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Energy development status and emerging technologies in China

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Abstract

Although countries around the world have increased the utilization of renewable and clean energy, the consumption of fossil fuels is still increasing, leading to an increasing emission of greenhouse gases, especially CO_2, into the atmosphere. The fundamental problem with this phenomenon is that most renewable energy sources are characterized by instability, low energy density, and difficulty in storage. The existing energy conversion technologies convert these primary energy sources into power energy, which is not a carrier and is not easy to transport and store. However, turning renewable energy resource into energy carriers, such as hydrogen, can solve the fundamental problem. This paper takes China as an example to deeply explore the current situation and shortcomings of the energy supply system, as well as the important tasks of energy development. The green, efficient, and low-cost production of sufficient hydrogen/power is the prerequisite and core, and low-cost long-term storage and transportation of sufficient hydrogen/power is the key. After years of research, State Key Laboratory of Multiphase Flow in Power Engineering has developed emerging technologies for preparing energy carriers based on renewable and fossil fuels. The development of these efficient and low-cost large-scale hydrogen/power generation technologies, as well as low-cost long-term hydrogen/energy storage and transportation technologies, can provide reliable core support for large-scale reduction of CO_2 emissions and sufficient and inexpensive green hydrogen/power supply, and strategic technical support for building a new green energy supply system and ensuring national energy security.

***Keywords**: H_2 production, Power generation, CO_2 reduction, Net zero, Poly-generation.*

1. Introduction

Energy is a necessity of human civilization and plays an irreplaceable role in various aspects of social development [1-3]. From the data released in the "World Energy Statistical Yearbook" from 2005 to 2020, it is evident that global consumption of oil and natural gas is on the rise. However, traditional consumption methods of fossil fuels such as oil, coal, and natural gas have always been the direct cause of serious climate and environmental problems. Greenhouse gas emissions, particularly CO_2, from the combustion and conversion of fossil fuels significantly hinder efforts to achieve the net-zero CO_2 emissions goal for global energy systems [4-7]. The significant amount of CO_2 and other greenhouse gases added to the atmosphere through the burning of fossil fuels is the main cause of extreme global climate change (El Niño, La Niña phenomena), which is irreversible on a time scale of several centuries to several thousands of years [8].

There is data indicating that global warming has been associated with the concentration of greenhouse gases in the atmosphere for a long time. In the past half century, the global average temperature has risen sharply, by about 1 °. The continuous increase in the concentration of free CO_2 in the atmosphere is currently a direct factor affecting global climate extremes, and until the mid-20th century, the annual net emissions of CO_2 have been growing slowly. However, the global emissions of CO_2 increased to 6 billion tons in 1950, and exceeded 22 billion tons by 1990. With the continuous growth of carbon emissions, the annual CO_2 emissions in recent years have exceeded 34 billion tons. Although the growth of carbon emissions has slowed down with the increase in the proportion of renewable energy utilization in recent years, it has not yet reached its peak. In addition, greenhouse gas emissions and air pollutants are usually generated from the same emission source. In 2021, PM2.5 levels in 96% or more of regional capital cities severely exceeded the upper limit values announced by the World Health Organization for air pollutants. The rapidly expanding cities are causing serious deterioration accidents in urban and surrounding air quality, and if no intervention is taken, the concentration of pollutants will continue to rise. Therefore, targeted policies must be introduced to stabilize and reduce air pollution levels. Air pollution within the biosphere will directly endanger human health, leading to approximately 4.2 million premature deaths worldwide each year. According to the research data of environmental epidemiology, the deterioration of air quality will increase the incidence rate of cardiovascular and respiratory related diseases, and further increase the mortality in serious cases. In this regard, the world urgently needs to achieve the net-zero goal as soon as possible to prevent the sustained increase in greenhouse gas and air pollutant concentrations from disrupting climate stability and endangering human health [9-10].

At present, in various fields, the energy conversion process based on fossil fuel mainly consists of two sub processes. Fossil fuel first converts chemical energy into thermal energy through violent oxidation reactions, and then converts internal energy into other forms of energy such as mechanical energy or internal energy which is directly used. However, the first process will generate a large amount of greenhouse gases mainly composed of CO_2 and harmful gases, composed of NO_x and SO_x. Numerous studies and technologies have been developed to reduce the emissions of these gases, such as carbon capture and storage technology, catalytic reduction and adsorption technology of NO_x and SO_x, IGCC (Integrated Gasification Combined Cycle) technology, etc. [11-15].

Nonetheless, the above-mentioned technologies have not yet been industrialized and applied on a large scale. The thermal power conversion in the second process is mainly used for power generation, and this process is mainly limited by the combustion efficiency of the fuel and the thermal efficiency. The thermal power generation device currently capable of achieving the highest overall plant thermal efficiency, with supercritical and ultra-supercritical devices capable of achieving approximately 46-47% and 50% plant thermal efficiency, respectively [16]. As to renewable energy, the energy conversion process is relatively simple. The most widely used renewable energy currently are wind energy, hydraulic energy, and solar energy. The utilization of wind energy and hydraulic is mainly aimed at converting mechanical energy into electrical energy, while solar energy is mainly directly converted into electrical energy through the photoelectric effect or directly converted into thermal energy through concentrated solar energy devices. Although wind power generation technology has advantages such as renewability and sustainability, environmental protection, and low operating costs, it can only generate electricity when wind drives wind turbines within a specific speed range. This fatal intermittent drawback means that wind energy cannot provide continuous and reliable power supply, and usually requires energy storage systems or backup power sources to solve this problem [17]. For hydraulic energy, it does not consume fossil fuels, does not emit harmful gases, and provides a continuous supply of clean energy. Hydroelectric power generation has almost no downtime because the water flow is only interrupted during regular maintenance and upgrades, which makes it more stable. However, the impact of hydroelectric power on the environment is its most significant drawback. The construction of dams requires the construction of additional roads and power lines, resulting in environmental damage. Dams often form reservoirs, flooding large areas and replacing natural habitats. Dams can create stagnant water areas, kill plant communities, and emit pollutants and greenhouse gases [18-19]. In comparison to wind power and hydropower, solar photovoltaic power generation is a relatively straight forward process, with no mechanical rotating parts. It does not consume fuel, nor does it emit any substances, including greenhouse gases. Furthermore, solar energy resources are widely distributed and inexhaustible, and the process is entirely noise-free and pollution-free. However, it has low energy density, large footprint, low conversion efficiency, poor stability, and also has fatal intermittent drawbacks [20-21].

