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The Path for Green Development and Utilization of Energy in China

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Abstract: The green development and utilization of energy is an important component of the new energy security strategy and ecological civilization in China. This study first summarizes the development status and challenges of China's energy sector and discusses the concept and principles of green development and utilization of energy. In addition, a green development evaluation model and an energy utilization system evaluation index model are established to evaluate the economic and environmental benefits of the green development and utilization approach; development goals are then predicted for 2030 and 2050 using these two models. Green energy development and utilization can be implemented in two respects. In terms of energy distribution, China should focus on the clean and efficient development and utilization of fossil energy, the large-scale development and utilization of clean energy, and the intelligentization of energy systems, particularly emphasizing green coal engineering, oil stabilization and gas enhancement, and energy intensification and conservation. In terms of scientific and technological innovation, China should promote research on the safe, efficient, and clean utilization of coal; develop key technologies for deep-seated and unconventional oil and gas exploration and development; and advanced scientific and technological innovation for large-scale development and utilization of clean energy. Suggestions are proposed in terms of energy management system innovation, energy price marketization, performance evaluation, and technology innovation systems to build a clean, low-carbon, safe, and efficient energy system.
Keywords: energy; green development and utilization; green development evaluation model of energy; green coal engineering; energy intelligence

1 Introduction

The new energy security strategy of Four Revolutions and One Cooperation reveals the general trend of the world's energy development, the characteristics and trends of China's energy development in the new era, and points out the direction and path for ensuring China's energy security and promoting the high-quality development of China's energy industry from the overall and strategic perspective. Wider adoption of green development and utilization of energy is crucial for implementing the new energy security strategy.

The green development and utilization of energy is guided by the new energy security strategy, which adheres to the principle of coordinating the safe and efficient development and utilization of energy while protecting the ecological environment, and realizing the high efficiency of energy development (efficiency, resource recovery rate, and economic benefit), and the clean, low-carbon, intensive, and economical utilization of energy through

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scientific, technological, and institutional innovation. This can support the sustainable development of economy and society.

Scholars worldwide have conducted a significant amount of research on the status and mode of green development and utilization of energy. Guo Chaoxian [1] explained the trends in international green energy development and utilization and discussed the existing problems in energy development and utilization in China. Zhao Suli [2] analyzed the forms of energy utilization in China and gave directions for the rational development and utilization of green energy. Experts also conducted special studies on the development and utilization of geothermal energy, hydropower, and bioenergy [3–5]. This paper analyzes the current situation and existing problems in China's energy development, puts forward the definition and principles of green development and utilization of energy, and uses the green development and utilization evaluation model to provide goals for sustainable energy development and utilization for 2030 and 2050. The implementation path of green development and utilization is based on energy layout and scientific and technological innovation, which provides references and guidance for building a clean, low-carbon, safe, and efficient energy system.

2 Current situation and problems of energy development in China

2.1 Current situation and achievements of energy development in China

At present, through the continuous reform and development of new and old energy sources, China has gradually formed the world's largest energy supply system and built an energy supply pattern where coal constitutes the main body, electric power is the focus, and oil, natural gas, and renewable energy sources are comprehensively developed. This has promoted the rapid development of the national economy and society [6].

2.1.1 Fossil energy becoming the main body of energy supply in China

In 2019 (Fig. 1), coal, oil, and natural gas accounts for 84.7% of China's energy consumption structure, and fossil fuels play a dominant role in China's energy supply. China's coal have accounted for more than 60% of the primary energy production and consumption structure for a long time. Coal provides security for the national energy needs and plays an important role as ballast and stabilizer of energy supply. Since the founding of the People's Republic of China over 70 years ago, the country has produced approximately 8.47×10^{10} t of coal, of which approximately 7.74×10^{10} t have been produced since the reform and opening up in 1978, accounting for approximately 75% of the country's total primary energy production. China's coal mining technology is safe and efficient and is among the world's most advanced, owing to its large capacity and high parameter units. China's ultra-low emission technology for air pollutants has also reached the world leading level. New coal conversion technologies such as one-million-ton direct coal liquefaction and 600000-ton coal to olefin have been pioneered in the world. With the large-scale exploration and development of oil and gas resources, China's oil and gas production has increased each year, and the oil and gas reserve system has been continuously improved, which has reduced the need for oil and gas imports and provided critical support for the national energy security supply [7,8].

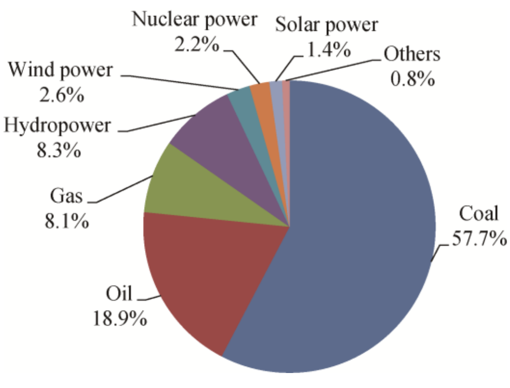

Fig. 1. China's energy consumption structure in 2019.

2.1.2 Rapid development of new energy and renewable energy

The proportion of new and renewable energy in China's energy consumption structure is shown in Fig. 1. Presently, advanced pressurized water reactor nuclear power technology with independent intellectual property rights has been developed, and the third generation nuclear power technology and equipment have been globalized;

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wind energy, photovoltaics, solar thermal utilization, and other non-water renewable energy equipment products and technologies are among the most developed globally.

