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Views & Comments

Large-Scale Underground Storage of Renewable Energy Coupled with Power-to-X: Challenges, Trends, and Potentials in China

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1. Introduction

Promoting the green and low-carbon transition of energy systems and constructing a new renewable-dominated power system is essential to achieving carbon neutrality in China [1,2]. Furthermore, implementing electrification and hydrogenation strategies to address energy consumption is necessary for a successful energy transition. China's share of electricity in its total energy consumption is estimated to increase from 26% in 2021 to more than 70% by 2060. By 2060, the national total electricity consumption will triple, and the power supply capacity will reach approximately 3.0×10^{13} kW·h. Therefore, renewable energy plays a crucial role in China's new power system development. Wind and solar power accounted for 11.5% of China's total electricity production in 2021 (Fig. 1(a)) and are expected to reach 85% by 2060. At that time, wind and solar power will generate approximately 2.6×10^{13} kW·h (approximately 25% will originate from energy storage coupled with power-to-X, of which more than 80% will be expected to be generated by large-scale underground energy storage (UES), accounting for 20% of total production). As one of the leading countries in renewable energy development, Germany's share of renewable energy power generation surpassed 50% in 2020 [3]. Benefitting from the well-organized German Power Future (from 15 min to 10 years), a smart energy system, and sufficient storage capacity, Germany's power system still operates reliably. According to estimates, Germany's electricity storage demand will be 4.5×10^{10}–9.0×10^{10} kW·h in 2030. In comparison, China's annual electricity consumption is approximately 11 times that of Germany's. As a result, the demand for reserved power in China will be 5.0×10^{11}–1.0×10^{12} kW·h in 2030, and 6.0×10^{12}–7.0×10^{12} kW·h in 2060 (Table 1), corresponding to 70%–82% of the total electricity consumption of 8.5×10^{12} kW·h in 2021. Therefore, massive demand is anticipated for the implementation of large-scale (especially underground) energy storage technologies (Fig. 1(b)), which will play a vital role in China's future energy system.

Compared with aboveground energy storage technologies (e.g., batteries, flywheels, supercapacitors, compressed air, and pumped hydropower storage), UES technologies—especially the underground storage of renewable power-to-X (gas, liquid, and e-fuels) and pumped-storage hydropower in mines (PSHM)—are more favorable due to their large-capacity (> 10^{12} kW·h) and long-term (several months) storage characteristics (Fig. 1(b)). In comparison with aboveground energy storage, UES is safe, efficient, and inexpensive, with the six key functions of peak regulation, frequency regulation, phase regulation, energy storage, backup systems, and black start [4]. Furthermore, UES can effectively reduce land requirements and ecosystem damage and benefit the agriculture and construction industries [5–7]. The synergistic effect is also crucial in coordinating UES with the rapid response and flexible deployment of aboveground energy storage technologies. To ensure the efficient and stable operation of energy systems in accomplishing carbon neutrality goals, there is an urgent need to rapidly develop large-scale (especially underground) energy storage technologies. In this study, we propose four insightful portfolios that can integrate renewable UES coupled with power-to-X. We then analyze their potential, challenges, and development trends. Finally, we provide corresponding suggestions as a reference for the development of China's large-scale energy storage technologies and its strategy of achieving a carbon peak and carbon neutrality.

2. Four modes of large-scale UES coupled with power-to-X

2.1. Pumped-storage hydropower in mines (power-to-potential energy)

PSHM uses the drifts and goafs of underground mines as multi-level water storage reservoirs. When the electricity supply exceeds the demand, water is pumped to the upper-level reservoirs, and excess power is converted into gravitational potential energy

