls for the market to play a decisive role in resource allocation. Except for photovoltaic poverty alleviation and household photovoltaics, the remaining photovoltaic power generation projects requiring state subsidies shall, in principle, adopt competitive allocation methods such as bidding |
| 4 | 2019.12.04 | National Development and Reform Commission<br>National Energy Administration<br>Ministry of Finance<br>Department of Natural Resources<br>Ministry of Ecology and Environment<br>Ministry of Housing and Urban–Rural Development<br>Ministry of Agriculture and Rural Affairs<br>Department of Emergency Management<br>People's Bank<br>State Administration of Taxation | Guidelines on promoting the industrialization of bio-natural gas | The nation should adhere to the new development concept, with the goal of realizing the sustainable development of industrialization and commercialization of biogas and forming a green, low-carbon, clean, and renewable gas emerging industry, incorporate biogas into the national energy system, strengthen overall planning and coordination, give full play to the role of the market, establish a distributed production and consumption system, innovate the system and mechanism, and improve policies and measures. It calls for accelerating the professional, market-oriented, and large-scale development of bio-natural gas, increasing the supply of natural gas, protecting the urban and rural ecological environment, and promoting the construction of ecological civilization |
| 5 | 2020.3.5 | National Energy Administration | Notice of the National Energy Administration on matters related to the construction of wind power and photovoltaic power generation projects in 2020 | The notice clarifies relevant requirements for all parties concerned in project construction management |
| 6 | 2020.9.16 | National Development and Reform Commission<br>International Finance Department<br>International Energy Bureau | Implementation plan for improving the construction and operation of biomass power generation projects | Adhering to the principle of set compensation by revenue, division between new and old, orderly construction and steady development, further improvement in the construction and operation management of biomass power generation, rational arrangement of new biomass power generation subsidy funds from the central government in 2020, full implementation of various supporting policies, promotion of industrial technological progress, improvement in project operation and management, and gradual formation of an effective market-based operation mechanism for biomass power generation will promote the sustained and healthy development of the biomass power generation industry |

(Continued on following page)

**TABLE 7 (*Continued*) China's major new energy policy from 2019 to 2023.**

| Number | Date | Publishing department | Document | Content |
|---|---|---|---|---|
| 7 | 2020.9.30 | National Energy Administration | Notice on the announcement of photovoltaic bidding to parity projects | According to the document, two kinds of bidding projects will be directly converted into parity internet access projects: one is the scale of photovoltaic power generation projects that have been selected by national subsidy bidding in 2019 but have not been connected to the grid after the deadline of 3.89 GW, with 21 projects; the other category is the 2020 photovoltaic power generation subsidy project which was declared by bidding but not selected, with a scale of 4.1089 GW and 1,017 projects |
| | 2020.12.16 | CPC Central Committee<br>The State Council | Opinions on effectively connecting the achievements of consolidating and expanding poverty alleviation with rural revitalization | It has identified the key tasks of consolidating and expanding the achievements in poverty alleviation to help rural revitalization, including five categories: modernization of rural power grids, efficient and clean energy in rural areas, upgrading rural electrification, integrating urban and rural services, and comprehensively consolidating and expanding the achievements in poverty alleviation. It covers 17 key tasks, including implementing the project to consolidate and upgrade rural power grids; realizing coordinated development of rural power grids in the eastern, central, and western regions; promoting the transformation and development of smart power grids; realizing the electrification of farmers' lives; reducing the cost of electricity in rural areas; strengthening the construction of rural power supply centers; and consolidating the effectiveness of fixed-point assistance work |
| 9 | 2021.1.27 | National Energy Administration | Notice on heating with renewable energy based on local conditions | First, it is necessary to scientifically plan related works and rationally distribute renewable energy heating projects. Second, promote all kinds of renewable energy heating technology according to local conditions and give full play to the positive role of all kinds of renewable energy in heating. Third, continue to promote pilot demonstration work and construction of major projects and explore advanced project operation and management experience. Fourth, further improve the government management system and strengthen research and development support for key technologies and equipment. |
| 10 | 2021.2.21 | CPC Central Committee<br>The State Council | Opinions of the CPC Central Committee and The State Council on comprehensively promoting rural revitalization and accelerating agricultural and rural modernization | Carrying out a project to build clean energy in rural areas. Step up efforts to build rural power grids, comprehensively consolidate and improve rural electricity supply, promote the supply of gas to rural areas, and support the construction of safe and reliable rural gas storage stations and micro-pipe network gas supply systems for developing biomass energy in rural areas |
| 11 | 2021.2.24 | National Development and Reform Commission<br>Ministry of Finance<br>People's Bank of China<br>China Banking and Insurance Regulatory Commission<br>National Energy Administration | On guiding to increase financial support to promote wind power and a notice on the healthy and orderly development of photovoltaic power generation and other industries | Financial institutions negotiate with renewable energy enterprises to extend or renew loans in accordance with commercial principles. For renewable energy enterprises with great short-term repayment pressure but promising future development prospects, financial institutions may, in accordance with the principle of controllable risk, on the basis of independent consultation between banks and enterprises, and according to the actual and expected cash flow of the project, extend the loan, renew the loan or adjust the repayment schedule and other arrangements. The circular also clarified the responsibilities of the six financial institutions. Financial institutions should help enterprises effectively defuse production, operation, and financial security risks and promote the healthy and orderly development of the renewable energy industry. |

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**TABLE 7 (*Continued*) China's major new energy policy from 2019 to 2023.**

