International Journal of Coal Science & Technology (2024) 11:29
https://doi.org/10.1007/s40789-024-00676-y

RESEARCH

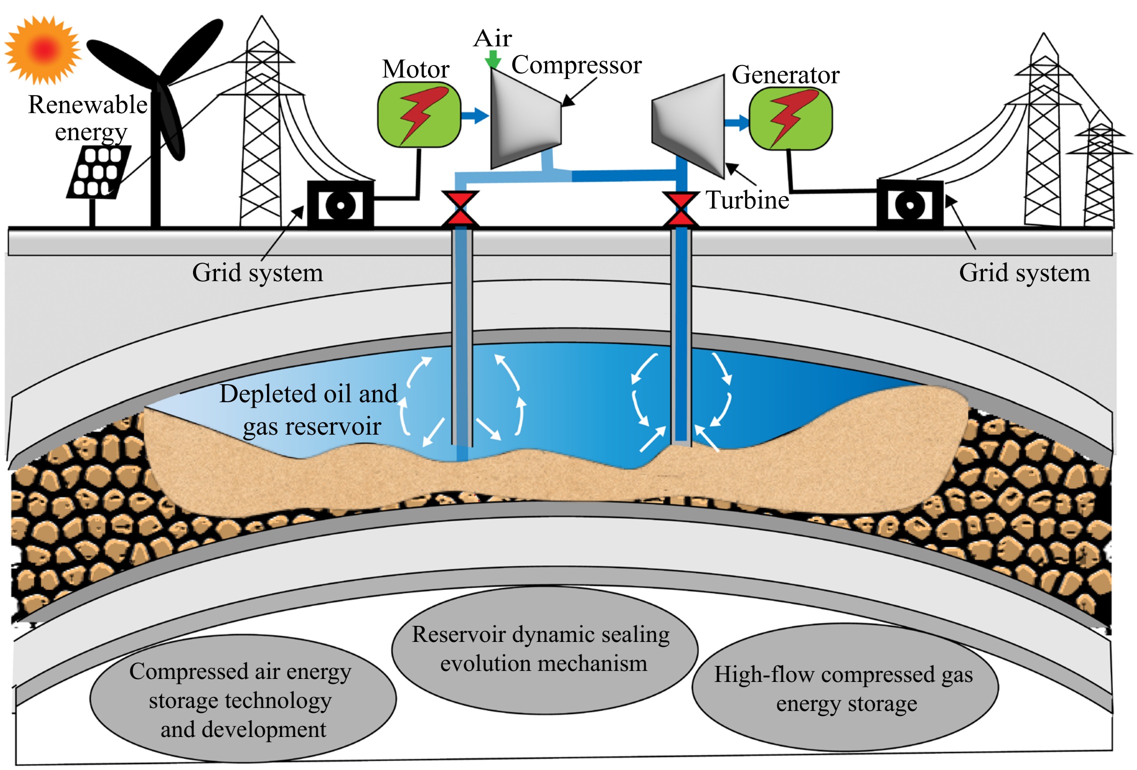
Development and technology status of energy storage in depleted gas reservoirs

Jifang Wan[1] · Yangqing Sun[2] · Yuxian He[2] · Wendong Ji[1] · Jingcui Li[1] · Liangliang Jiang[3] · Maria Jose Jurado[4]

Received: 29 October 2023 / Revised: 24 November 2023 / Accepted: 4 March 2024

Abstract
Utilizing energy storage in depleted oil and gas reservoirs can improve productivity while reducing power costs and is one of the best ways to achieve synergistic development of "Carbon Peak–Carbon Neutral" and "Underground Resource Utilization". Starting from the development of Compressed Air Energy Storage (CAES) technology, the site selection of CAES in depleted gas and oil reservoirs, the evolution mechanism of reservoir dynamic sealing, and the high-flow CAES and injection technology are summarized. It focuses on analyzing the characteristics, key equipment, reservoir construction, application scenarios and cost analysis of CAES projects, and sorting out the technical key points and existing difficulties. The development trend of CAES technology is proposed, and the future development path is scrutinized to provide reference for the research of CAES projects in depleted oil and gas reservoirs.

Graphical abstract



Keywords Depleted gas reservoirs · Technology and development · Siting analysis · Safety evaluation · Compressed air energy storage

Extended author information available on the last page of the article

Published online: 12 April 2024

1 Introduction

Due to accelerated industrialization and increased energy consumption, substantial amounts of carbon dioxide have been released into the atmosphere, resulting in a series of changes in the Earth's climate and weather systems. While countries around the world are actively engaged in carbon dioxide storage projects, these efforts are still insufficient to mitigate global temperature changes (Su et al. 2022; Li et al. 2023; Kumar and Eswari 2023). Since the late 1990s, humanity has started to acknowledge the environmental risks associated with fossil fuels and has shown a growing interest in green energy sources such as solar and wind power. However, renewable energy sources including wind and solar cannot reliably serve as grid-scale power sources due to their intermittent nature unless excess energy can be stored and supplied later during periods of shortage (Jarvis 2015; Sun et al. 2023a). Compressed Air Energy Storage (CAES) is considered a promising solution for mitigating short-term fluctuations in renewable energy production. It achieves this by rapidly increasing energy output and enabling efficient part-load operation (Succar and Williams 2008; Fushimi 2021). CAES system generally includes six main components: (1) compressor, generally multi-stage compressor with intermediate cooling device; (2) expander, generally multi-stage turbine expander with interstage reheat equipment; (3) combustion chamber and heat exchanger for fuel combustion and recovery of waste heat.; (4) storage device, underground or above ground cavern or pressure vessel; (5) motor/generator, connected to the compressor and the expander through the clutch; (6) control system and auxiliary equipment, including control system, fuel tank, mechanical drive system, piping and accessories. As shown in Fig. 1. With advantages such as substantial storage capacity, extended storage duration, high system efficiency, long operational lifespan, flexibility, intermittency management, low cost, and scalability, CAES is regarded as one of the most promising large-scale energy storage technologies (Ozarslan 2012; Wan et al. 2023a; Wang et al. 2018).

These facilities typically take two primary forms:

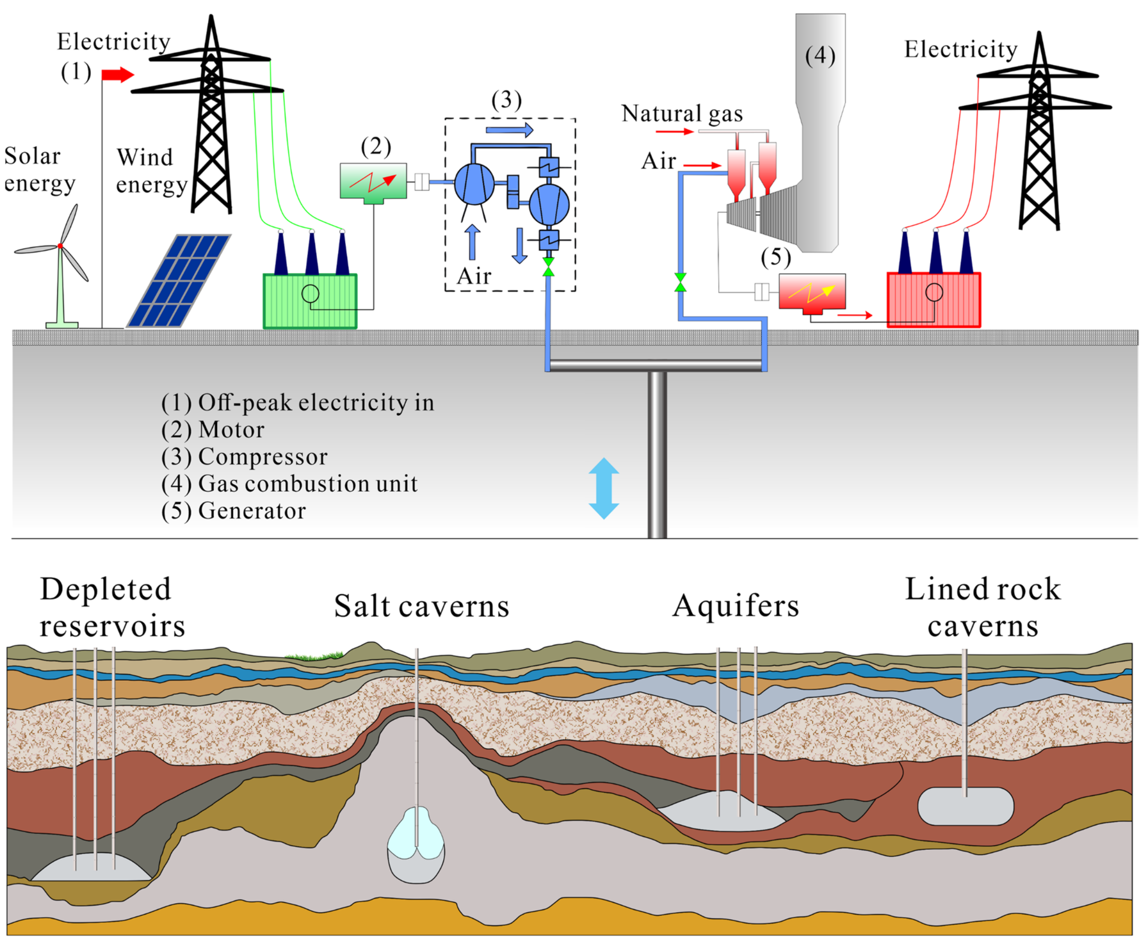


Fig. 1 Working principle and main components of a CAES station

aboveground liquefied natural gas (LNG) ball tanks and underground gas storage (UGS) (Liu et al. 2014). UGS encompasses various types, including gas reservoirs, oil reservoirs, salt caverns, and abandoned pits (Cooper et al. 2011). Notably, more than 75% of the world's gas reservoirs are currently of the depleted reservoir type, and 81% of globally stored underground natural gas is found in depleted oil and gas fields (Xie et al. 2009). CAES brings economic benefits by using depleted, hydraulically fractured oil and gas wells to store electrical energy in the form of compressed natural gas. The porous geologic environment of fracked wells, which is used to release hydrocarbons, is also conducive to storing and releasing gas on a daily or seasonal basis. Round-trip storage efficiencies are estimated to range from 40 to 70%, based on natural reservoir temperature, with storage costs estimated at \$70–270/MWh, making it comparable to pumped storage (Young et al. 2021).

The United States was the first country to show interest in CAES technology, with the publication of the first literature paper in 1976. However, Europe (EU-27) and China lead the way in research on CAES today, whose publication accounts for nearly half of the published literature on the subject. Notably, China has become the leading investor in CAES development, with several demonstration and commercial CAES plants currently under development and commissioning (Borri et al. 2022).

The types of gas storage include salt cavern, depleted oil and gas reservoir and aquifer. The surrounding rock of salt cavern has good creep property and the high salt content can inhibit some microorganisms, but the suitable sites are few and the gas storage is limited. Aquifers have large gas storage capacity. However, they have long construction period and high cost. The produced gas also needs to be dehydrated.

On August 17, 2023, the international first 300 MW-class advanced CAES system expander jointly developed by the Institute of Engineering Thermal Physics (IETP) of the Chinese Academy of Sciences and China National Energy Technology Co., Ltd. completed the integration test and successfully rolled off the production line. Its successful development will promote China's advanced CAES technology to a new level (Hou 2024; Agrawal et al. 2023; Yang et al. 2023a, b).

In recent years, more research has been conducted on the application of gas storage, including ground hydrogen storage for zero emissions (Al-Yaseri et al. 2023; Peng 2023; Nguyen 2023; Kalam et al. 2023) and carbon capture utilization and storage strategies for carbon dioxide injection (Gao et al. 2023a, b). The development of depleted oil and gas type reservoirs is of great significance to the change of energy structure and the promotion of the development of energy technology, and also lays a solid foundation for the construction and development of smart grids, energy internet and smart cities (Feng 2023). Urgent verification is needed for energy storage feasibility, for this reason, this paper combines the development history of CAES technology to research on the site selection of depleted gas reservoirs (DGR), reservoir dynamic sealing evolution mechanism, and high flow rate CAES injection and extraction technology, to support the development of the depleted gas storage type reservoirs.

2 Advancements in CAES technology

The overall goal of CAES is to store energy during periods of low power demand and then use it during periods of high demand. Conventional CAES satisfy the following concepts, excess electricity is utilized to compress the surrounding air, capturing and storing heat in a thermal energy storage system, which is applicable for adiabatic CAES. The compressed air is stored in a vessel, later released and preheated in a heat exchanger, and directed to a turbine generator to produce expensive electricity. Finally, the electricity is fed back into the electricity grid (Duhan 2018; Sun et al. 2023b; Zong et al. 2023).

2.1 Current status of CAES technology

2.1.1 Principles of operation

There are many types of CAES technologies, which can be classified into three categories according to whether they require preheated air in the combustion chamber, the size of the storage, and whether they utilize heat of compression as shown in Table 1 (Xu and Song 2021).

Figures 2a, b show the schematic diagrams of the supplementary fired CAES and non-supplementary fired CAES. The supplementary fired CAES system is based on the working principle of gas turbine, the supplementary fired chamber is set up at the entrance of the turbine, and the fuel is utilized to heat the air to increase the amount of work done by the turbine, which is a reliable and stable system. However, the fuel combustion will emit pollutants and cause environmental pollution, which does not conform to the requirements of the development of green environmental protection. The non-supplementary fired CAES system abandons the traditional compensatory fired chamber and utilizes a heat storage device to collect the compression heat generated during the air compression process, which is used to heat the inlet air of the first-stage turbine expander when releasing energy, thus realizing a zero-pollution working process (Xu and Song 2021; Li et al. 2022).

Isothermal CAES systems use certain measures (such as pistons, showers, bottom injection, etc.), through the specific heat capacity of the liquid (water or oil) to provide an approximate constant temperature environment, increase the

Table 1 Types of CAES technologies

Main type	Subcategory
Combustion chamber preheating air	Supplementary combustion system
	Non-supplementary combustion systems
Energy storage scale	Large-scale systems
	Small system
	Micro-system
Utilization of compression heat	Non-insulated
	Adiabatic
	Thermostatic

air–liquid contact area and contact time, In this way, the air in the process of compression and expansion is infinitely close to the isothermal process and the heat loss will be reduced to a minimum, improving the efficiency of the system (Dolatabadi et al. 2013; Hu et al. 2023).

Due to the high technical requirements and costs associated with the realization of single-stage adiabatic CAES concepts, great interest has been shown in Isothermal or Quasi-Isothermal CAES concepts in recent years. As shown in Fig. 3, the focus here is on dividing compression and decompression into several stages so that each stage is associated with only a slight temperature increase (Donadei and Schneider 2016).

Statistics on some isothermal CAES systems at home and abroad, as shown in Table 2. The isothermal CAES systems mainly use liquid piston technology, and the average circulation efficiency is about 70%.

In addition to the basic types mentioned above, researchers have proposed many CAES derivatives based on the fundamentals of CAES in the innovation stages. Among them, the more representative derivative schemes are:

(1) Liquid air energy storage (LAES)

As shown in Fig. 4, according to the liquefaction phase change properties of air, compressed air is liquefied and stored in low-temperature storage tanks. As the density of liquid air is more than 10 times that of CAES, the container volume required for air liquefaction storage will be greatly reduced, reducing the impact of geographical conditions, but its conversion efficiency needs to be improved (Morgan et al. 2015).

(2) Super critical compressed air energy storage (SC-CAES)

As shown in Fig. 5, its components and the existing CAES system and liquefied air energy storage system is more similar. It can be used as a heat and cold storage device for air compression. At the same time, which not only has much higher energy density than that of CAES, but also greatly improves the efficiency of LAES (Liu 2012; He et al. 2018).