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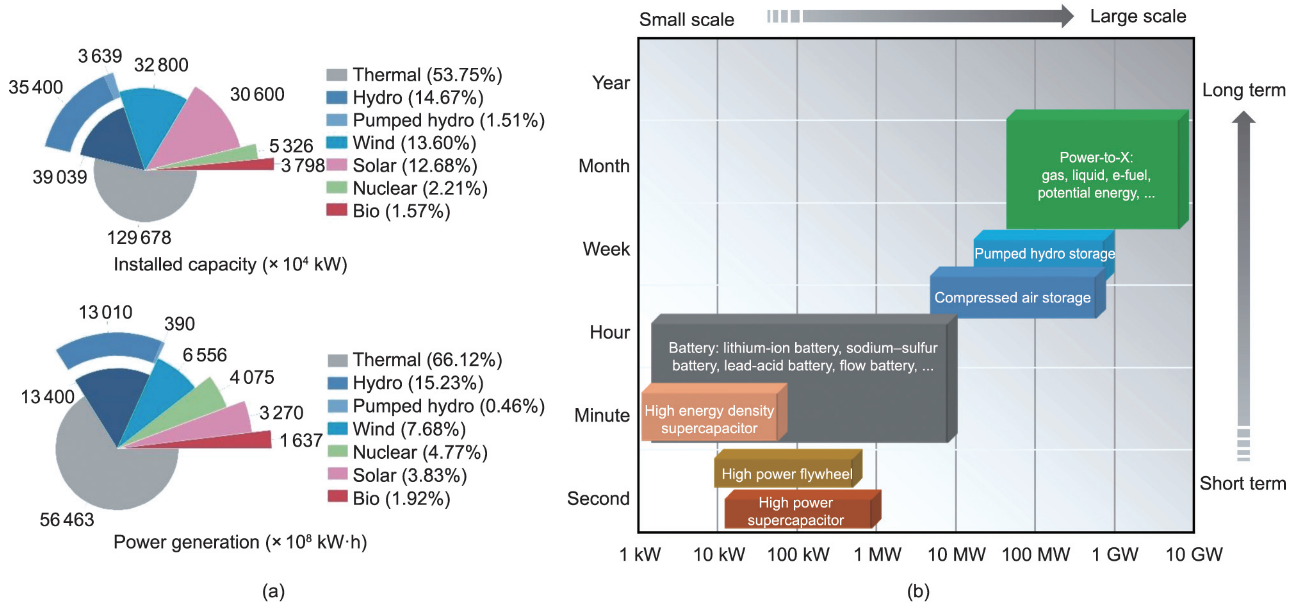

(a) (b)

Fig. 1. (a) Electricity structure of China in 2021; (b) comparison of various energy storage technologies.

Table 1
Characteristics and potentialities of various energy storage technologies.

Type	Energy storage technology		Main characteristics	Technology maturity	Potential ($\times 10^8$ kW·h)	
					2030	2060
Aboveground	Pumped-storage hydropower		Fast response, high efficiency, long life and discharge time, and large scale	Mature	3 300	8 900
	Batteries, flywheels, supercapacitors, etc.		Fast response, high efficiency, and flexible deployment	Mostly mature	1 500	3 800
Underground	Pumped-storage hydropower in mines		Fast response, high efficiency, large scale, long life and discharge time, and minimal external influence	Pilot, but mostly mature	—	11 300–13 500
	Salt cavern	Hydrogen (H_2)	Long discharge time, large scale, and minimal external influence	Pilot abroad, but mostly mature	5 000	10 500
		Methanol and e-fuels		Mature abroad	5 800	12 100
	Geothermal	Shallow	Long heat-release time, large scale, and minimal external influence (climate)	Mostly mature	—	5 300–21 000
		Deep		Pilot		2 700–11 000
	Depleted hydrocarbon reservoirs (DHRs)	Natural gas	Large scale and low cost	Mature	2 500–4 000	11 100–11 800
		Biomethanation	Large scale, low cost of underground methanation, renewable methane storage, carbon dioxide capture, utilization, and storage (CCUS), and carbon circular economy	Theoretical stage	—	32 900–44 200
Total power demand/power storage demand	—	—	—	—	14 000–15 000/5 000–10 000	~300 000/60 000–70 000
Total potential	—	—	—	—	—	98 600–136 800

(GPE). When the demand is higher, water is released from the upper-level reservoirs stepwise to the lowest reservoir to generate electricity. Consequently, the GPE of water is reconverted into electrical energy and transmitted back to the grid (Fig. 2). Considering the substantial and widely distributed abandoned mines in China [8], PSHM has unique benefits, because it enables depleted mine reutilization, renewable energy development, and power storage. In addition, PSHM can achieve water storage, energy storage, power generation, water circulation, renewable energy development and utilization, and so forth. Moreover, it is characterized by a short response time (minutes and seconds) and a long working life (40–60 years), with high energy efficiency (up to 80%). Furthermore, PSHM helps reduce the extreme weather impacts triggered by climate change (i.e., drought, flood, etc.) and can help control surface subsidence and maintain an ecological balance [9,10].