| Number | Date | Publishing department | Document | Content |
|---|---|---|---|---|
| 12 | 2021.3.12 | National Development and Reform Commission | Outline of the 14th Five-Year Plan for the National, Economic, and Social Development of the People's Republic of China and the long-range goals for 2035 | It calls to accelerate the intelligent upgrading of power grid infrastructure and the construction of smart microgrids, improve the complementarity and intelligent regulation capacity of the power system, strengthen the connection between the charge and storage of the source network, increase the consumption and storage capacity of clean energy, increase the capacity of transmission and distribution to remote areas, promote the flexible upgrading of coal power, and accelerate the construction of pumped storage power stations and large-scale application of new energy storage technologies. |
| 13 | 2021.3.23 | National Energy Administration | Work plan for comprehensive supervision of clean energy consumption | Optimize the grid-connected access and operation of clean energy, standardize the participation of clean energy in market trading, promptly identify prominent problems in the development of clean energy, ensure the efficient use of clean energy, further promote the high-quality development of the clean energy industry, and help achieve carbon peak and carbon neutrality. |
| 14 | 2021.4.19 | National Energy Administration | Notice on the development and construction of wind power and photovoltaic power generation in 2021 | It calls to achieve the goals of carbon peaking and carbon neutrality, raise the share of non-fossil energy in primary energy consumption to around 25% by 2030 and raise the total installed capacity of wind and solar power to over 1.2 billion kW by 2030. It calls to stick to the goal orientation, improve the development mechanism, free up room for consumption, improve the development environment, give play to the leading role of local governments, and arouse the enthusiasm of investors. These steps will promote high-quality development of wind power and photovoltaic power generation |
| 15 | 2021.6.28 | National Comprehensive Energy Department | Notice on submitting the pilot program of roof-distributed photovoltaic development in the whole county (city or district) | The circular put forward the principle of building as much as possible, clarifying that no less than 50% of the total roof area of party and government buildings can be installed with photovoltaic power generation. Schools, hospitals, village committees, and other public buildings shall not be less than 40%; the roofs of industrial and commercial plants shall not be less than 30%; and rural residents' roofs shall not be less than 20%. |
| 16 | 2021.7.1 | National Development and Reform Commission | The 14th Five-Year Plan for the Development of Circular Economy | It promoted the application of integrated systems of cogeneration, distributed energy, and photovoltaic energy storage; improved the recycling and traceability management system of power batteries for new-energy vehicles; and promoted the cascade utilization of energy resources to strengthen the promotion and application of advanced technology and equipment for recycling and step utilization of waste power batteries. |
| 17 | 2021.7.5 | National Development and Reform Commission | Notice on matters related to the investment and construction of new energy supporting delivery project | The circular said that the development of non-fossil energy such as wind power and photovoltaic power needs to be further accelerated in order to achieve the goal of carbon peaking and carbon neutrality. The asynchronous construction of new energy units and supporting delivery projects will affect the consumption of new energy connected to the grid |
| 18 | 2021.7.15 | National Development and Reform Commission<br>National Energy Administration | Guidelines on accelerating the development of new energy storage | The development target of 30 GW in 2025 will be defined. In the next 5 years, new energy storage will be transformed from the initial commercialization to large-scale development. By 2030, new energy storage will be fully marketized, diversified development of energy storage will be encouraged, energy storage price recovery mechanisms will be further improved, and shared energy storage development will be supported. |

(Continued on following page)

**TABLE 7 (*Continued*) China's major new energy policy from 2019 to 2023.**

| Number | Date | Publishing department | Document | Content |
|---|---|---|---|---|
| 19 | 2021.8.11 | National Development and Reform Commission<br>Ministry of Finance<br>National Energy Administration | Work plan for 2021 biomass power generation project construction | It proposed to further improve the development and construction management of biomass power generation and rationally arrange the central government's additional biomass power generation subsidy funds in 2021 in accordance with the idea of compensation based on revenue, sharing by the central government, classified management and stable development. |
| 20 | 2021.10.24 | The State Council | Opinions on fully, accurately, and comprehensively implementing the new development concept to achieve carbon peak and carbon neutrality | Firstly, speed up the building of a clean, low-carbon, safe and efficient energy system. Secondly, speed up the building of a low-carbon transport system. Thirdly, improve the quality of green and low-carbon development in urban and rural areas. Fourthly, we will increase the level of green and low-carbon development in opening up to the outside world. Fifthly, we will improve laws, regulations, standards and statistical monitoring systems. Sixth, we will improve policy mechanisms. |
| 21 | 2021.10.26 | The State Council | Action plan to peak carbon by 2030 | In order to implement the major strategic decisions of the CPC Central Committee and The State Council on carbon peaking and carbon neutrality, and in accordance with the working requirements of the opinions of the CPC Central Committee and The State Council on fully, accurately, and comprehensively implementing the new development concepts for carbon peaking and carbon neutrality, the focus is centered on the target of carbon peaking before 2030 and making overall arrangements for promoting carbon peaking. |
| 22 | 2021.12.29 | National Energy Administration<br>Ministry of Agriculture and Rural Affairs<br>National Rural Revitalization Administration | Implementation opinions on accelerating rural energy transformation and development to help rural revitalization | It calls to fully implement the new energy security strategy of four revolutions and one cooperation, take green and low-carbon energy development as an important foundation and driving force for rural revitalization, balance development with security, promote the building of a clean, low-carbon, and multi-energy integrated modern rural energy system, comprehensively improve the quality of rural energy use, and ensure that rural energy is available, affordable, and well-used. This will provide strong support for consolidating and expanding the achievements made in poverty alleviation and comprehensively promoting rural revitalization. |
| 23 | 2022.2.10 | National Development and Reform Commission<br>National Energy Administration | Opinions on improving the system, mechanism, policies, and measures for green and low-carbon energy transition | It calls to improve policies on green energy use and clean heating in buildings. China will improve standards for the application of renewable energy in buildings, encourage the integrated application of photovoltaic energy in buildings, and support the use of solar energy, geothermal energy, and biomass energy to build energy supply systems for renewable energy buildings. |
| 24 | 2022.2.26 | National Development and Reform Commission<br>National Energy Administration | Planning and layout scheme of large-scale wind power photovoltaic base focusing on the Gobi Desert and other desert areas | It calls for coordinating the development plan of the photovoltaic power generation industry with the national space plan and encouraging the use of unused land and stock construction land for the development of the photovoltaic power generation industry. Under the premise of strict ecological protection, the construction of large-scale photovoltaic bases is encouraged in the Gobi Desert and other arid areas. For oil fields, gas fields, and coal mining subsidence areas that are difficult to reclaim or repair, the planning and construction of photovoltaic bases in non-arable areas are promoted |

(Continued on following page)

**TABLE 7 (*Continued*) China's major new energy policy from 2019 to 2023.**

| Number | Date | Publishing department | Document | Content |
|---|---|---|---|---|
| 25 | 2022.3.22 | National Development and Reform Commission<br>National Energy Administration | The 14th Five-Year Plan for Modern Energy Systems | It calls to comprehensively promote large-scale and high-quality development of wind and solar power generation, giving priority to local and nearby development and utilization. Centralized development of wind power and photovoltaic power generation should be promoted in an orderly manner, and construction of large-scale wind power photovoltaic base projects focusing on the Gobi Deserts and other desert areas should be accelerated |
| 26 | 2022.4.2 | National Energy Administration<br>Ministry of Science and Technology | The 14th Five-Year Plan for Scientific and Technological Innovation in the Energy Sector | In the field of solar thermal power generation and comprehensive utilization technology, China will focus on tackling key problems and conducting research on thermochemical conversion and thermochemical energy storage materials and exploring complementary technologies for solar thermal chemical conversion and other renewable energy sources. Research and development of thermochemical fuel conversion reaction technology driven by medium-temperature solar energy and development of megawatt solar thermochemical power generation devices is proposed. |
| 27 | 2022.5.30 | National Development and Reform Commission<br>National Energy Administration | Implementation plan for promoting high-quality development of new energy in the new era | It calls to accelerate the construction of large-scale wind power and photovoltaic bases in the Gobi Deserts and other desert areas, promote the integrated development of new energy development and rural revitalization, and promote the application of new energy in industry and construction. |
| 28 | 2022.6.1 | National Development and Reform Commission<br>National Energy Administration<br>Ministry of Finance<br>Department of Natural Resources<br>Ministry of Ecology and Environment<br>Ministry of Housing and Urban–Rural Development<br>Ministry of Agriculture and Rural Affairs<br>China Meteorological Administration<br>National Forestry and Grassland Administration | The 14th Five-Year Plan for the Development of Renewable Energy | By 2025, the annual renewable energy generation will reach around 3.3 trillion KWH. During the 14th Five-Year Plan period, the increase in electricity generation from renewable energy sources accounted for more than 50 percent of the total increase in electricity consumption, and the electricity generation from wind and solar energy doubled. By 2025, China will have about 33 percent of the total amount of renewable energy electricity consumed and about 18 percent of the non-hydropower consumption of renewable energy electricity. The construction of onshore wind power and photovoltaic power generation bases should be coordinated, and the development of large-scale wind and solar power generation bases should be accelerated, focusing on the Gobi desert and other desert areas. The construction of offshore wind power bases in an orderly manner and the distributed development of wind power and photovoltaic power generation should be actively promoted. |
| 29 | 2022.6.30 | Ministry of Housing and Urban–Rural Development<br>National Development and Reform Commission | Implementation plan for carbon peaking in urban and rural constructions | In areas rich in solar energy resources and buildings with a stable demand for hot water, the application of solar energy in solar thermal buildings should be promoted. The use of renewable energy such as solar conservatories in light of local conditions, the use of renewable energy, the application of renewable energy sources such as solar energy, geothermal energy, air thermal energy, and biomass energy in the supply of gas, heating, and power in rural areas should be promoted. |
| 30 | 2022.10.9 | National Energy Administration | Action plan for energy carbon peaking, carbon neutrality, and standardization | Clean heating standards for biomass energy, solar energy, heat pumps, and clean stoves will be developed. |
| 31 | 2023.3.15 | National Energy Administration | Notice on organizing the construction of pilot counties for rural energy revolution | All localities should attach great importance to the construction of pilot counties for rural energy |