For fossil fuels, the CO_2 emissions from the production of electricity, H_2, and materials mainly come from coal, oil, natural gas, and other sources [22-24]. With the transformation of the global energy supply structure system, the contribution of different fuel sources to CO_2 emissions has changed. Furthermore, as to renewable energy, a single utilization model is the main reason restricting its development towards larger scale. It is urgent to build a new type of green and low-carbon energy supply system in this regard [25-27]. The development of composite and multifunctional green H_2/electricity production technologies to achieve complementary advantages and disadvantages is a major trend in the future. The main structure of this article is as follows. The second part introduces the principles of energy conversion and utilization under traditional methods, summarizes the current status of China's energy supply structure system, and analyzes its existing problems. The third part provides a detailed introduction to the research and current status of green, efficient, and low-carbon H_2 production/power generation technologies in China. The fourth part proposes some policy recommendations for China's national strategy of achieving the "Dual Carbon" goal as soon as possible.

2. Development status of traditional energy conversion and utilization technology, industry, and supply system

Currently, traditional energy can be divided into process energy and carrier energy based on their storage capacity. The current energy supply system in our country mainly rely on renewable energy and fossil fuels converting into power energy through certain conditions to meet consumption terminals. Considering the process endowment of power energy, it has the defect of being difficult to store, which leads to the phenomenon of overproduction and large-scale abandonment of power energy in China. In this regard, the first part of this section introduces the principles and current development status of China's main power generation/ H_2 production technologies, while the second part analyzes the problems existing in related technologies, industries, and their supply systems.

2.1 The principles and current development status of the main power generation/ H_2 production technologies in China

2.1.1 Coal-fired power generation

Due to the richness of coal and the low cost of mining, China's energy relies on coal. Coal is the safest and most stable energy source in China. On a global scale, China ranks first in coal consumption. Coal accounts for approximately 65% of its energy structure, and in addition, China's coal production areas are almost ubiquitous in every region of China [28-29]. The global available coal reserves are sufficient to meet the coal production demand for 153 years. From a regional perspective, the Asia Pacific region has the highest proven reserves (46.5%). As of 2016, China's coal reserves were approximately 11.45 billion tons, accounting for 21.4% of the world's total reserves, reaching the highest level in the world, followed by India and the United States. China's coal production increased rapidly from 1981 to 2013, and then gradually declined from 2013 to 2016. Despite a decrease in production, China's total coal production in 2016 was 341 million tons, still accounting for about half of the world's total production [30]. China's household electricity and heating are mainly composed of coal, and small coal-fired boilers and stoves can meet the energy needs of rural households, accounting for about 22% of the total energy consumption. And the total energy demand of urban house-holds accounts for about 50% [31-32]. It can be seen that coal-fired power generation accounts for a significant proportion in China's energy supply system.

The process of coal-fired power generation in China mainly consists of the following parts: block coal is first sent to the coal mill for pulverization into coal powder, and the ground coal powder is sent to the separator through the hot air blown by the air preheater. The separator sends qualified coal powder to the powder bin, and finally the coal powder is fed into the burner by the powder feeder and sent to the boiler for combustion. Next, the heat released during the combustion of coal powder is used to convert liquid water into superheated steam. This process converts the chemical energy of the fuel into thermal energy. The high-temperature and high-pressure superheated steam drives the turbine to rotate, which is then converted into mechanical energy. The turbine then drives the generator to rotate, ultimately converting mechanical energy into electrical energy. The pollutant containing flue gas generated after coal powder combustion is transformed into clean flue gas through desulfurization and denitrification devices and finally discharged into the atmosphere. The schematic diagram is shown in the Figure 1.

In the context of the current national strategy of "dual carbon", China is striving to find ways to raise the threshold for new coal-fired units. For example, the average coal consumption for the power supply of newly built coal-fired units should be less than 300 gce/kWh; Newly built units of 600 MW and above should be suitable for ultra-supercritical steam conditions; 300 MW and above cogeneration and circulating fluidized bed (CFB) units should adopt supercritical steam conditions; In addition, new coal-fired units should be equipped with advanced and efficient desulfurization, denitrification, and dust removal facilities. At present, China is steadily promoting the transformation of existing thermal power generation facilities towards ultra-low emissions in the eastern, central, and western regions. China is striving to build an efficient, sustainable, and relatively low emission intensity coal-fired power industry [33].

