2024 Volume 2, Issue 2
Progress of Electrical and Electronic Engineering
ISSN: 2630-4643

Overview of Electric Power Energy Structure and Hydropower Construction Trends

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Abstract:

This paper investigates the global electric power energy structure, analyzing its distribution and development. It further explores the status quo and trends of hydropower construction, focusing on aspects such as installed capacity, power generation, and the level of development. Taking Iceland and Finland as examples, where renewable energy accounts for a significant proportion, the study examines the energy distribution structure with a high level of renewable energy and hydropower development, providing valuable insights for energy transformation. Additionally, the paper briefly describes the historical development of dam construction (hydropower) scale and the current status of hydropower construction in China. It also analyzes China's energy transformation trends and hydropower development plans in the context of "carbon peak" and "carbon neutrality" goals.

Keywords:

Hydropower
Energy structure
Dam construction
Carbon peak
Carbon neutrality

Online publication: December 13, 2024

1. Current global power energy structure distribution characteristics and development trends

1.1. Distribution characteristics

As of 2019, the total global electricity generation reached 27,005 TW·h. Among this, non-renewable energy sources accounted for 72.7%, while renewable energy sources only accounted for 27.3%. Within renewable energy generation, hydropower generated 4,294 TW·h, accounting for 15.9% of total electricity generation and 58.2% of renewable energy generation. Wind power generated 1,593 TW·h, accounting for 5.9% of total electricity generation and 21.6% of renewable energy generation. Solar photovoltaic generated 756 TW·h, accounting for 2.8% of total electricity generation and 10.3% of renewable energy generation [1]. Vigorous development of renewable energy has become an important trend for countries to address climate change, ensure energy security, and build a low-carbon society [2].

Figure 1 shows the global power structure from 2011 to 2019. The total global electricity generation has shown a steady growth trend, with an average annual

growth rate of 2.5%. From **Figure 1**, the following changes and trends in the global power structure can be observed:

(1) The proportion of non-renewable energy generation in total electricity generation has shown a decreasing trend year by year. From 2011 to 2019, the proportion of non-renewable energy generation decreased from 79.7% to 72.7%, a decrease of 7.0%. Among them, the decline was most significant from 2011 to 2017, with an average annual decrease of 1.03%. The decline began to slow down in 2017 and remained almost unchanged in the following two years.

(2) The proportion of renewable energy generation in total electricity generation has shown an increasing trend year by year, increasing from 20.3% in 2011 to 27.3% in 2019, an increase of 7.0%. Among them, the average growth rate was 3.5% from 2013 to 2016, and the fastest growth occurred from 2016 to 2017, with an annual growth rate of 8.16%.

(3) The proportion of renewable energy generation has been increasing year by year, and hydropower generation has been growing at an average annual growth rate of 3.0%. The proportion of hydropower generation in total electricity generation has remained stable at around 15%~17%, with an average of 16.23%.