(Continued on following page)

**TABLE 7 (*Continued*) China's major new energy policy from 2019 to 2023.**

| Number | Date | Publishing department | Document | Content |
|---|---|---|---|---|
| | | Ministry of Ecology and Environment | | revolution, intensify efforts in organization and coordination, and establish working mechanisms to ensure practical results as soon as possible. |
| | | Ministry of Agriculture and Rural Affairs | | |
| | | National Rural Revitalization Administration | | |

Data source: National Policy Document.

### 3.1.2 Production stage of new energy resources in rural areas

1) Benefit target of new energy resource production. It is to build the rural new energy production system. On the one hand, it is to build the distributed production unit of industrial resources, and on the other hand, it is to build the system information platform. For the construction of the system, the common construction methods include BT mode and improved PPP mode.
   ① BT mode. BT is building and transfer, for the first construction, after the transfer construction mode. Through bidding, the initiator signs a construction BT contract with the winning bidder, entrusts the project to the winning bidder for construction, and accepts the project after completion of construction, as shown in Figure 11.
2) Improved PPP mode. The conventional PPP mode refers to the cooperation between the government and private capital to participate in the construction of public infrastructure. In the construction process of energy internet + rural energy (Yang et al., 2021), an improved PPP model can be adopted, that is, based on the cooperation alliance in the PPP model, the cooperative subjects will be expanded to include government departments, power grid companies, new comprehensive energy construction companies, and social capital, and the power grid companies and new comprehensive energy construction companies will take the lead. Multi-party cooperation in the construction and operation of the rural new energy industry (Yu et al., 2022) is shown in Figure 12.
2) Interest behavior of new energy resource production. Based on the key business, in the resource production stage of the rural new energy industry, the partners are mainly equipment manufacturers, system developers, social subjects, and the government. Purchase equipment from equipment manufacturers; rely on the technology of system developers to develop a modern internet platform, to realize the construction of the system equipment layer and platform layer; cooperate with social subjects and the government to absorb social capital and obtain national policy support so as to reduce investment costs and improve investment efficiency.

### 3.1.3 Utilization stage of rural new energy resources

As can be seen from Figure 13, a basic business includes energy supply service, auxiliary service, and clean energy service. Energy supply service is based on rural energy, carrying out distributed power generation in the local consumption, supplying energy to end-users at the same time, the surplus online; auxiliary service refers to the frequency modulation, voltage regulation, and reserve and other services provided by the pointer to the power grid. Clean energy service is a policy subsidy for promoting green electricity to end-users. The extended business includes energy management services and energy-saving transformation services. Energy use management services refer to providing end-users with energy use solutions, energy use quality management and customization, equipment operation and maintenance services, etc. Energy-saving transformation service refers to the end-users, the use of demand response, energy package, and other means to provide energy efficiency management, energy-saving transformation, and other services. Value-added services include energy financial services and information services. Energy financial services refer to providing consumers with financial services such as power failure compensation insurance. Information service refers to the energy use data based on the consumption end. On the one hand, it provides energy use data and energy use plans for consumers at the consumption end; on the other hand, it provides differentiated user portraits for producers at the production end.

Benefit behavior of new energy resource utilization. Based on key services, in the market-oriented operation stage, the main partners are end-users and power grid companies. For end-users, on the one hand, they sign an energy use contract with the investor (the manager of the investor is assumed in this paper) and reach a supply–demand cooperative alliance (Zakaria et al., 2020). On the other hand, energy management contracts are signed with the investors and builders to achieve demand response cooperative alliance. The power grid company, on the one hand, can sign a two-way auxiliary service contract with the investor (assuming the investor is a new comprehensive energy construction company here) to provide backup, frequency modulation, and other services to each other and reach a backup cooperation alliance. On the other hand, the investors signed the surplus Internet contract and reached the consumption of clean energy cooperation alliance.

## 3.2 Interest relationship of rural new energy connection and development

### 3.2.1 Interactive analysis of interest linkage

Based on the design of the rural new energy business model, this section further analyzes the interest relationship of multi-subject capital flow under different development stages, as shown in Figure 14.

It can be seen from Figure 14 that in the development stage of rural new energy resources, stakeholders mainly include project

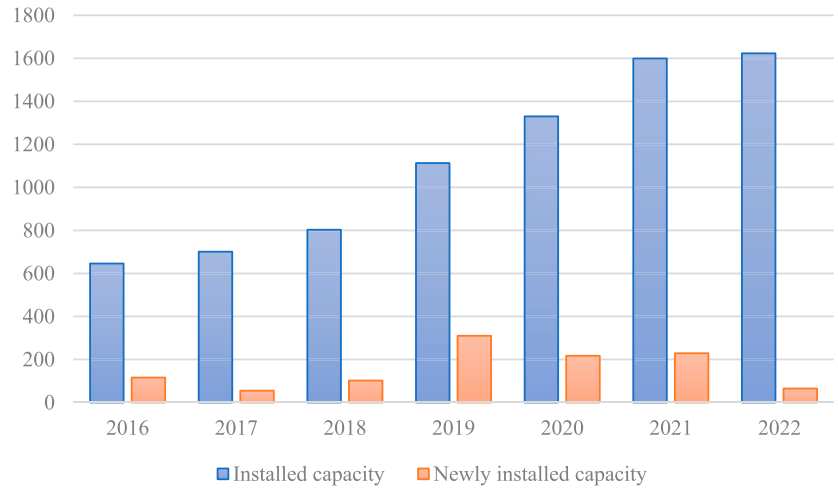


FIGURE 10
Installed capacity and newly added capacity of agricultural and forestry biomass power generation in 2016–2022 (10 MW). Data source: China Biomass Energy Industry Development Yearbook (2023).

