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Invited review

# Compressed air energy storage in salt caverns in China: Development and outlook

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**Abstract:**
With the promotion of China's carbon peaking and carbon neutrality goals, the energy industry is transforming from traditional fossil energy to renewable energy, which is sustainable, clean and safe. The development of renewable energy is not only an important measure to achieve the above goals but also a significant factor to alleviate the global energy crisis. Salt caverns, with good air tightness, have been considered as the best choice for large-scale underground energy storage. To elaborate on the research and future development of salt cavern compressed air energy storage technology in China, this paper analyzes the mode and characteristics of compressed air energy storage, explores the current development, key technologies and engineering experience of the construction of underground salt caverns for compressed air energy storage at home and abroad. Focusing on salt cavern compressed air energy storage technology, this paper provides a deep analysis of large-diameter drilling and completion, solution mining and morphology control, and evaluates the factors affecting cavern tightness and wellbore integrity. The future development and challenges of underground salt caverns for compressed air energy storage in China are discussed, and the prospects for the three key technologies of large-diameter drilling and completion and wellbore integrity, solution mining morphology control and detection, and tubing corrosion and control are considered. This paper aims to provide a useful reference for the development of underground salt cavern compressed air energy storage technology, the transformation of green and renewable energy, and the realization of carbon neutral vision.

## 1. Introduction

Wind energy, hydropower and solar energy play significant roles in the energy transition and have become major sources of electricity (Succar and Williams, 2008; Yuan et al., 2018). However, they possess inherent disadvantages such as regional limitations, intermittent supply and uneven demand, which pose challenges for the stable operation of power grids and networks, impeding the rapid development of clean renewable energy (Wang et al., 2017; Razmi et al., 2021; Hematpur et al., 2023). One of the effective approaches internationally approved to overcome the issue of unstable clean energy supply is utilizing underground space for large-scale storage (Koohi-Fayegh et al., 2020; Alirahmi et al., 2021b). Salt cavern energy storage, as one of the important forms of underground energy storage, can make full use of underground space to realize large-scale and efficient storage of various forms of energy, with the advantages of large storage capacity, high storage pressure, safety, and reliability (Li et al., 2021). This is an equally important development direction in the field of energy storage in China and a significant requirement for achieving the national "carbon neutrality" strategic goals (Zou

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et al., 2021).

In salt cavern hydrogen storage, hydrogen storage technology is rapidly advancing in developed countries, represented by the United States and the United Kingdom (Lankof et al., 2022). The experience of salt cavern hydrogen storage (Clemens Dome and Moss Bluff in the US, Teeside in the UK) has proved that hydrogen can be stored safely for a long period of time. At present, Germany, Canada, Poland, Turkey, and Denmark have formulated plans for hydrogen storage in salt caverns (Caglayan et al., 2020; Aftab et al., 2022; Hematpur et al., 2023). Compared with the above countries, China's underground hydrogen storage research is lagging behind, with no underground hydrogen storage practice developed yet. As a form of clean energy, hydrogen energy can be used for power generation without harmful emissions, which also features high energy storage efficiency. Besides, it can be used in the transportation and industrial fields (Posdziech et al., 2019; Elberry et al., 2021). On the downside, the cost of production and storage is high for hydrogen, which is prone to leakage and explosion.

In salt cavern natural gas storage, salt cavern gas storage reservoir construction and operation has seen 60 years of global development, mainly in North America and Europe, especially in the United States and Germany (Li et al., 2017). Compared with foreign countries, there is still a large gap in the construction of underground gas storage reservoirs in China. In 2018, China's first salt cavern gas storage — Towngas China Jintan Gas Storage — was put into operation (Zhao et al., 2022). According to the overall deployment plan of the country, China will form four major gas storage clusters in the future, including the Northeast Storage Cluster, the North China Storage Cluster, the Middle and Lower reaches of the Yangtze River Storage Cluster, and the Pearl River Delta Storage Cluster. There is a good technical basis for storing natural gas, so that electricity can be generated when needed (Sedaee et al., 2019). However, suitable geological conditions for salt caverns or rock salt formations for gas storage are not available in every region.

Salt cavern compressed air is often used to establish a certain scale of underground energy storage or storage group to meet the needs of urban power supply and is one of the important storage alternatives. compressed air energy storage (CAES) technology has numerous advantages, including large storage capacity, long storage cycle, high system efficiency and long operating life, and as such is considered to be one of the most promising large-scale energy storage technologies (Lund et al., 2009; King et al., 2021). Related research about salt cavern CAES in China began only recently (Luo et al., 2014; Tong et al., 2021). In May 2022, the Jiangsu Jintan salt cavern CAES project successfully generated power, which is currently the world's first non-supplementary CAES commercial power station, marking a new stage of CAES technology (Li et al., 2022). In July 2022, China's first 300 MW CAES demonstration project was initiated in Yingcheng City, Hubei Province. Upon the completion of the project, the annual power generation is expected to reach 500 million kW·h. This system adopts the large-capacity non-supplementary fired high-pressure hot water storage medium-temperature adiabatic compression technology, which was independently developed by China Energy Engineering Group Co., Ltd. The core technical index, i.e., energy conversion efficiency, reaches 70% (Wan et al., 2023).

To date, China has achieved significant progress in the field of salt cavern CAES and accumulated certain development experience, while it possesses abundant salt mine resources for future development. This paper analyzes the storage mode and characteristics of underground large-scale salt caverns for CAES, and discusses their development status and construction in foreign countries. Focusing on the key technology of salt cavern energy storage, we perform a comprehensive analysis of large-diameter drilling and completion, solution mining, cavern tightness testing, and wellbore integrity testing. Finally, the future development of underground salt cavern energy storage in China is projected, and suggestions for accelerating the energy storage capacity of salt caverns are put forward.

## 2. Development of underground salt caverns for CAES

### 2.1 Types of CAES geological body

The carriers of underground reservoirs can be underground caverns or caves that can store gas due to the impermeability of the surrounding rocks. They can also be porous media formations, such as depleted gas reservoirs and aquifers, which have high porosity and good permeability and are suitable for rapid gas injection and production (Chen et al., 2021b; Yang and Liu, 2021; Aftab et al., 2022). Underground reservoirs are generally classified into four types: depleted oil and gas reservoirs, salt caverns, aquifer reservoirs, and lined rock caverns, as shown in Fig. 1. Table 1 includes a comparison of the strengths and weaknesses of different geological reservoirs.