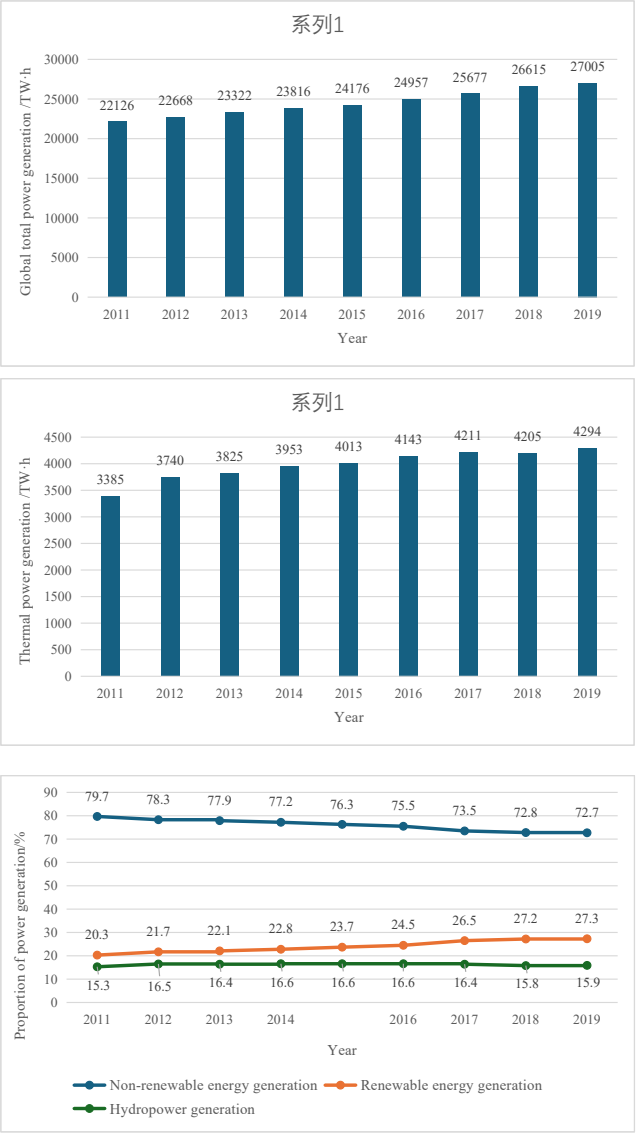

Figure 1. Global power structure 2011–2019

1.2. Development status

1.2.1. Global hydropower development level

In 2019, the global installed capacity of conventional hydropower was approximately 1 billion kW, with an average development level calculated based on electricity generation of 26%. In terms of continents, Europe and North America have achieved development levels of 54% and 39%, respectively, which are higher than the global average hydropower development level. However, South America, Asia, and Africa have hydropower development levels of 26%, 20%, and 9%, respectively [3], which are below the average level. In terms of countries, developed countries generally have higher hydropower development levels. For example, Switzerland, France, Italy, Germany, Japan, and the United States have development levels higher than 65% [4]. On the other hand, developing countries have lower hydropower development levels. China's hydropower development level is 37% [5].

1.2.2. Energy structure of countries with high renewable energy development levels

Iceland and Finland are European countries with high levels of renewable energy utilization. From 1914 to

2014, Iceland replaced fossil fuels with renewable energy, achieving a reduction of 350 million tons of carbon dioxide emissions [6]. **Figure 2** shows the power energy structure of Iceland in 2015. Iceland's installed capacity for hydropower generation was approximately 1.99 million kW, with an annual hydropower generation of 13.8 billion kWh. Hydropower accounted for 73.30% of total electricity generation, while geothermal energy contributed 5 billion kWh, accounting for approximately 26.60% of total generation. Wind power generation only accounted for 0.10%. Although the installed capacity of oil-fired power generation was 117,000 kW, it was rarely used, and its electricity generation can be ignored. Evidently, Iceland's electricity supply almost entirely comes from renewable energy, and it is expected to completely eliminate its dependence on oil resources by 2050.