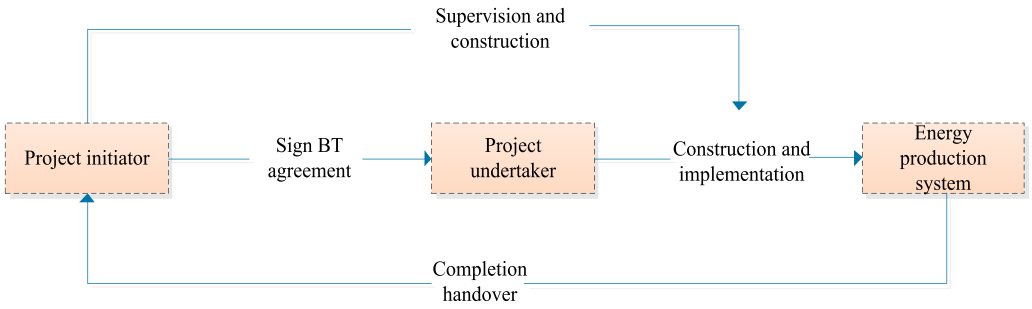


FIGURE 11
BT construction mode.

construction and initiator, social subjects, scientific research institutions, logistics companies, and agricultural users (Dong et al., 2023). In this stage, the power grid company or the new comprehensive energy construction company is the construction and initiator of the project, which is the outflow of funds. If the social subject participates in the construction cooperation, it needs to pay the investment fee for the construction, which is also the outflow of funds. If the social subject does not participate in the construction but can provide services for the construction, it can get the construction service fee, which is the inflow of funds. Agricultural users, logistics enterprises, and research institutes for distributed unit siting need to pay biomass resource recycling waste fee, logistics service fee, and research fee, respectively, belonging to the inflow of funds. In the production stage of rural new energy resources, stakeholders mainly include project construction and initiator, social subjects, government, system developers, and equipment manufacturers. In this stage, the role positioning of construction and initiator and social subject is consistent with that of the resource development stage. For the government, it can be either capital outflow or capital inflow. By formulating policies, the government designs subsidy policies for investment and construction on the one hand and investment funds and punishment measures on the other hand so as to obtain benefits in case of violations by the investors (such as violation of occupation of farmland). For equipment manufacturers and system developers as equipment providers and platform developers, the investors need to pay equipment purchase fees and platform development fees to them, respectively, which belong to the capital inflow. In the utilization stage of rural new energy resources, stakeholders mainly include the construction and initiator of the project, the power grid (if the power grid does not belong to the construction and initiator of the project), the government, and the end-user. In this stage, the construction and sponsors, the power grid, and the government have both capital inflows and outflows. Among them, for builders and initiators, capital inflow mainly includes service income from the government, power grid, and end-users. Capital outflow mainly includes penalty cost paid to the government, standby service cost paid to the power grid, and demand response cost paid to users. As for the end-users, they need to pay service fees for various services to the investors, which belong to the outflow of funds (Yu and Yin, 2023).

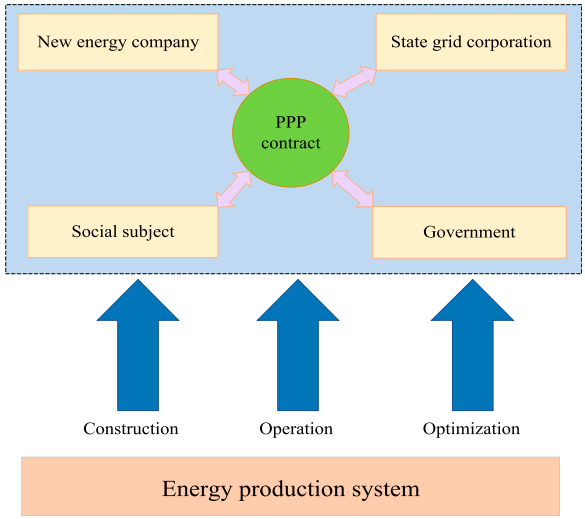


FIGURE 12
Improved PPP construction mode.

### 3.2.2 Analysis of benefit components

Based on the analysis of the flow direction of multi-agent value, the cost and value components of rural new energy are sorted out, with the participant as the main body. As shown in Figure 15, the benefit components mainly include cost measurement and value measurement. The cost is divided into three stages: development, production, and utilization. The development stage includes biomass recycling fee, logistics service fee, scientific research fee, and development service fee. The production stage includes equipment purchase fee, platform development fee, policy penalty fee, and development service fee. The utilization stage includes standby service fee, policy penalty fee, demand response fee, and utilization service fee. The utilization stage of value measurement includes seven parts: energy supply income, energy management income, energy management income, energy insurance income, auxiliary service income, demand response income, data realization income, and policy subsidy income.

## 4 Optimization of rural new energy system construction

### 4.1 Main problems of rural new energy system construction

In recent years, China's rural new energy industry has been developing rapidly. The state also attaches great importance to it and has introduced relevant policies to support it. However, due to the limitations of the rural economy and technology, the rural new energy industry of China has a certain gap between the realization of the double carbon goals, and problems still persist.

1) Low energy efficiency and imbalance of the supply and demand structure

At present, China's new energy resource utilization efficiency is low and does not conform to the requirements of promoting green development. According to statistics, at the end of 2020, the proportion of new energy usage in China was only approximately 15%, the main energy sources still being coal, oil, straw, firewood, and so on, caused by coal, oil, and other traditional energy carbon emissions of more than 85% (Li J. et al., 2023), and the most extensively used method is direct combustion, with low utilization efficiency, producing large amounts of soot, polluting the environment, and aggravating haze. Rural areas are rich in solar energy, wind energy, small hydropower, and other resources. However, due to the scattered distribution in rural areas, the high cost of new energy technology development, and the insufficient understanding of new energy technology in rural areas, the development and utilization level of new energy in rural areas is low, and the imbalance between supply and demand exists. With the acceleration of urbanization and industrialization in the medium and long terms, the lifestyles of farmers and urban residents are becoming increasingly similar, and traditional energy sources are increasingly unable to meet the needs of rural production and living.