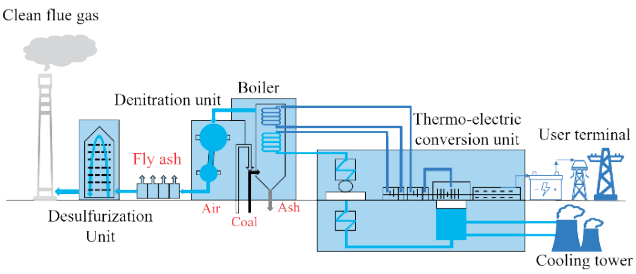

Fig. 1 Schematic diagram of coal-fired power generation

2.1.2 Renewable energy based power generation

Currently, China mainly relies on renewable energy generation technologies such as wind power, hydropower, and photovoltaic power generation. Based on publicly available data, In the first half of 2023, China's renewable energy generation, mainly consisting of photovoltaic, wind, and hydroelectric power, reached 1.34 trillion kilowatt hours, accounting for 36.2% of the country's total power generation; Among them, wind and photovoltaic power generation reached 729.1 billion kilowatt hours, accounting for 54.4%, and hydropower power generation reached 516.6 billion kilowatt hours, accounting for 38.6%. As of the first half of 2023, the installed capacity of renewable energy in China has exceeded 1.3 billion kilowatts, reaching 1.322 billion kilowatts, a year-on-year increase of 18.2%, historically surpassing coal-fired power, accounting for approximately 48.8% of the total installed capacity in China. Among them, the installed capacity of hydropower is 418 million kilowatts, wind power is 389 million kilowatts, photovoltaic power is 470 million kilowatts, and biomass power is 43 million kilowatts [34-36]. Unlike the principle of coal-fired power generation technology, the principle of energy conversion in the process of renewable energy generation is relatively simple. Taking wind power generation as an example, wind power is used to drive the rotation of wind turbine blades, and then the speed of rotation is increased by a booster engine to promote generator power generation. According to windmill technology, a gentle wind speed of approximately three meters per second (the degree of gentle wind) can start generating electricity, as shown in the Figure 2.

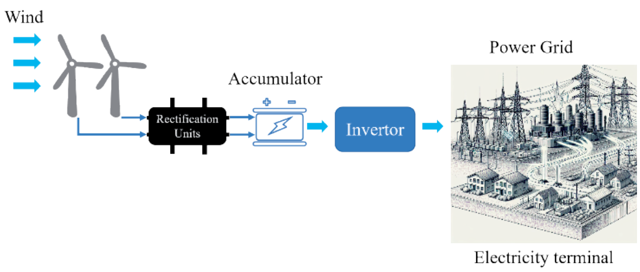

Fig. 2 Schematic diagram of wind power generation

Wind power generation is forming a trend around the world because it does not require the use of fuel, nor does it generate radiation or air pollution. Due to the unstable air volume, the output of wind turbines is alternating current ranging from 13 to 25V, so the electricity generated by wind turbines cannot be directly used. This requires rectification by the charger, followed by charging the storage battery, to convert the electrical energy generated by the wind turbine into chemical energy. Then, using an inverter power supply containing a protective circuit, the chemical energy in the battery can be converted into AC 220V mains power to ensure stable use [37-38].

The basic principle of Hydropower is to use the water level drop and cooperate with a hydroelectric generator to generate electricity, that is, to use the gravitational potential energy of water to convert it into the kinetic energy of a hydraulic turbine. The kinetic energy of a hydraulic turbine is converted into electrical energy through the generator, and then electricity is obtained, as shown in Figure 3. Scientists use the natural conditions of the water level drop to effectively utilize mechanical energy conversion devices and carefully combine them to achieve the highest power generation, providing people with cheap and pollution-free electricity. At the same time, low-level water circulates and distributes throughout the Earth by absorbing sunlight, thereby returning to high-level water sources. Despite the numerous irreplaceable advantages of hydropower, its impact on the ecological environment is enormous. It requires the submergence of dams in a wide range of upstream areas, which can damage productive lowlands, forests, wetlands, and grasslands along river valleys, greatly affecting biodiversity. Reservoirs built for hydropower can also cause habitat fragmentation in surrounding areas and lead to soil erosion deterioration [39-40].

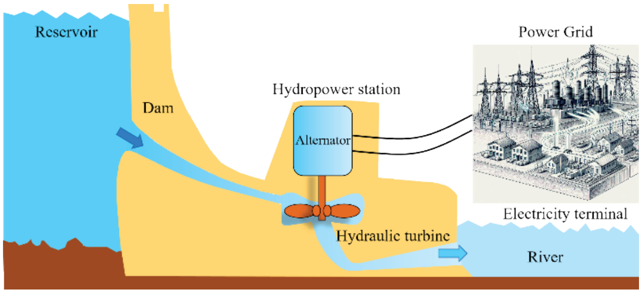

Fig. 3 Schematic diagram of hydroelectric power generation

The main principle of photovoltaic power generation is the photoelectric effect of semiconductors. Silicon atoms have four outer electrons. If an atom with five outer electrons, such as phosphorus, is doped into pure silicon, it becomes an N-type semiconductor. If atoms with three outer electrons, such as boron atoms, are doped into pure silicon, a P-type semiconductor is formed. When P-type semiconductors and N-type semiconductors are combined, the contact surface will form a potential difference, becoming a solar cell. When sunlight shines on the P-N junction, the energy absorbed by electrons is large enough to overcome the internal attraction of the atomic nucleus and do work, and escape to become photoelectrons. Electrons move from the N pole region to the P pole region, while holes move from the P pole region to the N pole region, forming an electric current. Based on this principle, the device that completes the photovoltaic conversion in the photovoltaic power generation system is called the Solar Module Array. Considering that the voltage of the solar cell module is affected by unstable radiation, it is necessary to connect a battery pack to store the energy emitted by the solar cell array when exposed to light and provide power to the load at any time. In addition, the number of cycles of charging and discharging and the depth of discharging are important factors that determine the service life of the battery. In order to prevent overcharging and discharging of the battery, a charging and discharging controller that controls overcharging or discharging of the battery pack is also an essential equipment. The schematic diagram of photovoltaic power generation is shown in Figure 4.

Solar energy, as an inexhaustible source of energy, is the most ideal new energy in the field of power generation. However, the cost of equipment used for power generation is high, the utilization rate of solar energy is low, and it is largely affected by the short service life of photovoltaics.