Depleted oil and gas reservoirs provide a basis for the construction of gas storage, that is, they utilize gas or oil reservoirs after depletion. Due to the low cost and reliable operation, using this kind of reservoirs has become currently the most common alternative for natural gas storage. For a satisfactory sealing and storing ability, the reservoir must have sufficient permeability and porosity, for which anticline is the ideal formation structure, as shown in Fig. 1(a). In terms of geological adaptability, these reservoirs are capable of storing hydrocarbons that migrate upward from the underlying hydrocarbon source rocks. Thus, depleted oil and gas reservoirs have been proven in practice to be able to store natural gas (Mahdi et al., 2021).

Salt rock formation can be in the form of underground salt mounds or layered rock salts. As for salt cavern gas storage, solution mining is employed to create cavities. Freshwater is injected from the surface into the underground salt layers, dissolving solid sodium chloride minerals to form brine containing sodium and chloride ions. Then, the brine is mined to the surface. In this way, salt caverns are formed in the underground salt layers, as shown in Fig. 1(b). Compared with other gas storage reservoirs, underground salt caverns have the advantages of low permeability, low porosity, good rheological properties, self-closing microfractures, low con-

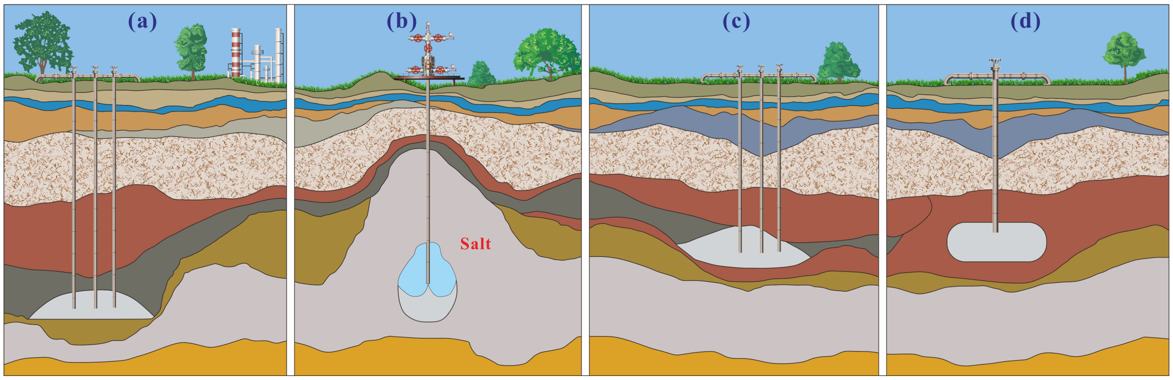



**Fig. 1**. Types of underground gas reservoirs. (a) Depleted oil and gas reservoirs, (b) salt caverns, (c) aquifers and (d) lined rock caverns.

**Table 1**. Comparison of the strengths and weaknesses of different types of geological reservoirs (Olabi et al., 2021).

| Type | Strengths | Weaknesses |
|---|---|---|
| Depleted oil and gas reservoirs | -Clear stratigraphic structure<br>-Residual gas in the formation can be used as buffer gas<br>-Existing infrastructure can be modified for later projects<br>-Huge storage capacity | -The stress field changes during alternating injection and production, thus affecting the tightness |
| Salt caverns | -Low permeability and good tightness<br>-Self-healing properties and low risk of gas leakage<br>-Simple engineering with mature technology<br>-Good economics and relatively low cost | -Strong creep capability and large volume shrinkage<br>-High-pressure oxygen corrosion<br>-Small injection and production pressure interval<br>-Limited range of sites |
| Aquifer reservoirs | -Good stratigraphic tightness<br>-Low engineering cost<br>-Large potential reservoir capacity | -Difficult to explore<br>-Limited range of site<br>-High requirements for overlying strata<br>-Needs additional measures such as grouting |
| Lined rock caverns | -Relatively easy site selection<br>-Good self-stability, low deformation and stable capacity<br>-Large operating pressure interval<br>-Many types of cavern sections | -High construction cost of building a warehouse<br>-Needs a separate sealing structural layer<br>-Complicated construction process |

struction cost, high injection-production conversion efficiency, less cushion gas, and so on (Wang et al., 2023). Their tightness and integrity are determined by the nature of the salt rock itself, with generally no other additional sealing measures required (Chen et al., 2023; Vandeginste et al., 2023). In the process of solution mining and injection-production operation of salt caverns, there are several times of stress redistribution. According to domestic and foreign geological surveys, salt rock deposits in China are generally thin salt layers, with a general thickness of tens of meters to more than 200 meters. By contrast, large salt mounds abroad can be more than 500 meters thick, where caverns of up to 100 meters in diameter and hundreds of meters in height can be built without artificial stabilization measures. The Mao 8 well salt cavern used in the CAES power station project in Jintan salt caverns is located about 1,000 meters underground. The maximum diameter of the pear-shaped cavern is about 80 meters, its height is more than 100 meters and it has a volume more than 220,000 $m^3$.

Underground aquifers are developed in areas with no available or suitable natural gas reservoirs for underground storage, and are called aquifer reservoirs (Zhen et al., 2019). This type of reservoir is usually a porous and permeable sandstone or carbonate rock with brine or freshwater contained in the pore space. A prerequisite for aquifer geological formation is that the top of the formation has a void for storing gravity water, so that gas can be concentrated at the top and sealed by the overlying strata. These strata may be dense shale, salt rock or anhydrite formation, as shown in Fig. 1(c).

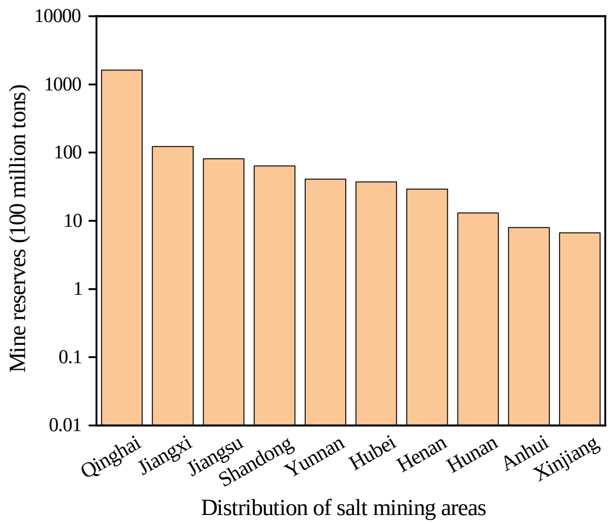



**Fig. 2**. Distribution of China's basic reserves and mining areas of salt mineral resources.

Lined rock caverns are generally constructed by conventional mining technology (shaft sinking, blasting or excavation), as shown in Fig. 1(d). The hard rock formation itself has a tight rock texture that facilitates the stability of the cavity, while its air sealing technology is the difficult point, which is usually maintained by installing a water curtain system and lining (Manca et al., 2014). The first shallowly buried lined rock cavern underground gas storage experimental reservoir in China was built using an exploration adit at Pingjiang Pumped Storage Power Station in Hunan Province by PowerChina Zhongnan Engineering Corporation Limited (Jiang et al., 2019).