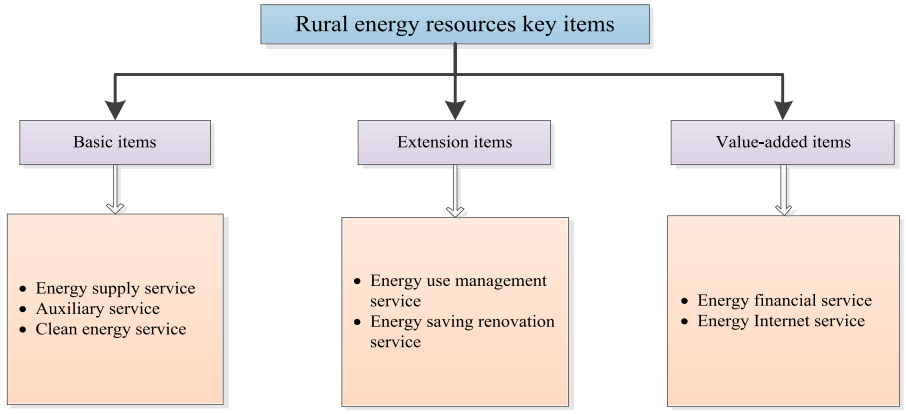


FIGURE 13
Rural energy resource utilization stage key business.

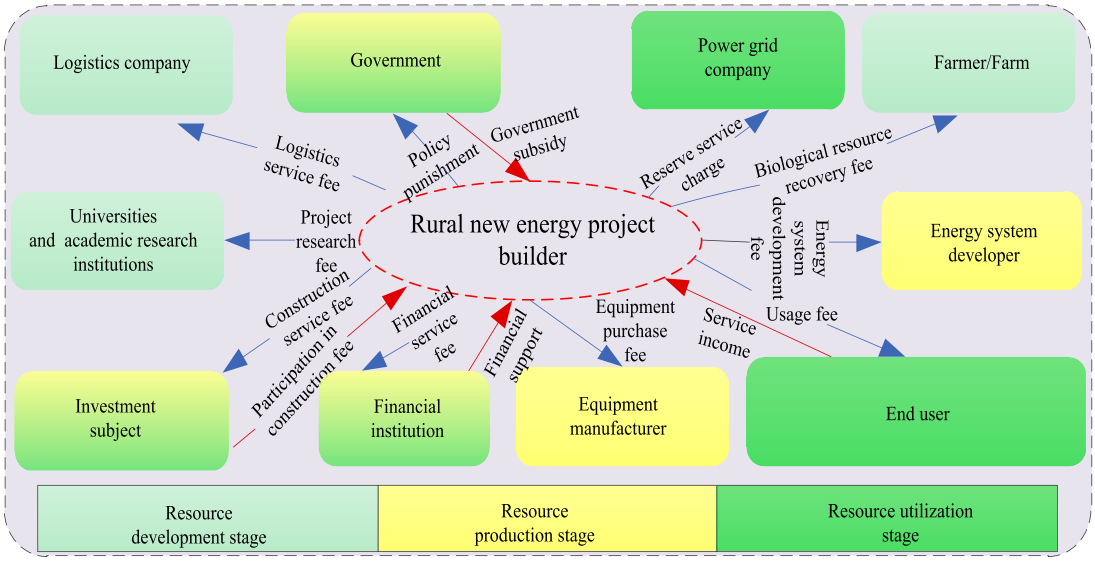


FIGURE 14
Analysis of multi-subject interest relationship in different stages.

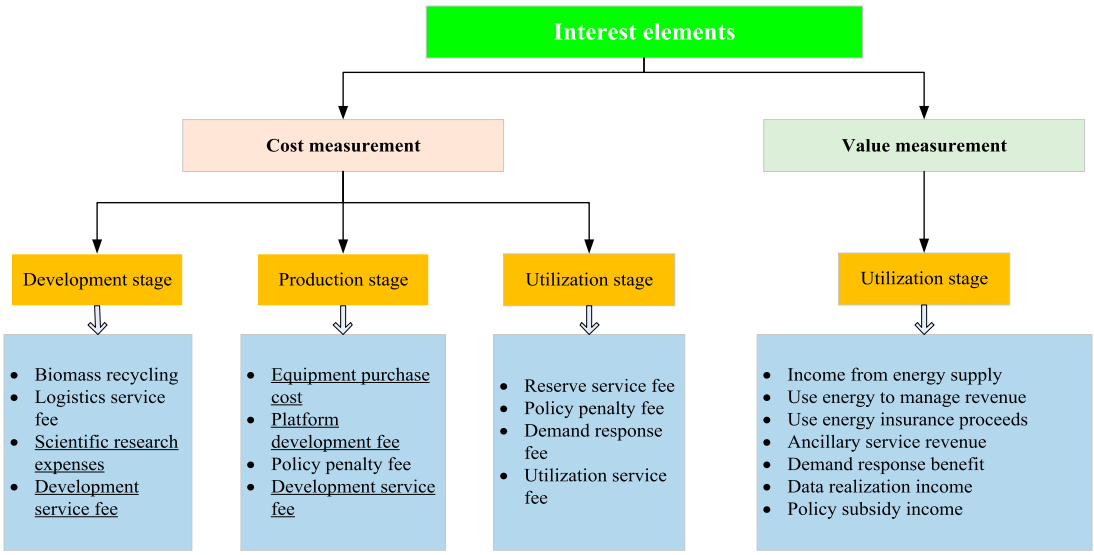


FIGURE 15
Different stages of interest components.

2) Backward infrastructure and a single source of funds

In China, new energy infrastructure is weak, technology development investment is insufficient, the modernization scale operation level is low, and the general energy service ability is insufficient (Wang, 2022). After the construction of new energy infrastructure projects in rural areas was put into use, the follow-up technical services could not keep up. For example, although China has a large agricultural population, the total installed power capacity of agricultural production and rural living is only 80 million kW, accounting for less than 4% of the total installed power capacity of the country, and the average power supply capacity of each household is only 1/10 of that of urban areas. The rural new energy construction investment scale has a long recovery cycle and high uncertainty. At present, our rural new energy industry is still mainly led by state investment, the capital gap is large, the capital source is single, and the new energy development level and the low level of economic development restrict the energy transformation (Naumann and Rudolph, 2020).

3) Loose policy structure and lack of long-term mechanisms

Since the reform and opening up, the new energy policy of the countryside needs to be adjusted and improved with the changing situation. However, the new energy policy needs to be implemented with integrity, long-term nature, and pertinence. Compared with Wang et al. (2022), this study found that in 2019–2023, China had promulgated more than 30 major new energy-related policies. In the formulation of new energy policies, China lacks overall consideration, often only considering new energy and the economy or new energy and the environment, rarely coordinating the three, which is not conducive to sustainable development. In the implementation of the new energy policy, the development of the new energy industry needs strong support and planning of the government; however, at present, the new energy industry policy support is weak, and the departments in the formulation of policies or examination standards have not specified the implementation standards (Wang and Yuan, 2023), resulting in the lower executive departments having too much free play space and scope, with a lack of unified planning and guidance. The implementation of new energy policies often lacks follow-up supervision and promotion, resulting in improper implementation.

4) The interest connection is not tight, and the interest relationship is unstable

Compared with He et al. (2022), this study found that from the current point of view, there are still some difficulties and constraints in the process of development, production, and utilization of rural new energy connection. The problem of interest connection among market entities has not been completely solved, and a close community of interests needs to be improved. The interest subjects of innovation and development of the rural new energy industry are not closely connected, the interest relationship is not stable enough, and the willingness to continue cooperation needs to be enhanced, hence resulting in lack of new energy exploitation, weak consumption power of farmers, and poor effect of industrial carbon reduction and efficiency improvement.