Aboveground pumped storage technology is considered a mature technology. However, due to diverse and complex mining areas, high falls (up to more than 1000 m), multilevel and clustered reservoirs, limited operation space, and a lack of real-world operation experience, PSHM still presents several key technological challenges:

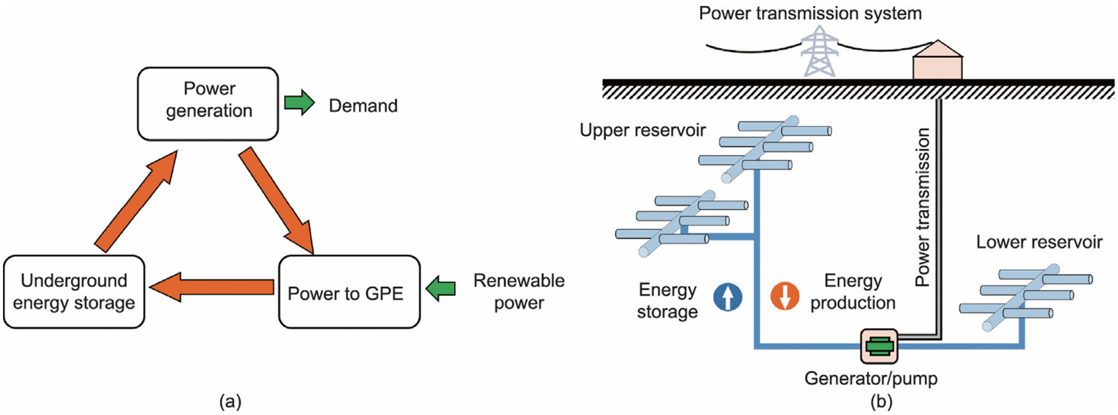

Fig. 2. Schematic diagram of mine pumped storage power generation system. (a) Workflow of underground pumped storage in mines; (b) schematic diagram of pumped storage in underground mines.

(1) Identifying the damage mechanism of the surrounding rock and the multi-physics coupled disaster mechanism (i.e., thermo–hydraulic–mechanical–chemical–biological fields, natural and man-made fracture fields, etc.) under alternating and thermal stress.

(2) Ensuring water loss and leakage control, the long-term operational stability and safety of the station, and real-time monitoring and remote intelligent warning systems.

(3) Retrofitting and reconstructing electromechanical facilities and the hydraulic structure to suit the restricted underground space.

(4) Conducting the multi-energy complementation, efficient coupling, and digital-intelligent management of PSHM, as well as geothermal parallel development and surface renewable energies (wind, solar, hydropower, etc.).

(5) Determining site selection and evaluation criteria and establishing an intelligent database containing ground and underground information based on a three-dimensional (3D) geographic information system (GIS).

(6) Performing a comprehensive quantitative analysis of the economics and developing an appropriate business model for and operation mechanism of PSHM.

As of the end of 2021, China had 36.4 GW of installed pumped storage capacity in operation, with an annual power generation of 3.9×10^{10} kW·h (Fig. 1(a)). According to a plan by the China National Energy Administration, pumped storage will generate more than 3.0×10^{11} kW·h by 2030. Based on an assessment of China's resource endowment, pumped storage (excluding PSHM) will be able to reach an energy storage potential of 8.9×10^{11} kW·h in 2060. China has numerous abandoned mines with considerable potential for development. According to previous studies, PSHM constructed only from abandoned coal mines (up to 2014) holds the potential to yields 7.3×10^9 kW·h [8]. In addition, the volume of available metal mines for PSHM is 1.2×10^8 m^3 in Yunnan Province alone, with a corresponding annual power generation capacity of 3.3×10^{10} kW·h [11], while PSHM can produces 6.7×10^{10} kW·h in Henan Province [12]; moreover, China's total potential PSHM power generation capacity ranges from 1.1×10^{12} to 1.4×10^{12} kW·h, based on our approximate computational conversion. Construction of the first domestic semi-underground PSHM (where the upper reservoir is an open-pit quarry) and a multi-energy complementary PSHM project has been commenced at the Shidangshan copper mine in Jiangsu Province and Zibo in Shandong Province, with a planned installed capacity of 1.0×10^6 and 2.2×10^5 kW, respectively. Compared with that of conventional pumped-storage projects, the investment and construction period of the new semi-underground PSHM plant is only half as long. Therefore, we suggest that small-scale mines (particularly metal mines) with stable geological structures and low technical difficulty should be employed to conduct an initial pilot study to gain experience and lay a foundation for the promotion and application of large-scale and standardized PSHM implementation.