From theoretical analysis, it can be established that the way of underground energy storage of gas is similar to the principle of natural gas storage. The engineering technology and operation experience of underground natural gas storage can be learned from the construction steps of underground energy storage, such as geological site selection, storage construction technology, injection and production operation, safety monitoring methods, and so on. Besides, natural gas storage can be converted into energy storage under suitable conditions. The relevant research in this area has already been established in Europe and Shengli Oilfield and Qinghai Oilfield in China (Cen et al., 2020). Therefore, it is possible to carry out tests of underground CAES including underground gas storage of depleted oil and gas reservoirs, aquifer reservoirs, lined rock caverns, and salt caverns (Donadei and Schneider, 2021). At this stage, underground salt caverns have the natural advantages of large volume, great tightness and high stability, providing excellent conditions for CAES. Therefore, these caverns are preferred for underground CAES.

## 2.2 Construction of underground salt cavern storage

China is rich in salt mine resources. According to the 2014 report of China Mineral Resource Reserves, there are nearly 200 salt mine areas in China, located in 20 provinces, cities and autonomous regions (Langer, 1993; Xuan, 1996; Leiby et al., 2000; Cao et al., 2018). The distribution of basic reserves and mining areas of salt mine resources in China is shown in Fig. 2. In general, the basic distribution law is sea salt in the east, lake salt in the west, and well salt in the middle (Cao et al., 2018; Zhu et al., 2021; Li et al., 2022). The distribution of various types of salt mines in China is shown in Fig. 3.

Cavern construction with solution mining for salt cavern gas storage is the most important technology for constructing storage space in salt rock strata, which requires complex system engineering (Wanyan et al., 2018, 2019). In Europe and America, the strata for building gas storage are generally salt mounds or thick salt strata. They are structurally intact and thick, with few interlayers and good physical properties. In Europe and America, there is more mature technology and industry standards for solution mining for salt cavern gas storage, and the storage capacity of large salt caverns in salt mounds or thick salt rock strata can reach 1,000,000 $m^3$ (see Fig. 4). In China, however, the geological conditions of salt rock strata are mainly continental layered salt rocks that are generally thin, interbed with many interlayers, low salt rock grade and with high insoluble content, resulting in slow cavern construction, difficult cavity geometry control, and small volume of completed cavity (Zhu et al., 2021). The capacity of natural gas storage in thin-bedded salt rocks in China is generally only about 200,000 $m^3$ (see Fig. 5).

## 2.3 International operation experience of CAES

At present, the only two operating CAES in the world both utilize salt caverns. Huntorf CAES power station in Germany (Jafarizadeh et al., 2020; Li et al., 2021) is the world's first commercial CAES power station, built by Nordwest Deutsche Kraftwerke in 1978, with a rated power of 290 MW. It is operated for a single cycle per day, including charging for 8 hours and generating for 2 hours. Huntorf has two salt caverns with a volume of 300,000 $m^3$. One of them is used for power generation and the other is used as a backup. This operation mode facilitates the regular inspection and maintenance of the caverns. The depth of the salt cavern is about 600 m and the operating pressure is 7.5-10 MPa. Since the construction of these two salt caverns, they have been successfully started up nearly 10,000 times and have been running properly.

McIntosh CAES station in the USA (Nakhamkin et al., 1992; Li et al., 2021): In 1991, the world's second commercial CAES power station was built by Alabama Electric Cooperative Company, Alabama, USA, with a rated power of 110 MW. It is capable of supplying power for 26 hours. The cavern at the McIntosh station is made of salt mound impregnated with freshwater and it is the largest cavern of CAES power generation system in existence. It can provide compressed gas for power generation for 26 hours. The approximately cylindrical rock and salt cavern is 300 m deep, 80 m in diameter (volume of 532,000 $km^3$), and with a gas pressure of 4.5 to 7.4 MPa. The McIntosh CAES plant was improved based on the Huntorf plant in Germany, which includes a waste heat recycling system that saves 25% of fuel. Table 2 shows all domestic and international salt cave CAES power plants.

