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Review Paper

International experience of carbon neutrality and prospects of key technologies: Lessons for China

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ABSTRACT

Carbon neutrality (or climate neutrality) has been a global consensus, and international experience exchange is essential. Given the differences in the degree of social development, resource endowment and technological level, each country should build a carbon-neutral plan based on its national conditions. Compared with other major developed countries (e.g., Germany, the United States and Japan), China's carbon neutrality has much bigger challenges, including a heavy and time-pressured carbon reduction task and the current energy structure that is over-dependent on fossil fuels. Here we provide a comprehensive review of the status and prospects of the key technologies for low-carbon, near-zero carbon, and negative carbon emissions. Technological innovations associated with coal, oil-gas and hydrogen industries and their future potential in reducing carbon emissions are particularly explained and assessed. Based on integrated analysis of international experience from the world's major developed countries, in-depth knowledge of the current and future technologies, and China's energy and ecological resources potential, five lessons for the implementation of China's carbon neutrality are proposed: (1) transformation of energy production pattern from a coal-dominated pattern to a diversified renewable energy pattern; (2) renewable power-to-X and large-scale underground energy storage; (3) integration of green hydrogen production, storage, transport and utilization; (4) construction of clean energy systems based on smart sector coupling (ENSYSCO); (5) improvement of ecosystem carbon sinks both in nationwide forest land and potential desert in Northwest China. This paper provides an international perspective for a better understanding of the challenges and opportunities of carbon neutrality in China, and can serve as a theoretical foundation for medium-long term carbon neutral policy formulation.

1. Introduction

In September 2020, Present Xi Jinping declared at the 75th session of the United Nations General Assembly that China's CO_2 emissions will reach its peak by 2030 and achieve carbon neutrality by 2060. This commitment demonstrates China's firm determination to address climate change. According to the Special Report on Global Warming of 1.5 °C (Guilyardi et al., 2018) published by the

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Abbreviations

CAES	Compressed air energy storage
CCUS	Carbon capture, utilization and storage
CFB	Circulating fluidized bed
CHP plant	Combined heat and power plant
EGR	Enhance gas recovery
EGS	Enhanced geothermal system
ENSYSCO	Clean energy systems based on smart sector coupling
EOR	Enhance oil recovery
FCEV	Fuel cell electric vehicle
HDR	Hot dry rock
IPCC	Intergovernmental panel on climate change
MRMD	Microbial restoration of methane deposit
PEM	Proton exchange membrane
PGP	Power to gas to power
PHES	Pumped hydro-energy storage
RNG	Renewable natural gas
UHS	Underground hydrogen storage
UPHES	Underground pumped hydro-energy storage

UN Intergovernmental Panel on Climate Change (IPCC), carbon neutrality means that an organization or country balances its CO_2 emissions with CO_2 removals per unit year (also termed as net-zero CO_2 emissions). As the second largest economy and the top carbon emitter in the world (Fig. 1a), China has actively addressed climate change and firmly implemented the Paris Agreement since the beginning of the 21st century. Although China has implemented carbon capture, utilization and storage (CCUS) and other carbon reduction technologies for more than 20 years (Li et al., 2016; Liu et al., 2017; Jiang and Ashworth, 2021), most of the technologies are still at the demonstration stage, and there are still many barriers to large-scale commercial application (Wei et al., 2021). Moreover, the major developed countries such as Germany, the United States, and Japan would need about 40–60 years in their transition from carbon peak to carbon neutrality, while China will strive to achieve this goal in only 30 years. These issues highlight the difficulty and urgency of China's carbon reduction target, especially under the constraints of high dependency on fossil energy (Fig. 1b). Therefore, the strategy and technical route concerning national and regional (provincial) carbon neutrality should be established as soon as possible. With continuous breakthrough of emerging technologies, innovations of low carbon, near-zero carbon, and negative carbon technologies in diverse industries should also be emphasized since they are the essential means to promote carbon reduction. In particular, the energy transition is an important foundation of carbon neutrality, mainly involving the production, storage, and utilization of various renewable energies and the improvement of the level of electrification in energy consumption terminals.

Since the declaration of China's carbon neutrality, numerous innovative ideas and specific suggestions have been proposed on the development and low-carbon transition of various industries such as new energy (Zou et al., 2021a), traditional fossil energy (Zhou et al., 2021; Zou et al., 2021b), buildings (Liu et al., 2021), transportation (Guo et al., 2021), electricity (Zhang et al., 2021c), CCUS (Fan et al., 2021b), and carbon trading system (Zhang and Liu, 2021c). Nevertheless, it is widely acknowledged that the current technical level is insufficient to support China's task of achieving carbon neutrality by 2060. Therefore, identifying the key technologies for reducing carbon emissions with future promise is a top priority (Hou et al., 2022). In addition, considering that China is actively involved in global cooperation to address climate change and the major countries worldwide are vigorously promoting a green and low-carbon transition, it is essential to insist on opening up and strengthen international cooperation. Although many countries have proposed their carbon neutral targets, the focus policies and technology development differ from country to country depending on their national conditions and capabilities (Li et al., 2021; Dong et al., 2022). As such, a systematic comparison and analysis of the similarities and differences between China and other countries in terms of energy status, carbon reduction technology level and natural resources, as well as learning from successful experiences or failures, is crucial for China to build an appropriate carbon neutral route that suits its conditions.

In this study, the key areas, technical challenges and their corresponding action plans for the implementation of China's carbon neutrality are clarified based on a comparison with other major developed countries in terms of the carbon neutral strategies and technical routes, and a comprehensive review of the status and prospects of the key technologies for low, near-zero and negative carbon emissions. The results provide an international perspective for a better understanding of the challenges and opportunities of carbon neutrality in China. They can also be adopted as theoretical foundations for medium-long term carbon neutral policy formulation.

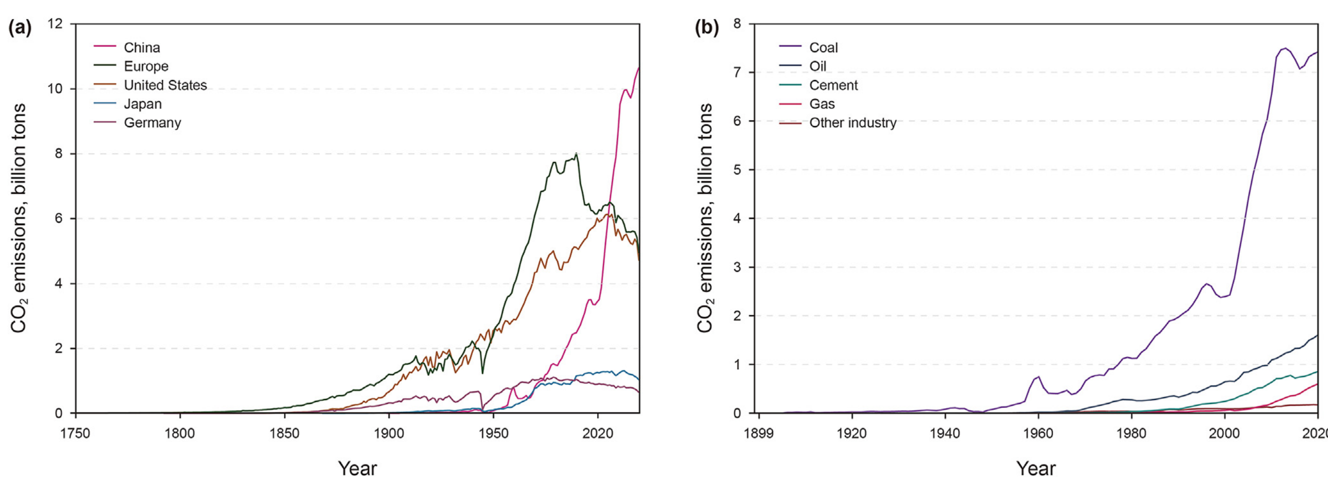

Fig. 1. (**a**) Annual carbon dioxide emissions of different countries. (**b**) Annual carbon dioxide emissions from different fuel types of China (data from https://ourworldindata.org/).

2. Carbon neutral strategies of the world's major economies

2.1. Germany

Germany achieved its carbon emission peak in 1990 (Fig. 1a). In September 2019, the German Federal Cabinet adopted the "Climate Action Programme 2030". In November 2019, the German Bundestag approved the "Climate Protection Act". In July 2021, the German parliament enacted an amendment to the "Climate Protection Act", which proposes Germany's medium-long term carbon reduction goal of reducing greenhouse gas emissions by 65% by 2030 (compared with its emission levels in 1990) and achieving net zero emissions by 2045.

Germany's carbon neutral strategy mainly includes three aspects (Salvia et al., 2021; Wang et al., 2021) (Fig. 2a). (1) A powerful legal system and a complete regulatory mechanism have been constructed. For instance, the "Climate Protection Act" stated a strict annual emission reduction target for various industrial sectors, including energy, industry, construction, transportation, agriculture and forestry. The Act plays as vital restraint role in exerting pressure, fulfilling responsibilities, and enforcing goals. (2) The investment in energy technologies such as new energy battery, modern utilization of hydrogen energy, and synthetic fuels is expected to be increased. Thus, enterprises are encouraged to develop and adopt climate-friendly low-carbon technologies. (3) Forests and grasslands protection are also emphasized to enhance the ecosystem's carbon sequestration capacity through sustainable management of wood usage, enhancing energy utilization efficiency in agriculture, and preservation of cultivated lands.

2.2. The United States

The United States achieved its carbon emission peak in 2007 (Fig. 1a). In November 2021, the US government officially released "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050", which announces that the country will reduce its emissions by 50%–52% in 2030 compared with its emission levels in 2005. In addition, the country will achieve the goal of 100% clean electricity by 2035 and carbon neutrality by 2050. Specifically, the energy transformation will contribute about 70% of total emissions reductions, and the soil carbon sinks enhancement and large-scale engineering carbon removal technologies will contribute about 30% of total emissions reductions.