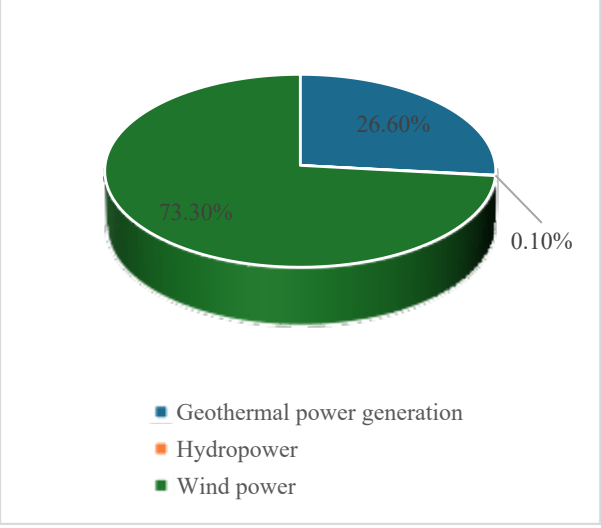

Figure 2. Power energy structure of Iceland in 2015

In 2018, Finland's total electricity generation was 67,476 GWh, an increase of 3.7% compared to the 65,041.6 GWh generated in 2017. **Figure 3** illustrates the distribution of Finland's power energy structure in 2018. Nuclear energy generated 21,889 GWh, accounting for approximately 32.44% of total electricity generation. Hydropower contributed 13,145 GWh, representing about 19.48% of the total. Thermal power generation amounted to 8,916 GWh, making up roughly 13.21% of the total. Wind power generated 5,859 GWh, equivalent to around 8.68% of total electricity production. Solar power added 162 GWh, while natural gas generated 3,496.5 GWh. Other energy sources (primarily biomass) produced 14,008.5 GWh. As seen in **Figure 3**, renewable energy sources accounted for nearly 50% of Finland's total electricity generation. These two countries are typical examples of high renewable energy development levels, with hydropower playing a significant role in their electricity mix, accounting for over 70% in Iceland and nearly 20% in Finland. Hydropower plays a crucial role in renewable energy generation, and countries worldwide can adjust their electricity energy mix based on their unique natural resources.

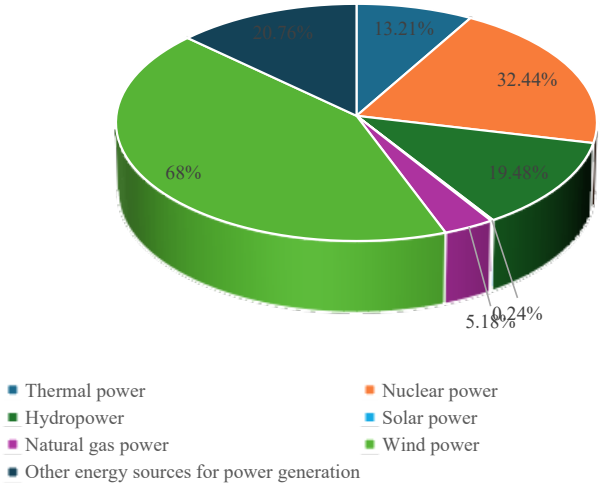

Figure 3. Power energy structure of Finland in 2018

1.2.3. Advantages of hydropower generation

Energy is the foundation that drives social development. **Table 1** compares the advantages and disadvantages of various power generation methods. Thermal power generation consumes large amounts of fossil fuels and causes environmental pollution. Nuclear power generation technology has gradually matured, but it poses significant safety risks. Wind power and photovoltaic power, as emerging energy forms, have high development costs and operational maintenance difficulties. In contrast, water resources are abundant, and hydropower generation aligns with the trend of low-carbon development. It offers advantages such as low cost, high return on investment, relatively mature technology, high efficiency of power equipment, and significant social comprehensive benefits, making it a preferred energy source [7].

Table 1. Comparison of power generation methods

Power generation methods	Advantages	Disadvantages
Thermal power generation	Utilizes fossil fuel resources with mature and stable power generation technology.	Causes environmental pollution, increases carbon emissions; non-renewable.
Wind power generation	It is clean, environmentally friendly, renewable, has a short infrastructure construction period, and flexible installed capacity.	Noise pollution; occupies large areas of land; unstable and uncontrollable; high cost; limited by geographical location.
Photovoltaic power generation	Solar energy has a wide range of sources, is renewable, and pollution-free.	High maintenance costs and difficulty; low development and utilization rate.
Nuclear power generation	Nuclear power generation has no air pollution, relatively stable power generation costs, and the fuel used in nuclear power plants is easy to transport and store.	High development and operation costs; safety and public acceptance issues.
Hydropower generation	Hydropower generation has low costs, mature technology, high efficiency of power equipment, and significant comprehensive social benefits.	Long construction period, affected by factors such as terrain, which can easily cause ecological damage.