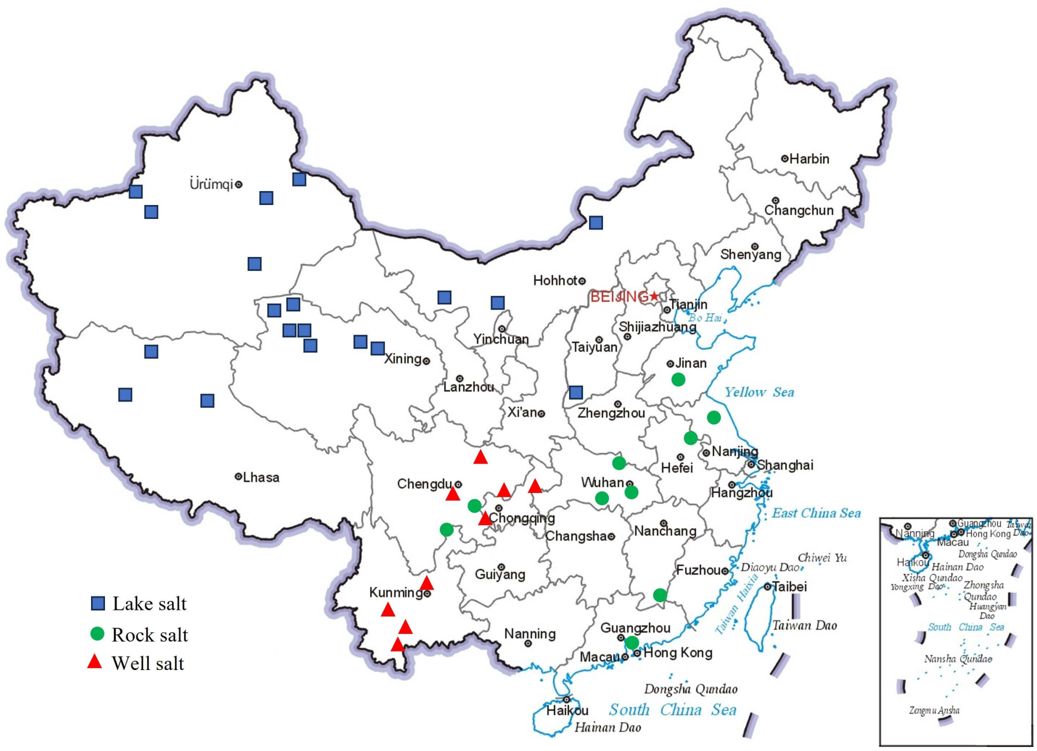



**Fig. 3**. Distribution of main salt mine in China.

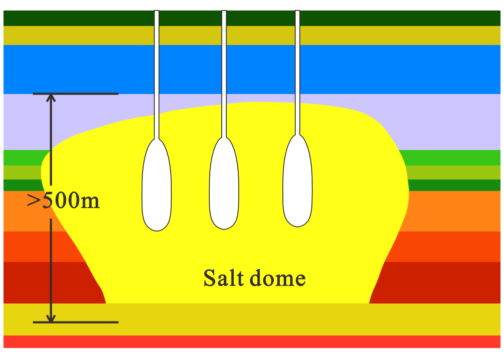



**Fig. 4**. Overview of foreign salt dome.

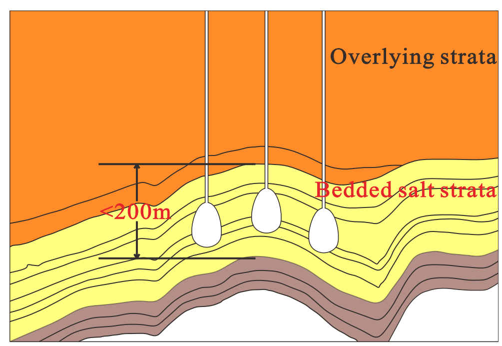



**Fig. 5**. Overview of domestic thinly-bedded salt strata.

The two CAES power plants mentioned above have adopted the supplementary fired method. In other words, they need to use NG as a supplementary fired material. Therefore, their energy conversion efficiency is low. In the future, the more efficient non-supplementary fired CAES may be used. Non-supplementary fired CAES involves both energy storage and discharge processes (Budt et al., 2016; Olabi et al., 2021; Kruk-Gotzman et al., 2023). In the energy storage process, the power system utilizes low-peak hour power to compress air and store it in underground salt caverns, while a heat exchange system is designed to capture and store the heat generated without additional gas refueling. During the discharge phase, the air compressed in the salt caverns is released and electricity is generated by a turbine generator. At the same time, the previously stored thermal energy is released and heats the expanded air, increasing the efficiency of the generator set. The application of this thermal energy management system further improves the energy conversion efficiency and gas storage efficiency of the system, making non-supplementary fired CAES a more efficient and reliable energy storage solution. The main disadvantage of the CAES power generation system is its dependence on topographic formation. The limited distribution of underground caverns will greatly restrict the availability of this kind of energy storage for power generation. However, where the terrain is suitable, the CAES power generation system is a viable method for large-scale long-term storage.

As far as the two operating CAES commercial power stations are concerned, their underground gas storage is in excellent condition. For instance, the test results of Huntorf CAES showed great tightness and stability of the salt caverns, making them a feasible alternative. With future requirements for the peak regulation of power grid, CAES needs more cavities and greater depth to obtain greater power generation

**Table 2**. Domestic and international salt cavern CAES power plants (Ren et al., 2023).

| Nations | Name | Years | Output (MW) | Operating efficiency (%) |
|---|---|---|---|---|
| Germany | Huntorf | 1978 | 321 | 29 |
| USA | McIntosh | 1991 | 110 | 54 |
| China | Feicheng | 2021 | First phase: 10; prospect: 310 | 60.70 |
| | Jintan | 2022 | First phase: 60; prospect: 1,000 | $\geq 60$ |

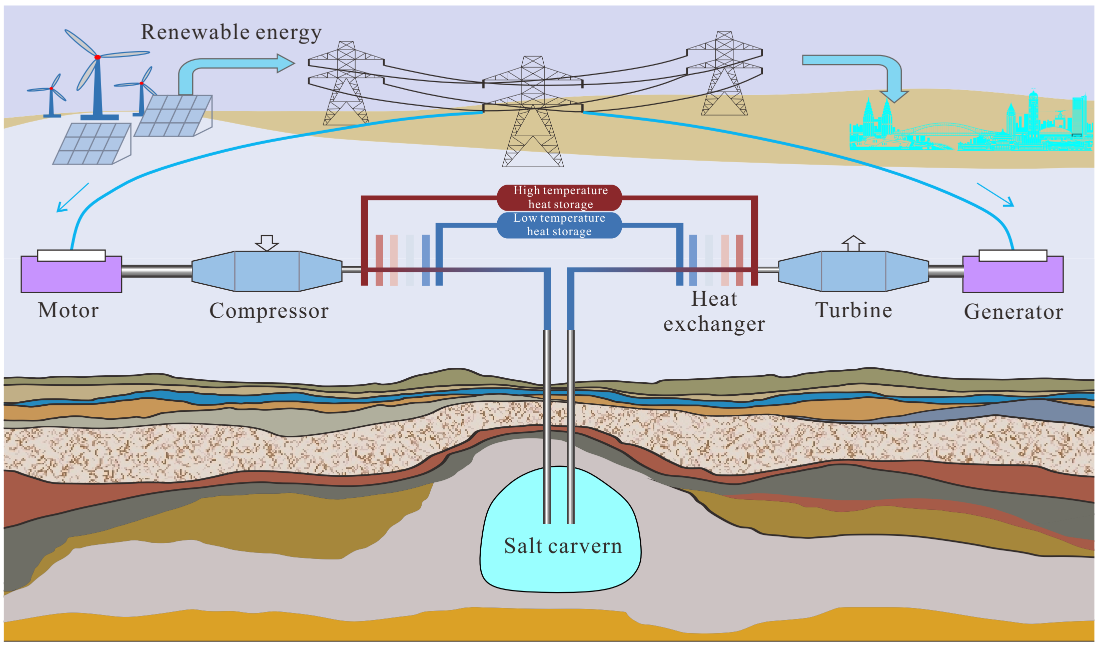



**Fig. 6**. Diagram of CAES in non-supplementary fired CAES in salt caverns.

capacity (Mirzaei et al., 2020; Piri et al., 2023). Therefore, future research should be carried out for CAES of gas with deeper formation and higher pressure.

