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Perspective

Integration of large-scale underground energy storage technologies and renewable energy sources

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Abstract:
Large-scale underground energy storage technology uses underground spaces for renewable energy storage, conversion and usage. It forms the technological basis of achieving carbon peaking and carbon neutrality goals. In this work, the characteristics, key scientific problems and engineering challenges of five underground large-scale energy storage technologies are discussed and summarized, including underground oil and gas storage, compressed air storage, hydrogen storage, carbon storage, and pumped storage. This perspective provides valuable theoretical and technical guidance for the construction and development of large-scale underground energy storage, further promoting the utilization of renewable energy and the realization of the "double carbon target" in China.

1. Introduction

Energy storage technology is vital for accomplishing the new national energy security strategy, addressing the major national strategic needs of renewable energy storage, conversion, and application. At present, large-scale underground energy storage technology is being developed at a fast pace in countries worldwide. The principle of most large-scale energy storage technologies is that when the consumption or price of electricity is low, the surplus or cheap electricity in the power grid is converted into other forms of energy (such as chemical energy, potential energy, etc.) and then stored in the deep and tight underground structures. Later, at the peak of electricity consumption, the stored energy is released to generate electricity and supplement the available power of the power grid. The working process follows the form of energy conversion from electric energy to other energy and then back to electric energy. The development of large-scale underground energy storage technology is driven both by the advancement of underground space construction and the growing demand for renewable energy storage. Underground storage spaces are particularly suitable for constructing large-scale physical energy storage systems, and large-scale energy storage technology plays a significant role in the high-quality development of renewable energy power systems. With the implementation of large-scale underground energy storage technology, renewable energy power systems could better achieve power translation, transferring the electricity from renewable energy generation systems to peak electricity demand periods and playing a role in balancing the power system and storing electricity on a large scale (Weitemeyer et al., 2015). Due to the advantages of safety and environmental friendliness, large-scale underground physical energy storage systems have become an important research direction.

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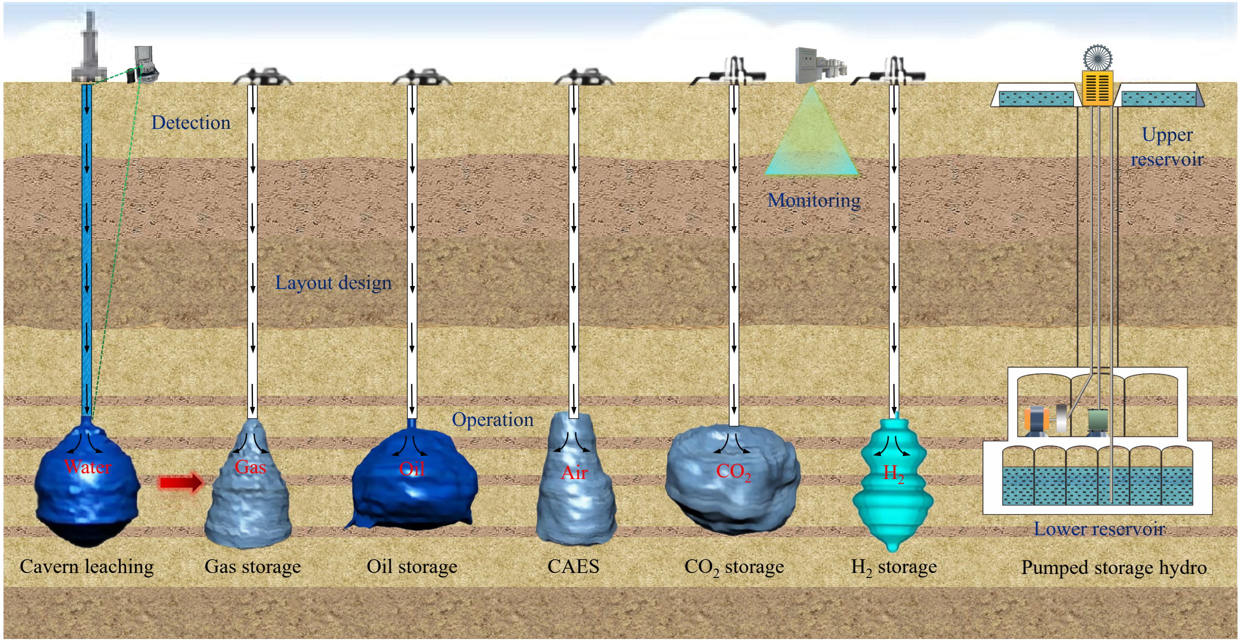