2.1.3 Significant optimization of energy consumption structure

Since the new energy security strategy was put forward, the proportion of renewable and clean energy consumption of the total has increased each year. The average annual growth of total energy consumption is approximately 2.2%, and the energy consumption per unit of GDP has decreased by approximately 20.3%, as shown in Fig. 2. Of the total consumption, natural gas consumption accounted for 8.2% of the total energy consumption, non-fossil energy consumption accounted for 15.2%, and electricity accounted for 25.5% of the terminal energy consumption [9].

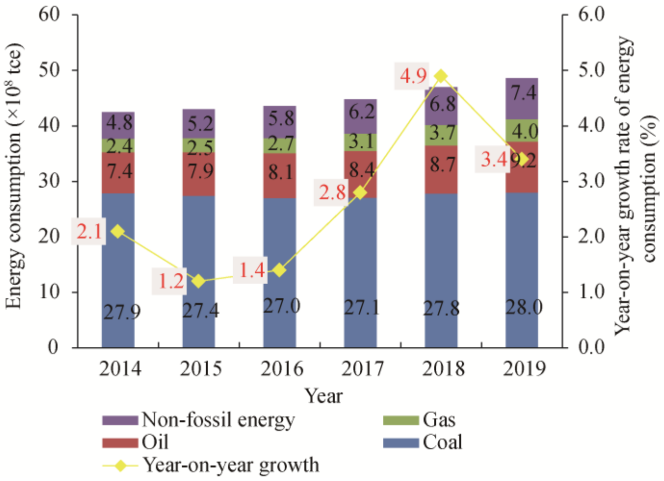

Fig. 2. China's energy consumption structure from 2014 to 2019.

2.1.4 Remarkable achievements in energy science and technology innovation

As the world's largest energy producer and consumer, China's energy technology innovation capability has greatly improved in recent years, with remarkable achievements in equipment localization and achievement industrialization, as well as in energy technology innovation and development. Specifically, in terms of the number and capacity of installed million kilowatt class coal-fired power units, China ranks first in the world. China is a world leader in terms of the technology of direct coal liquefaction with an annual output of million tons. The installed scale of photovoltaic power generation has continuously ranked first in the world, and the test production technology of seabed combustible ice ranks first in the world. The world's first multi terminal flexible DC transmission project was independently developed, constructed, and successfully demonstrated in Nan'ao, Guangdong Province. The million kilowatt turbine model of the Baihetan Hydropower Station broke the world record for hydropower equipment manufacturing. The primary technical and safety performance indexes of the third generation nuclear power Hualong-1 and CAP 1400, which were independently developed, reached the world leading level. In short, China's energy technology innovation continues to achieve new breakthroughs, and achievements in related key technologies lead the continuous development of China's energy industry [9].

2.2 Problems in China's energy development

2.2.1 Destruction of ecological environment caused by fossil energy development

The traditional extensive development of energy and non-clean utilization has led to the destruction of ecological environment through water pollution, air pollution, soil erosion, harmful gas emissions, and greenhouse gas emissions. Specifically, coal mining can cause surface subsidence, aquifer damage, vegetation degradation, and other problems. The annual land damage caused by coal mining is approximately 7.0×10^4 hm^2, and the surface ecological restoration rate is less than 30%. The annual damage of groundwater resources is approximately 7.0×10^9 t. The decline in groundwater levels caused by oil mining has an impact on the surrounding water quality. The non-clean use of fossil fuels has caused severe atmospheric pollution. At present, the pollutants generated by coal-fired power generation in China have decreased significantly, and the pollutant emissions have been reduced to meet the gas emission limit. However, the coal consumption for power generation only accounts for 53% of the total coal consumption, which is far lower than that in the United States, the United Kingdom, and other developed countries, and less than 65% of the world average. The amount of pollutants discharged from civil coal combustion is large, and it is difficult to deal with them in a centralized way. The annual amount of civil coal in China is approximately 2.0×10^8 t, and the pollutant per ton of coal is more than 10 times that of power plants. Additionally, the electric energy used by the terminals still needs to be continuously promoted [10].

2.2.2 Great challenge of emission reduction

At present, China's challenge concerning carbon peaking and carbon neutralization cannot be underestimated. In 2019, the global energy related carbon emissions were approximately 3.33×10^{10} t, of which the carbon emissions from China, the United States, and the European Union accounted for more than 50% of the global total. Among them, the emissions for China, the United States, and the European Union are 9.74×10^9 t, 4.77×10^9 t, and 3.98×10^9 t, respectively. China's carbon emissions account for approximately 29.2% of the world's total, and it is the world's largest carbon emitter. In 2019, China's carbon emission intensity was 8.4 t/USD, which was 8.3, 7.4, 5.1, and 3.2 times that of France, the United Kingdom, Japan, and the United States, respectively [11]. Corresponding to the carbon neutral target, that is, the carbon emission per unit power supply must be reduced from 600 g/kW·h to 100 g/kW·h, or even 50 g/kW·h. Therefore, to achieve the carbon emission peak in 2030 and carbon neutralization target in 2060, China's coal power installation must reach the peak in the 14th Five-Year Plan period and rapidly decline after 2030. Therefore, China not only needs to improve the carbon reduction level of the whole industry but also adjust the industrial structure, effectively reduce emissions, and improve energy efficiency in high energy consuming industries.