## 4.2 Suggestions on the construction and development of a rural new energy system

1) Accelerate the transformation of new energy consumption patterns in rural areas and improve energy efficiency

At present, most of the energy requirements of rural life depends on coal, straw, and so on, so efficient development of rural new energy needs to be driven by coal to electricity and coal to gas, gradually increasing rural distributed photovoltaic, biogas, biomass energy, etc., through the comprehensive energy system to improve energy efficiency so as to reduce the unit energy density and carbon emissions (Wu et al., 2023). At the same time, we should reduce the proportion of non-commercial energy use, promote the replacement of domestic electric energy and comprehensive energy supply, adapt to local conditions, reduce low-quality loose coal, choose new energy suitable for local use, improve energy efficiency, promote energy conservation and carbon reduction in important areas, and improve the quality of life of rural residents.

2) Optimize the development and construction of new energy infrastructure and increase financial investment

To enhance the development of distributed wind power and distributed photovoltaic systems in rural areas, it is essential to accelerate the classification and recycling of household waste. Additionally, expanding the resource development radius and standalone capacity of biomass energy, as well as solid waste such as straw, is crucial. Moreover, it is necessary to explore the promotion and utilization of carbon capture devices for biomass and waste power generation (Yu et al., 2023). We are committed to establishing standards for the operation and maintenance of new energy systems in rural areas to ensure safe energy production and guarantee a consistent and reliable supply of new energy. Additionally, we will enhance comprehensive energy operation and peacekeeping services in rural areas. We will actively encourage farmers to participate in the development and construction of new energy resources through initiatives like collective land and labor force investment, aiming to increase their engagement and recognition. By doing so, we can effectively reduce the development and supply costs associated with new energy resources in rural areas. Moreover, we will increase financial support and encourage financial institutions to innovate financing methods and service models. This will enable us to provide differentiated financial assistance to high-quality projects.

3) Improve the policy and system guarantee of new energy in rural areas and boost confidence in new energy development

With the completion of poverty alleviation in rural areas and the improvement of rural economy, relevant policies and system guarantee can consolidate the achievement of poverty alleviation to a certain extent (Wang S. et al., 2023). It is necessary to ensure the integrity, coherence, long-term stability, and pertinence of policies; actively explore new energy incentive policy support means; and stimulate the enthusiasm of participants by improving economic benefits. Economic incentives such as low-interest loans, tax cuts, and fee cuts are given to enterprises to enhance the enthusiasm and initiative of investing in the development of rural new energy, increase the training of relevant technical personnel, and promote the innovation and promotion of rural new energy technology, application mode, and commercial mode (Wang B. et al., 2023). The government should strengthen publicity in the pilot areas of rural new energy reform, while also conducting thorough research and demonstration on the economic value of rural new energy. It is crucial to promote feasible practices and amplify the demonstration effect to effectively achieve the double carbon goal.

4) Strengthen the coordinated development of interest-linked subjects and promote the realization of dual-carbon goals

At present, the interest-linking subjects of rural new energy development are more diverse, the interest-linking relations are more complex, and the interest-linking scenes are more sophisticated. Therefore, it is necessary to take the development, production, and utilization of rural new energy as a complex systematic whole; apply the complex system theory; strengthen the complementary advantages of multiple subjects, resource

sharing, mutual benefit, and synergy; and fully combine the rural resource endowment. It is important to explore a typical model of interest linkage based on local conditions, focusing on the principles of clean and low-carbon, nearby utilization, and benefiting the people. This will help achieve the synergistic effect of pollution reduction and carbon reduction in agriculture and rural areas (Finn and Brockway, 2023). In short, under the double carbon goal, the innovation and development benefits of the rural new energy industry should be connected according to local conditions, according to the current conditions, according to the needs of the situation, according to the situation, and according to the situation.

## 5 Conclusion

In view of the problems existing in rural energy development under the "dual carbon" goal, this paper integrates and summarizes the relevant data on rural new energy in recent years. The existing literature pays more attention to the development trend and reform path of rural energy, but pays less attention to the consumption, utilization, and linkage development mechanism of rural new energy. This paper analyzes the current development and utilization status of rural new energy in China and the linkage development mechanism. The results show the following: 1) Energy output in rural areas is mainly concentrated in wind energy, photovoltaic energy, and water energy, followed by biomass energy. The development and utilization of new energy has been increasing continuously, but the utilization efficiency is low and insufficient; 2) The total amount of new energy consumption in rural areas continues to increase, and its overall situation is good in terms of production and supply mode, consumption structure, and industrial development. However, due to the rising demand, the contradiction between the supply and demand of new energy in rural areas is aggravated, and there is still a certain gap in the construction process of a modern new energy system in rural areas. 3) The scale of the rural new energy industry increases, policy support is strengthened, and the industry development environment is optimized. However, there is an imbalance in policy development, which tends to direct financial allocation while ignoring the training of relevant technical personnel. 4) In the process of rural new energy connection development, interest subjects are not closely connected, the interest relationship is unstable, the interest connection among market subjects has not been completely solved, and a close community of interests needs to be improved. New energy resources are not fully tapped, farmers' consumption power is not strong, and industrial carbon reduction and efficiency is not good. In theory, this paper supplements and expands the current literature research and studies the development and utilization status of rural new energy development, linked development mechanism, and system construction from a new perspective. In reality, this paper starts from the current situation of rural new energy development and utilization; analyzes the scale of rural solar energy, rural wind energy, rural biogas energy, and other new energy industries; closely follows the national pace of rural new energy development; analyzes the latest policies of rural new energy industry; analyzes the development mechanism of rural new energy connection; and provides corresponding solutions to stakeholders. It also provides reference for the subsequent related research and rural new energy development.

At present, China's rural energy revolution is booming, and the results are remarkable. The model innovation, policy innovation, and path innovation formed in the process of promoting the development of rural new energy in China have a high degree of wide applicability. Rural areas are the resource base and hold an important position in new energy development. The biggest pressure on global sustainable development comes from the climate challenge, which requires all countries to implement carbon reduction strategies. In this historical trend, the development of rural areas all over the world has ushered in valuable opportunities. China's rural energy revolution has been further promoted to contribute to a new road and a new model, and in the process of promoting the strategic adjustment of China's energy structure, rural areas occupy a very prominent position. A series of important documents have been issued, and policies have become increasingly perfect. The global rural clean energy development faces many common technical problems, model problems, and policy problems, and the extraordinary practice of China's rural energy revolution provides valuable exploration experience and rich solutions for breaking through these problems.