The carbon neutral strategy of the United States comprises two major aspects (Sun et al., 2021) (Fig. 2b). (1) The role of federal and local government leadership is emphasized, which is critical to achieve the carbon neutrality target as it determines the investments and incentives for new technologies and financing markets. (2) The goal of complete decarbonization of electricity, terminal electrification, and clean energy usage is proposed. To achieve energy conservation and increase energy efficiency, more efficient equipment, comprehensive energy conservation in new and old buildings, and sustainable manufacturing processes will be developed. Preferential use of non-carbon hydrogen energy and sustainable biofuels in aviation, shipping, and other industrial processes are also encouraged. Moreover, large-scale soil carbon sequestration and engineering carbon removal strategies based on CCUS technologies will be implemented.

2.3. Japan

Japan achieved its carbon emission peak in 2013 (Fig. 1a). In December 2020, the Japanese government released the "Green Growth Strategy" to promote greenhouse gas emission reduction in fourteen key areas, including offshore wind power generation, electric vehicles, hydrogen energy, shipping, aviation, residential construction etc., aiming to achieve carbon neutrality by 2050.

Japan's carbon neutral strategy mainly includes the following two aspects (Sugiyama et al., 2019; Ohta, 2021) (Fig. 2c). (1) The central and local governments will utilize policies to guide the

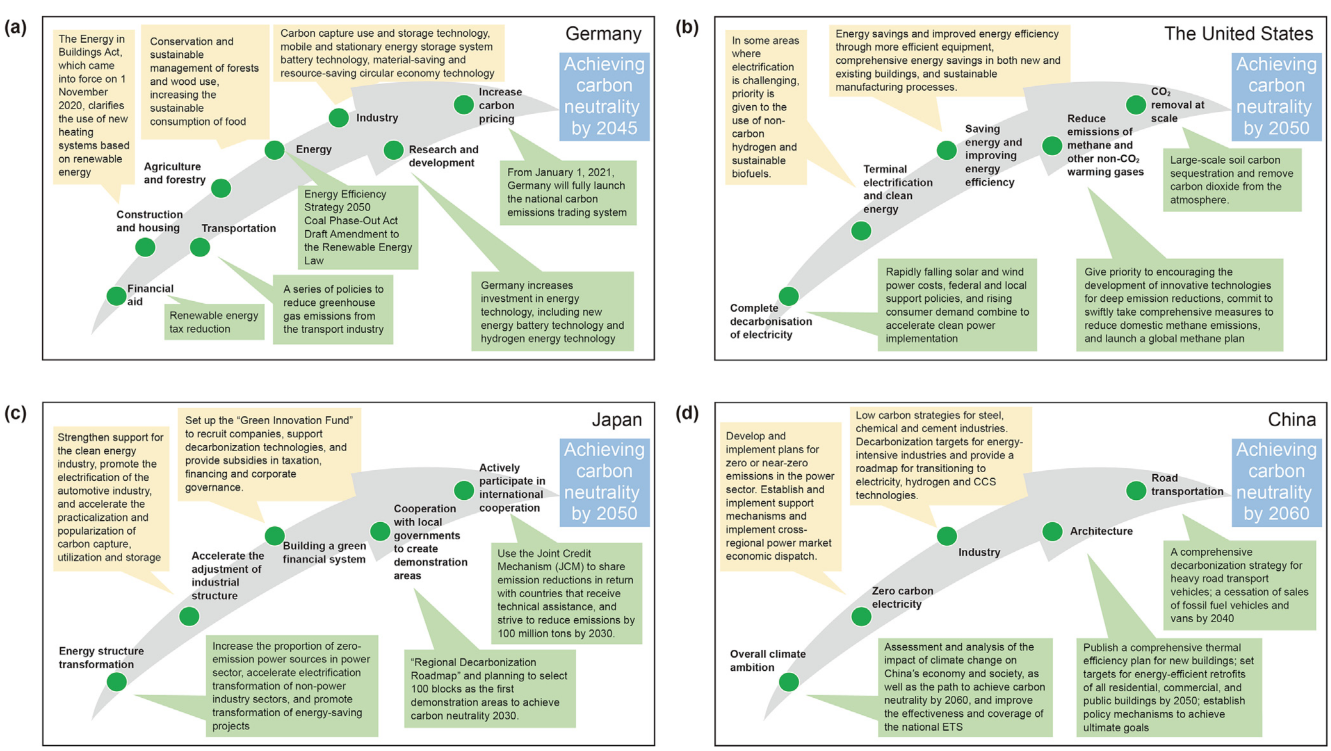

Fig. 2. The key strategies towards carbon neutrality of (**a**) Germany, (**b**) the United States, (**c**) Japan, and (**d**) China, respectively.

implementation of the carbon neutrality, establish an appropriate financial system to support carbon neutrality investment, and construct a carbon trading market with a carbon tax system. (2) The government will increase funding for developing key low-carbon technologies such as green electricity, hydrogen energy, and carbon recycling technologies. In addition, international cooperation will be encouraged to promote innovative technology research and industrial application. Renewable energy, nuclear energy, and a hydrogen-based energy supply chain will be particularly focused.

3. Status and prospects of key technologies for carbon neutrality

3.1. Low-carbon technologies

3.1.1. In situ fluidized coal mining

In many developing countries, coal is used as a traditional fossil fuel due to its low cost. Nevertheless, traditional coal mining and coal-based power generation lead to serious problems such as high CO_2 emissions and severe environmental pollution. Therefore, clean mining and combustion of coal resources, environmentally friendly utilization, and CO_2 reduction have been critical research areas in the coal energy field. In addition, considering that the current shallow earth coal resources are gradually mined out and coal resources mining keeps moving to the deep earth, the green, safe and efficient production of deep coal is facing severe challenges. Against such backdrops, a new theoretical and technological conception for deep coal mining, i.e., the fluidized mining for deep coal resources, has been proposed recently (Xie et al., 2017, 2018). In general, there are four main ways to realize fluidized coal mining: (1) gassing (underground conversion of coal into hydrogen and methane); (2) liquidization (underground liquidization of coal through high temperature biological and chemical transformation); (3) hybridization (conversion of coal into explosive coal powder, water-coal slurry, etc.); (4) in-situ energy conversion (deep in-situ electrification of coal). Accordingly, disruptive theories and technologies related to the above pathways have been analyzed, such as physical fluidized mining, fluidized mining of chemical transformation, fluidized mining of biodegradable, and fluidized mining of physical grinding (Xie et al., 2017; Ju et al., 2019).

The proposition of the theoretical and technological conception of fluidization mining for deep coal resources can realize the in-situ, real-time, and integrated development of deep coal resources that couples exploitation, separation, filling, gasification, electricity, and heat generation. It can further help to improve the efficiencies of development and transportation, as well as the conversion efficiency of deep coal resources. The disruptive revolution and green environmental protection of coal resource exploitation, represented by “coal-free ground and unmanned underground mine” (Xie et al., 2019), will be achieved. In the next step, the research of in situ fluidized coal mining technology should focus on the multi-field coupled model and visualization theory for multi-mechanism of stress-temperature-hydro-chemical-biological in the deep rocks (Ju et al., 2021), which will shed light on the rock constitutive behavior, seepage mechanism and deformation breaking law under different fluidized mining methods.

3.1.2. Clean coal-fired power generation

Given that coal-fired power generation is still the main mode of electricity production and secondary energy supply in many countries (especially in developing countries like China and India), clean coal-fired power generation technology can play an important role in carbon emission reduction. In particular, ultra-supercritical power generation is a key technology for efficient coal-fired power generation, contributing to carbon emission reduction (Rocha and Silva, 2019; Boretti and Castelletto, 2021; Tong et al., 2022). Further combined with advanced steam cycle technologies (e.g., circulating fluidized bed (CFB) that allows cascade utilization of coal resources and pollutant emissions control at a relatively lower cost), the ultra-supercritical power generation technology can achieve higher thermal efficiencies and lower exhaust emissions than conventional coal-fired power plants (Lee et al., 2019). Currently, the 600 °C ultra-supercritical power generation technology is relatively mature and is undergoing continuous technological improvement and application (Fan et al., 2018). Promoted by the double reheat technology (Zhao et al., 2017; Fan et al., 2021a), the coal, heat and electricity consumptions of ultra-supercritical power plants can reduce by 14 g/(kW·h), 150 kJ/(kW·h) and 0.8%, and exhaust gas (i.e., CO_2, SO_2, NO_x and soot) emissions reduce by more than 5% (Shuai et al., 2022). Furthermore, research on 700 °C efficient coal-fired power generation technology has also been carried out in Europe, Japan, and other countries, mainly depending on developing high-temperature materials for future power stations.

3.1.3. Other important industrial low-carbon technologies

In addition to the above low-carbon technologies with related to the major traditional coal energy in China, some other industries, such as cement and steel industries, also have relatively high carbon emissions and carbon reduction potential. The development and application of low-carbon technologies for these key industries should also be emphasized.

The cement industry is another industry with high energy consumption and high carbon emissions, as shown by 113.5 kg of standard coal consumption and 0.8 t of carbon dioxide emission for producing 1 t of cement (Luo et al., 2022). The CO_2 emissions originate from the decomposition of raw materials (mainly calcium carbonate), fuel combustion and electricity consumption are about 55%, 33% and 13%, respectively. It should be noted that the CO_2 emission from the decomposition of raw material cannot be avoided by changing the fuel types or improving energy efficiency, which makes the cement industry a challenging field for reducing carbon emissions. Given the larger shares of raw material decomposition and fuel combustion in overall CO_2 emission, raw-fuel substitution technology is the key to carbon reduction in the cement industry and is also the focus of current research (Naqi and Jang, 2019). Specifically, the calcium carbonate-based raw material can be replaced by substances with high calcium oxide content, such as calcium carbide slag, paper sludge, desulfurization gypsum, and volcanic ash (Mikulčić et al., 2016; Costa and Ribeiro, 2020). For instance, a case study for the Chinese cement industry shows that adding 60% calcium carbide slag into raw materials can achieve a 40% reduction in CO_2 emissions (Liu and Wang, 2017). Nevertheless, caution should also be taken concerning the pre-treatment of alternative raw materials, costs, and possible changes in the properties of the cement product. The key to fuel substitution is to maximize the proportion of high-calorific-value, low-carbon-emission fuels. Various waste fuels, such as waste oil, fee tires, and municipal waste, are considered available and economical alternative fuels (Xu et al., 2014; Nidheesh and Kumar, 2019).