2.2.3 Generally low in energy efficiency

Energy efficiency can be expressed by energy consumption per unit GDP and correlation coefficient. Over the years, China's GDP growth has been primarily driven by investment and export. The rapid development of high-energy consumption industries makes China's energy consumption per unit GDP 1.4 times of the world's average. In 2019, China's consumption per 10000 CNY of GDP was 0.49 tce, which was 4.84% lower than that in 2018. China's energy efficiency is only 33%, approximately 10% lower than that of developed countries. [12] It can be seen that China's energy utilization level is far lower than the international advanced level, and energy saving and consumption reduction has great potential. In 2019, the elasticity coefficient of China's energy consumption was 0.77, which was higher than that in 2018, but lower than 1.0 [12], indicating that the growth rate of China's energy consumption has been lower than that of China's national economy. China is still in the process of industrialization, urbanization, and modernization, and the total energy consumption will continue to increase, so it is extremely urgent to further improve the energy efficiency.

2.2.4 Energy security situation remains grim

According to the project research and calculation from the Chinese Academy of Engineering, China's predicted coal resources weigh approximately 5.97×10^{12} t, and the proved coal reserves are 1.3×10^{12} t. However, China's green coal resources are only 5.05×10^{11} t, accounting for 10% of the national coal resources. The average recovery rate of coal resources is only approximately 50%. According to the national energy strategy, the exploitable life of green coal resources is only 40–50 years [13]. Since China became a net oil importer in 1993, its dependence on foreign oil has risen from 32% at the beginning of the 21st century to 70.8% in 2019. In 2019, China's dependence on foreign natural gas surpassed that of Japan, reaching 43% and making China the world's largest natural gas importer [13]. With changes in the global geopolitical situation, the increase in the international energy demand, and the intensification of resource market competition, China's energy security situation is still grim.

3 Strategic connotation and goal of green energy development and utilization

3.1 Connotation and development principles of green energy development and utilization

3.1.1 Connotation of green energy development and utilization

The green development and utilization of energy should adhere to the principles of prioritizing ecology and benefit, conducting scientific planning, and focusing on innovation. Through scientific and system innovation, we should promote the safety, environmental friendliness, and efficiency of energy development, as well as the clean, low-carbon, intensive, and economical utilization of fossil fuel based energy; this can help in providing energy security for promoting the construction of ecological civilization and achieving the two Centennial goals of the Chinese nation [10].

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3.1.2 Development principles of green energy development and utilization

(1) Promote the optimization of an environment-friendly energy supply structure. It is necessary to greatly increase the proportion of new and renewable energy, gradually reduce the proportion of fossil energy, and accelerate the construction of a green, low-carbon, safe, and efficient modern energy supply system. (2) Promote safe, efficient, and eco-friendly energy development. China should improve the level of safety and occupational health in the process of energy development, continuously reduce the cost of energy exploitation, minimize the disturbance and ecological impact of energy development on the surface, stratum structure, underground water system, etc., and build a competitive energy industry system. (3) Promote energy conservation, emission reduction, and material recycling in energy development and utilization. The key point is to improve the recovery rate of energy resources, deal with the coordinated development and utilization of energy associated resources, reduce the development energy consumption, improve the energy utilization rate, reduce the generation of pollutants and greenhouse gas emissions, and strengthen the comprehensive recycling of waste. (4) Promote clean, low-carbon, intensive, and economical energy utilization. We should minimize the pollutant and carbon emissions in energy utilization, improve the intensive utilization level of coal with ultra-low emission coal power, improve the terminal electrification level, and promote the green energy consumption mode. (5) Promote energy transformation relying on advanced intelligent means. The focus is to promote the comprehensive integration of energy technology and information technology, accelerate the complementary advantages and scientific development of fossil fuel based energy, new energy, and renewable energy, improve the allocation rate of energy resources, and build an intelligent energy system.

3.2 The necessity and urgency of green energy development and utilization

3.2.1 Green development and utilization of energy is an important measure for implementing the new strategy of energy security

The report of the 19th National Congress of the Communist Party of China emphasizes that we should actively promote the revolution of energy production and consumption and accelerate the construction of a clean, low-carbon, safe, and efficient energy system. Xi Jinping has expounded the construction of ecological civilization in the new era, which must adhere to the principle of harmony between man and nature, prioritize protection to restore nature, adhere to the development concept that lucid waters and lush mountains are invaluable assets, and increase institutional innovation. The green energy development and utilization strategy is crucial for the realization of ecological civilization, the construction of a beautiful China, and the scientific development of the energy industry in a new era [14].

3.2.2 Green development and utilization of energy is an important task of implementing the new strategy of energy security

The implementation of the new energy security strategy requires us to adhere to the concept of green development and the basic national policy on resources conservation and environmental protection. Energy should be developed and utilized on the premise of ecological environment protection, providing clean energy for economic and social development and high standards of living for residents.

3.2.3 Green development and utilization of energy is an important way to solve the problems in the field of energy in China

In view of the existing problems in China’s energy field, such as “poor oil, less gas, and relatively rich coal,” the relative shortage of per capita resources, and the impact of energy development and utilization on the ecological environment, the development of green energy is necessary to effectively promote the revolution of energy production and consumption and achieve sustainable development of economy and society [15].