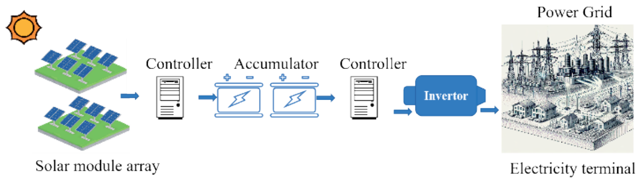

Fig. 4 Schematic diagram photovoltaic power generation

2.1.3 Industrial H_2 production technology

Hydrogen energy is the most promising new energy source in the 21st century, and its prospects have attracted great attention worldwide [41]. China has already laid out a relatively complete hydrogen energy industry chain. At present, China's H_2 production technology is relatively mature and has a certain industrialization foundation. China has become the world's largest producer of H_2, with a total H_2 production capacity exceeding 20 million tons per year [42].

China is a country with extensive coal resources, but lacks oil and natural gas. From the perspective of energy consumption structure, China still relies mainly on coal consumption. According to data from the National Bureau of Statistics, coal consumption in China accounted for 57.7% of the total energy consumption in 2019. By 2050, coal consumption will still account for about 50% of China's energy consumption [43]. The main H_2 production industry relies on two methods to produce H_2 by utilizing coal: coal coking and coal gasification. As to the coal coking H_2 production technology, it is produced by reacting coal with water, air, or oxygen under high temperature and pressure to produce syngas, which is mainly composed of CO and H_2. Subsequently, CO in the synthesis gas further reacts with steam to generate H_2 and CO_2. Finally, CO_2 and other impurities in the H_2 containing flow are removed by a pressure swing adsorption device, resulting in high-purity H_2 gas [44]. However, natural gas is also a good raw material for H_2 production [45]. There are five main H_2 production technologies using natural gas as raw material: methane steam reforming, methane catalytic partial oxidation, methane self-thermal reforming, methane dry reforming, and methane pyrolysis [46]. For petroleum, the H_2 produced by the petroleum industry comes from by-products such as naphtha, heavy oil, petroleum coke, and refinery dry gas. The technology of producing H_2 from naphtha is similar to methane steam reforming technology. In recent years, due to the tight international supply of naphtha, which results the price rising sharply and increasing the cost of H_2 production from naphtha [47]. Therefore, China does not use naphtha to produce H_2 in industrial production. The H_2 production technology from petroleum coke is similar to the H_2 production technology from coal gasification. In recent years, the production of high sulfur petroleum coke in China has been continuously increasing, facing the problems of low utilization rate and excess production [48]. Producing H_2 from petroleum coke has become an ideal way to utilize petroleum coke. It can not only achieve effective utilization of high sulfur petroleum coke, but also reduce the cost of H_2 production. This technology has good development prospects in China [49-50].

Electrolysis of water for H_2 production is also a commonly used method. According to different electrolytes, water electrolysis can be divided into three categories: alkaline (ALK) water electrolysis, proton exchange membrane (PEM) water electrolysis, and solid oxide water electrolysis (SOEC) [51]. In addition to traditional water electrolysis for H_2 production, renewable energy can also be used for power generation, and then H_2 can be produced through water electrolysis. This process can convert the remaining electricity generated by renewable energy into hydrogen energy, achieving efficient utilization of renewable energy [52-53].

In addition to power generation, renewable energy can also directly produce H_2. Biomass is not only widely distributed, but also has a very large total amount. It is one of the main energy sources that replace fossil fuels such as coal, natural gas, and oil. Biomass H_2 production technology is mainly divided into thermochemical method and microbial method. There are three main types of biomass thermochemical H_2 production technologies: biomass gasification H_2 production, biomass pyrolysis H_2 production, and biomass supercritical conversion H_2 production [54]. Biomass gasification for H_2 production uses air, oxygen, or steam as gasification agents to gasify biomass into H_2 rich gas under high temperature conditions. Biomass pyrolysis for H_2 production involves drying heated biomass under air isolation, converting it into H_2 rich gas, bio-char, and bio-tar. Biomass supercritical conversion for H_2 production involves a series of reactions such as pyrolysis, hydrolysis, condensation, and dehydrogenation between biomass and water under supercritical conditions, resulting in H_2 rich gas and residual carbon.

2.2 Issues in the current main power generation/ H_2 production technologies, industries, and supply systems

2.2.1 Power generation technology and industrial issues

For coal-fired power generation, an important feature of building a new power system is the cleanliness of electricity. Further promoting the cleanliness of coal-fired power has become a trend. Coal power enterprises in various regions have completed a round of ultra-low emission and energy-saving technology transformation, but they still face many difficulties in further investing in deep cleaning transformation. At present, there are still many technological bottlenecks in the clean utilization of coal-fired power. Coal fired power generation technology is at the international advanced level in many indicators such as coal-fired power efficiency, emission level, and power generation performance. However, breakthroughs are still needed in technologies such as supercritical CO_2 power generation, carbon capture, utilization, and storage, coal gasification fuel cell power generation, and coal-fired coupled biomass power generation. At present, the difficulty and cost of technology research and development are high, and it is difficult for coal-fired power enterprises alone to achieve greater breakthroughs. Many coal-fired power companies have reported that the relevant support policies for promoting clean utilization are not yet perfect, and the transformation motivation and enthusiasm of power generation enterprises are insufficient. Coal power enterprises are constantly undergoing technological transformation to adapt to new development requirements, but the increase in power generation costs puts a heavy burden on the enterprise. Relevant departments have problems in promoting clean utilization of coal power, lacking top-level design and collaborative cooperation, making it difficult to implement supporting policies, and sometimes not timely and discounted. Due to various factors, coal-fired power enterprises are currently facing widespread difficulties, and their willingness to undergo clean transformation is not high. Affected by multiple factors such as coal supply shortage, high coal prices, and inverted coal electricity prices, coal-fired power enterprises have been losing money for years and generally face certain operational difficulties. The clean utilization of coal-fired power requires a large amount of technology and capital investment, which puts great pressure on enterprises [55-57].