The low-carbon transformation of the steel industry is also essential for realizing carbon neutrality. Overall, carbon reduction in the steel industry can be achieved by eliminating backward production capacity, controlling output, developing innovative technologies, and improving production structures (Griffin and Hammond, 2019; Zhang et al., 2021b). The development of innovative technologies is important, especially hydrogen steelmaking technology, which is the key to low-carbon steel production (Germeshuizen and Blom, 2013; Ozturk and Dincer, 2021; Toktarova et al., 2021). For the conventional process, the production of 1 t pig iron requires about 300 kg coke and 200 kg pulverized coal as reducing agents in the blast furnace. In contrast, hydrogen energy steelmaking aims to replace coke with hydrogen (as the reducing agent), during which the CO_2 emissions can be significantly (or even completely) avoided. Meanwhile, the energy consumption of the blast furnace can also be shifted from coal combustion to hydrogen energy, which further reduces CO_2 emissions. Hydrogen steelmaking technology is growing rapidly in European countries like Germany, Austria, and Sweden (Karakaya et al., 2018; Kushnir et al., 2020). In 2017, *Voestalpine AG*, together with *Siemens AG*, started the H2FUTURE project (Buergler and Prammer, 2019), which aims to reduce CO_2 emissions during steel production by developing a breakthrough hydrogen replacement coke smelting technology with the goal of reducing CO_2 emissions by 20% by 2022; 30% by 2030; and near-zero emissions by 2050. This project, which is financially supported by the EU for 18M€, plans to build a 6 MW PEM electrolyzer at the Voestalpine's Alpine site in Linz, Austria, with a hydrogen production rate of 1200 Nm^3/h and a target electrolytic hydrogen production efficiency of more than 80%. In November 2019, the electrolytic hydrogen-making equipment for the project was officially put into initial operation, which was the first time worldwide that hydrogen instead of coke was used in the industrial-scale steelmaking process.

3.2. Near-zero carbon technologies

3.2.1. Renewable energy production and consumption

Renewable energy are diverse, mainly including wind energy, solar energy, geothermal energy and bioenergy. This paper does not provide detail explanations of each energy type since their classification, electric-generation principle and technical status and prospects have been frequently reported. Instead, here we emphasis the importance of integrating different energy types into the smart grid because this is crucial to obtain a higher energy efficiency in the future that includes both renewable energy production and consumption. Although research on renewable energy is ongoing, integrating renewable energy into the power system remains one of the challenges of grid modernization and grid intelligence. Traditionally, electricity has flowed in one direction, from the power station to the consumer. As renewable energy sources increase, electricity must enter the grid from multiple locations. Grid automation, bi-directional currents, and modern controls are needed to bring renewable energy into the distribution grid and deliver it to its destination. New equipment used to coordinate renewable energy in smart grid systems must be able to integrate with existing equipment. Computer tools for integrating renewable energy into energy systems have also emerged to reproduce better, simulate and predict what happens in the energy system (Hou and Feng, 2022). In summary, energy digitization, combined with digital technology and traditional power electronics technology, will be important in achieving carbon neutrality.

3.2.2. Renewable power-to-X

Large-scale underground energy storage technologies can be divided into three types (Fig. 3). The first type is to convert power into gravitational potential energy, representative of which is underground pumped hydro-energy storage (UPHES). The second type is to convert power into gas energy mainly including hydrogen, synthetic natural gas and compressed air energy storage (CAES). The storage facility of hydrogen and synthetic natural gas could be an artificial salt cavern or a naturally depleted gas reservoir, while the CAES is conuducted commonly in salt caverns. The third type is the so-called Power to Heat or EGS (Enhanced Geothermal System), which is stille in its conceptual stage.

3.2.2.1. Power to gravitation potential energy. Pumped hydro-energy storage (PHES) provides a possiblity to balance the power grid and fill the power gap, which has been successfully used for over 100 years. It converts excess power to gravitational potential energy during low demands and releases electricity when power is in high demand. So far, PHES is the most reliable, economic, and mature technology for electricity storage. By the end of 2021, the cumulative installed capacity of energy storage in China was 46.1 GW and 86.3% of which is provided by PHES. However, the potential of PHES is predictably constrained in the future since it requires a sufficiently high drop height between the upper and lower reservoirs. As such, underground pumped hydro-energy storage (UPHES), which stores and adjusts electricity in disused mined underground space that is less impacted by landscape, environment and society (Kucukali, 2014), might be a preferred option.

A typical UPHES power plant comprises three major parts: upper reservoir, powerhouse, and lower reservoir (Fig. 4). When power is excess, water from the lower reservoir is pumped to the upper reservoir, during which the electrical energy is converted into gravitational potential energy. Conversely, during power peak, massive water from the upper reservoir will flow through the powerhouse (for generating electricity) and finally reach the lower reservoir. The upper reservoir can be constructed on the surface or underground, while the power house and lower reservoir are implemented underground (Pummer and Schüttrumpf, 2018). Given that the UPHES plant is built based on closed mines, existing infrastructure and caverns must be excluded to reuse. Therefore, three options are alternatives for lower reservoir construction (Zillmann et al., 2015): (1) excavating and securing additional cavities; (2) existing drifts; (3) new digged tunnels. Moreover, a favorable lower reservoir should provide a large storage volume and a high head to ensure the storage cycle.

3.2.2.2. Power to gas. Power to gas is to coverts power into hydrogen, synthetic methane, and CAES. Hydrogen could be produced by electrolysis of water and stored in favorable sites using surplus electricity. In addition to hydrogen to power; the produced hydrogen could also be used jointly with carbon dioxide to synthesize methane (Fig. 3). All the stored hydrogen and synthetic methane could be implemented for gas to power. So far, more than 220 projects of power to gas involving hydrogen have been identified in Europe (Wulf et al., 2020). Unlike hydrogen or synthetic methane, compressed air is not produced from power to gas. Typically, the air is obtained atmospherically and then compressed to store energy and heat when power is in low demand. For high power demand, the stored compressed air is reversely converted into power.

Since the first gas storage test carried out in the Welland gas field in Canada in 1915, more than 600 underground gas storage fields have been built worldwide. Normally, there are four depot types of gas storage: depleted oil reservoir, depleted gas reservoir, salt cavern, and aquifer. Given the unique geological conditions in China, depleted gas reservoirs and salt caverns are constructed as gas storage including 24 depleted reservoirs and 3 salt cavern fields. Accordingly, the storage sites of power to gas in China are considered on these two types. Since hydrogen is the lightest gas in the world and has the characteristic of easy diffusion, underground storage of hydrogen has stringent requirements on airtightness. Salt cavern is the preferred choice for large-scale underground hydrogen storage (UHS) because of its good air tightness and non-reactivity with hydrogen. For depleted gas or natural reservoirs, hydrogen may react with the exiting microorganisms and rock minerals, which may consume part of the stored hydrogen and produce reactants that may further block the porous media. As

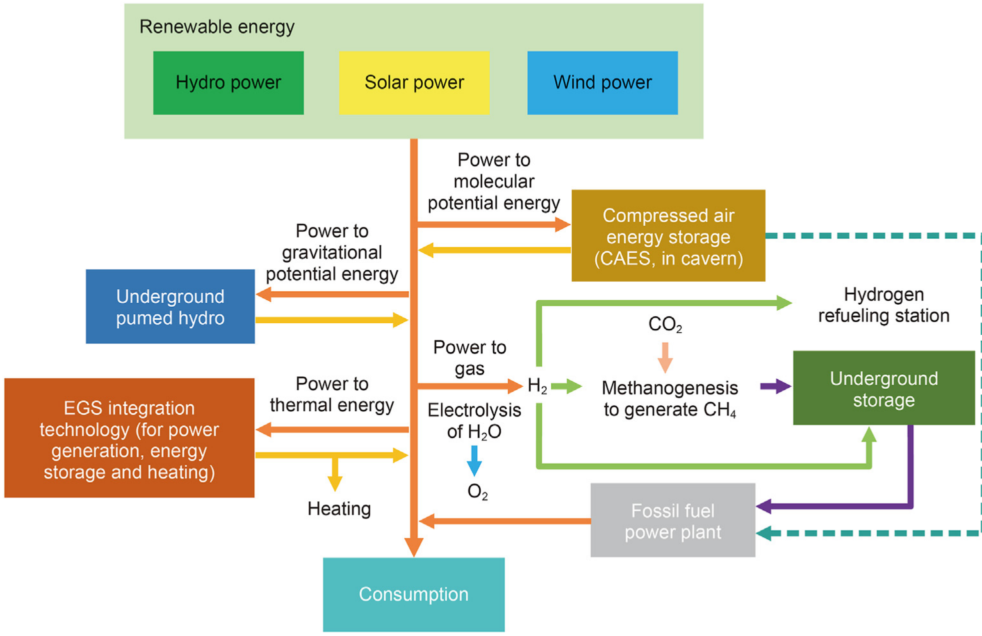

Fig. 3. The flowchart of power to X.

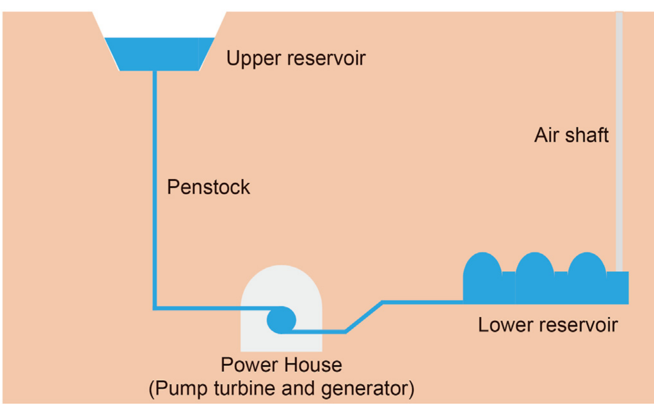

Fig. 4. Schematic diagram of a typical UPHES plant in a closed underground mine.

such, depleted gas reservoirs are suggested to store impure hydrogen or synthetic methane (Xiong et al., 2022).