1.3. Development trends

Hydropower generation, with its advantages of stable operation and significant comprehensive benefits, plays a crucial role in the low-carbon transition of clean energy [8]. So far, developed countries have achieved a high level of hydropower development, and the future direction mainly involves equipment upgrading and river basin optimization. It is predicted that renewable energy generation will surpass coal-fired power by 2025, becoming the world's largest source of electricity [9]. By 2035, the global installed capacity of hydropower generation will reach 1.75 billion kW, with an annual generation of 6.1 trillion kWh. The global hydropower development ratio will reach 38.6% [10]. By 2050, renewable energy generation will account for 85% of global electricity generation [11], and the global hydropower development ratio will reach 50% of the exploitable potential, with an installed capacity of hydropower generation reaching 2.05 billion kW.

2. Current distribution characteristics and development history of China's energy structure

2.1. Distribution characteristics

Figures 4 and **5** show China's installed capacity for power generation and the proportion of renewable energy generation in 2020, respectively. In 2020, China's installed capacity for power generation reached 220,058 million kW. Among them, the installed capacity of thermal power reached 124,517 million kW, accounting for 56.58% and still dominating in China. The installed capacity of hydropower generation reached 37,016 million kW, accounting for 16.82% of the total installed capacity. The installed capacity of wind power was 28,153 million kW, representing 12.79% of the total. The installed capacity of solar power generation reached 25,343 million kW, accounting for approximately 11.52%. The installed capacity of nuclear power was 4,989 million kW, accounting for about 2.27%. In 2020, China's installed capacity of renewable energy generation reached 934 million kW [12], accounting for 42.42% of the total installed capacity. Compared to European countries, China's level of renewable energy development is still relatively low. The electricity generation from renewable energy mainly comes from hydropower, wind power, and photovoltaic power, accounting for 39.61%, 30.09%, and 27.13% of the total renewable energy generation, respectively.