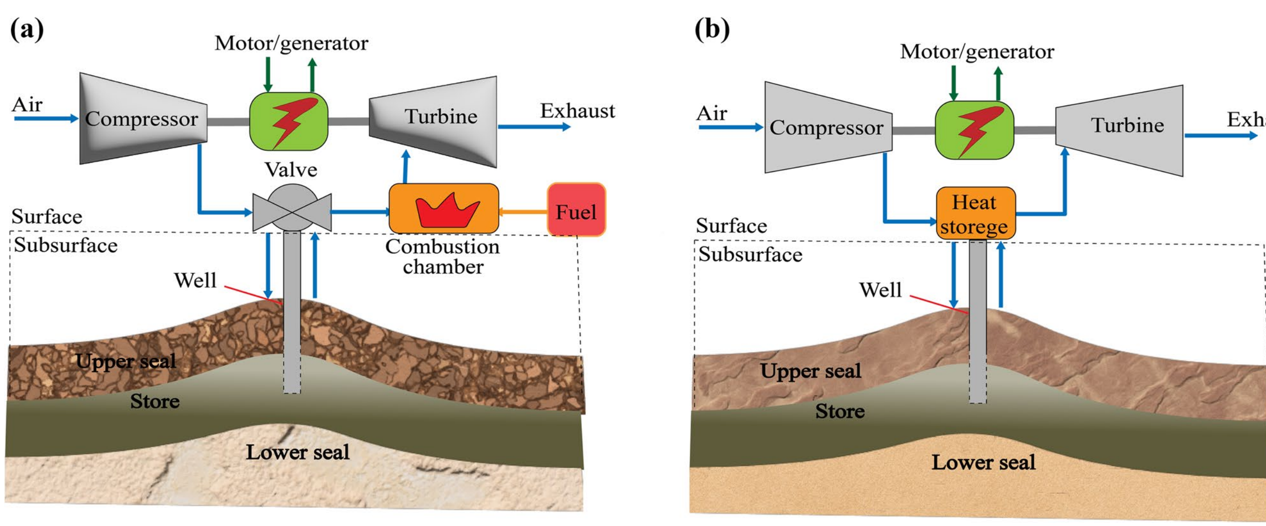


Fig. 2 The difference between supplementary fire and non-supplementary fired systems. **a** Supplementary fired system **b** Non-supplementary fired system

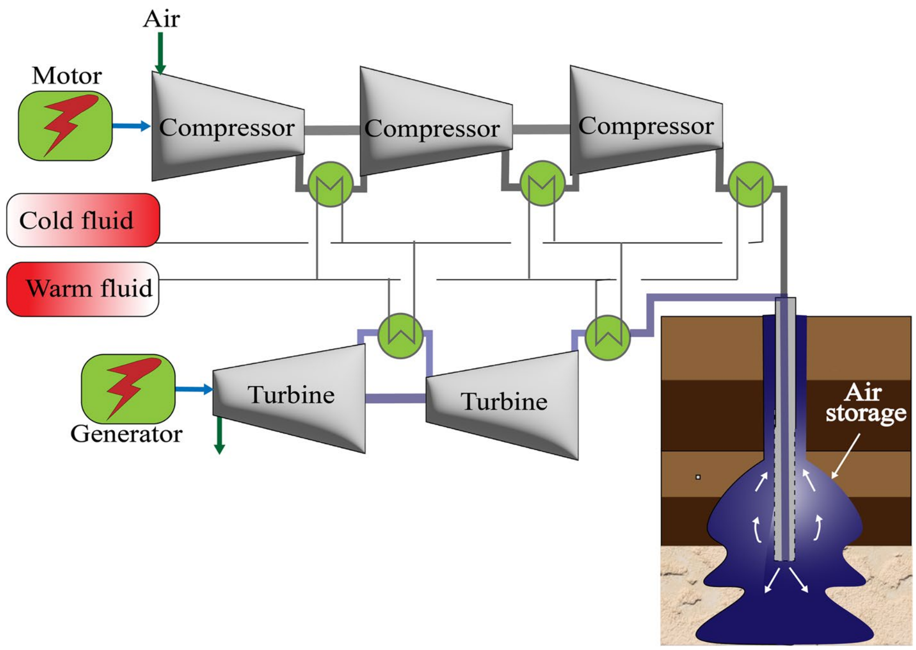


Fig. 3 Sketch of the principle behind the isothermal concept

Table 2 Current researches and technical characteristics of isothermal CAES

Project or company	Area	Cycle efficiency (%)	Technical characteristics	Literature
Enairys Powertech (2011)	Switzerland		Using liquid piston technology	Dib et al. (2021)
LightSail Energy (2012)	United States	70–90	Using liquid spray, liquid piston and waste heat recovery technologies	He et al. (2022), Luo et al. (2016)
Sustain X (2013)	United States	70–90	Using premixed aqueous foam to achieve isothermal technology	Fu et al. (2019)
FLASC (2015)	Malta, Netherlands	75	Using liquid piston technology, which can be integrated with offshore wind projects	Buhagiar and Sant (2017)
GLIDES (2015)	United States	66–82	Using liquid piston, liquid spray and heat exchange technology	Odukomaiya et al. (2016)
Gravity Energy Storage (2017)	Morocco		Using liquid piston technology to combine CAES with gravity energy storage	Berrada et al. (2017)
SEGULA Technologies (2018)	France	70	Using liquid piston technology, which can be used in the marine environment	Maisonnave et al. (2018)
Liquid Control CAES (2019)	China	70–85	Using liquid piston technology and porous media technology	Fu (2019)
Air-Battary (2020)	Israel	81	Using liquid piston, heat exchange and other technologies	Ackerman and Pacheco (2020)

(3) Small scale CAES (SS-CAES)

Small scale CAES system has less requirements for the geographic location, and it can be used in the form of tank storage of compressed air storage. In order to maintain a constant temperature and high-pressure safety of tank, it can be buried in the ground, and the efficiency of this system can be up to about 50% (Xu et al. 2021) (Table 3).