3.2.2.3. Power to EGS. Power to EGS is to converted power into heat combined with a geothermal system. In China, geothermal resources exist mainly in hot dry rock (HDR; high temperature (more than 150 °C) rocks buried in several kilometers with no internal fluid or only a small amount of underground fluid inside). As a type of high-temperature geothermal resource and renewable energy source, HDR is characterized by large thermal energy, wide distribution, and weak seasonal effects (Wang et al., 2017). In order to exploit the geothermal energy in HDR, a regenerative EGS concept with multi fractures has been proposed recently (Haris et al., 2022). The depleted multi-fractured EGS is adopted to store surplus energy, which can further prolong the lifetime of EGS by making it regenerative (Fig. 5a). The complete cycle from energy storage to recovery is accomplished by switching wells for injection during the storage period and production during the recovery period (Fig. 5b). Meanwhile, the injection of pressurized hot water helps to clean the piping assembly.

3.2.3. Renewable energy storage

Renewable energy storage technologies can be categorized into mechanical (e.g., PHES and CAES), electrochemical (conventional rechargeable batteries and flow batteries), electrical (capacitors, supercapacitors and superconducting magnetic energy storage), chemical (synthetic hydrogen storage and methane storage) and thermal energy storage (Luo et al., 2015). According to the statistics from CNESA Global Energy Storage Projects Database, the installed capacity of global operational energy storage projects was 191.1 GW by the end of 2020. Specifically, pumped hydro-energy storage accounts for 90.3% of the global installed capacity, followed by electrochemical energy storage with a total capacity of 14.1 GW.

Electrochemical energy storage (e.g., batteries) has various applications and also flexible sites for construction. Relatively low cycling times and high maintenance costs have been currently considered as the main barriers to implemente large-scale facilities (Luo et al., 2015). In addition, the disposal of dumped batteries must be taken seriously. The main advantages of electrical energy storage such as supercapacitors are their high power density, short charging time, and long cycling times. However, high self-discharge rate, relatively low energy density, and hihg cost of supercapacitors remain issuses (Raza et al., 2018). Both electrochemical and electrical energy storage are short-term patterns, mainly from hours to days (Chen et al., 2009).

Moreover, renewable energy storage using the huge underground spaces is regarded to host promising prospect in future energy system (Hou et al., 2022). The technical principles, statues, and prospects of PHES, CAES, and UHS have been explained in Section 3.2.2.

3.2.4. Nuclear energy

Nuclear energy is an important non-fossil energy source with the advantages of low carbon emissions, high energy density, no intermittency, small footprint, and less constrained by climate conditions. In 2021, China proposed in the "Government Work Report" to "actively and orderly develop nuclear power under the premise of ensuring safety". This reflects the importance that China attaches to the development of nuclear energy and the importance

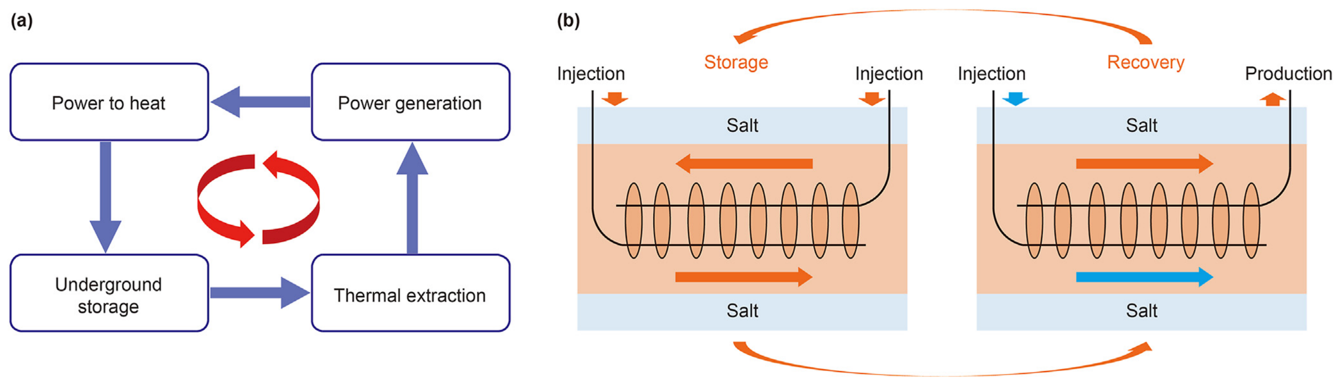

Fig. 5. The concept of the regenerative method for EGS in HDR (modify after Haris et al., 2022). (**a**) Schematic of the working flow in a regenerative geothermal facility; (**b**) energy storage and recovery cycle in a multiple fracture system.

of nuclear power in China's future energy system and in the process of achieving carbon neutrality. By the end of 2020, China had 48 operating nuclear power units with a total installed capacity of 49.89 million kW, which ranks third in the world in terms of the total installed capacity, and China's annual nuclear power generation capacity ranks second in the world (after the United States) (Wang et al., 2022). However, the share of nuclear power in total electricity generation in China (only 4.7% in 2020) is significantly lower compared to that of the major nuclear power generating countries such as the US (about 20%) and France (over 70%), which shows the huge development potential and market space of nuclear power in China.

Under the goal of carbon neutrality, especially given the current situation of China's energy structure, which relies too much on coal and oil and gas, vigorously developing nuclear energy is one of the inevitable choices to accelerate energy transformation. On the one hand, considering the instability of renewable energy sources such as wind and solar power and the need for basecount energy in clean power systems, nuclear energy will further replace part of thermal power and complement the diversified renewable energy sources to ensure the safe and stable operation of the power system (Jing et al., 2022). Moreover, nuclear thermal energy can be used for industrial steam supply, civil heating, hydrogen production and seawater desalination, etc., thereby achieving the efficient use of nuclear energy (Wu, 2022). On the other hand, it should be noted that China still lags behind other advanced countries in terms of the maturity of its nuclear energy technology, such as nuclear fuel processing, nuclear waste disposal, and the quality of key equipments. This has led to limitations in the scale of nuclear energy development in China. Nevertheless, with the progress of technology, it can be expected that nuclear energy will play an important role in promoting the sustainable development of carbon cycle economy in the future. Its functional positioning will gradually evolve from the current strategic reserve supplement to a favorable guarantee for the supply of low-carbon clean power system and the comprehensive utilization of multi-energy complementary.

3.2.5. Sector coupling

Sector coupling refers to the progressive process of substituting fossil energy sources with electricity, mainly generated from renewable sources or with other sustainable forms of energy in new cross-sector applications or through increased use of the known cross-sector (Wietschel et al., 2018). Traditionally, the electricity, heating (or cooling), transport, and industry sectors were considered independently. The idea behind the concept is to leave behind single-sector approaches that only consider solutions within each sector and instead move towards a holistic view of all sectors that enables a better and cheaper overall system (Lund et al., 2017). Sector coupling has three main advantages. (1) It enables all sectors of the economy to be decarbonized with the help of renewable energy. (2) The intelligent coupling of sectors can significantly reduce energy consumption with the help of energy-efficient technologies such as heat pump heating, CHP (combined heat and power) plants, and electric vehicles. (3) Sector coupling creates great flexibility in the demand for electrical energy, which can be used to balance the fluctuations of supply-dependent renewables such as wind energy and solar energy. Meanwhile, energy security increases through sector coupling (Joanna, 2018).

Precisely because sector coupling enables synergy effects in the integration of high shares of renewable energies, it is regarded as a key concept in the energy transition and the development of energy systems with 100% renewable energy (Mathiesen et al., 2015). It is widely accepted that sector coupling is necessary to implement the energy transition and achieve climate protection goals (Stiller and Weikl, 2017).

3.3. Negative carbon technologies

3.3.1. CO_2-EOR/EGR/fracturing

3.3.1.1. CO_2-EOR. Under the goal of global carbon neutrality, CO_2 sequestration coupled with enhanced oil recovery (EOR) serves not only an environment-friendly method of greenhouse gas treatment but also an important technology for developing oil reservoirs (Cooney et al., 2015; Alfarge et al., 2017; Sun et al., 2019). Since the 1960s, China and the United States have been pioneers in CO_2-EOR technology (Hill et al., 2013). An increasing countries, such as Brazil, Norway, and Trinidad, have also implemented large-scale carbon capture projects recently based on CO_2-EOR process (Liu et al., 2020b).

The displacement mechanisms of CO_2-EOR mainly include: (1) reduced oil viscosity; (2) reduced oil density; (3) reduced oil swelling resulted from CO_2 solution; (4) vaporization and extraction of light hydrocarbon component; (5) dissolved gas drive; (6) reduced interfacial tensions; and (7) improved permeability via acidification effect (Alfarge et al., 2018). In conventional oil reservoirs, the rock matrix dominates CO_2 flow in the reservoir and the injected CO_2(aq) can reduce oil density and viscosity, increase oil mobility, and eventually improve oil recovery (Jia et al., 2019). For unconventional tight (or shale) oil reservoirs, fracturing is an essential process for exploiting and the CO_2 flooding in tight oil reservoirs is different from that of the conventional oil reservoirs, with the flow of CO_2 in the fractures rather than in the rock matrix. Hawthorne et al. (2013) summarized the four-step flow process of injected CO_2 in a tight reservoir. Moreover, diffusion is an important mechanism for CO_2-enhanced oil recovery in tight or shale oil reservoirs with well-developed natural fractures and artificial fractures generated by hydraulic fracturing at the initiation of development. Some studies have shown that the recovery factor can be increased by 5%–10% with consideration of the diffusion mechanism (Wan et al., 2014; Yu et al., 2015). In future studies, characterizing the flow behavior of CO_2 and oil in low permeability and pressure conditions and the diffusion mechanism in on-site and laboratory CO_2 injection are encouraged to be emphasized.