Fig. 1. Large-scale underground energy storage (Liu et al., 2023).

2. Underground storage of natural gas/oil

For underground natural gas storage, different countries have created a pattern of diversified development of depleted oil or gas reservoirs, salt caverns and aquifers based on their own geological conditions, in which depleted gas reservoirs are the main type of gas storage. In recent years, salt cavern gas storage has been favoured by many countries due to its high gas production capacity, flexible injection-production conversion and low cushion volume, and thus has become the preferred target for gas storage construction. It can be predicted that with the increase in the scale and volume of natural gas storage, the relevant construction conditions are becoming more complicated. Therefore, the high-quality construction and efficient operation of underground gas storage under complex geological conditions are inevitable requirements (Wan et al., 2023a). Currently, the key research directions of underground natural gas storage include efficient construction in low-permeability reservoirs, high-pressure and large-flow injection and production, real-time monitoring and early warning for the trinity of formation-wellbore-surface, and the digital construction and intelligent operation of gas storage (Ma et al., 2018).

Underground oil storage includes concealed oil tank depots, cave oil tank depots and underground cavern oil depots, among others. Concealed tank depots and cave tank depots have been gradually eliminated due to the high associated investment and long construction periods. Underground cavern oil depots are the common choice and mainly include abandoned oil and gas reservoirs, aquifer structures, underground salt caverns, mining pits and caves, and so on, among which underground salt caverns play a key role in oil storage (Wei et al., 2024).

With the integrated transformation technology of brine extraction and cavern building in salt mines, the storage construction speed is greatly improved. Compared with other storage methods, salt cavern storage is large-scale, low-cost, has good sealing characteristics, high-safety, and comes with rich technical and engineering experience. Therefore, large-scale underground gas/oil storage in salt caverns is the straightforward solution to improve national strategic energy reserves.

3. Underground compressed air energy storage

Underground compressed air energy storage is a kind of physical energy storage technology, which can realize energy storage by converting electric energy into potential energy (Ibrahim et al., 2008). It has the advantages of large installed capacity, long energy storage time and service life, cleanliness and environmental protection, and a flexible layout of power stations. Both the energy storage and energy release side can operate under a wide rande of working conditions and variable loads, and this technology has the potential to gradually replace thermal power generation under the guidance of the strategic goal of double carbon (Chatzivasileiadi et al., 2013).

The geological sites that can be used for underground compressed air energy storage mainly include abandoned mine caves, natural salt caverns, hard rock, and artificial caves. The excavation amount and the operation cost of abandoned mines are small, albeit there is a limited selection of sites and the stability and sealing of abandoned mines are generally poor. Natural salt caverns feature self-healing and natural sealing properties, as well as low construction cost, but the space utilization rate is low and the number of suitable sites is limited by the distribution range of rock salt resources. Under long-term operation, the surrounding rock of salt caverns shrinks and deforms greatly. Besides, the salty environment is corrosive to equipment and facilities. Hard rock chambers are widely distributed and have good stability, but they are notorious for sealing problems and their construction is difficult and uneconomical. Artificial caves have a controllable scale, where site selection is less limited by geographical conditions, whereas the sealing of the caves is difficult and expensive. Obviously, these energy storage sites each have their specific advantages and disadvantages. At present, salt cavern is the only storage type that has reached successful commercial operation, while the construction of hard rock caves and artificial caverns still needs to be engineered and industrialized. Research on compressed air energy storage should mainly focuses on the stability of surrounding rock, site selection, air thermodynamics and structural air tightness, and so on. Fortunately, the related technologies and specifications of underground compressed air energy storage are becoming mature (Wan et al., 2023b).