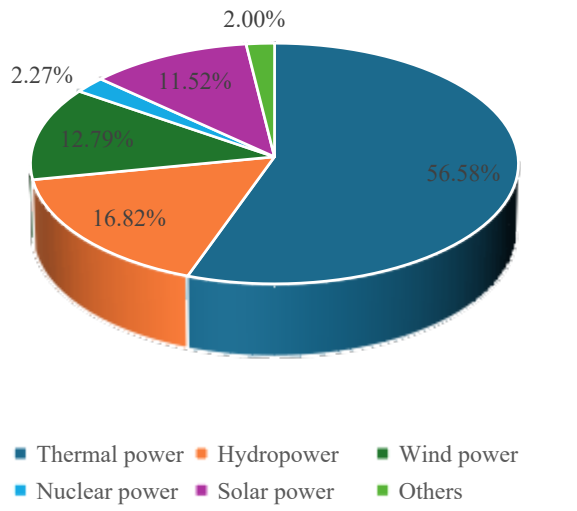

Figure 4. Proportion of installed power generation capacity in China in 2020

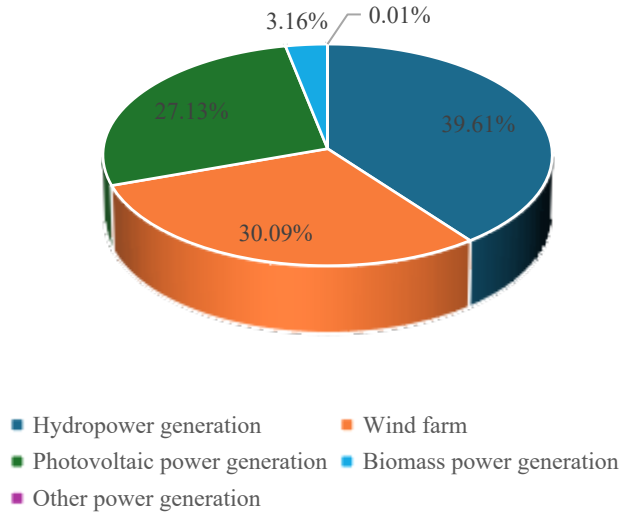

Figure 5. Proportion of renewable energy power generation in China in 2020

2.2. History of dam construction and development status of hydropower generation in China

2.2.1. History of dam construction in China

From the beginning of the 20th century to the end of the 1940s, China's hydropower generation construction technology was backward, and the construction scale was small. In 1912, China built its first hydropower station, the Shilongba Hydropower Station in Yunnan, with an installed capacity of 480 kW. By 1949, China's installed hydropower generation capacity was only 360,000 kW, and the annual power generation was only 1.2 billion kWh [13].

From the early 1950s to the late 1970s, the construction speed of dams accelerated, and the total installed capacity also increased significantly. Among them, the number of dams above 30 m increased from 21 to 3,651, and the total storage capacity increased to about 298.9 billion m^3. However, the majority of dams were between 30 m and 100 m in size, and only 11 dams above 100 m were built, with the largest being the Wujiangdu Hydropower Station dam, which was 165 m high. The total installed capacity of hydropower generation in China increased from less than 400,000 kW to 20.32 million kW.

From the early 1980s to the end of the 20th century, the speed of dam construction gradually slowed down, and the number of newly built dams showed a downward trend. However, there were significant improvements in construction scale and unit capacity [14]. The average height of dams increased from 30 m to over 70 m, and 29 new high dams above 100 m were built. The Ertan Hydropower Station, with an arch dam height of 240 m, was the first hydropower station in China with a high arch dam exceeding 200 m [15]. The number of 1 million kW-class hydropower stations increased to 18. By the end of 1999, China's total installed capacity and annual power generation of hydropower were 72.97 million kW and 212.9 billion kWh, respectively, both ranking second in the world [16]. China's hydropower generation construction gradually reached a climax.

Since the 21st century, the Three Gorges Project and the South-to-North Water Diversion Project have been put into operation, and the construction technology of completed projects such as the Xiaowan Project, the Longtan Hydropower Project, the Shuibuya Project, and the Jinping First-Level Hydropower Station Dam Project has continuously set new world records [17]. China's hydropower generation development has entered a stage of accelerated development. Comprehensive hydropower planning has been carried out in river basins, and the construction of nine major river basins and 13 hydropower bases is accelerating. By 2020, the total installed capacity of hydropower generation in China had reached 370.16 million kW, which is 5.1 times the national annual installed capacity of hydropower generation at the end of the 20th century; the annual power generation was 1,355.2 billion kWh, which is 5.8 times the national annual hydropower generation at the end of the 20th century.