On May 26, 2022, China's first salt cavern CAES power station, which is the National Pilot Demonstration Project of air energy storage, was successfully connected to the grid and put into operation in Jintan, Jiangsu Province. This power station achieved zero-carbon power generation with compressed air for the first time in the world. The total investment in the demonstration project was 1.5 billion yuan, of which 534 million yuan was spent in the first phase to construct a set of 60 MW salt cavern non-suppensatory CAES system. In the second phase, the 150 MW salt cavern CAES power generation system is planned to be built. Besides, a micro-grid project based on the salt cavern CAES power generation system can be constructed in combination with the load development and renewable energy development in the region where the project is located. The annual utilization time of power generation is about 1,660 hours and the efficiency of electricity conversion is 60%. There is no fuel consumption in the whole process of power generation. All technologies and equipment within the system are fully localized. A non-supplementary fired salt cavern CAES is shown in Fig. 6 (Bauer et al., 2021; Olabi et al., 2021).

## 3. Key technical issues in CAES

Salt cavern energy storage is characterized by large gas injection and production capacity, high injection and production frequency, and a storage medium that is easy to cause wellbore corrosion. These features bring more challenges for the construction and safe operation management of the storage (Samanta and Samaddar, 2019). The core technologies involved in salt cavern CAES mainly include large-diameter wellbore integrity, solution mining and morphology control, which necessitate the evaluation of factors affecting cavern tightness.

### *3.1 Large size borehole drilling and completion*

In the drilling process, borehole rock is replaced by drilling fluid to bear the stress that should be borne by the rock. The rock supported by three principal stresses of different value is replaced by drilling fluid with the same three triaxial stresses, and the pressure provided by the drilling fluid is generally lower than the lowest of the three principal stresses. Therefore, the local stress of the borehole will change, which will make the sidewall rock deform to fracture. According to the rock mechanics analysis of wellbore instability, in-situ stress exists in the formation rock before drilling any oil and gas well. Before drilling, the underground rocks are in a state of equilibrium under the action of overburden pressure, horizontal crustal stress, and formation void pressure. After drilling, the pressure of drilling fluid column replaces the support provided by the drilled rock formation, which breaks this equilibrium, causing a redistribution of the rock stress. This can lead to wellbore instability if the redistributed stress exceeds the compressive or tensile strength of the rocks (Ma et al., 2022). The injection and production well of the energy storage has dual functions of cyclic gas injection and production. Furthermore, the maximum peak gas production and injection volumes are much larger than the working gas volumes of the production wells. Therefore, the borehole size is larger in the design of well structure, which brings more difficulties in keeping the tightness of wellbore for a long time under cyclic injection, and sets higher requirements for drilling and completing the transformation process.

The top and bottom depth of underground cavity of the Huntorf CAES power station is 650 and 800 m, respectively. Diameters of $24^1/_2$ inches for production casing and 20 or 21 inches for the injection and production pipes are used (Jafarizadeh et al., 2020).

The well structure of Jintan CAES is as follows: in the primary stage, the surface casing of Φ473.1 mm is used and moved to the well depth of 530 m, and the formation that is prone to leakage is sealed. In the secondary stage, a production casing of Φ339.7 mm is used and moved to 862 m, ensuring that the lowered casing setting depth is not less than 8 m from the top boundary of the cavity. In the tertiary stage, a drill bit of 304.8 mm is used to drill into the existing salt cavern and complete the drilling.

## 3.2 Solution mining and morphology control

The construction method of salt cavern storage is mainly single-well-oil-blanket leaching, which is the most widely used approach for constructing underground salt cavern storage at home and abroad (Wan et al., 2019). In the process, the injection and production of cavern construction with solution mining can adopt positive and reverse circulation technology according to the specified capacity and shape of the salt cavern (Li et al., 2017; Wan et al., 2020). This can be combined with fine tubing/oil pad lifting operations to achieve maximum control of the salt cavern shape. Different tubing lifting methods are described for comparison in Table 3.

The positive circulation technology comprises injecting clean water from the central tubing and flow into the bottom of the well through a downhole guiding device. After dissolution in the cavern, the saturated or nearly saturated brine returns through the annulus between the inner tubing and outer tubing, forming a sealed circulation loop (Reda and Russo, 1986), as shown in Fig. 7. To protect the top salt rock layer, the outer tubing should be installed below the height of the protective fluid. The outlet of clear water is close to the bottom of the salt cavern, which can fully dissolve the bottom and surrounding part of the cavern. Due to the slow propagation of high-concentration brine to the low-concentration upper brine strata, the rate of cavern construction with solution mining in positive circulation is slow, and the concentration of brine at the outlet

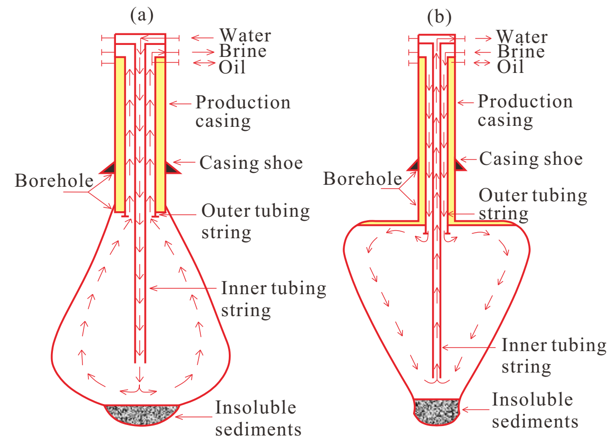


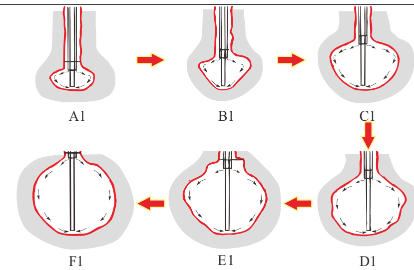
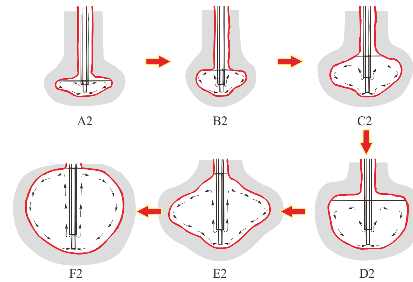
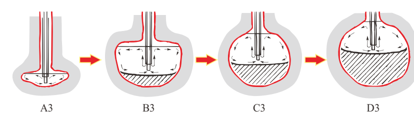
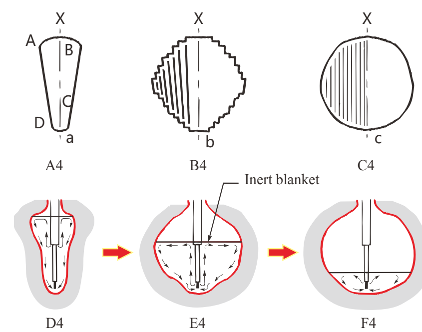

**Fig. 7**. Schematic diagram of single well circulation; (a) Direct-circulation method: forward circulation, (b) reverse circulation.

of discharge is also low, thus a teardrop or pear shape is formed with a small upper part and a large lower part. The maximum diameter of the cavern is generally located at a certain height between the middle pipe and the central pipe.