In recent years, China has ushered in a peak in the construction of compressed air energy storage power stations in salt caverns. As a competitive short-term peak-shaving energy storage method for renewable energy, there will be a great demand for underground salt cavern compressed air energy storage (Luo et al., 2014). The future development directions of this technology should include the suitable depth range of the reservoir, the priority utilization of large-volume old caverns, and the development of large-scale borehole construction technology.

4. Underground hydrogen storage

Hydrogen energy is recognized as a renewable, clean and efficient energy source, with the advantages of wide availability, high energy density and no carbon emissions. These assets make hydrogen the most ideal future energy source for human beings. Underground hydrogen storage technology bears the advantages of high safety, low cost, large-scale, and long-term operation, attributing it great significance in realizing renewable energy utilization and large-scale hydrogen utilization. However, due to the active chemical properties, strong diffusion and high permeability of hydrogen, the implementation of underground hydrogen storage technology brings certain scientific problems, such as high-pressure hydrogen corrosion, microbial reaction, formation mineral reaction, and tightness. Therefore, it is necessary to ensure the safe operation of hydrogen storage from the aspects of geological site selection, research and development of hydrogen embrittlement resistance equipment, and design of the operation scheme (Liu et al., 2024).

Three types of geological structures exist for underground hydrogen storage: salt caverns, depleted oil and gas reservoirs, and aquifers. A salt cavern is an artificial cavern built in the salt rock layer. The reaction between rock salt and hydrogen is inert thus it will not easily produce impurities. The caprock has good integrity and the sealing level, resulting in almost no diffusion of hydrogen in the salt rock, which is suitable for storing pure hydrogen (Liu et al., 2020). The depleted oil and gas reservoir is characterized by a large storage volume, good sealing, and complete geological information; what is more, the surface and underground facilities can be reused and the initial geological exploration and infrastructure investment is low. However, hydrogen is easily mixed with the residual natural gas, which is not conducive to pure hydrogen storage. Besides, the injection-production frequency is low and the construction of reservoir is time-consuming (Wan et al., 2024). Aquifers are porous and permeable underground rock formations filled with fresh water or brine, which have a wide distribution range but strict site selection requirements and high construction cost. The relevant geological research needs to be strengthened to determine the compactness and mineral composition of the caprock and surrounding rock.

Salt caverns are the only underground place where large-scale pure hydrogen storage technology has been successfully applied, while depleted oil and gas reservoirs and aquifers are still in the planning or construction stage. Compared with other underground places, salt caverns provide the most economical option to store hydrogen. However, the construction of salt cavern hydrogen storage is limited by the geographical distribution of rock salts. As we can see, aquifers and depleted oil and gas reservoirs are still the main development directions of large-scale underground hydrogen storage sites.

Developed countries such as Europe and the United States have obvious advantages in geological site selection evaluation, reservoir capacity design, reservoir construction technology, and hydrogen storage operation monitoring. Related studies started late in China and have mainly focused on the sealing property of hydrogen in the caprock and interlayer, the biochemical reaction mechanism, and the stability and sealing property of the surrounding rock of the hydrogen storage in layered salt rocks. Additionally, most of these researches are still in the stage of computer simulation and laboratory testing. The Hubei Daye Deep Hydrogen Storage Scientific Research Base Project began in January 2024, which is the first scientific research pilot base for hydrogen storage in caverns and the first underground distributed hydrogen storage in China. It will carry out research in the basic theory of hydrogen storage, including the hydrogen embrittlement resistant material, the core construction processes, the intelligent management and control platforms and other research fields, with the aim to provide valuable experience and guidance for the construction of large-scale underground hydrogen storage in China.