For renewable energy generation, China has made significant achievements in the development of renewable energy, and the policy system to encourage and support the development of renewable energy is becoming increasingly rich. However, energy planning and policies have not been fully sorted and adjusted according to the logic of energy transformation. Many policies following the Beaten Track still continue or strengthen in the name of promoting low-carbon energy transformation and renewable energy development. In the name of promoting the development of renewable energy, some policies that are not conducive to improving the operational efficiency of the power system still prevail. While the central and eastern regions vigorously promote the construction of photovoltaic power generation and offshore wind power, the western region still continues to invest in the construction of large-scale wind and photovoltaic power generation bases, as well as supporting policies for ultra-high voltage long-distance power transmission. However, optimizing regional power interconnection, distribution networks, and improving load side response technology capabilities are conducive to improving the flexibility of the power system, which is conducive to improving the volatility of power consumption capacity. Investment has not been prioritized; The policy of shutting down coal-fired power units below 300000 kilowatts to improve energy efficiency and reduce emissions, as well as the policy of requiring flexible retrofitting of units of 600000 kilowatts and above, did not take into account the significant decrease in operating hours of thermal power units and further increase in peak valley load differences as the share of volatile renewable energy electricity increases. This means that although energy transformation and energy revolution have become widely accepted concepts, many policies have not truly conducted systematic research and formulation from the logic of energy transformation, and still only formulate and implement renewable energy development policies from the technical level or a single indicator [58-59].

2.2.2 H_2 production technology and industrial issues

According to data provided by Maggio et al and Moliner et al [60-61]. It can be seen that the main technologies for H_2 production abroad are natural gas H_2 production and petroleum H_2 production, accounting for approximately 78% of the total. However, due to the resource characteristics of "coal rich, oil poor, and gas scarce" in China, the main raw material for H_2 production is still coal, accounting for about 62% of the total. In the short term, there are still many technological bottlenecks in the electrolysis of water for H_2 production technology. For renewable energy H_2 production technology, taking photovoltaic H_2 production as an example, the power generation efficiency of commercial photovoltaic panels is between 15% and 25%, and the commercial electrolysis water H_2 production efficiency is between 60% and 90%. Therefore, the theoretical efficiency of photovoltaic electrolysis water H_2 production is 9% to 22.5%. In actual solar power generation, the loss of substation grid connection and grid power downloading to the electrolysis tank device will further reduce the efficiency by about ten percentage points. Therefore, the actual efficiency of solar H_2 is often about 6% to 8%, which is too low [62-63]. Furthermore, the average energy consumption of current commercial electrolysis water H_2 production technology is higher than 4 kWh / standard cubic feet, and besides equipment costs, the operating energy consumption cost is also very expensive. Calculated at an average electricity price of 0.1 USD / kWh, the cost is 0.4 USD / standard square feet; Even if the current costs of solar power generation, wind power, and hydropower are 0.04 USD / kWh, 0.0756 USD / kWh, and 0.046 USD / kWh, respectively, the H_2 production costs are as high as 0.157 USD, 0.3 USD, and 0.184 USD per standard cubic feet, making it difficult to afford [64]. Therefore, the effective utilization efficiency of renewable energy needs to be further developed.

In the next 5-10 years, China's H_2 production raw materials will still be mainly fossil fuels. In addition, through the comparison of various fossil fuel H_2 production technologies, traditional H_2 production processes using coal, natural gas, and oil as raw materials have the following problems: (1) Traditional H_2 production technologies have high carbon emissions and poor environmental benefits. (2) Traditional H_2 production technology not only has high raw material costs, but also requires complex post-processing, resulting in poor economic benefits. (3) Traditional H_2 production technology requires high reaction temperature. It has a high energy consumption and resources have not been fully utilized. The development of low-carbon and green H_2 production technology has become the key to the development of hydrogen energy in China. Therefore, China should further develop low-cost carbon capture, storage, and utilization technologies based on its own resource characteristics, in order to reduce production costs. Finally, achieving green and efficient development of fossil fuel H_2 production technology.

At present, coal-based H_2 production technology holds an important position in China. It has the advantages of large H_2 production capacity and low cost. However, it has drawbacks such as high carbon emissions and incomplete pollutant removal. The H_2 produced by electrolysis water H_2 production technology has high purity, but it also has drawbacks such as high energy consumption and high cost, and the proportion of this technology adopted globally is very low. Although solar energy and biomass are pollution-free and renewable, their application in the field of H_2 production still has drawbacks such as low H_2 production efficiency and high cost. Currently, they are still in the laboratory research stage. If renewable energy, especially wind energy, solar energy, and hydraulic energy, can be reasonably and effectively utilized, the production cost of electrolytic water for H_2 production will be greatly reduced. According to the data provided by [65], it can be found that the electricity potential of "wind, solar, and water" in China can reach 51.5 billion kWh. If China can make more rational use of renewable energy, it will greatly promote the development of hydrogen production through electrolysis of water.

2.2.3 Energy supply system issues

Power energy and hydrogen energy are both secondary energy sources, both of which are artificially produced from primary energy sources. But power energy is a process energy that is hard to store while hydrogen energy belongs to the category of energy carriers and can conveniently store and transport. The main technology of the current global energy supply system is to convert all primary energy (including fossil fuels and renewable energy) into power energy, and then rely on the transmission and distribution of power energy to meet the needs of user terminals. When humans rely on fossil fuels as the main source of primary energy source, we rely on the easy storage and transportation characteristics of fossil fuels as energy carriers. We adopt manual allocation at the source of primary energy to overcome the mismatch between user terminals and energy supply systems in time, space, and geography in social production and life. However, the current power generation is mainly based on fuel combustion and thermal power cycle, emitting huge amounts of harmful substances and greenhouse gases, causing environmental pollution and ecological damage. When the supply structure of energy is transitioned into using process energy such as solar, wind energy and hydraulic energy as the main source of primary energy, it is no longer possible to adopt manual allocation at the source of traditional primary energy. The process endowment of power energy makes it hard to achieve low-cost, sufficient, and long-term storage. This is the fundamental flaw in traditional energy conversion and utilization technologies, industries, and their supply systems. At present, the amount of abandoned power energy produced by renewable energy such as wind and solar power that has been over 100 billion kilowatt hours per year [66]. The fundamental reason for large-scale power energy abandonment is that the existing energy supply system only has a sole power generation unit, and the produced power energy is still process energy, which is difficult to store even when not in use.