The flow direction of water (brine) in reverse circulation technology is completely opposite to that of positive circulation technology (Reda and Russo, 1986). As seen in Fig. 7, the outlet of fresh water is close to the top of the salt cavern, which can fully dissolve the surrounding rocks in the upper part of the cavern. The dissolved low-concentration brine can spread to the bottom and around cavern with the outlet as the center via the concentration difference and gravity, thus achieving the exchange between concentrations. This method causes a faster dissolution of salt rock at the top and side of the cavern and a high concentration of brine at the outlet of the brine discharge tubing. Since the top of the cavern is protected by diesel fuel to prevent excessive upward dissolution of the cavern, that is, an oil-blanket, the reverse circulation method tends to form a cone shape (or pear or mushroom shape) with a large top and small bottom, and the maximum diameter of the cavern will be usually located at a certain height near the blanket. Compared with the positive circulation technology, the reverse circulation technology yields a higher degree of brine saturation. Because of the increased volume and turbulent flow of unsaturated water in the upper part of the cavern, more attention should be paid to the control of protective fluid. The differences in the morphology of the cavern constructed by positive and reverse circulation technology are determined by the injection method of positive and reverse circulation and the distribution of concentration field inside the cavern.

In order to construct an underground salt cavern gas storage with a volume of more than hundreds of thousands of cubic meters and a stable shape in the salt strata or salt mound, its tightness and stability during the process of compulsory natural gas production and injection should be ensured to avoid the creep of the cavern over time (Das et al., 2014; Cornet et al., 2018; Namjesnik et al., 2022; Diaz-Acosta et al., 2023). Building on the experience in the construction of underground

**Table 3**. Comparison of tubing/oil-blanket lifting methods (API, 2013).

| Method | Description | Cavern expansion process |
|---|---|---|
| Moving tube column method | 1. Two concentric recirculating tubing columns.<br>2. The inner tubing is fixed and kept near the bottom of the cavern.<br>3. The outer tubing is movable and remains at the oil-water interface. |  |
| Fixed tube column method (lifting oil pad only) | 1. Two concentric recirculating tubing columns.<br>2. The inner and outer tubing are fixed and kept in a constant position near the bottom of the cavern.<br>3. The level of the oil-water interface is moved in stages for shape control. |  |
| Moving column/oil-blanket method | 1. Two concentric circulation columns.<br>2. Both circulation column and the oil pad can be moved.<br>3. The vertical boundary is controlled by the oil pad at the top and the saturated brine at the bottom.<br>4. High degree of control, but the location of the column is critical. High cost. |  |
| Laminar method | 1. The volume element formed by rotating quadrilateral ABCD about the vertical axis X is illustrated (A4).<br>2. If the width and height of the segments are controlled (B4 and C4), multiple rotations of ABCD can produce spheres from successive thin-walled segments.<br>3. Multiple concentric pipe columns can be used to eliminate the need for pipe movement.<br>4. Pipe string position is constant. The interface height between the oil pad and the water is initially set at the top of the cavern and then gradually moved downward (D4 to F4). |  |

salt caverns for gas storage in Europe and America, it is necessary to check the cavern regularly to control its shape (Zhu et al., 2021). After a long period of research and practice, the technology of ultrasonic detection as the measurement means and the method of using sonar detector to inspect the caverns have been widely accepted (Gong et al., 2019; Matos et al., 2019). The stage detection of cavern construction is predominantly used to evaluate the cavern morphology as a basis for adjusting the dissolution process parameters. Meanwhile, the stage detection of gas injection and production operation is mainly applied to evaluate the volume of cavern as a basis for calculating the gas storage volume.

### 3.3 Evaluation of factors affecting cavern tightness

The tightness of the salt cavern should be closely monitored during construction to ensure proper use and operation of storage; hence, cavern tightness detection is important and is key for the evaluation of cavern tightness (Zivar et al., 2021). The main factors affecting the tightness of gas reservoir are as follows: quality of wellbore tubing and cementing, pressure of salt cavern, tightness of overlying strata and interlayer. Studies have established three main leakage channels in the salt cavern: (1) wellbore tubing and fittings; (2) production casing shoes; (3) cavern. Several factors may cause leakage in these three parts, such as geological factors, engineering factors, process factors, management factors, etc. Table 4 entails the evaluation of factors affecting the tightness of the salt cavern.

Two main methods have been derived in foreign countries for detecting salt cavern tightness. One of them is recommended by API, which is widely used in North America (Tian et al., 2010; Schultz et al., 2023). This method has large nitrogen consumption, special interface measuring

**Table 4**. Evaluation of factors influencing the sealability of salt cavern gas reservoirs.

| Indicators | Influence degree | Adverse effect |
|---|---|---|
| Quality of casing cand cementing | High | (1) Production casing corrosion, non-gas-tight buckle. Not set into the salt layer or too small distance set into the salt layer.<br>(2) Service life or quality of accessories such as string, safety valve, etc.<br>(3) Poor quality of production casing cementing, especially near the casing shoe. |
| Storage Pressure | High | (1) Excessive operating pressure causes damage to the cavern, especially to its neck area.<br>(2) Low operating pressure causes collapse of the cavern roof, especially in the production casing shoe area where the rock salt falls off. |
| Caprock and interlayer sealing | Medium | (1) The lithology of the caprock is not good, and the microporosity, microvoid or microfracture are connected with each other under high pressure.<br>(2) Small breakthrough differential pressure of caprock (should be more than 9 MPa in the 1,000 m deep area)<br>(3) Cracks or large cavities exist in the interlayer.<br>(4) The starting pressure of the rock salt is too small (less than 0.05 MPa/m).<br>(5) The gas leakage exceeds 2.8 scalar in 24 hours. |
| Rock salt creep | Low | Wellhead is sealed for a long time, failing to release pressure in time. |
| Thermal expansion of brine | Low | Wellhead is sealed for a long time, failing to release pressure in time. |
| Rock salt dissolution | Low | The production casing shoe part is dissolved during the cavern construction process. |
| Rock salt permeability | Low | The creep can be reduced and pressure can rise in the cavern caused by the thermal expansion of brine, which is beneficial to the sealing performance. |