3.3 Green energy development evaluation model

3.3.1 Framework of the evaluation index system for green energy development

When establishing green energy development evaluation indicators and models, it is necessary to reflect the comprehensive benefits of green development and carry out a comprehensive evaluation in terms of resources, the environment, and economic benefits. The evaluation ideas and index system framework of green energy development are shown in Fig. 3 and Table 1.

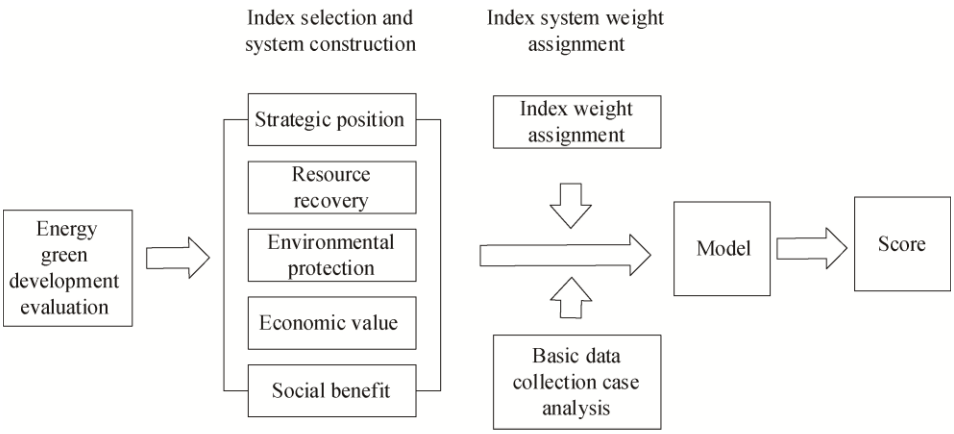

Fig. 3. Evaluation ideas for green energy development.

Table 1. Indicator system framework for green energy development evaluation.

First level indicator	Secondary indicator
Strategic position	National defense and energy security
	External dependence
	This type of energy accounts for the proportion of total national energy consumption
Resource recovery	Resource recovery rate
	Mining efficiency
Environmental protection	Impact on groundwater
	Impact on groundwater quality
	Main pollutant discharge
Economic value	Output value
	Profit
Social benefit	Tax
	Science and technology contribution

(1) The strategic position primarily refers to the importance of a certain energy in China's energy mineral sequence. The value of this indicator is determined by three factors: the status of a certain energy in national defense security; the degree of resource scarcity, which is reflected by the degree of external dependence; the proportion of this type of energy in the total energy consumption of the country, reflecting the importance of this type of energy in China's energy consumption structure.

(2) The benefits of resource extraction are reflected through the resource recovery rate and extraction efficiency indicators.

(3) Environmental protection: Groundwater and pollutant discharge have a greater impact on the environment during the development of various energy minerals. Among them, the impact on groundwater includes the impact on groundwater volume and groundwater quality, and this is a negative indicator.

(4) Economic value primarily reflects the economics of the project, which is reflected by two indicators of output value and profit.

(5) Social benefits are reflected through taxation and scientific and technological contributions [16]. Taxation primarily refers to the taxes and fees paid to the state and localities in the process of energy and mineral development; scientific and technological contributions reflect the promotion of energy and mineral mining plans.

3.3.2 Index weight

The index weight refers to the relative importance of a certain index in the overall evaluation, and the scientific determination of the index system weight directly affects the accuracy of the evaluation results. The methods for determining index weights include expert scoring method, analytic hierarchy process, entropy weight method, principal component analysis method, and comprehensive weighting method. This paper adopts the analytic hierarchy process to assign weights to the green energy development evaluation indicators. Specifically, using the analytic hierarchy process, a pairwise comparison judgment matrix is established, the judgment matrix of the first-level index and the second-level index is solved, and the weight analysis of each index in the evaluation index system is carried out, as shown in Table 2.

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Table 2. Calculation results of the evaluation index weights of green energy development.

First level indicator	Weights (%)	Secondary indicators	Weights (%)
Strategic position（a1）	38.35	National defense and energy security (a11)	19.58
		External dependence (a12)	8.51
		This type of energy accounts for the proportion of total national energy consumption (a13)	10.26
Resource recovery (a2)	13.63	Resource recovery rate (a21)	7.12
		Mining efficiency (a22)	6.51
Environmental protection (a3)	21.70	Impact on groundwater (a31)	6.99
		Impact on groundwater quality (a32)	8.62
		Main pollutant discharge (a33)	6.09
Economic value (a4)	17.43	Output value (a41)	5.87
		Profit (a42)	11.56
Social benefit (a5)	8.89	Tax (a51)	3.30
		Science and technology contribution (a52)	5.59

3.3.3 Calculation of individual index evaluation index

The index value is determined by calculating the individual evaluation index of the secondary index, and the corresponding score is assigned. The individual evaluation indicators in the indicator system include positive indicators and reverse indicators. The positive indicators promote comprehensive evaluation indexes, such as strategic position, resource extraction efficiency, economic value, and social benefits; reverse indicators can reduce the comprehensive evaluation index, such as environmental protection indicators.