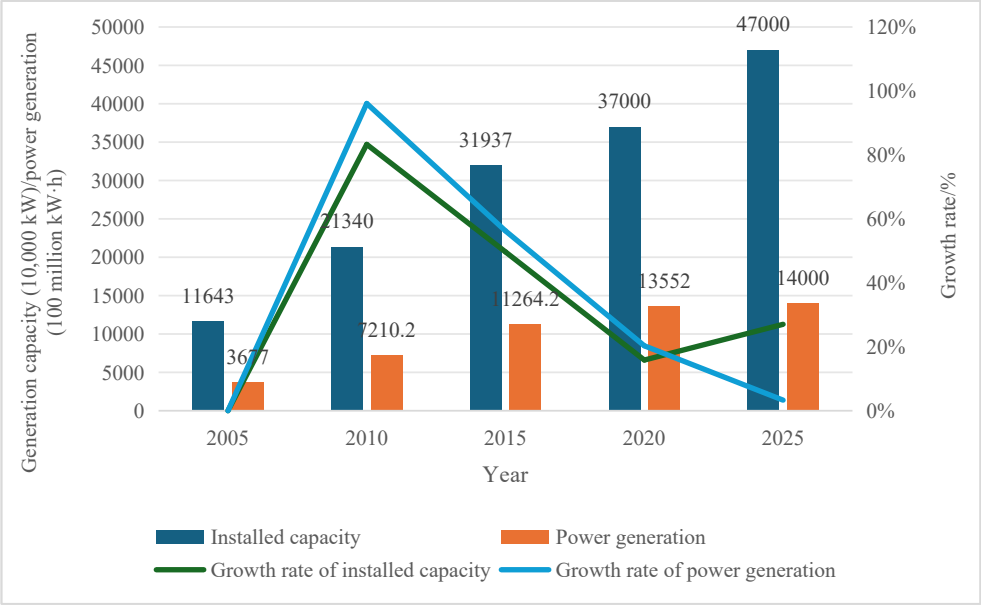

Figure 6. Water conservancy and power generation development at the end of China's five-year plan in the 21st century

2.2.2. Development of installed capacity and power generation of hydropower in China

Since the reform and opening up, China's hydropower generation development has accelerated, with installed capacity increasing from 17.28 million kW in 1978 to 370 million kW in 2020. **Figure 6** shows the current status and future expectations of hydropower development in China since 2005.

(1) In 2005, the installed capacity of hydropower generation was approximately 116.43 million kW, accounting for 22.2% of the total installed capacity; the power generation was 367.7 billion kW·h, accounting for 14.7% of the total power generation. Compared with 2000, the growth rate of installed capacity was 46.7%, and the growth rate of power generation was 63.3%.

(2) In 2010, the installed capacity of hydropower generation reached 213.4 million kW, accounting for 22% of the total installed capacity in China; the power generation was 721.02 billion kW·h, accounting for 17.2% of the total power generation. From 2005 to 2010, the growth rate of installed capacity was 83.3%, and the growth rate of power generation reached 96.1%.

(3) In 2015, the total installed capacity of hydropower generation in China reached 319.37 million kW, accounting for 20.9% of China's power generation installed capacity; the power generation was approximately 1.12642 trillion kW·h, accounting for 19.4% of the national power generation. From 2010 to 2015, the growth rate of installed capacity reached 49.7%, and the growth rate of power generation was 56.2%.

(4) In 2020, China's total installed capacity of hydropower generation reached 370 million kW, accounting for 16.82% of China's power generation installed capacity; the annual power generation was 1.3552 trillion kW·h. From 2015 to 2020, the growth rate of installed capacity was 15.8%, and the growth rate of power generation was 20.3%.

(5) In 2025, it is estimated that the installed capacity of hydropower generation in China will reach 470 million kW, and the annual power generation is expected to be 1.4 trillion kW·h. From 2020 to 2025, the growth rate of installed capacity is expected to reach 27%, and the growth rate of power generation is expected to be 3.3%.

In summary, since the 21st century, the installed capacity and power generation of hydropower in China have shown a steady growth trend. The fastest growth rate was during the period from 2005 to 2010, with a growth rate of over 80%, and then the growth rate gradually stabilized.

2.3. Distribution characteristics of hydropower generation and dams in China

In 2004, China's total installed capacity of hydropower generation reached 100 million kW, ranking first in the world [18]; in 2010, China's installed capacity of hydropower generation exceeded 200 million kW; in 2014, China's installed capacity of hydropower generation exceeded 300 million kW, and the power generation historically exceeded 1 trillion kW·h [19]; in 2020, the installed capacity of hydropower generation reached 370 million kW, and the power generation was 1,355.2 billion kW·h, with a water energy utilization rate of approximately 96.61%.

Large hydropower stations in China are mainly distributed in the Jinsha River section of the Yangtze River basin, concentrated in Sichuan, Yunnan, Tibet, and other southwestern regions [20], fully utilizing the abundant water energy resources of the Yangtze River basin. Followed by the southwest river area, which flows through regions with large terrain drops, its water energy resources rank second in China. Among the 13 hydropower construction bases planned in China, six are located in the Yangtze River basin. The hydropower construction in the Yangtze River basin has been relatively well-developed. The next step is to focus on the development of the southwest region, especially the Yarlung Zangbo River basin [21].