The green energy transformation and development in rural areas are essential to meet the people's aspiration for a better quality of life. Moreover, it plays a vital role in the establishment of a modern energy system. This endeavor holds great significance in not only consolidating and expanding poverty alleviation achievements but also promoting rural revitalization, achieving carbon peak and carbon neutrality, and modernizing agriculture and rural areas. To realize the double carbon goal, it is imperative to vigorously develop rural new energy. This entails increasing the proportion of new energy utilization and enhancing relevant infrastructure. Additionally, expediting the green transformation of the rural new energy structure is crucial. Providing strong institutional support for rural new energy development is necessary, along with fostering coordinated development of stakeholders involved. By improving the quality of life for residents in rural areas, a modern rural new energy development system can be established. This will contribute to the support of rural revitalization and the achievement of the carbon peak and carbon neutral goals.

The research in this paper focuses on theoretical research, without actual research, and individual data are not updated to the latest year, resulting in incomplete data. Rural areas are rich in new energy resources such as wind energy, solar energy, and biomass energy, which is an important field for realizing the double carbon goal. With the rapid development of new energy in rural areas, the complexity of energy use in rural areas will continue to increase in the future. To address the limitations of this paper, it is hoped that more detailed data can be collected and detailed practical research can be conducted in subsequent studies in order to accelerate the construction of a modern rural new energy system and achieve the double carbon goal.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

## Author contributions

SY: Conceptualization, Project administration, Resources, Writing–original draft, and Writing–review and editing. ZZ: Data curation, Formal Analysis, Investigation, and Writing–review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Correction note

A correction has been made to this article. Details can be found at: 10.3389/fenrg.2025.1699265.

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## References

Chen, F., Qiu, H., and Zhang, J. (2022b). Energy consumption and income of the poor in rural China: inference for poverty measures. *Energy Policy* 163, 112865. doi:10.1016/j.enpol.2022.112865

Chen, M., Cheng, J., Zhou, Y., Ding, Z., and Ma, H. (2022a). Origin, realization path and key scientific issues of carbon neutrality: climate change and sustainable urbanization. *J. Nat. Resour.* 37 (05), 1233–1246. doi:10.31497/zrzyxb.20220509

Chen, Y., Guo, M., Liu, Y., Wang, D., Zhuang, Z., and Quan, M. (2023). Energy, exergy, and economic analysis of a centralized solar and biogas hybrid heating system for rural areas. *Energy Convers. Manag.* 276, 116591. doi:10.1016/j.enconman.2022.116591

Choudhury, S., Parida, A., Pant, R. M., and Chatterjee, S. (2019). GIS augmented computational intelligence technique for rural cluster electrification through prioritized site selection of micro-hydro power generation system. *Renew. energy* 142, 487–496. doi:10.1016/j.renene.2019.04.125

Clausen, L. T., and Rudolph, D. (2020). Renewable energy for sustainable rural development: synergies and mismatches. *Energy Policy* 138, 111289. doi:10.1016/j.enpol.2020.111289

Cong, H., Zhao, L., Wang, J., and Yao, Z. (2017). Current situation and development demand analysis of rural energy in China. *Trans. Chin. Soc. Agric. Eng.* 33 (17), 224–231.

Cui, X., Guo, L., Li, C., Liu, M., Wu, G., and Jiang, G. (2021). The total biomass nitrogen reservoir and its potential of replacing chemical fertilizers in China. *Renew. Sustain. Energy Rev.* 135, 110215. doi:10.1016/j.rser.2020.110215

Ding, L., Hu, J., Liu, Q., Lv, H., Li, L., and Wang, M. (2021). Analysis of rural energy consumption structure and typical suggestions for energy efficiency improvement. *Energy Conserv.* 40 (04), 65–68.

Dong, T., Yin, S., and Zhang, N. (2023). New energy-driven construction industry: digital green innovation investment project selection of photovoltaic building materials enterprises using an integrated fuzzy decision approach. *Systems* 11, 11. doi:10.3390/systems11010011

Finn, O., and Brockway, P. E. (2023). Much broader than health: surveying the diverse co-benefits of energy demand reduction in Europe. *Energy Res. Soc. Sci.* 95, 102890. doi:10.1016/j.erss.2022.102890

Guo, H., and Li, B. (2023). Review of China's energy policy in 2022 and the direction of adjustment in 2023. *Int. Pet. Econ.* (2), 48–55. Available online at: https://www.cnki.net/KCMS/detail/detail.aspx?dbcode=CJFD&dbname=CJFDLAST2023&filename=GJJJ202302007&uniplatform=OVERSEA&v=X-f4rPSRs8s2q8RwL3PWAJwhG-a3Csm0N2zaZ0zt-gLicxNxP1xbXfugBNe4TG.

Han, J., Zhang, L., and Li, Y. (2022). Spatiotemporal analysis of rural energy transition and upgrading in developing countries: the case of China. *Appl. Energy* 307, 118225. doi:10.1016/j.apenergy.2021.118225

He, G., Zhang, X., Xiong, J., He, W., and Yi, Z. (2022). Research on the business model of rural energy cooperatives in China -- based on the consideration of the interests of multiple participants. *Price theory Pract.* 05, 95–99+206.

Hu, C., Sun, T., Yin, S., and Yin, J. (2023). A systematic framework to improve the digital green innovation performance of photovoltaic materials for building energy system. *Environ. Res. Commun.* 5 (9), 095009. doi:10.1088/2515-7620/acf550

Li, J., Gao, M., Luo, E., Wang, J., and Zhang, X. (2023b). Does rural energy poverty alleviation really reduce agricultural carbon emissions? The case of China. *Energy Econ.* 119, 106576. doi:10.1016/j.eneco.2023.106576

Li, L., Fan, F., and Liu, X. (2021). China's rural energy policy from the perspective of policy tools. *Coal Econ. Res.* 41 (06), 41–47.

Li, W., Yu, Y., He, Q., Xu, D., Qi, Y., and Deng, X. (2023a). Impact of clean energy use on the subjective health of household members: empirical evidence from rural China. *Energy* 263, 126006. doi:10.1016/j.energy.2022.126006

Liu, J., Shuai, J., Shuai, C., Wang, Z., and Huang, F. (2023). Impacts of solar photovoltaic projects on sustainable livelihoods: evidence from rural China. *Energy Sustain. Dev.* 74, 314–327. doi:10.1016/j.esd.2023.04.007

Liu, W., and Li, Y. (2023). Research on the evolution mechanism of promoting clean power supply under the background of rural energy reform in China. *Energy Rep.* 9, 2592–2603. doi:10.1016/j.egyr.2023.01.097

Luo, F., Liang, C., Ma, X., Li, Y., and Dong, X. (2022). Evaluation method considering rural new energy utilization. *J. Phys. Conf. Ser.* 2358 (1), 012009. doi:10.1088/1742-6596/2358/1/012009

Ma, W., Vatsa, P., and Zheng, H. (2022). Cooking fuel choices and subjective well-being in rural China: implications for a complete energy transition. *Energy Policy* 165, 112992. doi:10.1016/j.enpol.2022.112992

Naumann, M., and Rudolph, D. (2020). Conceptualizing rural energy transitions: energizing rural studies, ruralizing energy research. *J. Rural Stud.* 73, 97–104. doi:10.1016/j.jrurstud.2019.12.011

Shen, Y., Qin, W., Zhang, J., Li, C., Wang, S., Zhang, C., et al. (2022). Business models for promoting rural new energy development and utilization. *Power & Energy* 43 (04), 326–331.