2.2. UES in salt cavern (power-to-gas, power-to-liquid, and power-to-e-fuel)

UES in salt caverns consists of a subsurface system of artificial caverns built in rock salt that can store energy in gaseous or liquid form (e.g., as hydrogen (H_2), natural gas, compressed air, or oil; Fig. 3). As a rock with ultra-low permeability (usually 1×10^{-22}–1×10^{-19} m^2), rock salt exhibits good creep performance, ultra-high tightness, and self-healing capacity. In addition, rock salt is an optimum energy-storage medium, due to its high water solubility and ease of forming large-capacity cavities [13–15]. Conversely, as the most promising form of clean energy, with zero carbon-emission characteristics [16,17], H_2 exhibits vast application capabilities. Hence, salt caverns are ideal for storing high-purity hydrogen.

Based on renewable power and underground hydrogen storage (UHS) in salt caverns, H_2 is not only a potential medium for large-scale energy storage but also a bridge connecting electricity, heating/cooling, and transportation (i.e., sector coupling). H_2 can also serve as the material for fuel cells (which can be used in trucks, buses, long-distance cars, regional trains, aviation, and water

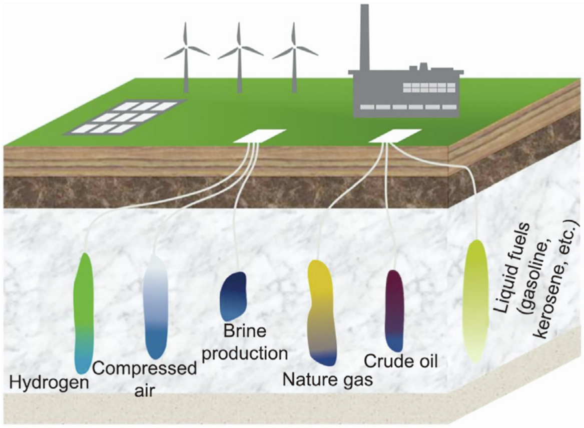

Fig. 3. Schematic diagram of multi-functional rock salt cavern storage.

transportation). In addition, it can be used as a fuel for distributed (oxygen-rich) power generation. Green power-to-gas (H_2, compressed air, methane, etc.), liquid (methanol, dimethyl ether, etc.), and e-fuel (gasoline, diesel, aviation kerosene, etc.) techniques enable safe and efficient renewable energy conversion, storage, and utilization. Simultaneously, it not only enables the complete carbon cycle between energy carriers and the natural environment, but can also store any renewable clean gaseous and liquid energy, helping to achieve the net-zero carbon target. At present, the technologies of UES salt caverns in Europe and the United States are approaching maturity, with approximately 60 years of operation experience for salt cavern oil and gas storage. The world's first salt cavern compressed air storage (CAS), in Huntorf plant, Germany, has stably operated since 1978; salt cavern hydrogen storage has been successful in Teesside, UK, and Clemens Dome, TX, USA, for nearly 30 years; and Germany is transforming 32 existing salt cavern natural gas storages into hydrogen storages in batches. Moreover, Jintan, China, has 15 years of practice operating a salt cavern for natural gas storage [13] and began a pilot project of a small salt cavern for CAS in September 2021.

The main challenges presented by UES salt cavern development involve the UHS salt cavern and include the following:

(1) H_2 is a highly reactive chemical element, owing to its low electronegativity and small atomic size. It combines readily with other elements to form compounds that cause metal corrosion, rubber failure, and cement degradation.

(2) With its high permeability and diffusion coefficients, H_2 is likely to deteriorate the mechanical properties of materials (e.g., hydrogen embrittlement). Consequently, UHS has rigorous requirements for leakage and seepage prevention, long-term operational stability and safety, real-time monitoring, remote warning systems, and pipe material performance.

(3) Owing to microorganism diversity in salt caverns, differences in biochemical reactions and interaction with H_2 require attention and study.