Wei et al. (2015) approximated the technical potential of CO_2-EOR in China, showing an capacity of storing 2.2 Gt of CO_2. Moreover, according to the Ministry of Environmental Protection of China, CO_2-EOR can sequester approximately 5.1 Gt of CO_2 in the subsurface (Cai et al., 2021). Given this huge carbon reduction potential, China has focused heavily on CO_2-EOR technology to utilize and store CO_2 under the carbon neutrality goal. However, compared to reservoir properties in North America, the geological conditions of the oil reservoirs in China are relatively poor, particularly for tight reservoirs characterized by ultra-low permeability, low brittleness of rock, and poor mobility (Song et al., 2020). Therefore, more attention should be paid to reservoir evaluation and selection, operating strategies, and CO_2 monitoring technologies in future study. Furthermore, infrastructure investments, such as pipelines, surface separation, and recycling facilities for CO_2, should be improved.

3.3.1.2. CO_2-EGR. CO_2-EGR is another CCUS technology that improves gas recovery by injecting CO_2. The gas displacement effect and re-pressurization in depleting or depleted gas reservoirs are the primary mechanisms. On the one hand, CO_2 injection can lower the dew point pressure of reservoir fluids in wet gas reservoirs. On the other hand, the separated CO_2 from the produced gas can be injected back into the reservoir to improve gas recovery (Al-Hasami et al., 2005). Generally, CO_2 injection is suggested to enhance performance by up to 10% (Odi, 2012).

Several experimental and numerical simulation studies have been conducted to assess the feasibility of CO_2-EGR (Clemens et al., 2010; Khan et al., 2013; Eliebid et al., 2018). According to their results, CO_2 breakthrough is the major challenge in EGR since Early CO_2 breakthroughs resulted in unfavorable gas production. Thus the geological formations, particularly microstructures, are thought to significantly impact CO_2 flow behavior and sweep region. Furthermore, irreducible water saturation influences the mixing of CO_2 and CH_4. Engineering parameters also play an important role in determining CO_2-EGR performance. It is concluded that injecting CO_2 with a horizontal well in the lower reservoir while extracting CH_4 in the upper reservoir could reduce CO_2 breakthroughs in the production well. CO_2 injection during the early decline phase of natural gas production is advantageous for achieving a high CH_4 recovery because it ensures supercritical displacement and reduces CO_2 and CH_4 mixing. In terms of injection rate, numerous studies have shown that a high injection rate is beneficial for gas recovery, while a relatively lower injection rate of CO_2 (compared with CH_4 production rate) is also proposed to prevent early CO_2 breakthrough. Furthermore, parameters such as diffusion coefficient, viscosity, and permeability are important in gas displacement.

It should be noted that the CO_2-EGR is still a developing technology and more effort is expected in addressing issues such as mitigating CO_2 breakthrough and achieving favorable performance in both CH_4 production and CO_2 storage. Particularly, given the complicated reservoirs condition and relatively poor CO_2 supply (including pipeline transportation) in China (Hou et al., 2023), the current CO_2-EGR technology in China facies major challenges including technical maturity (serious CO_2 breakthrough and uncertainty of engineering parameters), site selection and reservoir geological assessment, a lack of sufficient and cost-effective CO_2 supply, and the complexity of anti-corrosion and anti-blocking technologies of equipment and pipelines.

3.3.1.3. CO_2-fracturing. CO_2-fracturing refers to a new type of fracturing technology that uses carbon dioxide as the fracturing fluid (Fig. 6). Carbon dioxide fracturing can be divided into liquid carbon dioxide fracturing (carbon dioxide dry fracturing) and supercritical carbon dioxide fracturing according to the phase state of carbon dioxide after reaching the reservoir.

During the fracturing process, part of carbon dioxide reacts with water to form H_2CO_3, which is further dissociated into HCO_3^- and CO_3^{2-}. Thus, carbon dioxide will be dissolved and stored in reservoir solution in the form of CO_2(aq), H_2CO_3, HCO_3^- and CO_3^{2-} (Zhang et al., 2016). In addition, the injection of carbon dioxide will result in the formation of many acidic zones, the dissolution of feldspar, clay and carbonate minerals, and the release of metal cations such as CA^{2+} and Fe^{2+}. These metal cations could combined with CO_3^{2-} and other anions to produce carbon-containing minerals such as calcite, dolomite, etc., and achieve mineralization of carbon dioxide (Gundogan et al., 2011). For CO_2-fracturing in unconventional oil and gas reservoirs, carbon dioxide can compete with methane adsorbed on the rock surface, thereby realizing the adsorption and storage of carbon dioxide (Fan et al., 2019). Moreover, compared with hydraulic fracturing, CO_2-fracturing has the advantages of reducing rock breakdown pressure, forming complex fracture networks, reducing reservoir damage and water resources dependence (Wang et al., 2019; Luo et al., 2021).

Nevertheless, the low viscosity and high filtration of carbon dioxide fracturing fluid lead to narrow fracture width, poor sand carrying effect, and easy sand plugging (Zhang et al., 2021a; Wu et al., 2022), which limits the large-scale application of CO_2-fracturing technology in the field. The technological challenges of the current CO_2-fracturing mainly includes a poor understanding of the fracturing mechanisms (e.g., fracturing initiation and expansion), a relatively low sand-carrying ability, the difficulty to precisely control the phase of CO_2. As such, further invertigation of fracturing mechanisms, development of new proppant and new equipments that have better sealing and corrosion resistance are likely to become the focuses of future research to improve the economic feasibility of industrial CO_2-fracturing.

3.3.2. CO_2-EGS

Due to the finite nature of fossil fuels and environmental concerns, renewable energy resources are inevitable to fulfill

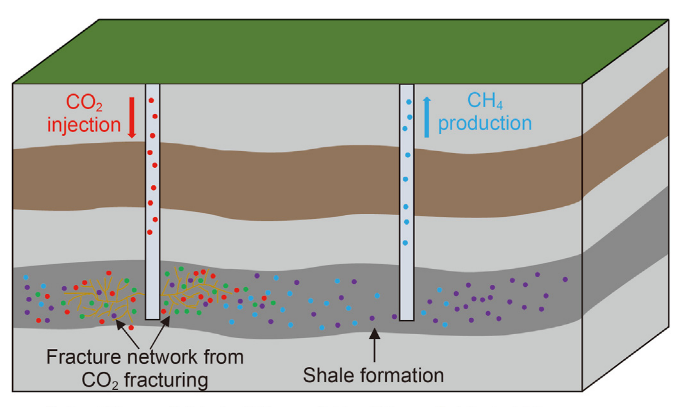

Fig. 6. Schematic diagram of supercritical CO_2 fracturing for enhanced shale gas recovery (modified after Zhou et al., 2019).

increasing energy trends. Among these, the exploitation of geothermal energy resources has fascinated widespread consideration due to its exceptional characteristics, like being stable, sustainable, clean, and independent of the weather. In addition, geothermal energy has a higher utilization rate, i.e., 5.2 times solar energy and 3.5 times wind energy (Li and Wang, 2015). Earth is considered a tremendous thermal energy resource due to hot molten core and decay of radioactive minerals. Besides, the earth's crust is a strong absorber of the sun's energy and acts as a solar heat accumulator (Olasolo et al., 2016; Haris et al., 2020). Despite ample geothermal energy resources, the commercial extraction of geothermal energy is limited to hydrothermal resources, which allow fluid circulation through natural high-permeable formations. In order to boost geothermal energy exploitation through low-permeable reservoirs, many countries are focusing on developing enhanced geothermal systems (EGSs) that are evolved from the hot dry rock using hydraulic fracturing.

Conventionally, water has been used as fracturing and heat extraction fluid due to its high density and specific heat levels. In order to ensure successful continuous operation by maintaining the reservoir's thermal pressure, a large amount of water is required (Harto et al., 2014). Generally, more than 20% of water is lost during fracturing and heat extraction processes in EGS, which can accelerate costs and raise environmental concerns about groundwater degrading (Wang et al., 2012). It has been proposed that water can be replaced by supercritical CO_2 for EGS exploitation due to the significant advantages like low pumping power requirement having lower fluid density, abolishing scaling issues in surface/subsurface assembly, and enhanced thermodynamic efficiency (Brown, 2000). In addition, supercritical CO_2 is documented to have good mobility with higher compressibility and expansivity in HDR. It has been estimated that the heat flow rate using CO_2 as a working fluid could be five times larger than formation brine (Randolph and Saar, 2011). The high cost of CO_2 capture and the potential threats of CO_2 leakage during storage in deep-ocean, mineralized, and shallow depleted oil/gas reservoirs have been the major constraints in promoting CO_2 geological storage techniques. However, combining geothermal heat extraction and CO_2 geological storage in deep EGS is a promising alternative to improve the economic feasibility of CCUS.

Several studies have investigated the thermophysical, thermodynamic, and chemical perspectives of CO_2 in reservoirs during the last two decades. Pruess (2006) analyzed CO_2 fluid dynamics and heat transfer issues considering CO_2 thermodynamic properties and found that CO_2 is superior to water in terms of heat mining ability. Sun et al. (2018) established a numerical model to investigate CO_2 performance for heat extraction through abandoned horizontal wellbores. They concluded that a larger mass flow rate is required to obtain a higher energy extraction rate. Shi et al. (2018) investigated CO_2-EGS performance for different well schemes and determined that higher heat extraction can be achieved using multilateral wells compared to conventional doublet CO_2-EGS. Despite the considerable advantages of CO_2-EGS and numerous numerical efforts, it is still at the conceptual/demonstration stage worldwide to the best of our knowledge.