3. The new renewable and fossil energy conversion technologies

Based on the current shortcomings of H_2 production from renewable and fossil energy sources, the State Key Laboratory of Multiphase Flow in Power Engineering (SKLMFPE) has developed clean and efficient H_2 production and power generation technologies based on solar energy and coal, respectively, after years of research. This section will focus on introducing the principles, advantages, and applications of the above-mentioned technologies, including new forms of renewable energy conversion and utilization, as well as green, low-carbon, efficient, and pollution-free fossil energy conversion and utilization methods.

3.1 Poly-generation from full-spectrum solar energy

3.1.1 Principles of poly-generation from full-spectrum solar energy

Photocatalytic H_2 production is a process that utilizes photocatalysts to absorb light energy and produce H_2 through the water photolysis. It is a renewable and environmentally friendly method for preparing H_2 as an energy resource [67]. Photocatalytic materials utilize photons from the sun, such as visible or ultraviolet light, to excite electrons in the valence band of the material. This causes the electrons to jump into the conduction band, creating a band gap. The excess electrons in the valence band are referred to as excited state electrons. The excited state electrons subsequently move through the semiconductor and undergo a reduction reaction with water present in solution on the semiconductor surface [68], producing H_2. In solar energy, UV and some visible light with wavelengths between 250 nm and 600 nm can ionize and excite water when absorbed.

Light with a wavelength ranging from 600 nm to 1100 nm is commonly used in photoelectric conversion due to its low energy. This energy is insufficient to directly stimulate the photolytic reaction of water, but it can be absorbed by solar cells. The photoelectric conversion devices are typically made of semiconductor materials that contain energy bands and Fermi energy levels. When light strikes the semiconductor material, it excites the free electrons in the semiconductor band, causing them to move into the conduction band and leaving behind holes. The movement of electrons and holes creates structures such as heterojunctions and PN junctions within the semiconductor material, generating an electric field in the semiconductor. The photocurrent is then driven through the electric field, producing electrical power that is output through an external circuit. Light with wavelengths ranging from 1100 nm to 2500 nm, commonly known as near-infrared light, has low energy levels that are insufficient to directly excite most substances into high-energy states. However, near-infrared-responsive photocatalysts materials can absorb this energy to produce a photothermal effect [68]. This effect relies on both photocatalytic and thermocatalytic processes to increase the rate of H_2 production.

The system of poly-generation from full-spectrum solar energy combines photocatalytic H_2 production, photothermal catalysis, and photoelectric conversion (**Fig. 5.**) to provide stable electricity and heat, and to produce high-quality H_2 as a clean energy reserve. The integration of solar photoelectric technology with poly-generation represents a new form of renewable energy, which can complement local power generation units and H_2 production, and enable flexible and intelligent coupling and decoupling with the power grid. By utilizing this technology, we can transform existing energy systems and build new, stable energy supply systems with renewable energy as the primary source.

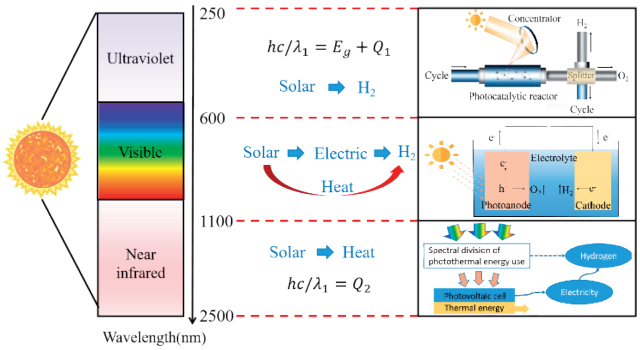

Fig. 5 Ways of utilizing light energy at different wavelengths.

3.1.2 Novel photocatalyst

Catalysts play a crucial role in photo-hydrogen conversion. However, catalysts used for photocatalytic H_2 production often lack high photocatalytic performance due to their composition of a single material. Therefore, optimization of catalysts through modification, hydrothermal treatment, and other methods is necessary to enhance their light absorption, photogenerated carrier separation, and surface reactive sites.

Common catalysts can be divided into sulfide catalysts, oxide catalysts, and organic polymer graphite phase carbon nitride (**Fig. 6.**). Sulfide catalysts, such as CdS [69, 70] and ZnS [71, 72], are mainly composed of metal sulfides with high catalytic activity and stability. Composite catalysts formed by multiple sulfides [73, 74] have higher H_2 production efficiency. Oxide catalysts are mainly based on TiO_2 [75, 76, 77, 78] due to their high efficiency, nonpolluting nature, and renewability. It can be compounded with other oxides or metal sulfides to form highly efficient composite catalysts [79, 80]. The composite catalysts can enhance photocatalytic H_2 production through the photothermal effect by absorbing both UV and near-infrared light. Catalysts for H_2 production based on graphitic-phase carbon nitride (g-C_3N_4) are often doped or modified to enhance their catalytic activity. ZnCr layered double hydroxide (ZnCr LDH) [81], α-FeOOH [82] and MoO_3 [83, 84] have been found to be excellent modifiers of g-C_3N_4. The majority of the modified composite catalysts have the morphology and electronic structure of a Z-type heterojunction, which further contributes to promote the rate of the H_2 production. Moreover, it can be modified with Cu-Ni bimetallic nanoparticles to broaden the range of absorbable spectral for photothermal-assisted photocatalysis [85]. Additionally, the H_2 production efficiency of the catalyst can be enhanced by attaching quantum dots (QDs) such as Co_3O_4 [86], Ti_3C_2 [87], or Zn-In-Se colloids [88] to g-C_3N_4.