Shi, X., Cui, L., Huang, Z., Zeng, P., Qiu, T., Fu, L., et al. (2023). Impact of internal migration on household energy poverty: empirical evidence from rural China. *Appl. Energy* 350, 121780. doi:10.1016/j.apenergy.2023.121780

Song, M., Zheng, H., Shen, Z., and Chen, B. (2023). How financial technology affects energy transformation in China. *Technol. Forecast. Soc. Change* 188, 122259. doi:10.1016/j.techfore.2022.122259

Sun, H., Wang, E., Li, X., Cui, X., Guo, J., and Dong, R. (2021). Potential biomethane production from crop residues in China: contributions to carbon neutrality. *Renew. Sustain. Energy Rev.* 148, 111360. doi:10.1016/j.rser.2021.111360

Sun, R., Yang, M., Su, J., Du, S., Li, P., and Zheng, Y. (2020). Current situation of rural energy development and its development and utilization modes in China. *J. China Agric. Univ.* 25 (08), 163–173.

Wan, R., Tang, L., Guo, J., Zhai, W., Li, L., Xie, Y., et al. (2023). Cost-benefits analysis of ultra-low emissions standard on air quality and health impact in thermal power plants in China. *J. Environ. Manag.* 345, 118731. doi:10.1016/j.jenvman.2023.118731

Wang, B., Wang, J., Dong, K., and Dong, X. (2023d). Is the digital economy conducive to the development of renewable energy in Asia? *Energy Policy* 173, 113381. doi:10.1016/j.enpol.2022.113381

Wang, C., Raza, S. A., Adebayo, T. S., Yi, S., and Shah, M. I. (2023a). The roles of hydro, nuclear and biomass energy towards carbon neutrality target in China: a policy-based analysis. *Energy* 262, 125303. doi:10.1016/j.energy.2022.125303

Wang, C., Wang, Y., Zhao, Y., Shuai, J., Shuai, C., and Cheng, X. (2023b). Cognition process and influencing factors of rural residents' adoption willingness for solar PV poverty alleviation projects: evidence from a mixed methodology in rural China. *Energy* 271, 127078. doi:10.1016/j.energy.2023.127078

Wang, J., and Yuan, T. (2023). Analysis on the evolution of China's agricultural green development policy and policy tools. *Hebei Acad. J.* 43 (02), 130–139.

Wang, R., and Jiang, Z. (2017). Energy consumption in China's rural areas: a study based on the village energy survey. *J. Clean. Prod.* 143, 452–461. doi:10.1016/j.jclepro.2016.12.090

Wang, S., Yin, C., Yang, X., and Richel, A. (2023c). Barter mode: the institutional innovation for affordable and clean energy (SDG7) in rural China. *Biomass Bioenergy* 170, 106725. doi:10.1016/j.biombioe.2023.106725

Wang, Y. (2022). The achievements, problems and countermeasures of rural energy transformation. *Resour. Habitant Environ.* 11, 51–55.

Wang, Y. (2023). Rural energy transformation should be gradual. *Econ. Dly.* 003, 03–26.

Wang, Y., Yang, C., and Liu, X. (2022). The impact of clean energy policies on promoting rural economic development: an empirical analysis based on provincial panel data. *Price theory Pract.* 10, 192–195.

Wu, S. (2020). The evolution of rural energy policies in China: a review. *Renew. Sustain. Energy Rev.* 119, 109584. doi:10.1016/j.rser.2019.109584

Wu, S., and Han, H. (2022). Energy transition, intensity growth, and policy evolution: evidence from rural China. *Energy Econ.* 105, 105746. doi:10.1016/j.eneco.2021.105746

Wu, S., Hu, S., Frazier, A. E., and Hu, Z. (2023). China's urban and rural residential carbon emissions: past and future scenarios. *Resour. Conservation Recycl.* 190, 106802. doi:10.1016/j.resconrec.2022.106802

Wu, S., and Zheng, X. (2022). Revisit of household energy ladder——empirical evidence from a household survey in rural China. *China Econ. Q.* 22 (01), 45–66.

Yang, B., and Li, Y. (2022). The *status quo*, difficulties and suggestions of our rural energy transition development. *Agric. Dev. Finance* 04, 37–40.

Yang, S., Tan, Z., Xue, F., Li, P., Li, H., and Zhang, Y. (2021). Study on typical scenarios, business models and cost-value accounting of Energy Internet + Rural Energy. *Distrib. Energy* 6 (03), 19–31. Available online at: https://www.cnki.net/KCMS/detail/detail.aspx?dbcode=CJFD&dbname=CJFDLAST2021&filename=FBNY202103003&uniplatform=OVERSEA&v=wUZrUFEqAqHyVTKdUV3DtCSmvKZN22kxZQhuLqqrapM68PPYs5NyQIS76RQAic2.

Yu, S., Han, R., and Zhang, J. (2023). Reassessment of the potential for centralized and distributed photovoltaic power generation in China: on a prefecture-level city scale. *Energy* 262, 125436. doi:10.1016/j.energy.2022.125436

Yu, Y., and Yin, S. (2023). Incentive mechanism for the development of rural new energy industry: new energy enterprise–village collective linkages considering the quantum entanglement and benefit relationship. *Int. J. Energy Res.* 2023, 1–19. doi:10.1155/2023/1675858

Yu, Y., Yin, S., and Zhang, A. (2022). Clean energy-based rural low carbon transformation considering the supply and demand of new energy under government participation: a three-participators game model. *Energy Rep.* 8, 12011–12025. doi:10.1016/j.egyr.2022.09.037

Zakaria, A., Ismail, F. B., Lipu, M. H., and Hannan, M. A. (2020). Uncertainty models for stochastic optimization in renewable energy applications. *Renew. Energy* 145, 1543–1571. doi:10.1016/j.renene.2019.07.081

Zhang, H., Li, S., and Peng, M. (2022). Regional imbalance of carbon emissions from China's rural energy consumption and dynamic identification of driving factors. *Chin. Rural. Econ.* 01, 112–134.

Zhao, X., Chen, H., Ma, Y., Gao, Z., and Xue, B. (2018). Spatio-temporal variation and its influencing factors of rural energy poverty in China from 2000 to 2015. *Geogr. Res.* 37 (06), 1115–1126.

Zhao, Y., Zhang, Y., Song, Y., Yin, S., and Hu, C. (2023). Enhancing building energy efficiency: formation of a cooperative digital green innovation atmosphere of photovoltaic building materials based on reciprocal incentives. *AIMS Energy* 11 (4), 694–722. doi:10.3934/energy.2023035

Zhou, Q., Liu, Y., and Qu, S. (2022). Emission effects of China's rural revitalization: the nexus of infrastructure investment, household income, and direct residential CO2 emissions. *Renew. Sustain. Energy Rev.* 167, 112829. doi:10.1016/j.rser.2022.112829