For the positive index, the calculation of the single evaluation index is shown in formula (1); for the reverse index, the calculation of the single evaluation index is shown in formula (2).

$$S_i = \frac{S_{xi}}{S_{oi}} \times 100 \quad (1)$$

$$S_i = \frac{S_{oi}}{S_{xi}} \times 100 \quad (2)$$

In the formula, S_i is the single evaluation index of the item i evaluation index; S_{xi} is the actual value of the item i evaluation index; S_{oi} is the reference value of the item i evaluation index (the maximum value of the sequence).

3.3.4 Comprehensive evaluation score calculation

The green energy development evaluation score is based on the evaluation index system, and the comprehensive evaluation score, P, is calculated using:

$$P = \sum_{i=1}^{n} \sum_{k=1}^{m} S_{ik} \times Q_{ki} \quad (3)$$

In the formula, P is the comprehensive evaluation score, S is the individual index score, Q is the index weight, n is the number of first-level indicators, and m is the number of the second-level indicators.

3.4 Evaluation index model of energy utilization system

The energy utilization system is divided into two parts: the conversion process of energy as a raw material and the utilization process as a fuel. In the construction of energy utilization models, a combination of mechanism analysis and statistical regression analysis is often used, that is, semi-empirical models are the mainstay.

3.4.1 Construction of raw material conversion index system

The raw material conversion index system includes five categories: product scale, technology, environment, macroeconomics, and corporate finance. The index system composition is shown in Fig. 4.

3.4.2 Construction of fuel utilization index system

The fuel utilization indicator system includes five types of indicators: product scale, technology, macroeconomics, and corporate finance. The indicator system composition is shown in Fig. 5.

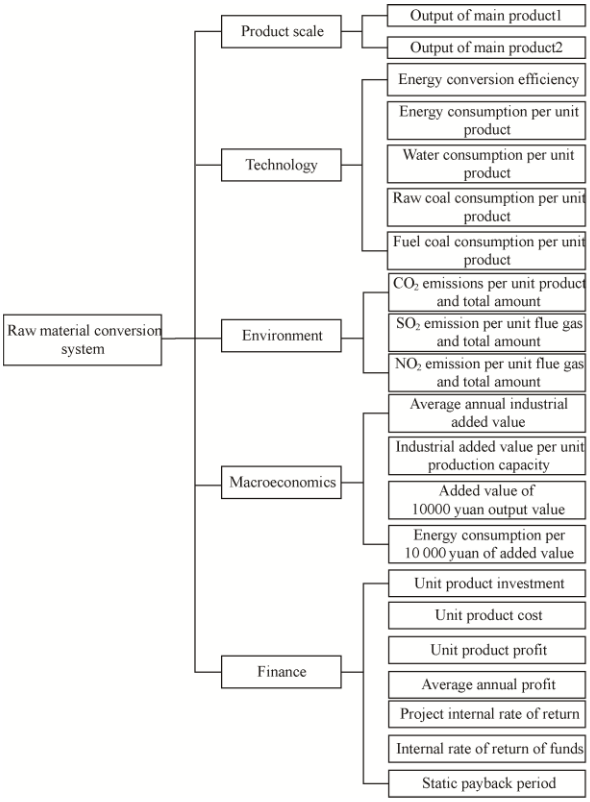

Fig. 4. Composition diagram of raw material conversion index system.

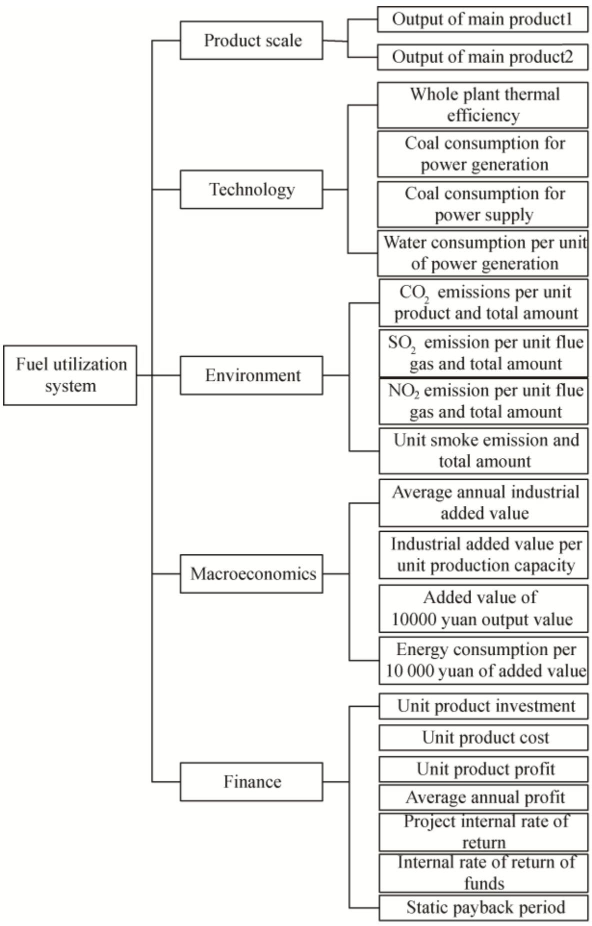

Fig. 5. Composition diagram of fuel utilization index system.