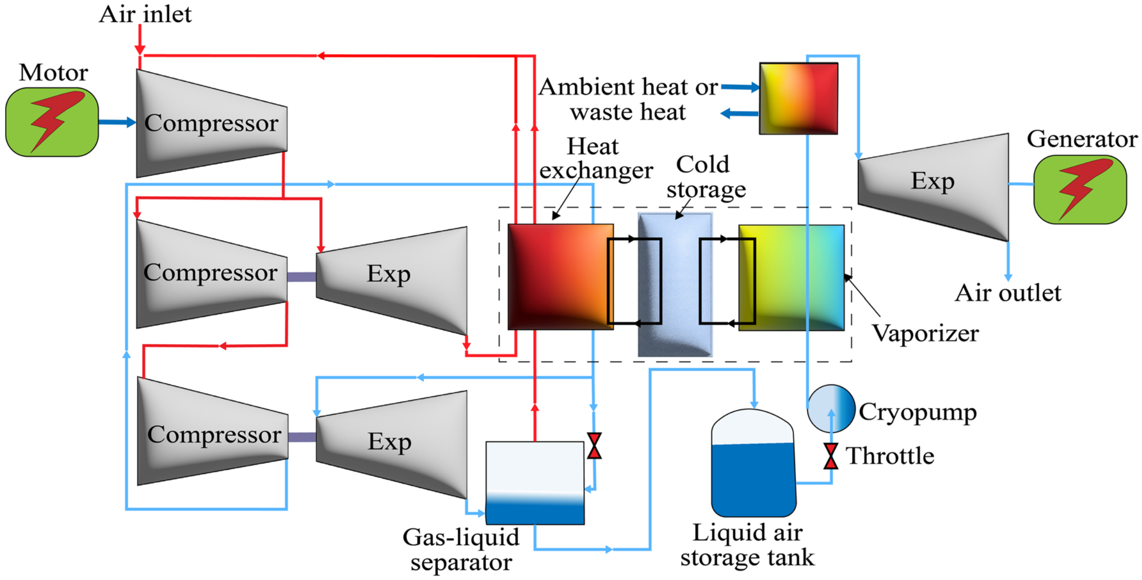


Fig. 4 Liquid CAES system schematic

Fig. 5 SC-CAES system schematic

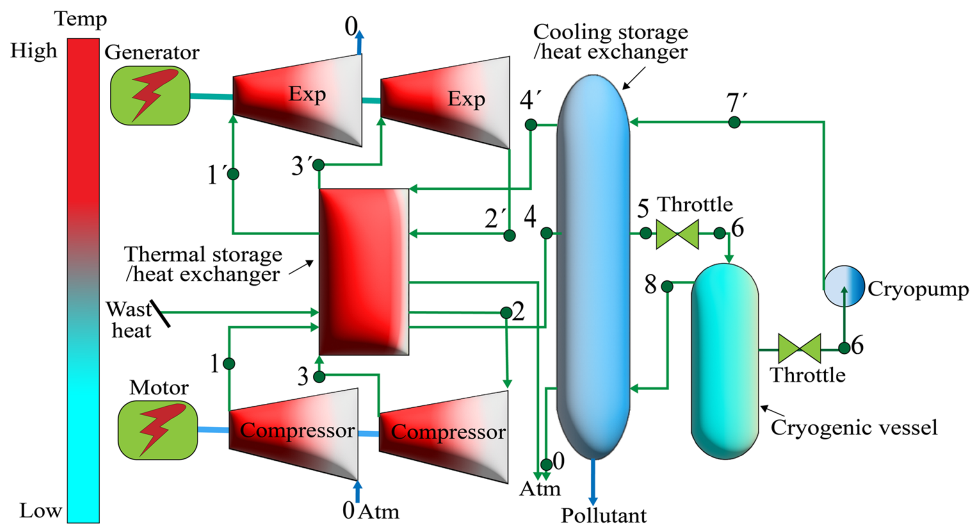


Table 3 Comparison of the characteristics of several major energy storage technologies

Type	Peculiarity	Main equipment	Shortcoming	Literature
LAES	High-pressure air is liquefied and stored to increase energy density	Liquefaction unit and cryogenic storage tank	Poor liquefaction performance、low efficiency and complex system	Chino and Araki (2000), Rabi et al. (2023)
SC-CAES	Combine the characteristics of adiabatic CAES system and liquid air energy storage system	Heat storage device, liquefaction unit and cryogenic storage tank	Complex systems and low overall efficiency when heat storage and liquefaction units are inefficient	Guo (2013)
SS-CAES	Store higher pressure compressed air in air receivers or gas pipelines, free from geographical restrictions	High-pressure storage tanks and gas storage pipelines	Underground pipelines are more expensive	Yang et al. (2020), Brahim et al. (2008)

Table 4 Technical parameters of Huntorf project in German (Guo 2013)

Parameter	Value
Turbine power (MW)	290
Compressor power (MW)	60
Turbine air flow rate (kg/s)	417
Compressor air flow rate (kg/s)	108
Flow rate ratio	0.25
Number of salt caverns	2
Salt cavern volume ($m^{3)}$	3.1×10^5
Top of the salt cavern is buried deep (m)	650
Salt cavern bottom buried deep (m)	800
Minimum operating pressure of air in the salt cavern (MPa)	4.3
Maximum operating pressure of air in the salt cavern (MPa)	7.0
Maximum pressure reduction of air in the salt cavern (MPa/h)	1.5

Table 5 Technical parameters of McIntosh project in USA (Succar and Williams 2008)

Parameter	Value
Turbine power (MW)	110
Turbulent air flow rate (kg/s)	154
Compressor air flow rate (kg/s)	96
Number of salt caverns	1
Salt cavern volume (m^3)	5.6×10^5
Top of the salt cavern is buried deep (m)	459
Bottom of the salt cavern is buried deep (m)	807
Minimum operating pressure of air in the salt cavern (MPa)	4.5
Maximum operating pressure of air in the salt cavern (MPa)	7.04

2.1.2 Development status

The development of CAES technology is inseparable from the change of energy structure, which can be roughly divided into three stages: rapid development, slow development, and then rapid development. Since 1949, the German engineer Stal Laval put forward the concept of energy storage using compressed air in underground caverns. Each country has carried out a lot of research and practice. The world's two earliest CAES systems, were established in Germany in 1978 with a power of 290 MW Huntorf CAES system, as well as the United States in 1991, the power of 110 MW McIntosh CAES system (Guo 2013; Budt et al. 2016). The parameters of these two systems are shown in Tables 4 and 5.

Combining the actual circumstances of oilfield enterprises, utilizing underground porous media space to rebuild energy storage can reduce the cost of electric power consumption in oil and gas fields and improve production efficiency. This is one of the best paths to realize the synergistic development of "energy storage" and "underground resource utilization". Domestic oilfield enterprises such as Shengli Oilfield, Daqing Oilfield, Qinghai Oilfield, and Jilin Oilfield have already deployed plans to convert depleted gas reservoirs into energy storage and have conducted preliminary exploration. In June 2022, Shengli Oilfield completed the project in collaboration with Tsinghua University and other units. In April 2023, Qinghai Oilfield conducted bidding for the horizontal well fracturing and construction of CAES project. The other projects are shown in Table 6.

After China completed the 0.5 MW Wuhu non-supplementary fired demonstration project in 2014, the 10 MW CAES validation platform in Bijie, Guizhou and the 10 MW CAES peaking power plant in Feicheng (Phase I) went into operation in 2021, and the 100 MW CAES project in Zhangbei entered the power-carrying commissioning stage in 2022 with the technical support of the IETP (Zhao et al. 2023).

The development history of CAES projects is shown in Fig. 6 The earliest program was Stal Laval in Germany in 1949, followed by the rapid growth of the CAES program in China in recent years. With the support of Tsinghua University, the 100kW composite CAES industrial demonstration project in Xining, Qinghai was put into operation in 2016, the 60 MW salt cavern CAES in Jintan, Jiangsu Province has been connected to the grid for power generation in May 2022 (Guo et al. 2019). In addition, the projects of Hubei Yingcheng 300 MW, Gansu Jiuquan 300 MW, and Shandong Tai'an 350 MW, under China Energy Digital Technology Group Co.,Led., have already started construction.

2.2 Key equipment for CAES

As shown in Fig. 7, CAES system contains compression, gas storage, heat/cold storage, heat/cold return, expansion power generation and other sub-systems. The key equipment mainly includes compressors, heat exchangers and expanders and the technology of the relevant equipment is relatively mature. Through the project demonstration and construction, it has a certain industrial chain basis.

2.2.1 Compressor

Compressor, mainly divided into turbine, piston and screw type, is a kind of compressed gas to increase gas pressure or transport gas machine. It can be used for CAES system compressor and has the characteristics of large flow rate

Table 6 Domestic CAES Projects (Wan et al. 2023b)

Time	Project name	Scale	Efficiency of energy storage systems	Major Participating Units	Current state
2013	Hebei Langfang 1.5 MW Supercritical CAES Demonstration Project	1.5 MW	52.1%	Institute of Engineering Thermophysics, Chinese Academy of Sciences	Completed
2014	Anhui Wuhu 500KW CAES Demonstration Project	500 KW	33%	Institute of Physical and Chemical Technology, Chinese Academy of Sciences Tsinghua University China Electric Power Research Institute	Completed
2017	Guizhou Bijie 10 MW CAES Validation Platform	10 MW	60.2%	Institute of Engineering Thermophysics, Chinese Academy of Sciences	Completed
2018	Jiangsu Tongli 500 kW Liquid Air Energy Storage Demonstration Project	500 kW	/	State Grid Corporation of China	Completed
2021	China Salt Group Jintan 60 MW Salt Cavern CAES Demonstration Project	60 MW/300 MWh	58.2%	China Salt Group, Tsinghua University China Huaneng Group	Completed
2021	Shandong Feicheng 10 MW CAES and Peaking Power Plant Project (Phase I)	10 MW	60.7%	Institute of Engineering Thermophysics, Chinese Academy of Sciences	Completed
2022	Zhangjiakou 100 MW CAES Demonstration Project	100 MW/400 MWh	70.2%	Institute of Engineering Thermophysics, Chinese Academy of Sciences Zhong-Chu-Guo-Neng (Beijing) Technology Co. Ltd	Completed
2019	Yungang Abandoned Tunnel CAES Power Station	100 MW		Academician Lu Qiang's team and Tus-Holdings	Under construction
2021	Advanced Salt Cavern CAES Plant, Ye County, Pingdingshan City, Henan Province, China	200 MW		Pingdingshan Shengguang Energy Storage Co., Ltd China Mechanical Equipment Engineering Co., Ltd Institute of Engineering Thermophysics, Chinese Academy of Sciences Zhong-Chu-Guo-Neng (Beijing) Technology Co. Ltd	Under construction
2022	Shandong Feicheng Salt Cavern Advanced CAES and Peaking Power Plant	300 MW/1500 MWh		Institute of Engineering Thermophysics, Chinese Academy of Sciences Zhong-Chu-Guo-Neng (Beijing) Technology Co. Ltd	Under construction