3.3.3. Underground bio-methanation

Methanation of carbon dioxide is regarded as an effective method for CO_2 conversion and utilization, and it has been extensively studied in laboratories through isothermal catalytic methanation and adiabatic fixed-bed methanation, with the aid of metal-based catalysts (Karelovic and Ruiz, 2013; Tada et al., 2014). In contrast, underground methanation coupled with renewable natural gas (RNG) production from CO_2 reduction by virtue of microbial metabolism is a rising field of research and is attracting increasing attention (Hagemann et al., 2016; Ma et al., 2018; Strobel et al., 2020). Xiong et al. (2022) reviewed the biogeochemical mechanism and potential applications of biological CO_2 methanation and renewable natural gas storage in depleted petroleum reservoirs. With an external injection of CO_2 and H_2, the subsurface reservoir can be a natural bioreactor for bioconversion metabolism of indigenous methanogenic archaea by providing favorable conditions such as geothermal temperature, formation-water-filled porous media, anoxic environment, organic nutrient and trap structure (Aitken et al., 2004; Maier et al., 2009). Specifically, CO_2 captured from industrial productions or CO_2-bearing biogas via anaerobic fermentation, together with external green hydrogen (potentially produced via water electrolysis using surplus renewable energy in local areas), are the major substrates. The complex biogeochemical processes of CO_2 and bioconversion to CH_4 can be explained by a so-called Wolfe cycle of hydrogenotrophic methanogens (Fig. 7; Zabranska and Pokorna, 2018). The methanogen plays a key role during these processes by providing essential functional groups or electron carriers involved in the biochemical reactions, such as coenzyme and redoxin.

Biological methanation, coupled with CO_2 utilization and renewable natural gas storage, expands the scope and idea of CO_2-EGR, which brings additional commercial value to CCUS operations. Bio-methane related energy conversion and storage can be achieved by coupling the MRMD concept (microbial restoration of methane deposit; Koide and Yamazaki, 2001) with CO_2 emission-free gas-fired power plants (Fig. 7). More importantly, underground bio-methanation is expected to be integrated into the future “power-gas-power” (PGP) energy chain, which has advantages in flexibility, large-scale capacity, long-term storage cycle, and CO_2-reduction effect compared to pumped hydro storage and compressed air energy storage. According to the current techno-economic models (Aicher et al., 2014; Götz et al., 2016), the majority of overall cost and energy loss originates from electrolysis and methanation processes. This suggests that the economic feasibility of a biological methanation-based PGP system is largely determined by the cost of the “power to gas” stage (electrolytic hydrogen generation and storage) and the methanation efficiency (the cost of the bioconversion process itself is relatively low). As such, it is predictable that the biological methanation integrated into the PGP energy conversion and storage system has great potential if the bioconversion efficiency can be improved on an industrial scale (by enhancing hydrogen utilization and controlling microbial activity).

In general, underground bio-methanation makes it possible that some depleted petroleum reservoirs have the double functions of a bioreactor (from green hydrogen and CO_2 to renewable natural gas) and huge underground gas storage. It provides the twin dividend of reducing CO_2 emissions and producing potential natural gas resources. Compared with metal-catalytic methanation under surface or laboratory conditions, this approach makes full use of the inherent advantages of the porous reservoir medium. Although present studies have indicated the twin dividend of energy and environmental significance, the practical application of bio-methane production by microbial-mediated CO_2 methanation is still in its infancy. A few technical barriers remain to future industrialization, especially the uncertainty of hydrogen utilization via gas-liquid mass transfer and the difficulty in controlling microbial activity in practical subsurface reservoirs.

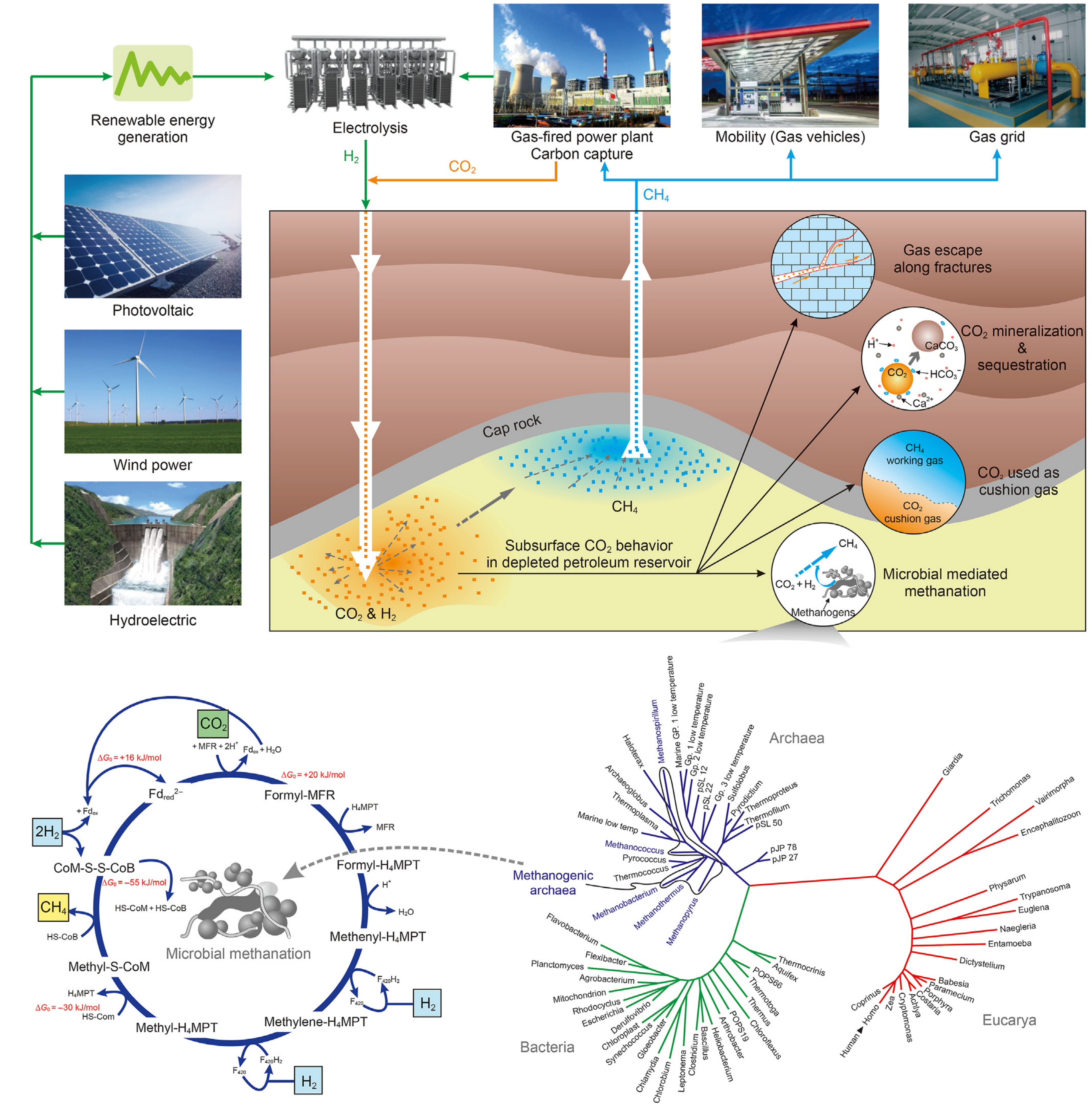

Fig. 7. Conceptual model of renewable energy-based underground bio-methanation coupled with renewable natural gas production (modified after Zabranska and Pokorna, 2018; Xiong et al., 2022).

4. Lessons for the implementation of China's carbon neutrality

4.1. Transformation of energy production patterns

Due to the coal-dominated resource endowment, China has a unique energy structure and is also world's largest consumer of fossil energy. The coal combustion emissions account for nearly 80% of total carbon emissions, far exceeding the global average. In 2020, coal, oil, and natural gas consumption in China accounted for 56.8%, 19.3%, and 8.7% of the primary energy structure, respectively (Fig. 8), inferring that China's energy structure is destined to undergo major adjustment and resource integration under the goal of carbon neutrality. In the short term, it is particularly crucial to introduce low-carbon technology into the coal industry.

Coal remains a major energy source and essential raw material for China, and it will be difficult to totally replace it in the near future. Given the various factors such as resource endowment, energy security, environmental capacity, and social and economic level, adhering to the clean and efficient utilization of coal is a better choice in light of the Chinese condition and energy status. In addition to promoting new energy-saving technologies in coal-

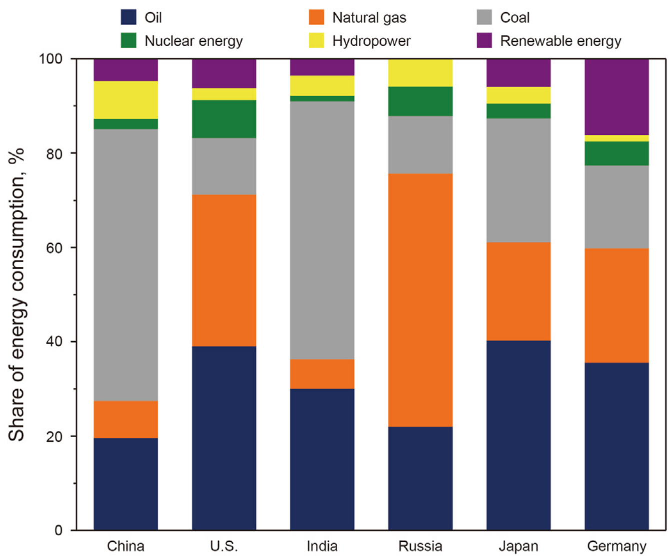

Fig. 8. Primary energy consumption structure in 2020 of several major countries (data from the *British Petroleum*).

fired power plants and factories, it is also necessary to develop clean and efficient coal conversion technologies such as coal pyrolysis technology, coal gasification technology, and coal liquefaction technology. In the last few decades, China has achieved considerable progress in coal chemical technologies, such as coal-to-liquids, coal-to-olefins/aromatics, and coal-to-ethylene glycol. Besides, the industrialization of these technologies is also at the forefront of the world (Wei et al., 2019). The focus of future research on clean and efficient coal conversion and utilization is to carry out basic scientific research on the reaction and catalysis of coal/syngas directly converted to fuels and chemicals, such as coal-to-clean gas, coal-to-liquid fuels, etc. Moreover, given that the natural gas accounts for only 8.7% of China's primary energy which is far lower than that of the United States and Germany. Unlike coal and oil, natural gas is relative clean and thus should be significantly increased in its consumption and proportion, mainly for gas-fired power generation and industrial fields to replace coal.