However, the capacity and potential of UHS salt caverns are substantial. For example, 269 underground rock salt structures in the North German Basin have a combined storage capacity of approximately 1.6×10^{12} kW·h for UHS. Similarly, Liu et al. [18] expect hydrogen storage of up to 3.7×10^{10} kW·h to be possible using only 4.0×10^{7} m^3 of the salt caverns in Jiangsu Province, China, by 2050. Salt cavern volumes in China have reached 1.3×10^{8} m^3, with an annual increment of more than 5.0×10^{6} m^3. China has the potential for approximately 5.0×10^{11} kW·h of hydrogen storage in 2030 and is expected to reach 1.1×10^{12} kW·h by 2060. The prospects for methanol storage are more substantial, with an estimated 5.8×10^{11} and 1.2×10^{12} kW·h by 2030 and 2060, respectively. At present, with the combination of renewable power-to-X, worldwide attention is being focused on UES salt caverns. Germany has already begun storing liquid e-fuels in salt caverns for industries that have high-density energy demand but cannot use electric and hydrogen fuels. UES salt cavern development is comparatively slower in China, and no hydrogen or liquid storage practice exists as yet. Consequently, research and pilot projects on strategic petroleum reserves—especially UHS salt caverns—should be conducted, demonstrated, standardized, and implemented in China.

2.3. Renewable enhanced geothermal system (REGS) integrating cogeneration and energy storage (power-to-heat)

By injecting a surplus green-power-heated exchange medium into a deep geothermal reservoir, the integrated cogeneration, energy storage, and REGS combines large-scale wind, solar energy conversion, and subsurface storage with two operational modes [19]:

(1) **Energy production mode:** The heat-exchange medium (HEM; typically, water or supercritical carbon dioxide) in the thermal reservoir is naturally heated to the formation temperature (e.g., $\geq$ 160 °C in the North German Basin). Subsequently, the HEM is extracted to the surface in order to comprehensively utilize cogeneration and is then reinjected (at 50–60 °C) into the reservoir. This process can achieve multistep energy utilization (power–heat coproduction: cogeneration) and circulation of the HEM (i.e., to extract heat but not water).

(2) **Energy storage mode:** Renewable energy, such as surplus wind or solar energy, is applied to heat and pressurize the HEM in order to enhance the energy density. For example, the boiling point of pure water increases to about 350 °C under 16 MPa. After the ultra-high-temperature HEM is injected into the reservoir, the heat exchange is completed with the rock formation through a multi-stage hydraulic fracturing network to accomplish renewable energy storage and renewable geothermal reservoir utilization. The process of injecting an ultra-high-temperature medium into an underground (natural or artificial) heat-exchange system is conducive to cleaning both the production and injection wells and prolonging the life cycle of the geothermal system (Fig. 4). The integrated enhanced geothermal system (EGS) of cogeneration and energy storage is coupled with green power-to-heat technology, which stores renewable energy in the form of thermal energy, achieves a geothermal cascade, and recycles, and can consume renewable wind and solar energy efficiently and in a high proportion.

Efficient REGS operation depends on a sizeable heat-exchange surface (> 2 km × 5 km) and a fracture network with high penetration. The main technological challenges are as follows:

(1) Developing ultra-large-area, multi-stage hydraulic volume fracturing technology and optimal fracturing design based on 3D multi-physics-coupled numerical simulations.

(2) Optimizing the hydraulic fracturing scheme to prevent or reduce induced earthquakes.

(3) Achieving subversive breakthroughs in deep-earth mid/low-temperature geothermal power generation and improving energy efficiency and the input–output ratio.

(4) Achieving anti-corrosion, anti-scaling, anti-blocking pipes, and ensuring service life extension.

(5) Establishing resource exploration requirements and building site-selection standards.

Overall, after the technical and economic challenges have been overcome, REGSs have the potential to eliminate environmental and climatic burdens and achieve long-term stable operation [20]. A numerical simulation study based on Germany's GeneSys geothermal energy storage project demonstrated that an REGS substantially promotes renewable energy usage and storage, and extends the system lifetime. The results show that, at an injection rate of 144 $L \cdot s^{-1}$ and a utilization rate of 90%, the annual early-stage power generation potential of the REGS reaches 49.14 GW·h, and the cumulative output within 30 years exceeds 1200 GW·h [19].

China's shallow geothermal energy, deep hydrothermal resources, and hot dry rock resources are remarkable, accounting for 7.9% of the world's reserves, with an annual availability of 3.1×10^{18} kW·h and an extensive renewable power consumption capacity [21]. According to calculations, the use of only 5%–15% of China's wind and solar power can realize geothermal heat storage of approximately 8.0×10^{11}–3.2×10^{12} kW·h through power-to-heat technology by 2060. Of these storages, the shallow geothermal energy storage potential mainly used for heating/cooling is 5.3×10^{11}–2.1×10^{12} kW·h, whereas the potential of a deep renewable geothermal system for cogeneration is 2.7×10^{11}–1.1×10^{12} kW·h. In China, the type of geothermal energy usage has been developed, and the scale of development has