Table 6 (continued)

Time	Project name	Scale	Efficiency of energy storage systems	Major Participating Units	Current state
2022	Hubei Yingcheng 300 MW CAES plant	300 MW/1800 MWh		China Energy Digital Technology Group Co., Ltd	Under construction
2022	Shandong Tai'an 350 MW Salt Cavern CAES Innovation Demonstration Project	350 MW/1400 MWh		China Energy Digital Technology Group Co., Ltd	Under construction
2022	Gansu Jiuquan 300 MW CAES Plant	300 MW		China Energy Digital Technology Group Co., Ltd	Under construction
2022	Liaoning Chaoyang 300 MW CAES plant	300 MW		China Energy Digital Technology Group Co., Ltd	Under construction
2023	Hunan Wangcheng CAES Power Station Demonstration Project	300 MW/1200 MWh		China Energy Digital Technology Group Co., Ltd	Underconstruction
2023	Advanced CAES Demonstration Project for Gas Storage Tanks in Ulan County, Haixi Prefecture	200 MW/800 MWh		China Energy Engineering Group, China Power Engineering	Under construction
2023	Air Liquide Energy Storage Demonstration Project in Golmud City, Qinghai Province	60 MW/600 MWh		China Green Development Corporation	Under construction
2023	Datang Zhongning CAES Green Low Carbon Technology Research Project	100 MW/400 MWh		China Datang Corporation	Under construction

and high pressure. Currently, there are more manufacturers of compressors on the market and the technology is more mature. The main manufacturers include Atlas Copco, Comp Air, Sull Air and Siemens, etc. Atlas Copco has the most mature air compressor manufacturing technology and the highest global market share. Comp Air is a leading supplier of world-class rotary screw, reciprocating, centrifugal, and portable compressors. Sull Air Compressors originated in Michigan City, Indiana, USA, and has specialized in the development and manufacturing of screw air compressors for more than 50 years, with the following product types: stationary oil-flooded, stationary-oil-free, vacuum pump and other product types.

In China, China National Petroleum Corporation(CNPC) Jichai Power Company Limited has a wide range of products with power ranging from 10 to 7500 kW and maximum working pressure of 70 MPa, which can meet the different needs of natural gas booster and gathering and transportation.

The parameters of the two compressor systems are shown in Table 7, where the maximum discharge pressure reaches 52 MPaG.

(2) Heat exchangers

Heat exchangers are mainly categorized into shell and tube type and plate type. They are heat exchanger equipment that transfer part of the heat from the hot fluid to the cold fluid. Among them, the parameters of heat exchanger system have a greater impact on the energy storage efficiency of the system. If the heat storage temperature and heat return temperature are higher, there will be lower loss of the system and higher energy storage efficiency of the system.

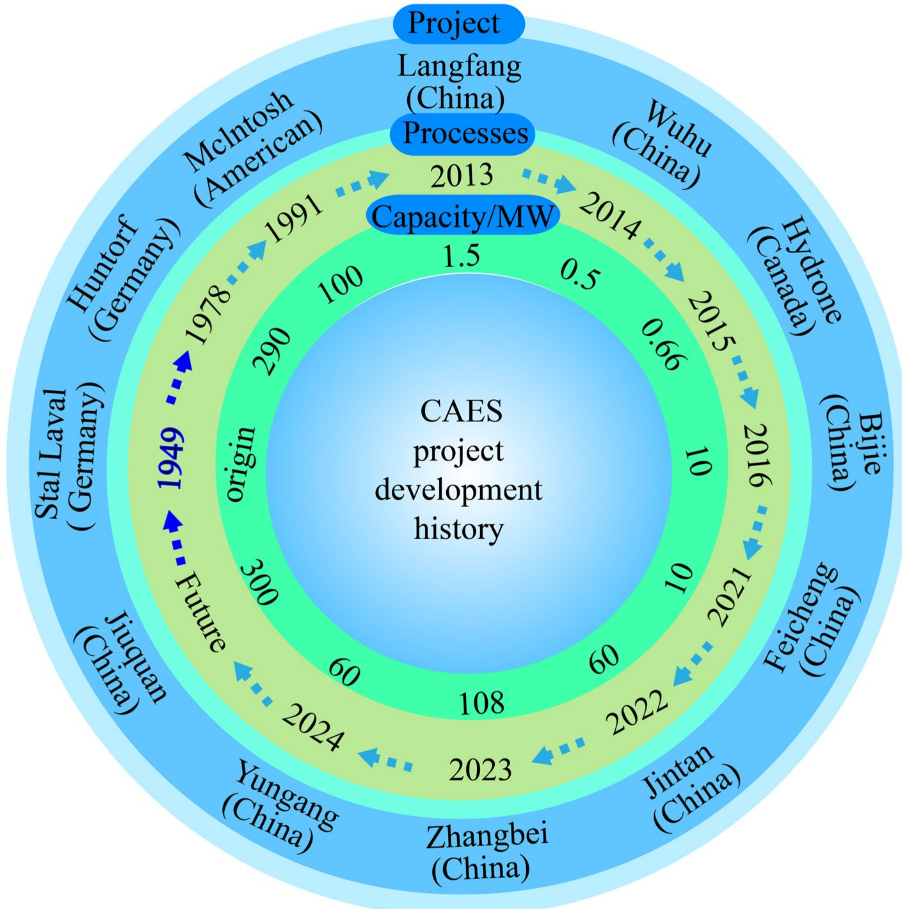


Fig. 6 CAES project development history

By improving the heat storage temperature and heat transfer efficiency of the heat storage and return system, the overall efficiency of the system can be further improved. ARD's heat exchanger production technology is more mature, and its main products include detachable plate heat exchanger, heat exchanger gasket and heat exchanger plate.

(3) Expansion machines

Expansion machine according to the structure and form of movement can generally be divided into turbine and piston type. It can be used to compress the gas expansion and decompression and output power to the outside, so that the temperature of the gas is lowered. Piston type is mainly suitable for small flow and high-pressure ratio of small and medium-sized high and medium pressure cryogenic equipment, while the turbine type has a small size, simple structure, high flow, high efficiency and long operating cycle, etc., suitable for large and medium-sized deep cryogenic equipment. The turbine expander is generally used in CAES system.

Now in its 150th year, Atlas Copco's centrifugal turbine compressor solutions utilize either integral gear drive technology or single-shaft drive technology, and are capable of handling pressures up to 20 MPa and volumetric flow rates up to 480,000 m^3/h (Quoilin et al. 2012).

Atlas Copco has a wide range of expansions with the product characteristics shown in Table 8, and its maximum inlet temperatures is up to 510 °C.

3 Siting analysis of depleted gas reservoir CAES

The requirements for CAES site selection in DGR mainly include four aspects: reservoir geological conditions, geologic safety, historical factors, and economic efficiency factors. The CAES project for DGR conducted by PG&E in California, USA, is taken as an example for analysis. A detailed analysis is carried out on it, and its comprehensive evaluation system for CAES is shown in Fig. 8 (Jia et al. 2015).