3. Development trends of hydropower generation in China

3.1. Hydropower generation development planning

The distribution of hydropower resources in China is uneven. From the perspective of river distribution, most of China's hydropower resources are located in the middle and upper reaches of the Yangtze River and Yellow River, as well as the Yarlung Zangbo River, Lancang River, Pearl River, Nu River, and Heilong River. The total amount of exploitable hydropower resources in these rivers accounts for approximately 90% of the country's small and above-scale hydropower resources [22].

In terms of regions, although the scale of electricity development in China is characterized by a larger western region and a smaller eastern region, the degree of hydropower development is higher in the east and lower in the west. The development of regional hydropower in China has adopted a three-step development strategy as shown in **Table 2** [23-25].

(1) According to the plan, by 2020, China's installed capacity of conventional hydropower generation can reach 350 million kW, with an annual electricity generation of 1,322 billion kW·h [23]. The development levels of the eastern, central, and western regions will reach 100%, 90%, and 54%, respectively. This goal has now been achieved and exceeded.

(2) By 2030, China's installed capacity of conventional hydropower generation will reach 520 million kW, with an annual electricity generation of 1,853 billion kW·h [24,25]. The development of the eastern and central regions will be basically completed, and the development level of the western region will reach 69%.

(3) By 2050, the installed capacity of conventional hydropower generation will reach 670 million kW [24], with an annual electricity generation of approximately 1,405 billion kW·h. The development level of the western region will reach 86%.

At this stage, the first step has been successfully completed, and as China enters the "14th Five-Year

Table 2. Three step development strategy of water conservancy and power generation in China

Year	Installed capacity of conventional hydropower stations/100 million kW	Electricity generation/100 million kW·h	Total development scale in each region		
			Eastern region/10,000 kW	Central region/10,000 kW	Western region/10,000 kW
2020	3.5	13220	3520	3150	25400
2030	5.2	18530	3550	6800	32600
2050	6.7	14050	3550	7000	40600

Plan" period, it will focus on developing the western region. In the future, China's largest hydropower generation base will be the hydropower construction project developed in the Yarlung Zangbo River basin. It is expected that China's hydropower development level will increase significantly, from nearly 40% to more than 90% by 2050 [26], which will be beneficial to optimizing the energy structure and accelerating the process of "carbon peaking" and "carbon neutrality."

3.2. Energy transformation under the goals of "carbon peaking" and "carbon neutrality"

The goals of "carbon peaking" and "carbon neutrality" provide clear directions for the development of renewable energy. By 2030, the proportion of renewable energy installed capacity for power generation in China may reach 75% [27]. Among them, the total installed capacity of hydropower generation will reach 450 million kW, with an electricity generation of approximately 1.45 trillion kW·h. The annual carbon emission reduction will be 1.18532 billion tons, and the proportions of hydropower installed capacity and electricity generation will be 18.8% and 16.9%, respectively.

4. Conclusion

In recent years, global total electricity generation has shown a steady growth trend, with the proportion of hydropower generation remaining basically unchanged, while the proportions of wind power and photovoltaic power generation have been increasing. As a relatively mature renewable energy generation method, hydropower generation, with its stability and potential carbon emission reduction effects, will maintain a stable upward trend in installed capacity and electricity generation. China's hydropower generation exhibits regional development characteristics. During the "14th Five-Year Plan" period, China will focus on developing the southwestern region, especially the Yarlung Zangbo River basin. Under the goals of "carbon peaking" and "carbon neutrality," China's energy structure will trend towards green and low-carbon, and the proportion of hydropower generation in the energy structure will further increase.

Funding

National Innovation and Entrepreneurship Training Program for University Students (202010108015)

Disclosure statement

The authors declare no conflict of interest.

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