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3.4.3 Modeling method of raw material conversion system

Combining energy efficiency, environment, and economy, through processing and sorting a large number of engineering design and actual operation data, according to the law of conservation of mass and energy, the basic physical characteristics (such as scale) of unit process, the empirical data mathematical model of technical evaluation of each unit including technical characteristics, drainage level, economic input, and other factors can be established. According to the system logistics and energy flow diagrams, the energy efficiency evaluation index of energy utilization system based on the first law of thermodynamics is established; the main pollutant emission index based on the system material balance is established, and the economic index based on the unit process and the scale and characteristics of the system is established.

3.4.4 Modeling method of fuel utilization system

The first law of thermodynamics analysis method (quantitative calculation) is used to build the fuel utilization system model, and the effect of thermal power conversion is evaluated from the quantity of energy conversion, including the input–output heat method (positive balance method) and heat loss method (reverse balance method); the statistical regression model of production and operation data is the primary method, supplemented by a mathematical model. The theoretical calculation method is primarily used for the emission of gaseous pollutants.

3.4.5 Evaluation index model of energy utilization system

(1) Energy efficiency evaluation index model

Energy conversion efficiency (%) = total energy output (main product + by-product + electricity) / total energy input (raw coal + fuel coal + purchased electricity +...) (4)

(2) Evaluation index model of energy consumption per unit product

Energy consumption per unit product = (total energy input − total by-product energy)/main product output (5)

(3) Evaluation index model of coal consumption

Coal consumption per unit product = total coal (raw coal + fuel coal) / output of main product (6)

(4) Energy consumption evaluation index model of ten thousand CNY added value

Energy consumption per ten thousand CNY of added value = energy consumption per unit product / added value per unit product (7)

(5) Evaluation index model of thermal efficiency of the whole plant

$$\eta_{cp} = \frac{\text{Generation in calculation period (kW}\bullet\text{h)} \times 3600}{\text{Standard coal consumption for power generation in calculation period (kg)} \times 29\,271} \times 100\% \quad (8)$$

Where, η_{cp} is the thermal efficiency of the whole plant, unit is %; 29 271 is the low calorific value of standard coal, unit is kJ / kg; 3600 is the time conversion of hours and seconds.

(6) Evaluation index model of coal consumption for power generation and power supply

$$\text{Standard coal consumption for power generation design} = \frac{\text{Guaranteed heat consumption of steam turbine}}{\text{Boiler guaranteed efficiency} \times \text{Pipeline efficiency} \times 29.271} \quad (9)$$

$$\text{Standard coal consumption of power supply design} = \frac{\text{Standard coal consumption for power generation}}{\text{1-Auxiliary power consumption rate}} \quad (10)$$

(7) Evaluation index model of air pollutant emission in power system

① SO_2 emission concentration

$$C_{SO_2} = \frac{\sum\left[2B_g \times \left(1-\frac{\eta_{S1}}{100}\right)\left(1-\frac{\eta_{S2}}{100}\right)\left(1-\frac{q_4}{100}\right) \times \frac{S_{t,r}}{100} \times K\right] \times 10^9}{\sum V_g \times 3600} \quad (11)$$

where C_{SO2} is the emission concentration of SO_2, in mg/m^3; B_g is the actual coal consumption of boiler, in t/h; η_s is the desulfurization efficiency; V_g is the actual dry flue gas, in m^3/kg; q_4 is the incomplete combustion loss of solid, in kg; $S_{t,r}$ is the total sulfur content of coal, in %, and K is the conversion rate of sulfur in coal to SO_2.

② NO_x emission concentration

$$c_1 = \frac{10^6 G}{B_g V_g} = \frac{10^6 \times 1.63 B\left(\beta x_4 + c V_g 10^{-6}\right)}{B_g V_g} \quad (12)$$

where c_1 is the NO_x emission concentration in mg/Nm^3.

③ Calculation model of CO_2 emission

$$W_{gr} = W_{coal} \times C_{ar}\left(1 - q_4\right) \times \frac{44}{12} \tag{13}$$

where W_{gr} is CO_2 emission, W_{coal} is actual coal consumption and C_{ar} is carbon content of as received basis.

3.4.6 Development goal of green energy development and utilization

According to the above-mentioned connotation and principles of green energy development and utilization, taking the optimization of energy structure as the objective function, technological progress, capital investment, and economic contribution as variables, combining with different periods and scenarios, taking resource reserves, ecological environment, and carbon emissions as constraint dynamic variables, and through optimization calculation and integrating relevant research results in China and abroad, the goals of green energy development and utilization in 2030 and 2050 are predicted [17].

From 2021 to 2030, China will enter the strengthening period of green development and utilization of energy. China will significantly optimize its energy consumption structure, achieve green transformation of energy supply, and strive to achieve a 5:3:2 consumption ratio of coal, oil and gas, and non-fossil fuel based energy by 2030.

From 2031 to 2050, China will enter the finalization period of green energy development and utilization. China will establish traditional and new energy systems in an all-round way, realize the safe, green, and intelligent development and utilization of energy, form a diversified energy supply structure of coal, oil, natural gas and non-fossil energy, and strive to achieve a 4:3:3 consumption ratio of coal, oil and gas, and non-fossil energy by 2050.