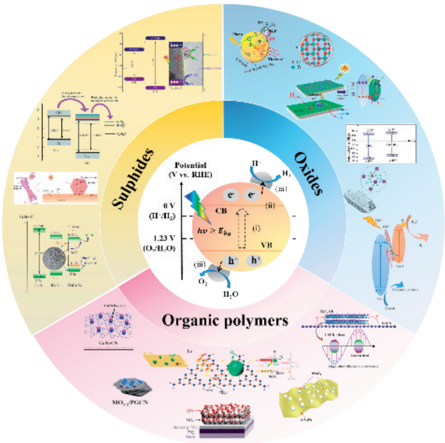

Fig. 6 photocatalysts for H_2 production from full-spectrum solar energy

3.1.3 Reactor design

With the further enhancement of reactor functions, the traditional photocatalytic H_2 production reactor cannot meet the demand of poly-generation anymore. The new reactor is designed with a multi-functional suspended fluid collector, which is able to play three roles simultaneously as liquid lens, crossover filter and photothermal reactor device, significantly increasing irradiation uniformity and improving the power output of the solar photovoltaic module. Under typical daytime solar irradiance and ambient temperature, the system's average electrical, thermal and total energy efficiencies are increased to 11.39%, 64.72% and 76.11%, respectively [89]. The liquid spherical lenses (**Fig. 7.**) act as secondary optics that concentrate and filter infrared light, simultaneously intensifying solar panel heat dissipation and increasing the operating temperature of the electrolyser. The reactor has achieved solar power and H_2 production efficiencies of 31.7% and 22.1% [90], respectively. The study presents the theory of efficient synergistic regulation of field flow. It demonstrates a non-linear acceleration of the rate of H_2 production with increasing light intensity concentration. Additionally, it explains the influence of photoexcitation and thermal excitation on the photo-thermal coupling effect. The photocatalytic and thermocatalytic reactions are accelerated by thermal acceleration and photo-regulation, which effectively reduce energy barriers. Zeng et al. [91] have developed a poly-generation system for full-spectrum solar energy utilization. The system's performance and the ratio of H_2 and electricity production can be regulated by adjusting the parameters of the spectral beam splitter (LSBS) and the photocatalytic loading.

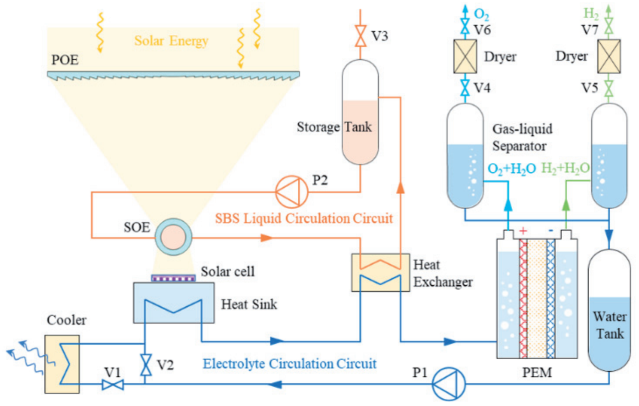

Fig. 7 Flow schematic of poly-generation from full-spectrum solar energy [90]

3.2 Poly-generation based on supercritical water gasification of coal

3.2.1 Principles and advantages on supercritical water gasification of coal

Supercritical water (SCW) is liquid water that forms under high temperature and pressure, after undergoing processes such as compression or heating. It is often considered an ideal medium for the reaction of non-polar organics due to its high density, high solubility, high chemical activity and low viscosity. The process of SCWG of coal consists of two main steps: pyrolysis reaction and gasification reaction. The SCW is used as a reaction medium at high temperature and pressure to convert coal into H_2 (Eq. (1)). It also oxidizes a portion of hazardous substances, such as CO_2 and H_2S, into harmless gases. The gas produced is dissolved in the SCW and exits the gasification reactor as a homogeneous supercritical mixed fluid (**Fig. 8.**) [92, 93].

$$Coal + H_2O \xrightarrow{P\geq 22.1MPa,\ T\geq 374^{\circ}C} H_2 + CO_2 + Ash_{pure} \qquad (1)$$

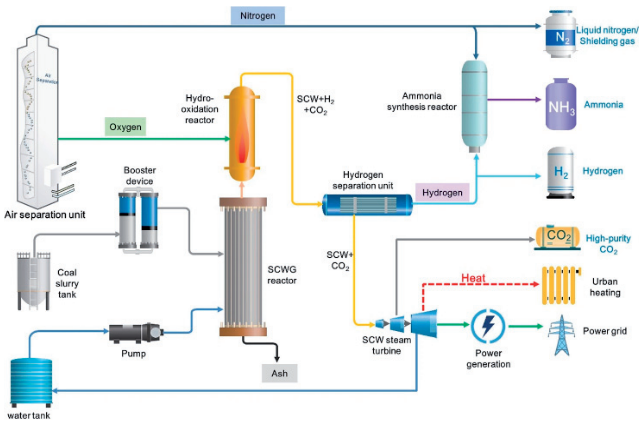

Fig. 8 Flow schematic of the Poly-generation based on supercritical water gasification of coal [94]

Compared to traditional coal-fired power generation, this technology has the following advantages [94]: (1) The power generation process does not emit harmful gases such as SO_x, NO_x, waste liquids, dust particles, or other pollutants. Additionally, it naturally enriches CO_2, achieving carbon-neutral emissions without any additional increase in energy consumption. (2) The efficiency of power generation from coal is greater than 50%. H_2 and CO_2 as well as high-value carbon-containing chemicals can be co-produced during the generation of electricity and heat. (3) The coal consumption is less than 250 g/kWh, and there is no water consumption during power generation. The water consumption of H_2 production is limited to the theoretical water consumption of water electrolysis for H_2 production.