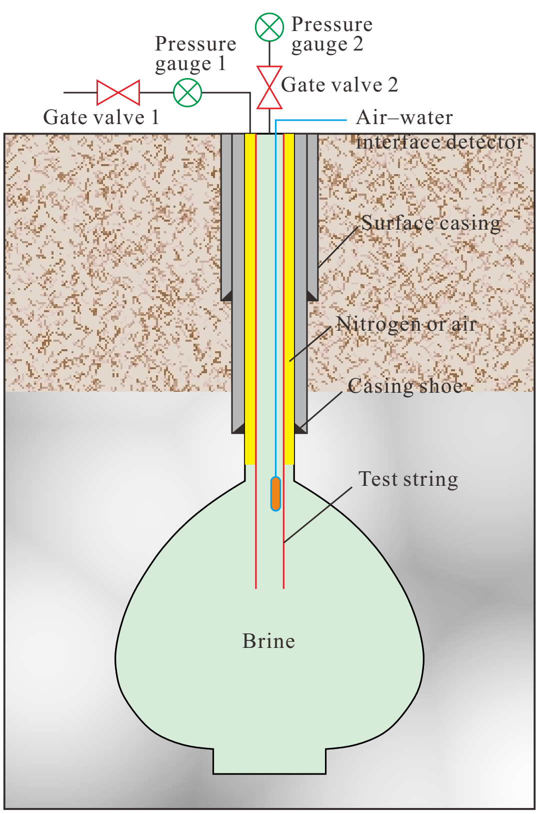



**Fig. 8**. Principle of the salt cavity gas sealing detection method.

instruments, single detection results, and inaccurate evaluation results. Another is recommended by Geostock, which is widely used in Europe (Chen et al., 2019; Liu et al., 2022). This method features long detection time, high cost, poor operability in the field, and the difficulty to determine the specific leakage location. With reference to the above two methods and the full consideration of the actual situation and characteristics of domestic salt strata and caverns, China has adopted the CSCT (Ma, 2022) cavern tightness detection method, as shown in Fig. 8.

The CSCT detection process contains the following steps: (1) put a set of pressure test tubing into the well cavern; (2) install a pressure test wellhead that can be mounted on a pressure test tubing; (3) lower the gas-water interface logging instrument to the neck of cavern below the production casing shoe; (4) inject an appropriate amount of saturated brine into the well cavern to make the brine pressure in the cavern reach the design pressure; (5) stop injecting nitrogen (or air) when the depth of gas-water interface reaches 5-10 m below the production casing shoe and when the gas pressure at the production casing shoe reaches 1.1 times of the maximum operating pressure of the reservoir; (6) make the gas-water interface depth return to 10 m below the production casing shoe by re-injecting gas after maintaining the temperature equilibrium of the whole system for 8-10 hours; (7) record the readings of each test instrument at the wellhead, the oil-water interface depth values, and the test time every 1 hour

**Table 5**. Classification of detection methods.

| Operation method | Detection method | Principle of action | Form of action | Detection capability |
|---|---|---|---|---|
| Downhole detection | Downhole acoustic noise logging | Acoustic | Passive | Multi-point |
| | Distributed fiber optic monitoring of downhole acoustic waves | Acoustic | Passive | Multi-point |
| | Mechanical seating and pressure testing | Pressure | Active | Multi-point |
| | Downhole micro-temperature differential logging | Temperature | Passive | Multi-point |
| | Distributed fiber optic monitoring of downhole temperatures | Temperature | Passive | Multi-point |
| | Spiral logging / dragging method | Flow Field | Passive | Multi-point |
| | Cross-sectional flow detection | Flow field | Passive | Multi-point |
| | Electromagnetic corrosion detection | Magnetic field | Active | Multi-point |
| Ground inspection | Wellhead receiving leak point acoustic wave | Acoustic wave | Passive | Multi-point |
| | Pressure balance inverse algorithm | Pressure | Passive | Single point |
| Combined downhole -surface testing | Isotope tracer localization | Flow field | Active | Single point |

for 24 hours of continuous logging. The gas-water interface depth can be controlled by interface logging, and the well cavern temperature can be obtained by data logging (Yuan et al., 2021). The parameters to detect (such as the volume of saturated brine injected, the amount of gas leakage, and so on) can be calculated according to the pressure calculation theory of bottom gas well and the equation of gas state. This method overcomes the shortcomings of the two foreign methods, and exhibits the advantages of strong field operability, low cost of pressure test, and accurate evaluation results.

### 3.4 Wellbore integrity detection and evaluation

Wellbore integrity detection is performed to identify the location and type of failure of tools such as casing, injection-production tubing and packers, thereby providing a clear understanding of wellbore integrity (Ebigbo et al., 2013). The forms of integrity failure mainly include tubing corrosion, perforation, cracking, debonding, tightness failure, and packer seating failure. Therefore, wellbore integrity detection is required to have the ability to locate and identify leakage points, independent of gas and corrosive fluids (Zhang et al., 2021; Ma, 2022).

The commonly used wellbore integrity detection methods include the pressure balance method, electromagnetic flaw detection, downhole acoustic and temperature, distributed optical fiber, mechanical setting pressure test, micro temperature difference, and so on. The classification of detection technology is detailed in Table 5, along with the advantages of each method. In terms of detection capability, electromagnetic corrosion detection is only suitable for leakage points with large pore diameters. The mechanical setting pressure test requires section-by-section isolation testing, which is not applicable to a deep well environment, and the pre-set distributed optical fiber allows the real-time monitoring of gas well dynamics. The acoustic detection method is highly susceptible to interference by near-ground and underground noise, and its detection capability is determined by the sensor sensitivity and leakage degree of micro-temperature differential logging. The pressure balance inverse algorithm and isotopic tracer mainly depend on adopted mathematical methods. Approaches such as isotopic tracer, cross-section flow detection, and spiral logging/dragging method have not yet been fully evaluated (Zhang et al., 2020). It is difficult to accurately determine the failure form and cause of wellbore tubing by a single method, so the combined downhole acoustic + temperature logging technology and distributed optical fiber detection technology can be used for integrity detection (Li et al., 2022).