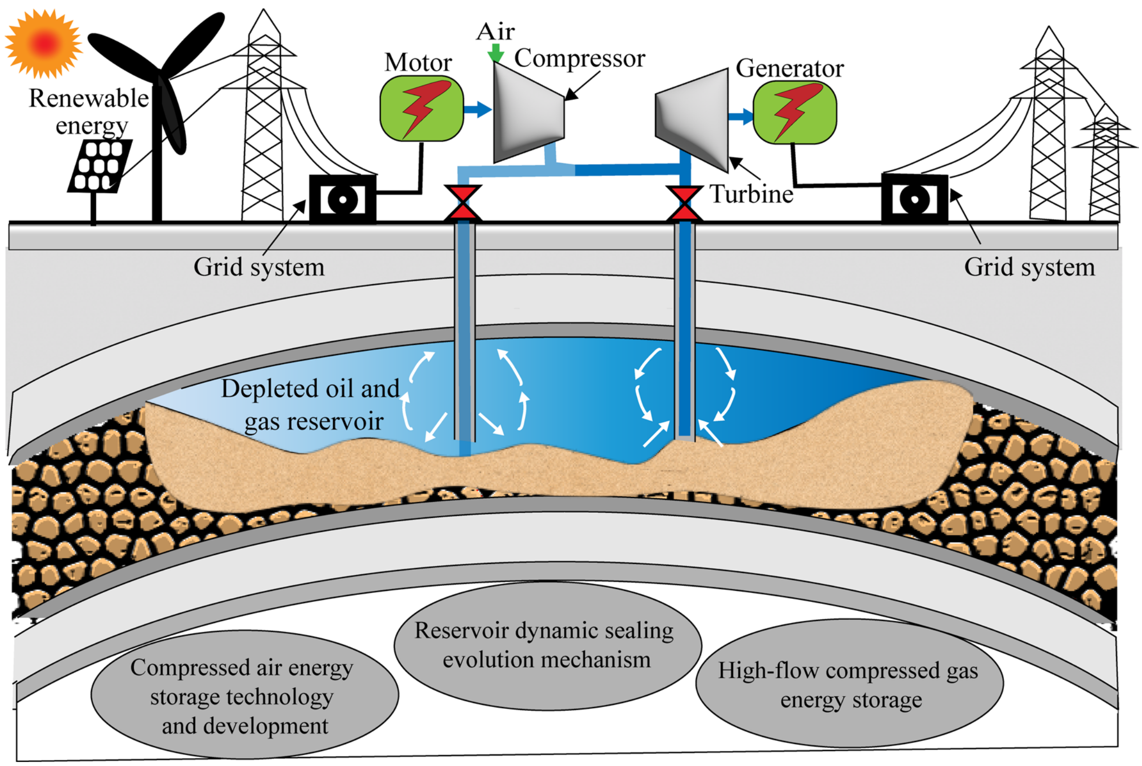


Fig. 7 Depleted gas reservoir CAES working principle and its main equipment

Table 7 Compressor at CNPC Jichai power company

Series	Range of power (kw)	Air displacement (Nm^3/d)	Max discharge pressure (MPaG)
Integral compressor unit	85–630	$0.1–10 \times 10^5$	35
Split compressor unit	10–7500	$0.1–50 \times 10^5$	52

Table 8 Expansion machines at Atlas Copco

Series	Inlet temperature (°C)	Inspiratory pressure (MPa)	Applications
EC	− 200 to 220	20	Hydrocarbon and petrochemical industries
EG	− 200 to 300	20	Geothermal and waste heat
ET	− 220 to 510	16	Hydrocarbon

The main purpose of the construction of pressurized gas storage power plants is to regulate the peaks and valleys of electricity and to improve the quality of electricity. Regulating power peaks and valleys is to alleviate the difference between day and night peaks and valleys in the power market, and to regulate the balance of power consumption in the power grid in time and space.

The improvement of power quality is mainly aimed at improving the unstable quality of intermittent power sources such as wind power and photovoltaic power generation, and storing a large amount of wind and light discarded power during the peak hours of grid supply. The construction purpose of the pressurized gas storage power plant is the primary factor in determining the regional siting of the storage reservoir, while the force characteristics of the underground storage reservoir are the key factor in determining whether it can be successfully sited. The selection principle of CAES is shown in Table 9.

3.1 Evaluation of reservoir property factors

3.1.1 Reservoir size and thickness

Reservoir size can be evaluated based on two dimensions: reservoir capacity and extent of distribution. The selection, of reservoir size depends on the storage and operational needs of the system as well as the value it can generate. Reservoirs that are too small do not have sufficient capacity to sustain gas recovery operations to meet project objectives, and reservoirs that are too large require the construction and maintenance of larger gas tops, which increases development and operating costs.

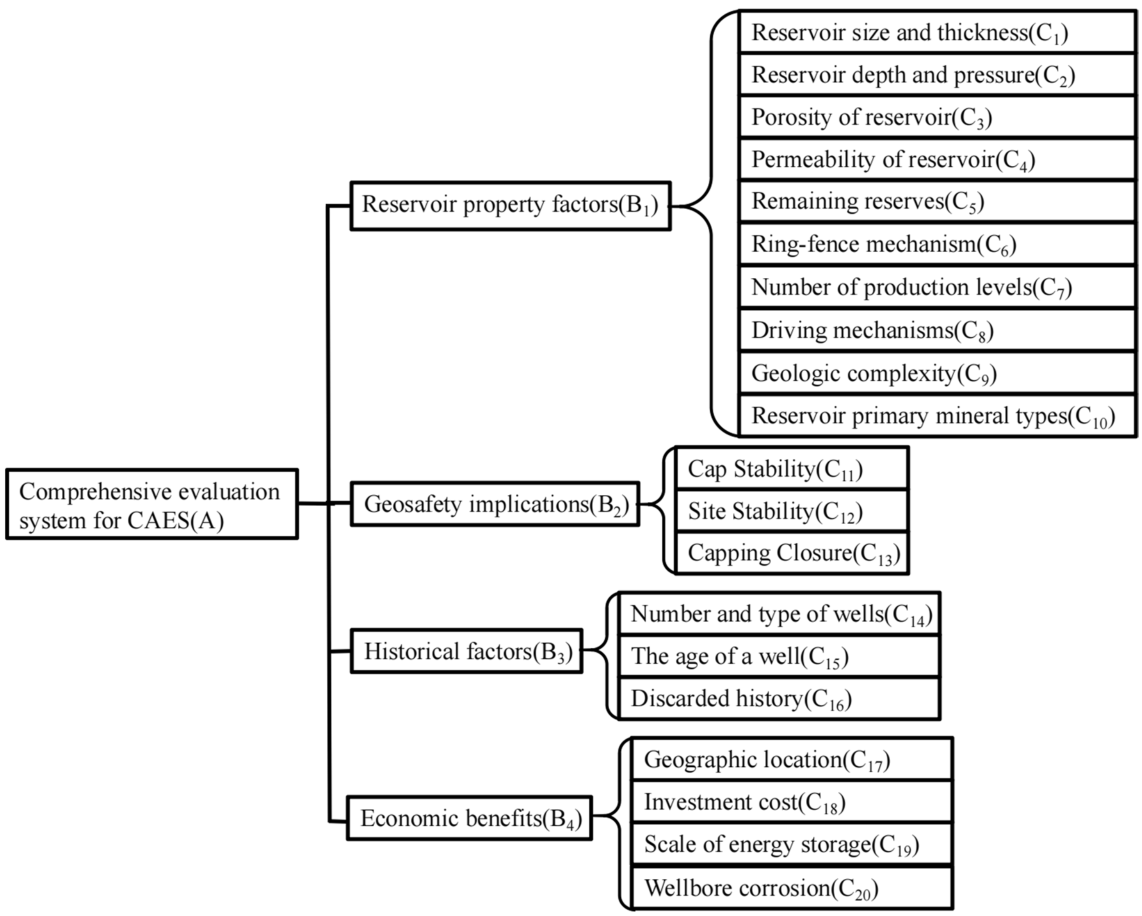


Fig. 8 Comprehensive evaluation system for CAES

Table 9 Principles of CAES site selection (Guo et al. 2022)