3.2.2 Catalysts for the SCWG of coal

The efficiency of SCWG is always influenced by the catalyst. Alkaline catalysts, such as K_2CO_3 and KOH [95, 96, 97, 98], increase the rate of the H_2 production from SCWG of coal by breaking up the coal matrix and forming formate [99]. Increasing the loading of these catalysts further promotes the rate of carbon gasification and H_2 production. Sun et al [96] compared the catalytic effect of K_2CO_3 in SCWG experiments of Zhundong coal in a batch reactor. The results indicated that K_2CO_3 significantly enhances the decomposition of aromatic structures during supercritical coal gasification. It greatly accelerates the process of hydrolysis, steam reforming, and water-gas shift reactions, greatly improving the efficiency of carbon gasification and the rate of H_2 production. Furthermore, alkali metals, including Na, K, and Mg, can enhance the SCWG reaction process by inhibiting the growth of graphite-like structures and promoting the strong chemisorption of H_2O on carbon structures [98]. Alkaline waste black liquor from pulping, an industrial waste liquid, can be used as an efficient and inexpensive additive for the SCWG of coal due to its alkali and lignin content [100].

3.2.3 Solar-powered CO_2 reduction

CO_2 reduction reaction (CO_2RR) powered by renewable energy can use catalytic technologies such as photo-catalysis to convert CO_2 and renewable energy into energy carriers, where the energy is easy to transport and storage (**Fig. 9.**). Several technologies, including photo-catalysis and photo-electrochemistry, have been developed to achieve solar-driven CO_2 reduction for the production of hydrocarbon fuels so as to achieve the reuse and sustainability of energy. In the whole process, CO_2 emission reduction and chemical production can be seamlessly connected, forming an efficient energy cycle system.

Photocatalysis drives electron leaps within the catalyst by absorbing solar energy. The electron-hole pairs resulting from this process will participate in the CO_2RR. Photo-electrochemistry generates electron-hole pairs in a photoelectrode to form an electric current in a closed circuit, while oxygen evolution reaction (OER) [101] and CO_2RR respectively occurs on the (photo) anode and (photo) cathode surfaces. Photovoltaic electrochemistry (PV-EC) is a technique that combines solar photovoltaic power generation and electrochemistry. The PV convert solar energy into electrical energy, which is then used to convert CO_2 into organic compounds in a reaction cell under specific potential and electrolyte conditions. Nowadays, the techniques mentioned above has been successfully used by scholars to reduce CO_2 and prepare various products, such as HCOOH [102], CH_4, CH_3OH, and CH_3COOH.

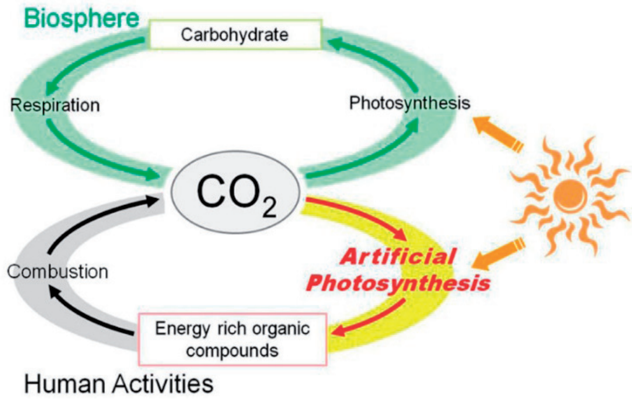

Fig. 9 CO_2RR powered by renewable energy in the production of chemicals [103].

4. Conclusion

Currently, the traditional ways of energy conversion and utilization are mainly by converting primary energy into power, which is a process energy that is difficult to store. Hydrogen energy is also a secondary energy source, but it is also an energy carrier. It can solve the problem of intermittency and consumption of renewable energy as well as the problem of energy storage. Increasing the proportion of primary energy converted to H_2 contributes to the increased renewable energy utilization. However, the current H_2 generation technologies based on renewable and fossil energy sources have many limitations, and there is an urgent need to develop new technologies that can generate H_2 on a large-scale and at low-cost.

After years of research, the SKLMFPE in Power Engineering has researched and developed H_2 and power poly-generation technology based on full-spectrum solar energy and poly-generation based on SCWG of coal:

(1) The technology for poly-generation based on full-spectrum solar energy utilizes different wavelengths of light in frequency division. By combining photothermal, photoelectric, and photocatalytic technologies, the efficiency of power generation and H_2 production can reach up to 31.7% and 22.1%, respectively.

(2) The poly-generation based on SCWG of coal enables the green, clean, efficient, and low-carbon use of fossil energy. These two technologies can form the basis for developing high-efficiency, low-cost, and large-scale poly-generation methods, constructing new types of renewable and fossil energy units, and transforming existing generating units.

5. Perspective

In the future, efforts should be paid to build a new energy system that integrates multiple energy sources. Multi-energy source complementarity and integration, as an advanced method of energy conversion and utilization, organically combines fossil energy and renewable energy through "energy complementarity and energy grade coupling", achieving complementary and efficient integration of different grades of energy. It will effectively overcome the bottleneck of the current rigid chain development model of large-scale renewable energy, tap into the active regulation potential of multi-energy complementarity systems, effectively alleviate regional and temporal supply-demand contradictions, ensure the continuous stability of energy production, and achieve energy matching and coordination between supply and demand sides. Multi-energy complementarity and integration will also form a low-carbon conversion method based on a system concept through the joint complementarity of various types of technology routes such as renewable energy conversion and utilization, fossil energy conversion and utilization, energy storage, and carbon capture，utilization and storage, breaking through the bottleneck of traditional inefficient utilization methods of the combustion on fossil energy and helping to achieve efficient and low-carbon energy conversion.

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