## 4. Prospects of underground CAES in China

### 4.1 Opportunities

Renewable energy, represented by wind and solar energy, is an important direction for low-carbon energy transformation. According to the International Energy Agency (IEA), the proportion of global power generation with renewable energy to total global power generation will reach 33% by 2030. In 2020, China abandoned about $1.66\times10^{10}$ kW·h of wind power and $52.6\times10^{8}$ kW·h of light power due to various reasons (Li et al., 2021). Building a new power system based on new energy is the key to ensure China's power and energy security and also to achieve the goals of carbon peak and carbon neutrality. In the context of severe inverse distribution of renewable energy, such as wind and solar energy and its consumption centers in China, CAES is a key technology to improve the controllability and flexibility of future energy systems. China has included CAES into the national "$14^{th}$ Five-Year Plan", which provides strong support for the research of CAES in salt caverns.

Underground salt cavern CAES technology can be regarded as a crucial part of the energy system. Firstly, it can diversify and improve the energy system. Secondly, part of the salt caverns represented by the old salt cavern are valuable underground resources, whereas they have certain shortcomings in storing natural gas. The injection, production and peaking, which are performed only 2-3 times a year, greatly increase the operating costs. By using salt caverns to compress and store air, injection and production can be achieved at any time. Moreover, they can not only make up for the shortcomings of salt caverns with poor stability but also improve the utilization efficiency of underground salt caverns, reducing investment and bringing good economic benefits (Zhou et al., 2019). CAES technology has been verified to realize large-scale energy storage (Cai et al., 2019; Mousavi et al., 2021). For the CAES system, it uses an air compressor to store the excess electric energy in the form of compressed air pressure potential energy in the underground salt caverns. When the demand for electricity increases in the peak period, the compressed air stored in the salt caverns is released and the energy stored is converted into electric energy through the turbine after heating to meet this demand (Alirahmi et al., 2021a; King et al., 2021). According to research, the actual conversion efficiency of CAES in salt caverns can reach 40% to 50%. The CAES system can realize the "peak cutting and valley filling" of the power grid to balance the power load, thus improving the stability and reliability of the power grid.

An old salt cavern is the most direct and effective way to accelerate the construction of salt cavern storage, reduce the investment and improve the economic benefits. Old caverns formed by domestic salt mining are expected to be fully utilized in this regard. For example, if only 10% of the total space of 300 million $m^3$ is utilized, a cavern volume of 30 million $m^3$ can be formed in a very short time, saving 12 billion yuan of direct cavern construction (estimated according to the cavern constriction cost of 400 yuan/$m^3$). If the CAES system injects gas for 8 h and produces gas for 4 h per day at a working pressure range of 10-14 MPa, a single injection and production cycle can generate $936.96 \times 10^4$ kW·h of electricity.

### 4.2 Challenges

The development of the latest large-scale underground energy storage technology has important strategic significance for China's future energy structure transformation and economic growth. The research on salt cavern energy storage started relatively late in China, and with a small number of salt caverns that have been utilized at this stage, which are mainly in the sedimentary salt layer of terrestrial salt lakes. Compared with Europe and America, there is still a gap in the quantity and technical level of salt cavern underground storage. The major difficulties of salt cavern CAES are risks associated with small molecule gas leakage, the insufficiency of micro-leakage detection and location technology, the selection of downhole tubing/tool material, and the lack of anti-corrosion treatment technology. Therefore, it poses a great challenge to carry out research on large-diameter drilling, completion and wellbore integrity, cavern construction, morphology control and cavern tightness detection, and tubing corrosion and control (Tong et al., 2021; Bazdar et al., 2022).

## 5. Conclusion and suggestions

Salt cavern CAES, as a new type of large-scale energy storage technology with great potential, plays a crucial role in large-scale energy storage. China is still at the initial stage of salt cavern underground CAES, facing numerous complex problems and lacking mature practical experience; therefore, it requires the concerted efforts of government, enterprises, universities, and industrial organizations. To improve the comprehensive utilization of salt cavern CAES and form a development path of salt cavern CAES in line with China's national conditions, the characteristics of rock salt deposits in China should be considered and foreign cases and experiences should be reasonably studied. Four suggestions are proposed in terms of large-diameter drilling and completion, as elaborated below: wellbore integrity, cavern construction morphology control, cavern sealing detection, tubing corrosion and control, and industrial planning. These can provide a reference for the development of underground salt cavern CAES technology in China, to promote the green transformation of energy sources and to realize the goals of carbon neutrality.

1) Large-diameter wellbore integrity: focus on the research and development of underground micro-leakage risk monitoring technology and the localization of supporting equipment for large-diameter wellbore in the process of high-speed injection and production of CAES, and the geological integrity protection of reservoirs and overlying strata; optimize the well structure of injection and production tubing, and form a method for the stability prediction of large-diameter well wall and destabilization control; improve the monitoring technology for the integrity status of injection and production facilities at the ground wellhead, and establish intelligent risk assessment and integrity management standards for a ground-wellbore-salt cavern, so as to provide guarantee for the safe operation of large-volume injection and production of CAES in salt caverns.
2) Cavern construction morphology control and cavern tightness detection: establish simulation prediction means of cavern formation morphology, design methods, control technology and evaluation guidelines of long-term injection and production stability; form air injection and brine discharge processes suitable for caverns in different states, and provide technical support for fast cavern construction and morphology control; improve the detection standards for salt cavern sealing of CAES and establish a salt cavern evaluation system with complete independent intellectual property rights.
3) Tubing corrosion and control: focus on the research and development of high-strength anti-corrosion well tubing and the prevention and control of underground microbial corrosion, and propose multi-dimensional control technology for tubing corrosion throughout the life cycle to further improve the durability of tubing materials and provide support for the safe service of CAES.
4) Accelerate and deepen the planning, policy and financial

support for the salt cavern CAES industry cluster, and promote the organic synergistic development of the salt industry and salt cavern energy storage industry. Set up special funds for salt cavern energy storage and increase financial support for enterprises and research institutes. Perform reasonable planning and design in salt cavern construction for the purpose of brine mining. Promote the transformation and development of the salt industry and pave the way for the development of salt cavern energy storage in line with China's national characteristics. Actively explore the existing salt cavern resources and the use of salt caverns. Study the operational and management issues about salt cavern energy storage to explore and improve the operation of the business model of storage. Optimize the path of industrial development to enhance the comprehensive utilization of salt cavern energy storage and to achieve the optimization of operating costs, carbon reduction and environmental protection.

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## Conflict of interest

The authors declare no competing interest.



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