4 Implementation path of green energy development and utilization

4.1 Layout of green energy development and utilization

It is necessary to adhere to the concept of green development, steadily and coordinately promote the clean and efficient development and utilization of fossil energy and the large-scale development of non-fossil energy based on national conditions, and promote the large-scale, integrated demonstration, and industrial application of the carbon capture, storage, and utilization technology. China should strengthen energy cooperation with countries along the Belt and Road using the concept of green and low-carbon development.

4.1.1 Clean and efficient development and utilization of fossil energy

This should be guided by the green energy development and utilization evaluation model, adhere to safe, ecological, scientific, and economical principles, formulate an energy development and utilization layout, and clarify the country into priority, restricted, and prohibited development zones.

(1) Implementing green coal projects. China should implement the coal green and safe development strategy, the clean and low-carbon utilization strategy, the diversified and coordinated development strategy, the Belt and Road initiative, and the new talent strategy, thus to establish a coal-based diversified and coordinated smart energy system after 30 years of efforts [18]. The layout of coal development should be reconstructed: Shanxi, Shaanxi, Inner Mongolia, Ningxia, and Gansu should be categorized as key development zones; East and South China as restricted mining areas; Xinjiang and Qinghai as resource reserve areas; and Northeast China as shrinking withdrawal areas. By 2025, the focus will be on the green development of coal resources in Shanxi, Shaanxi, Inner Mongolia, Ningxia, and Gansu. Coal resources development in other regions will be restricted. The national coal production capacity will be 4.4×10^9t, and the proportion of green development will reach 70%. By 2035, while focusing on the green development of coal resources in Shanxi, Shaanxi, Inner Mongolia, Ningxia, and Gansu, we will increase the green development of coal resource reserve area in Xinjiang and Qinghai district. The national coal production capacity will drop to 4.0×10^9t, and the proportion of green development of coal resources will reach 80%. By 2050, a coal resources green development zones will be formed in Shanxi, Shaanxi, Inner Mongolia, Ningxia, Gansu, Xinjiang, and Qinghai. The national coal production capacity will be maintained at $2.5-3.0\times10^9$ t, achieving green development of coal resources.

(2) Implementing oil stabilization and gas enhancement projects. China should adhere to the development concept of equal emphasis on land and sea, shallow and deep sea, conventional and unconventional resources, and maximize the role of both international and domestic resources and markets to achieve stable oil production and double natural gas production. It is necessary to increase the national petroleum strategic reserve, encourage

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private capital to participate in the reserve construction, promote the development of commercial reserves, improve energy reserve laws and regulations and related systems, build and improve the energy emergency guarantee system, greatly increase the oil reserve capacity, expand the scale of oil reserves, and improve the level of oil prediction, early warning and risk response, and China's energy security guarantee ability.

(3) Strengthening the intensive and economical utilization of energy. China should strengthen the coordinated development and utilization of energy co-associated resources and strengthen the integrated layout and intensive development and utilization of resources such as coal, petroleum, gas (including natural gas and coal-bed methane), uranium, water, and associated aluminum and gallium. It should also promote the electrification of energy terminal consumption, significantly increase the proportion of electricity in the final energy consumption, and promote combined heat and power, as well as the electrification of household heating, hot water, and cooking for urban and rural residents to improve the level of household electrification and advocate zero-emissions in household life. It is necessary to actively promote the development of electric vehicles and rail transit and accelerate the construction of power supply sources and power supply service facilities to promote the electrification of transportation. The recycling of energy resources should be strengthened: promoting the utilization of waste heat and pressure of industrial enterprises, strengthening the resource utilization of waste, and improving the recycling utilization rate of waste water. The industrial energy efficiency standards should be improved and plans should be implemented for improving the energy efficiency of key energy consuming equipment such as electric machinery, internal combustion engines, and boilers, improving the energy efficiency of energy consumption terminals and energy efficiency level of key energy consuming industries.

4.1.2 Large-scale development and utilization of clean energy

The demonstration and operation of CAP1000, CAP1400, and high-temperature gas-cooled reactor units should be accelerated while adhering to the principle of safety. The construction of units that meet the national nuclear safety standards and have independent intellectual property rights should be accelerated, actively exploring diversified utilization technologies of nuclear energy. Large-scale and low-cost offshore wind power and photovoltaic power generation should be promoted. Distributed generation and distributed energy should be encouraged, and a micro grid operation mode should be formed where power generated is consumed locally and fed to the power grid as well for regulation, thereby improving the energy utilization efficiency comprehensively.

4.1.3 Intelligent technology of energy system

Technologies for integrating energy development, transmission, distribution, and utilization should be developed to provide technical support for flexible, complementary, safe, and efficient production and consumption of energy systems. In terms of energy production, the focus is on the research and development of intelligent power generation equipment to promote the intelligent development of power production and grid connection operation. In the field of energy transmission, distribution, and application, the focus is on the development of smart grid and scientific energy utilization to provide guarantee for power dispatching, transmission, power grid, and safe power consumption [19]. It is necessary to realize energy security, greenness, and intelligence, and build a diversified energy supply system with coal, oil, natural gas, nuclear power, and renewable resources.

4.2 Scientific and technological innovation in the development and utilization of green energy

4.2.1 Scientific and technological research on safe, efficient, clean and low-carbon utilization of coal

Key technologies in coal safety, green, efficient, intelligent, and clean utilization should be developed relying on the rapid development of major scientific and technological projects on clean and efficient coal use. The advanced scientific and technological achievements should be applied and the level of clean and efficient use of coal be improved, thereby maximizing the basic role of coal in national energy security.