5. Underground carbon storage

The most popular research direction within underground carbon storage technologies is carbon capture, utilization and storage (CCUS). Carbon capture is the process of capturing CO_2 from industrial emission sources, power plants or the atmosphere, involving chemical absorption, physical absorption, adsorption and membrane separation, among other technologies. The utilization of captured carbon dioxide is another integral part of CCUS, which can further convert carbon dioxide into valuable chemicals and fuels through chemical transformation, fuel production, mineral carbonization, and agricultural applications, as well as improve oil recovery in tight and shale reservoirs. Finally, storage means storing the captured carbon underground or in the ocean, so as to prevent them from being released into the atmosphere again. The main forms of underground carbon storage include caprock storage and the cooperative storage of caprock and reservoir. Both of these can convert carbon monoxide into stable carbonate by physical or chemical reaction and realize long-term storage. Meanwhile, the latter can increase the storage capacity and reduce the risk of CO_2 leakage, thus has more development potential.

CO_2 leakage is the main threat to the long-term safe operation of CCUS geological storage projects (Lin et al., 2022), making the detection technology of CO_2 leakage particularly important. At present, most research on the safety and leakage risk of CO_2 storage is still in the theoretical analysis stage, lacking practical projects and quantitative research. Furthermore, the testing equipment is expensive, the monitoring results are not comprehensive and the monitoring system is not perfect. CCUS is also facing the problems of high implementation costs, low efficiency and high purity requirements of CO_2. As an emerging technology that is expected to realize large-scale CO_2 emission reduction and the low-carbon utilization of fossil energy, CCUS can provide new ideas of low-carbon transformation for industries that find it traditionally difficult to reduce emissions, such as the industries of steel and cement. CCUS has a good fit with new energy coupling, so more attention should be paid to it.

6. Underground pumped storage

A traditional pumped storage system includes two reservoirs at different altitudes, water pumps, turbines, and a water delivery system, to achieve the conversion between potential energy and electric energy (Morabito et al., 2020). It is the most mature energy storage technology in the world, while it is severely limited by site selection. The underground pumped storage system is less dependent on topography and can reduce environmental problems, but its preliminary geological exploration is time-consuming. The distinctive feature of underground pumped storage technology is that both reservoirs are located underground, and closed underground reservoirs can be built by using abandoned mines, quarries, or other caves (Yang and Jackson, 2011). There are a large number of closed and abandoned mines in China, about one-third of which being water-rich mines, hence most of the current research focuses on using abandoned mines as underground reservoirs. The necessary conditions for the development of underground reservoirs include sufficient underground space, abundant water sources, and mines that are not flooded. Two key scientific problems need to be solved urgently. The first is exploring the influence of hydrogeology and hydrochemical characteristics and water cycle process on site selection, and the second determining the effects of the stability and tightness of underground rock mass in abandoned mines on the operation. The key parameters to solve the above problems are the reservoir capacity, groundwater circulation, surrounding rock stability, and water quality (Nzotcha et al., 2019).

Thus far, with the concept of “guiding and storing for use”, underground reservoirs have been successfully built in coal mines, while there is no practical case for using abandoned underground space of coal mines as pumped storage underground reservoirs, so more attention should be paid to pursuing this research direction.

7. Conclusions and prospects

Large-scale underground energy storage technology integrated with renewable energy is the optimal choice to achieve carbon peaking and carbon neutrality goals. This paper summarizes the characteristics and development challenges of five major energy storage technologies, and draws the following conclusions:

1) Large-scale underground energy storage technology can realize energy conversion and storage by using surplus or cheap power from renewable energy, and has the main advantages of large energy storage scale, long energy storage time, long service life, cleanliness, and environmental friendliness. Therefore, it is of great significance for ensuring national energy security, promoting energy structure upgrading, and achieving the goal of double carbon.
2) At present, large-scale underground energy storage technology still faces theoretical and engineering challenges, such as reservoir site selection, engineering construction, management and operation, project cost, etc. The main future development directions of this technology should include perfecting and enhancing the theory of large-scale energy storage technology, improving the efficiency of engineering construction, ensuring the long-term operation safety of the project, and applying and popularizing the new technologies and concepts.

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Conflict of interest

The authors declare no competing interest.

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