From medium and long term perspective, gradual transition from fossil fuels to the various renewable energy is required. The proportion of renewable energy in China's primary energy consumption has climbed from 8.6% in 2010 to 15.9% in 2020, with an annual average increase of 0.73% (Gao, 2021). During the “14th Five-Year Plan” period, it is expected that the installed power generation capacity of renewable energy will take more than 50% of the total installed power generation capacity in China, and renewable energy will change from an incremental supplement to an incremental mainstay of energy and power consumption. To achieve the goal of carbon neutrality, the ratio of renewable energy to energy consumption is expected to reach 80%–90% by 2060 (Zeng et al., 2021). Furthermore, during the process of energy transition, it is necessary to continuously enhance the potential of renewable energy, establish an effective link between development and planning, and set aside space for the sustainable development of renewable energy. For instance, integration of renewable energy with emerging technologies, new urbanization, rural revitalization, and new infrastructure should be actively promoted to expand the potential development and application of renewable energy in new areas.

4.2. Large-scale underground energy storage

Integrating renewable energy into the electricity grid is significant in promoting carbon neutrality. Due to the intermittent characteristic of renewable energy, large-scale energy storage must be considered (Liu et al., 2020a). Large-scale energy storage can balance energy demand and supply and ensure better integration of renewable energy. For example, PHES, CAES, and UHS are three possible technologies to solve the “peak shaving and trough filling” for wind and solar power (Chatzivasileiadi et al., 2013). Compared to the large surface facilities, underground energy storage takes advantage of the capacity of underground reservoirs and has minor impact and influence on environment and society. The volume of geological formations to store fluids ranges from hundreds of m^3 for cavities excavated in rocks to km^3 for massive porous media in sedimentary rocks (Matos et al., 2019).

According to National Energy Administration, the installed capacity of renewable energy power generation has reached 1063 GW by 2021 in China, accounting for 44.8% of the total installed capacity. As the increase of power generated from renewable energy, reducing the power curtailment is another important issue. In 2020, the national curtailment of hydropower, wind, and solar power was 17.5, 20.2, and 6.52 TWh, respectively. In northwest China, the curtailment rates of wind and solar powers are noticeable. The curtailment rate of wind power in Xinjiang was about 8% in 2021. Nevertheless, there are numerous depleted oil and gas reservoirs in Xinjiang, which can be adapted to store surplus wind and solar energy. Given the specific geological features in China, development of underground energy storage should be a promising method to improve the consumption of renewable energy.

Available underground spaces can be depleted oil and gas reservoirs, porous aquifers, salt formations, and abandoned mines. Development of underground spaces should consider the locally existing underground resources and the specific geological settings. For example, in northwest, southwest, and northeast China, many reservoir sources are suitable for high-quality and large-scale gas storage construction (Zhang et al., 2020). Depleted petroleum reservoirs are mainly located in northeast China and the Bohai Bay Basin. As such, underground energy storage systems such as CAES can be developed in these areas by adopting depleted oil and gas reservoirs. In addition to petroleum reservoirs, there are high-grade salt formations in Anning, Jintan, Pingdingshan cities, etc. where UHS can be an alternative for large-scale underground energy storage. Furthermore, in regions rich in water resource and abandoned mines such as Yunnan province, UPHES can be developed.

4.3. Integration of green hydrogen production, storage, transport and utilization

As the most potential and clean secondary energy, hydrogen will play an important role during the process of carbon neutrality. Hydrogen and its synthetic fuels could be diversely utilized in different terms of end-use for deep decarbonization, such as industry (e.g., steel and iron making), transportation (e.g., fuel cell vehicles), electricity, and construction (Fig. 9). In 2020, nearly 40 Mt of hydrogen was used in oil refining, which was the largest consumption of hydrogen utilization. The industrial demand for hydrogen in 2020 was about 51 Mt, roughly three-quarters of which were used for ammonia production, and the rest 5 Mt was consumed in the process of iron and steel making. For transportation, more than 40,000 fuel cell electric vehicles (FCEVs) were on road globally by June 2021. Hydrogen only occupies less than

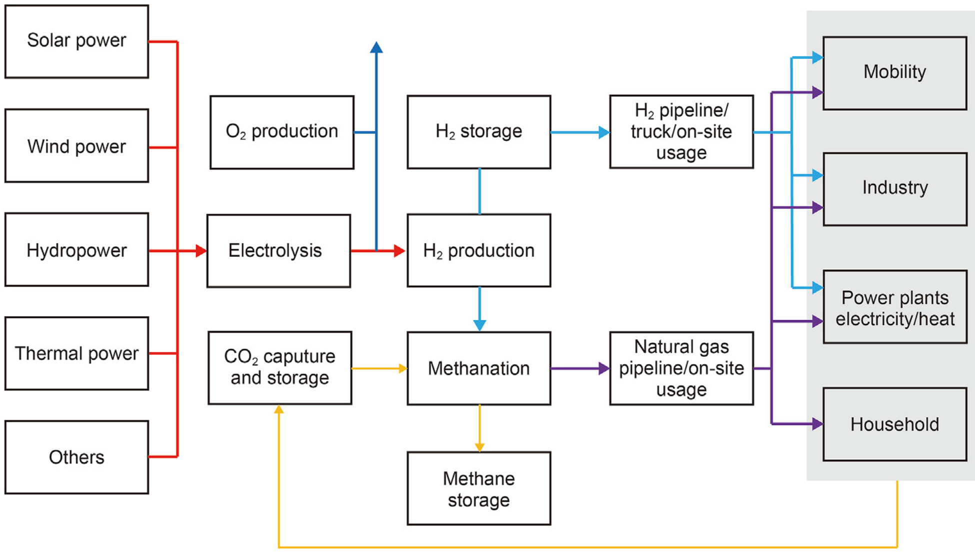

Fig. 9. The concept of coupled deep decarbonization and hydrogen utilization in different fields.

0.2% in the power generation sector, with related to hydrogen-containing gas mixtures from the steel industry, petrochemical plants, and oil refineries. On the one hand, pure hydrogen or hydrogen-containing gas mixtures (such as a mixture of hydrogen and natural gas) can be used as fuel for gas turbines and combined cycle gas turbines. On the other hand, hydrogen fuel cells can also be used as a flexible power generation technology. So far, reciprocating gas engines can use gases with a hydrogen content of up to 70% (on a volumetric basis), and engines running on pure hydrogen has been tested successfully. The rapid and diversified development of hydrogen also accelerates the research on large-scale hydrogen storage. Compared to the above-ground hydrogen storage, underground salt caverns have the advantages of large storage capacity (up to hundreds of megawatts or even gigawatts), adaptability to long-term or seasonal energy storage, and occupying fewer resources (Aneke and Wang, 2016).

Fang et al. (2022) proposed an integrated concept of the hydrogen industry that couples the whole production-storage-utilization chain (Fang et al., 2022). The three scenarios of hydrogen development are depicted in Fig. 10, which correspond to the recent, medium and long-term hydrogen development based on the Chinese condition. Notablely, the different scenarios would result in different functions of UHS. In scenario 1, the green hydrogen stored in the salt cavern is mainly used for FCEVs or iron and steel making for short-term (daily or monthly) storage. In scenario 2, two salt caverns are implemented, with one for green hydrogen storage, and the other for mixed CO_2—O_2 gas storage. The O_2 can be obtained from electrolysis, and the CO_2 can be used for

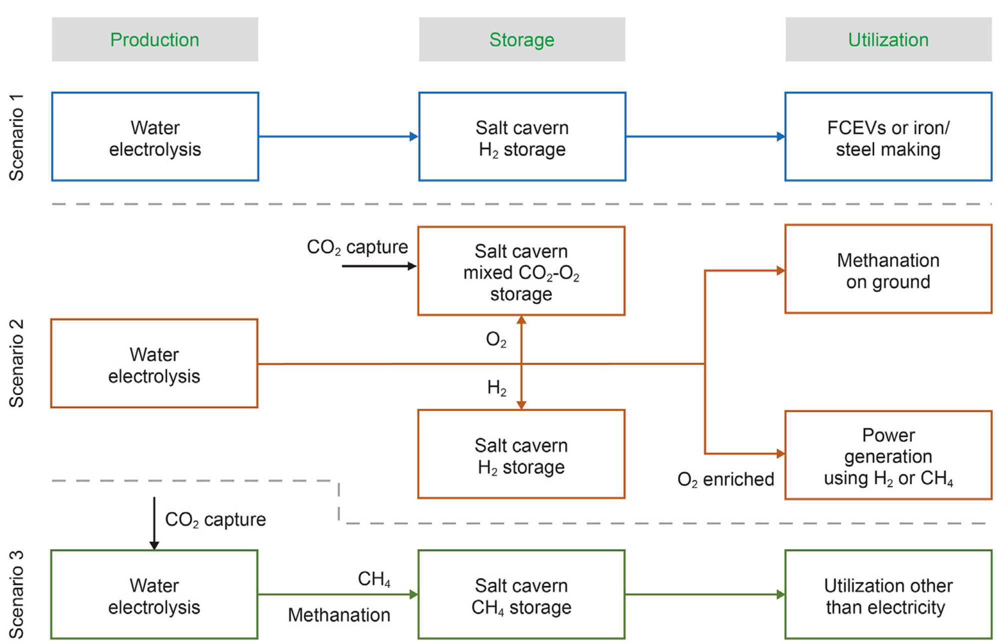

Fig. 10. The flowchart of the three scenarios of hydrogen production-storage-utilization.

ground methanation. The purpose of designing two caverns is to supply O_2-enriched power generation using hydrogen or CH_4. Unlike the scenario 2, in scenario 3, green hydrogen is first methanated on the ground and then directly stored in the salt cavern. For the storage of synthetic methane, the design and operation should refer to the China's current guidelines and specifications for natural gas storage. It should also be noted that whether for short-term or long-term storage, the stability, airtightness, and useability criteria of salt cavern energy storage should be assessed timely during operation.