Influencing factors	Site selection principles
Electric load centers and peak and valley power consumption	As close as possible to the center of the electrical load
Presence of intermittent energy sources	Proximity to intermittent power supply areas, location of selection points based on location of renewable energy sources
Regional geological stability	The regional geological structure is stable, there is no fracture zone, and the seismic intensity of the gas storage area is less than 8 degrees
Engineering geology and hydrogeological conditions	Where the stratigraphic structure is simple, the thickness of the rock is large, the form of production is gentle, the spacing of structural cracks is large, and the number of groups is small
Historical factors for the development of DGR	Utilize existing depleted gas reservoir development conditions to continue construction
Old wells can be utilized	Prioritize the use of abandoned caverns and old wells to reduce the cost of the construction project
Transportation and other supporting conditions	Facilitates the transportation of construction materials and equipment and lays a good external foundation
Environmental factors	Avoid development in formations with karst development, air-mining zones, hazardous gases and geothermal anomalies
Economic efficiency factors	Integration of various factors to maximize economic benefits

It is promising to utilize energy storage in coal goaf under the current "dual carbon" target (Wang et al. 2023b). In the context of underground coal seam gasification reactions, Greg Perkins proposed a 0-dimensional cavity growth sub-model based on the concept of surface reactions, which provide more accurate cavity growth rates with reasonable input parameters (Perkins 2019).

Reservoir thickness is usually expressed as gross, net and average thickness. Gross thickness is measured from the highest point in the reservoir structure to the gas or water contact that normally defines the lower limit of the reservoir, without regard to changes in lithology within that interval. The net thickness is derived from log interpretations and excludes those lithologies within the reservoir that are of poor quality. A higher average reservoir thickness may imply a relatively compact reservoir spread compared to gross thickness, and conversely, a lower average thickness may imply a wider and more extensive reservoir spread.

3.1.2 Reservoir depth and pressure

When selecting the site, the depth of the reservoir should be neither too small (small circulating pressure causes low energy efficiency and requires more storage space) nor too large (the pressure is limited by the safety of the system, the economy and the performance of the equipment) (Dong and Li 2021). The burial depth of the reservoir primarily determines the range of pressure variations in the CAES system during buffer gas injection and cycling.

Different pressure ranges have a significant impact on the overall design of the reservoir, the surface compressor and the expander. When the effect of depth on compressor and expander design is not considered, the greater the depth of the target reservoir, the greater the storage efficiency of the overall storage system. And the geothermal energy is more likely to be recharged from the surrounding strata. However, with the increasing depth, the pressure buildup from injecting buffer gas is greater, which may cause mechanical damage to the storage cap layer.

Tables 10 and 11 give the range of reservoir depths for selected projects and the range of reservoir depths considered by the researchers in their evaluation of CAES siting.

3.1.3 Reservoir porosity

The pore structure of the reservoir directly affects the physical properties of the reservoir and has an important influence on the reservoir storage and seepage capacity (Wang et al. 2021). The porosity of the reservoir reflects the size of the pore volume of the rock, which can be interpreted from bare-eye logging curves or indirectly obtained from core analysis. Stottlemyre and Allen et al. in 1978 and 1983, respectively, proposed a reservoir porosity of greater than 10% for the siting of CAES in aquifers, and Succar et al. in 2008 proposed a minimum porosity of 13% for the reservoir (Dong and Li 2021; Ngata et al. 2023).

3.1.4 Reservoir permeability

For low-permeability reservoirs, small changes in formation pressure will cause changes in reservoir porosity and permeability, which in turn affects the seepage capacity of the underground reservoir and ultimately affects the amount of gas injected into the underground reservoir. The lower the permeability of the reservoir is, the more drastic the change in permeability with the formation pressure will be (Guo et al. 2021; Zhang et al. 2019a). Permeability needs to be determined by analyzing core samples from the reservoir to determine actual vertical and horizontal permeability. The effect of permeability and reservoir thickness on reservoir performance needs to be assessed through reservoir modeling. Zhang et al. (2022) studied the injection and extraction simulation of low permeability gas reservoirs converted into underground storage reservoirs. Based on the inverse problem theory, the objective function was constructed by using the difference between the measured and calculated values of formation pressure, and the problem of inverse identification of reservoir physical parameters was transformed into an optimization problem (Stottlemyre 1978; Hostetler et al. 1983).

Table 10 Reservoir depth for planned and construction works

Name	Country	Type	Running status	Depth (m)	Literature
Huntorf	Germany	Salt cavern	The power station is in operation	650–800	Dong and Li (2021), Zhang et al. (2019b)
McIntosh	United States	Salt cavern	The power station is in operation	460–760	Holden et al. (2000)
Norton	United States	Limestone cavern	Power station is planning	670	Chen et al. (2016)
Iowa	United States	Aquifer	Power station plan is suspended	780–900	Holst et al. (2012)
Pittsfield	United States	Aquifer	The trial is complete	200–300	Wiles and Mccann (1983)
King Island	United States	Depleted oil and gas reservoir	Power station is planning	1424.94–1463.04	Allen and Gutknecht (1980)

Table 11 The range of reservoir depths proposed by the researchers

Type of reservoir	Depth (m)	Literature
Porous media	183–1220	Stottlemyre (1978)
Aquifer	200–1000	Allen et al. (1985)
	170–760	Succar and Williams (2008)
	500–2000	Carneiro et al. (2019)
	260–4000	Mouli-Castillo et al. (2019)
For H_2 storage	1500	Hassanpouryouzband et al. (2021)
	1100	Iglauer (2022)
	3000	Okoroafor et al. (2022)

3.1.5 Surplus oil and gas

All DGR contain a certain amount of residual gas, which can be estimated by analyzing the historical production data of the reservoir to estimate the original gas-in-place. Over time, the residual natural gas will gradually mix with the injected air, and the lower flammability limits of the methane-air fraction of a representative deep geologic reservoir are 3.8 mol% and 54.4 mol% at 25 °C and 85.5 atmospheres, respectively (Zhang et al. 2022; King and Apps 2013).

3.1.6 Trapping mechanism

As shown in Fig. 9, for depleted oil and gas fields, the effectiveness of the trap depends on (1) whether the burial depth and area of the trap are favorable for the economic construction of the reservoir, (2) whether the closure height of the trap, and the cap and faults in and around the trap are favorable for the preservation of the injected natural gas, (3) the effect of the trap overflow point and the pressure of the overflow on the escape and transport of the stored gas (Zheng et al. 2020).

According to foreign experience, simple formations such as backslopes or fault traps are easier to develop and operate than complex formations. The more complex the reservoir becomes, the more likely it will be to need