4.2.2 Key technologies of deep water and unconventional oil and gas exploration and development

Focus should be placed on promoting enhanced oil recovery technology, deep-water exploitation technology, unconventional oil and gas exploration and development technologies, conventional and unconventional oil and gas coordinated exploitation technology, and their demonstration projects. The construction of storage and transportation facilities and technology research should be established to promote the healthy development of the oil and gas industry.

4.2.3 Scientific and technological innovation in the large-scale development and utilization of clean energy

Core technologies including energy storage, smart grids, and distributed energy should be developed to ensure the low-cost and large-scale development and utilization of new and renewable energies. Focus should be placed on advanced nuclear power technology and diversified utilization of nuclear energy. Large-scale advanced pressurized water reactor units with independent intellectual property rights should be developed and research and demonstration should be conducted on spent fuel reprocessing of fast reactors. It is also necessary to develop floating nuclear power plant technology, seawater uranium extraction technology, and nuclear fuel closed cycle technology, and explore the multi-purpose application of nuclear energy in power generation, urban heating, industrial process steam supply, and seawater desalination.

4.2.4 Development of energy intelligence

It is necessary to integrate advanced energy storage technology and information technology, conduct smart grid technology research, and build an energy Internet based on backbone, wide area, and local area networks, thereby improving the power consumption capacity and utilization level of renewable energy and realizing the optimal allocation of energy resources and the new development of smart energy.

4.2.5 Strategic reserve technology for carbon emission reduction

The research and development of low-carbon emission technology of fossil energy and large-scale carbon capture technology should be strengthened, and the use of wind energy, tidal energy, solar energy, and other new energy should be promoted. Moreover, China should establish and improve a carbon emission reduction incentive system, and cultivate related industries.

5 Countermeasures and suggestions

5.1 Innovation of energy management system

It is necessary to comprehensively promote the market-oriented reform of energy industry, follow the laws of supply and demand, value, and competition, allow full play to the market forces in resource allocation, comprehensively deepen the reform of energy price mechanism, and clarify the price transmission mechanism of the whole value chain from energy natural resources to end users [20]. It is suggested to improve the marketization of energy industry, let more non-public capital enter the energy industry to participate in the exploration and development of energy resources, oil and gas pipeline network, and power infrastructure construction, and form a diversified investment and financing system composed of policy, commercial, and cooperative finance. China should also explore the establishment and promotion of renewable energy quota trading, ecological compensation and other systems, strengthen the overall layout of aboveground resources (wind energy, solar energy, etc.) and underground resources (coal, oil and gas, etc.), and form a coordination mechanism for the integrated development of underground energy resources such as coal, oil, natural gas, shale gas and uranium. Relying on the "Belt and Road" development initiative, strengthen international energy cooperation and interconnection, and coordinate the development and utilization of energy at home and abroad.

5.2 Formation of market mechanism of energy price

It has been suggested that establishing an energy price supervision mechanism, coordinating, and evaluating the relationship between central and local financial interests distribution, as well as improving the examination and approval standards of mineral resources exploitation rights, is needed to commodify energy. It is suggested to accelerate the reform of electricity market, improve the formation mechanism of fossil energy power generation and power transmission and distribution price, and establish the energy price formation mechanism reflecting the cost of resource scarcity and environmental externality; carry out the market-oriented reform of the pricing mechanism of refined oil, and gradually realize the transformation from government pricing to enterprise independent pricing; establish and improve the carbon trading system based on market pricing, promote the construction of diversified low-carbon development investment and financing system and enterprises to reduce carbon emissions independently.

5.3 Assessment of green energy development and utilization

Establishing a scientific green government performance appraisal system, changing the view of political performance that only pursues economic indicators, establishing statistics and appraisal indicators of green

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low-carbon economy, and forming a green low-carbon evaluation system can promote the green GDP. It is necessary to increase the pollutant emissions, toxic and harmful gas emissions, CO_2 emissions, forest coverage, vegetation greening rate, land reclamation rate, and other restrictive indicators, and incorporate the completion of atmospheric protection, ecological restoration, and environmental governance into local performance assessment [21]. It is suggested to strengthen the use of new energy by enterprises to jointly build a new mechanism for green ecology, and promote ecological construction and comprehensive utilization of green energy.

5.4 Establishment of a scientific and technological innovation system

We suggest to accelerate the establishment and improvement of energy science and technology innovation systems with industry–university–research integration that is suitable for China's characteristics. Pilot engineering and disruptive technology may be needed to determine the strategic focus of energy technology and increase the support for the research and development of energy strategic frontier technology. Innovate the form of scientific research organization, coordinate the industry–university–research scientific and technological research forces, and establish a common technology research and development platform to support and guide the establishment of industrial innovation alliance based on market mechanism. Actively promote the establishment of national major scientific and technological projects to implement the clean and efficient utilization of coal; establish a national laboratory for green development and utilization of coal; identify green development of coal, intelligent development of coal, efficient recovery of resources and coordinated development of resources as important units; gather innovative resources and innovative scientific research teams to conduct original and collaborative innovation research on energy development and utilization to lead the rapid development of energy development and utilization technology in China; and establish and improve the training mechanism for multiskilled professionals to meet the talent demand for green energy development and utilization.

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