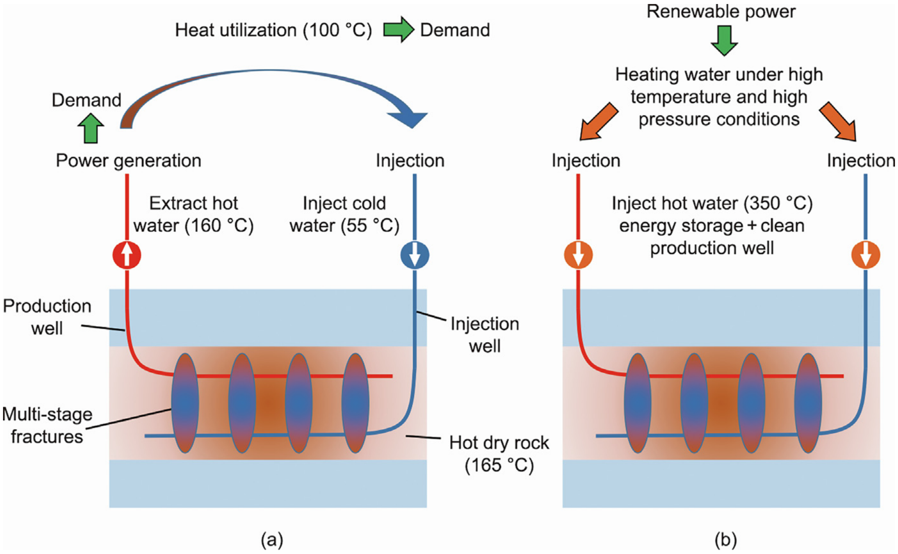

Fig. 4. Schematic diagram of an enhanced geothermal system (EGS) integrated with cogeneration and energy storage. (a) Energy production mode; (b) energy storage mode.

substantially increased in recent years. However, an effective combination and multi-energy complementation between geothermal and wind/photoelectric energy has not yet been achieved, and the degree of energy cascade and cyclic utilization remains low. Therefore, developing ground-source heat pump technology in China's heating/cooling areas and expanding pilot projects for the use of shallow geothermal heat is preferable. Cutting-edge investigations are required to mitigate the obstacles in engineering technology. In the next stage, it is desirable to conduct REGS pilot projects in Qinghai Province, western Sichuan, southern Xizang, and other regions in order to reduce operational costs and build a technological and economic basis for widespread promotion.

2.4. Utilizing depleted hydrocarbon reservoirs (DHRs) for gas storage (power-to-gas)

In China, DHRs capable of gas storage (i.e., impure hydrogen, natural gas, compressed air, and CO_2) are widely distributed and have considerable energy-storage potential [22,23]. In addition, future advancements in large-scale volume fracturing research and technology, combined with the copious tight hydrocarbon reservoirs in China, offer the potential for further expansion of DHRs [24,25]. The impure hydrogen stored in a DHR can be used for the surface/subsurface synthesis of methane (where manufactured natural gas is referred to as methanation). Similarly, in power-to-gas technology, DHR stores compressed air for direct or mixed natural gas power generation. Furthermore, as a significant aspect of carbon dioxide capture, utilization, and storage (CCUS), DHRs—particularly natural gas reservoirs—can be employed as natural biochemical reactors for methane synthesis (i.e., renewable natural gas). The production, flexible storage, and utilization of renewable natural gas can be achieved by injecting impure H_2 and proportional CO_2 into a DHR through induction and catalysis by means of microorganisms (i.e., methanogenic archaea) (Fig. 5). This UES mode effectively couples the zero (or negative)-emission economic utilization of impure hydrogen, CO_2 recycling and sequestration, underground natural gas synthesis and storage, and parallel geothermal development, thus furthering the development of a low-carbon circular economy [4,26].

The complex interaction among H_2, microorganisms, and water strongly influences the UHS in depleted oil and gas reservoirs. Thus, the site-selection and evaluation criteria, microbial chemistry, thermo–mechanical–hydraulic coupling process simulations, and anti-leakage technology are complex. CAS in DHRs has not yet been globally piloted, because it involves a series of technical challenges, such as pressure control, reservoir management, and energy conversion efficiency improvement. Natural gas storage in DHR is relatively mature, and its development trend and application prospects in China are favorable. However, issues such as site selection, evaluation criteria, and database establishment must be addressed urgently. It is necessary to develop unified norms and standards for operational management and safety requirements. Underground biochemical mechanization technology is currently in the stages of mechanism research and small-scale field trials, even in Europe and the United States. Before large-scale industrial application, the following challenges still need to be addressed:

(1) Screening specific strains and achieving large-scale efficient and low-cost nurture.