4.4. Clean energy systems based on smart sector coupling (ENSYSCO)

Based on the smart grid and the sector coupling concept of energy utilization raised by Germany, and taking into account the huge potential of large-scale underground energy storage in China and AI-based (artificial intelligence) monitoring, analysis, and forecasting, Hou and Feng (2022) proposed an integrated future framework, namely “Clean Energy Systems based on Smart Sector Coupling” (ENSYSCO). The fundamental goal of the ENSYSCO system is to solve the problem of heterogeneous distribution of intermittent renewable energy, ensuring the integration of multiple renewable energy into future clean energy systems in a more intelligent, safe, and stable way. The basic idea of the system is to adopt advanced AI technology and cryptographic settlement methods. Specifically, the ENSYSCO system comprises three major energy sectors (i.e., production, consumption, and storage) with an efficient transmission network and a management system based on lightweight AI technology (Fig. 11). An intelligent regulatory system based on AI technology and large-scale underground energy storage are the most prominent features of the ENSYSCO system.

Compared to the sector coupling concept proposed by Germany, which only focuses on three aspects of energy utilization (electricity, heating/cooling, and transportation), the ENSYSCO architecture adopts multiple renewable power-to-X to closely integrate the three major sectors of energy production, consumption, and storage/transportation. Meanwhile, given the abundant underground resources in China, such as petroleum reservoirs, geothermal energy and coal mine goafs (Liu et al., 2015; Zhang and Hu, 2018), large-scale underground energy storage, represented by salt-cavern hydrogen storage, enhanced geothermal system, and pumped hydro-energy storage, is expected to become the key to the energy storage sector. Compared with the various types of storage devices on the surface, underground energy storage has advantages in terms of safety control, large storage capacity, long-term stable operation, and relatively lower energy storage costs (Matos et al., 2019; Fan et al., 2020). It also saves many land resources and is more conducive to ecological protection, which is also very important for China. In addition, considering the complexity and high dynamics of renewable energy conversion and polymorphic transmission networks, an emerging method combining the lightweight AI with the cryptographic settlement is employed in ENSYSCO to identify, replicate, simulate, predict and document the complex practical scenarios in energy systems. The lightweight AI method driven by the hybrid of physics and data endows the governance system efficiently with robust analysis, decision-making, and feedback capabilities.

Although some of the technologies involved in the ENSYSCO system need further investigation and optimization, most of the key steps, e.g., pumped hydro-energy storage (Fan et al., 2020), hydrogen production by PEM water electrolysis (Kumar and Himabindu, 2019) and underground natural gas storage (Zhang et al., 2020) are currently available for industrial application. It can be expected that the construction and continuous improvement of the ENSYSCO system will help China achieve its carbon neutrality goal faster and better.

4.5. Improvement of ecosystem carbon sinks

Forests are the mainstay of terrestrial ecosystems and account for about two-thirds of the annual carbon sequestration in the

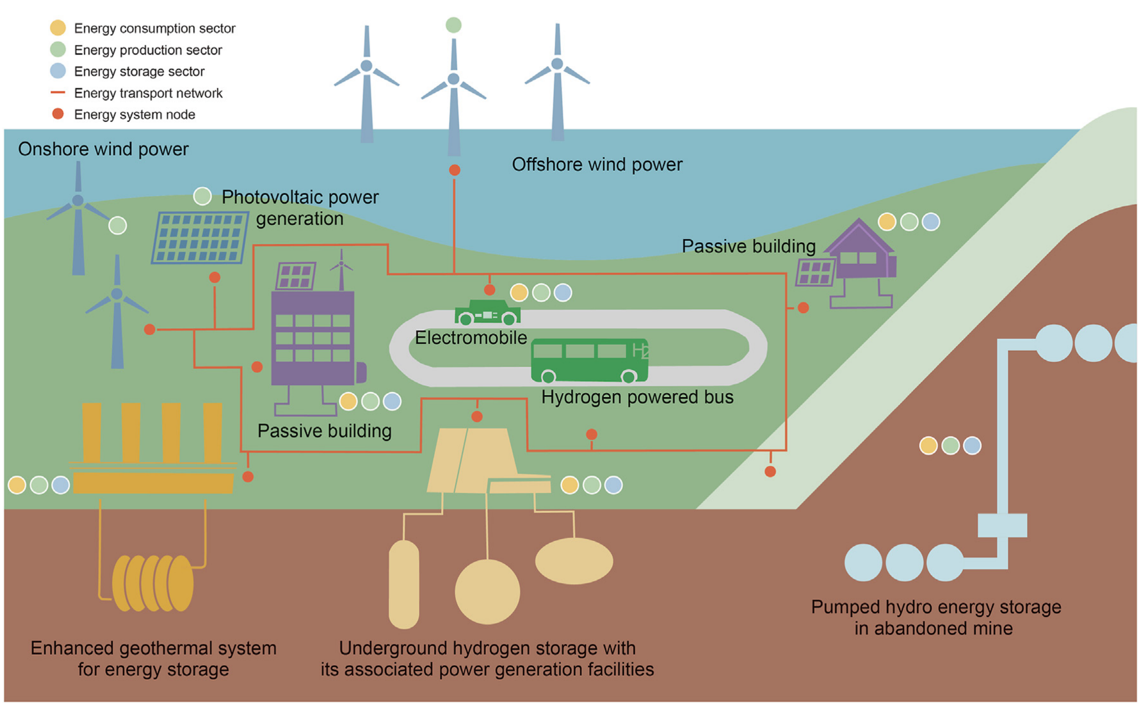

Fig. 11. Schematic diagram of the integrated energy system based on the ENSYSCO framework (modified after Hou and Feng, 2022).

entire terrestrial ecosystem. Therefore, forests play an irreplaceable role in regulating the global carbon balance, slowing the rise of CO_2 concentration in the atmosphere, and coping with climate change. Compared with industrial carbon emission reduction, forest carbon sink is more economical and efficient, and there are various benefits, such as improving the ecological environment and developing the tourism economy (Lin and Ge, 2019; Piao et al., 2022). In order to promote the completion of the carbon peak and carbon neutral targets, China has also clearly set out its forestry development goals, with the national forest coverage reaching about 25% and forest accumulation reaching 19 billion m^3 by 2030. At the end of 2020, the latest research findings of multinational scientists published in the Nature showed that the average annual uptake of carbon in China's terrestrial ecosystems from 2010 to 2016 was about 1.11 billion tons of carbon (Wang et al., 2020), accounting for about 45% of anthropogenic emissions during the same period. This result indicates that the carbon sink capacity of China's terrestrial ecosystems (about 350 million tons of carbon) was previously underestimated.

Despite the tight schedule and heavy task of carbon emission reduction in China, the better potential of forestry carbon sinks offers the possibility of carbon neutrality. At present, China has a forest area of 218 million hm^2 (square hectare), and there is still a total of ca. 40 million hm^2 of land that can be explored to expand the forest area (including 30 million hm^2 for afforestation and 10 million hm^2 for returning farmland to forest and grass). Zhang et al. (2022) recently predicted China's forest carbon sink potential. The results showed that China's forest carbon stock will reach 10.8 billion tons in 2030, with an average annual carbon sink of 225 million tons in 2018–2030; the forest carbon stock will reach 21.3 billion tons in 2060, with an average annual carbon sink of 312 million tons from 2018 to 2060.

In addition, it should also be recognized that with limited forest land resources, there is a limit to increase carbon stocks by expanding forest plantations. As such, improving the level of forest management and enhancing the utilization of forest resources through scientific and technological innovation will become an important way to increase China's carbon stock in the future. For example, the insufficient forest coverage, large desertified land area, and arid climate in northwest China have led to a fragile ecosystem. Rational development of desert resources in Northwest China, such as planting special desert vegetation for desert management (Zhao and Xu, 2022), combined with agricultural animal husbandry and desert tourism, can not only enhance the ecological level of Northwest China but also have the opportunity to make the vast desert a third active carbon pool in addition to forest plants and soil.

5. Conclusions

In this critical period of global economic recovery in the post-epidemic era, the carbon neutrality target is a strategic guideline for China to achieve sustainable development and promote ecological civilization, which also implies a profound change in China's energy and economic and industrial structures. Based on analyses of carbon neutrality goals and technical routes of several major countries, the urgency and challenges of achieving China's carbon neutrality have been highlighted. More importantly, implementing carbon neutrality will help China take the initiative in future international competition and accelerate the transformation from a developing country to a developed one and from a large country to a strong one.

Technological innovation is the main driver for achieving carbon neutrality, along which the status and prospects of the key technologies are reviewed comprehensively, including low, near-zero and negative carbon technologies. Specifically, low carbon technology has a wide range of applications, such as in coal mining, coal-fired power generation, cement and steel industries, etc. Near-zero carbon technologies are concentrated on renewable power-to-X and storage and nuclear energy. The sector coupling technique is also essential since it provides an effective coupling of the production, consumption, conversion, and storage, thereby promoting energy efficiency of future renewable energy systems. Negative carbon emissions are mainly achieved through CO_2 utilization technologies, especially in underground energy systems such as CO_2-EOR/EGR/fracturing, CO_2-EGS, and CO_2 bio-methanation.

Based on a comparison of the strategies and technical routes towards carbon neutrality of the world's major developed countries and a comprehensive review of the status and prospects of the key technologies, five lessons for implementing China's carbon neutrality are reached. First, gradually replacing fossil energy with renewable energy and changing the way of energy production is the most direct way to reduce carbon emissions. To address the problem of sensitivity of renewable energy to local climate and geographical conditions, large-scale underground energy storage technology should be vigorously developed. It is the key to make intermittent and fluctuating wind/solar/geothermal sources become high-quality and stable power supply. Moreover, hydrogen energy is expected to be the most desirable form of energy in the future (secondary energy), which can be applied in direct industrial or residential use and in large-scale transportation and storage of renewable electricity via green hydrogen. A concept of Clean Energy Systems based on Smart Sector Coupling (ENSYSCO), which closely couples the three sectors of energy framework (i.e., production, consumption and storage) through power-to-X-to-power techniques, is proposed. Finally, the improvement of China's ecosystem carbon sinks is emphasized, especially in exploring desert carbon sink potential using the vast desert resources in northwest China.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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