(2) Developing dynamic tracking and monitoring systems for biochemical catalytic reaction processes.

(3) Understanding the unknown biochemical processes and influencing factors in actual reservoirs.

(4) Activating and controlling microbial populations in the reservoir environment and inhibiting competing organisms.

(5) Establishing method of improving energy conversion efficiency and site-selection and evaluation criteria.

(6) Overcoming uncertainty in economic benefits, operating mechanisms, and business models. It is necessary to conduct quantitative financial model assessment in field tests (Sichuan Province is suitable for such tests) to obtain an appropriate business strategy.

According to the recent plans of related companies, China's natural gas storage capacity by 2060 will reach a total working volume of 1.2×10^{11} m^3, corresponding to 1.1×10^{12}–1.2×10^{12} kW·h. According to preliminary estimates, China's large-scale UES will reach 4.8×10^{12}–5.6×10^{12} kW·h (80% of the total power storage demand) by 2060. Regarding full capacity utilization to produce hydrogen and industrial byproduct hydrogen, the underground biochemical synthesis of methane with CO_2 and an energy storage

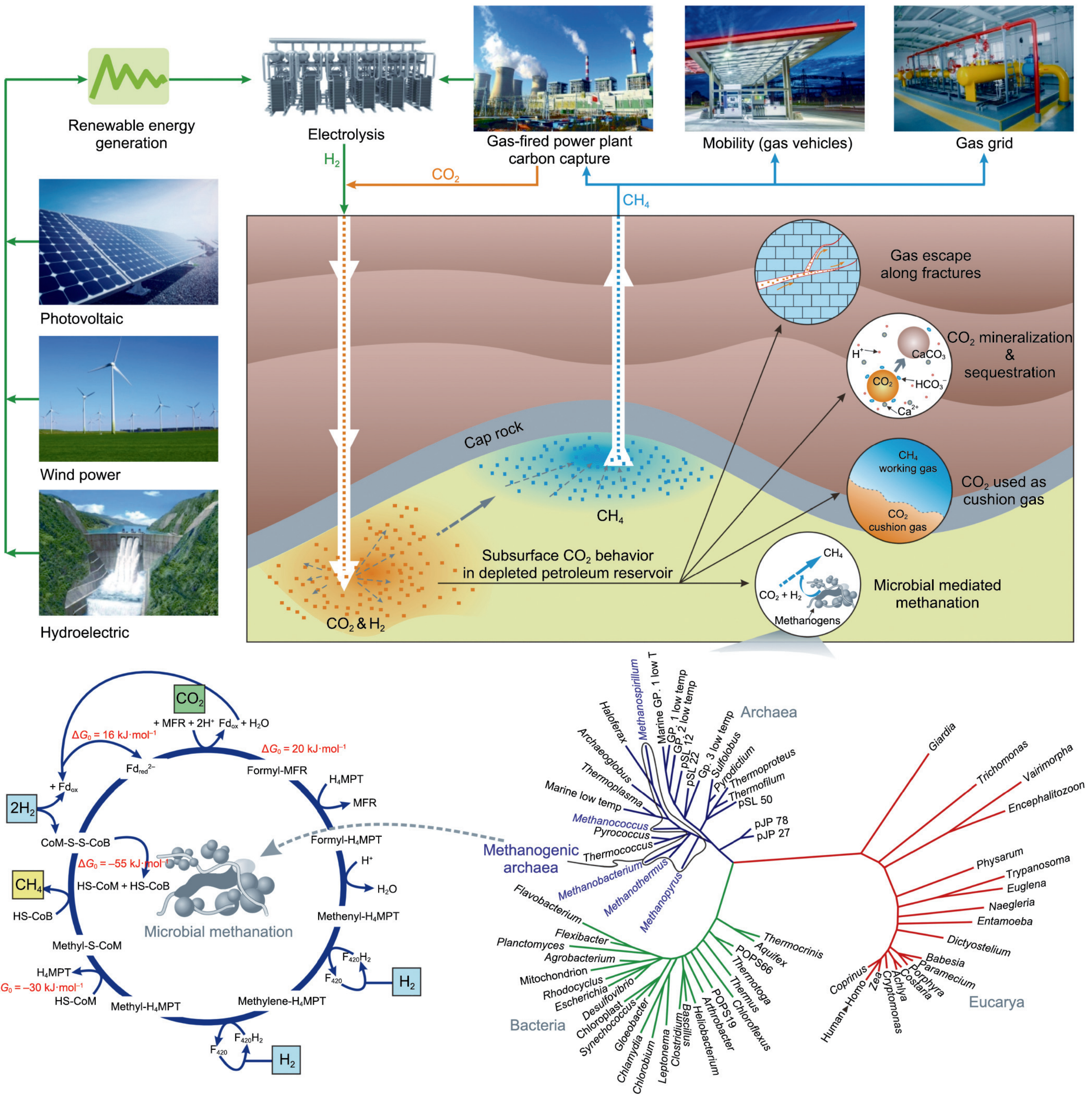

Fig. 5. A conceptual model of impure hydrogen-based underground biomethanation coupled with renewable natural gas production and storage. MFR: methanofuran; H_4MPT: tetrahydromethanopterin; CoM: coenzyme M; CoB; coenzyme B; Fd: ferredoxin; HS-CoM: sulfhydryl coenzyme M; HS-CoB: sulfhydryl coenzyme B; CoM-S-S-CoB: heterodisulfide coenzymes CoM and CoB; temp: temperature; Gp. 1, Gp. 2, Gp. 3, pSL 12, pSL 22, pSL 50, pJP 27, pJP 78, POPS66, and POPS19 represent gene sequence codes of uncultivated strains and unnamed strain types. Reproduced from Ref. [3] with permission.

of 3.3×10^{12}–4.4×10^{12} kW·h can be achieved (energy efficiency: 68.6%–79.2%) [26]. Biomethanation offers unprecedented development opportunities and substantial potential as an important carbon-negative technology.

3. Outlook

Carbon neutrality can be achieved by developing renewable energy and key technologies, such as coupling power-to-X with large-scale UES (e.g., in mines, salt caverns, DHRs, and geothermal reservoirs). In this work, the operational differences, development pathways, technical feasibility, and economic viability of each energy system were well considered for the four UES modes.

Based on the analysis of the potentialities and challenges in each UES mode, the evaluation of each mode's development trend, and practical experience in Europe and the United States, combined with a consideration of China's status quo and carbon neutrality goal, the following suggestions are made:

(1) Conduct a nationwide survey of underground waste mines, establish a set of site-selection and evaluation criteria for PSHM, construct a feasibility and economic evaluation system, and promote PSHM demonstration projects.

(2) Expand and improve the storage function of underground rock salt caverns, with a focus on promoting pilot work in gas storage (i.e., hydrogen, renewable natural gas, and compressed air, etc.) and accelerating the capacity building of rock salt caverns for liquid storage (e.g., oil, methanol).

(3) Promote shallow geothermal utilization in heating/cooling areas and combine heat pump technology to accomplish geothermal utilization for heating/cooling and energy storage. We encourage further studies on the application prospects and economics of REGS and the investigation of major control parameters and evaluation indicators to prepare for field testing.

(4) Investigate key technologies for hydrogen storage and compressed air in DHRs and propose pilot projects. Develop the use of depleted oil and gas reservoirs to store natural gas, and optimize site-selection and assessment criteria in order to develop a standard operating procedure. In addition, conduct in-depth field studies of depleted oil and gas reservoirs as natural biochemical reactors for methane synthesis.

(5) In combination with the authors' investigation and research, appropriately implement pilot work on UES in all localities. For example, in the copper mining area of the Dahongshan iron mine, Yunnan Province, a pilot study of PSHM coupled with direct hydropower generation in rainy seasons can be performed in dry seasons; in Pingdingshan of Henan Province and Anning of Yunnan Province, feasibility studies on UHS in rock salt caverns can be undertaken; a pilot study of depleted oil and gas reservoirs as natural biochemical reactors for methane synthesis can be organized in Sichuan Basin; and a pre-pilot REGS study can be launched in Qinghai Province.

Although some successful cases of the large-scale underground storage of renewable energy coupled with power-to-X exist, these are limited to hydrogen and CAS in rock salt caverns, and the energy efficiency and economic benefits can be improved. The government should support basic research in the relevant scientific fields and accelerate experimental exploration and technology reserves. The industrial standardization and application of large-scale UES technologies should be implemented as soon as possible in order to achieve China's dual-carbon target.

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