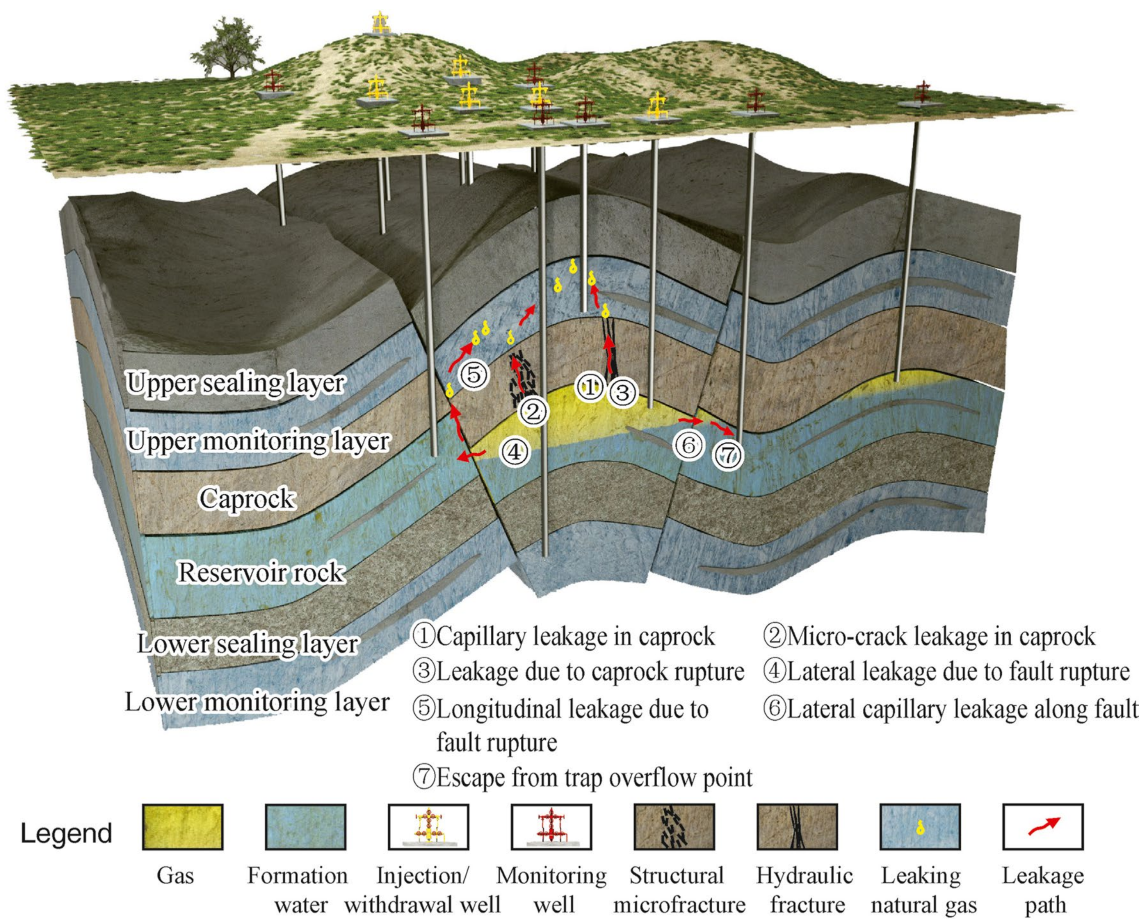


Fig. 9 Schematic diagram of geological body of a depleted oil/gas field UGS (Zheng et al. 2020)

additional wells. It will be more difficult to operate due to connectivity barriers within the reservoir.

3.1.7 Number of production layers

Some oil and gas fields are exploited with multiple producing horizons at different depths, which may be connected leading to mixing of oil and gas, or may be unconnected. Therefore, it is impossible to calculate the actual size of the reservoir based on the production records of a particular production formation. At the same time, the reserves of a single producing formation do not meet the economic efficiency and production requirements of CAES, resulting in increased construction costs. To predict the geological reserves, firstly, the geological structure, reservoir condition and obtained oil and gas layers of a certain block should be counted, and the reservoirs with clear stratification will provide certainty for the reservoir size and the convenience of development.

3.1.8 Drive mechanism

Gas reservoirs are usually gas-driven and water-driven for gas recovery, and gas-driven reservoirs usually have very high gas recovery rates, above 80%. To study the driving mechanism, it firstly should start from the microscopic pore characteristics of the reservoir, and the experimental testing methods such as physical property test, cast thin section, scanning electron microscope, high pressure mercury pressure, etc., should be used to classify and study the petrological characteristics, physical properties and microscopic pore structure characteristics of the cores taken from this reservoir. On this basis, the oil–water two-phase seepage experiments are carried out through the sandstone model to reflect the pore structure (He et al. 2020; Xiong et al. 2023).

3.1.9 Geological complexity

From the perspective of CAES development and operation, the simpler reservoir geology is better, so as to reduce potential development risks and save costs. Prior to the development of a depleted reservoir, the geology needs to be comprehensively evaluated combined with regional geological interpretations and logging records from exploration and production wells.

3.1.10 Types of reservoir native minerals

The chemical reaction of primary minerals with air in different reservoirs can have an impact on the economics and safety of the reservoir. Geochemical element logging, which provides access to the mineralogical composition of a reservoir, is a method of obtaining geochemical element data to determine the mineralogical composition of a tight reservoir. It is identified primarily by detecting gamma rays produced in the formation by neutron reactions. Oxygen from compressed air entering the reservoir will oxidize with the primary minerals in the reservoir. Newly generated oxides can reduce the permeability and porosity of the reservoir due to increased volume or precipitation, as well as reduce the oxygen in the output gas, affecting the combustion efficiency of the fuel that enters the fired chamber during subsequent power generation. Therefore, when site selection is carried out, the primary mineral type of the reservoir can be analyzed through geochemical elemental logging, and reservoir areas with primary mineral types of iron or calcium with high sulfur content can be avoided as much as possible (Liu 2022).

Ying et al. (2023) established a multilayer model based on the fluid properties of rocks in the Huangcaoxia gas field. In order to understand the removal process of H_2S from sulfur-containing UGS, the evolution law of H_2S in the underground reservoir of Huangcaoxia sulfur depleted gas field was simulated by the numerical simulation method.

3.2 Geological safety factors

The sealing and stability of the geologic structure plays an important role in the safety of the entire energy storage system. When evaluating the site selection for underground CAES, whether the whole site can be used for CAES, and the safety and stability of its energy storage system must be considered (Vandeginste et al. 2023).

3.2.1 Cap stability

For a gas storage reservoir, the capping capacity of the cap is the ability of the reservoir to prevent the escape of natural gas, which controls the vertical distribution, abundance, and working pressure of natural gas in the reservoir (Liu et al. 2021). The CAES process is prone to pressure buildup in the reservoir due to the need to inject a large amount of gas into the reservoir, and the excessive pressure may destabilize the cap layer. The stability evaluation of the cap layer is mainly a study of its geo-mechanical properties. Mechanical effects of the cap layer may cause opening of initial fractures in the cap layer, and destruction of the cap rock or rock mass. Higher injection pressures may make the cap layer incomplete and induce potential leakage channels. The geo-mechanical stability of the cap layer can be investigated by analyzing the stress–strain relationship of the rock through triaxial tests (Bai 2008).

3.2.2 Site stability

Site stability evaluation mainly refers to the evaluation of the impact of geological tectonic movements or natural disasters on the gas storage structures and ground supporting engineering facilities at the candidate site. Earthquakes and active faults can drastically disrupt the confinement conditions of the storage system, thus affecting the stability and safety of the entire storage system. Among them, fault activity has greater impact. The active faults are the main source of risk for destructive earthquakes and the main cause of near-surface tectonic deformation, and their existence implies potential and unpredictable earthquakes, surface deformation and related secondary disasters and hazards (Xu et al. 2012; Wu et al. 2022). Combined with the geological complexity, the stability of the sites is evaluated and people prioritize these sites without the above risks to avoid major safety accidents.

3.2.3 Cap tightness

The macroscopic influencing factors of cap tightness mainly include lithology, thickness, burial depth, distribution continuity, mechanical stability, fault and fracture development and closure. The evaluation of aquifer compressed air storage for the closure of the cap layer can draw on the evaluation method of cap layer confinement in oil and gas engineering and CO_2 geological storage engineering to a certain extent (Diao et al. 2011; Wang et al. 2023a).

3.3 Historical factors

Historical factors include human intervention for the reservoir, such as exploration and production wells, gas production from the target reservoir and surrounding reservoirs, and well plugging and abandonment. Four types of historical data from prior exploration and development efforts are also important for CAES development, including the number and type of wells in the gas reservoir, well age, and abandonment history.

3.3.1 Number and type of wells

The advantages of using depleted reservoirs for energy storage are the availability of detailed geological information and historical production records, lower exploration costs and shorter construction periods. According to statistics, the number of abandoned wells worldwide exceeds 20 million, and in 2023, the number of abandoned wells in China has exceeded 100,000 (Raimi et al. 2021; Fang 2023). If there is greater number of wells, there will be greater potential problems and higher additional development costs. When selecting a site, a variety of factors should be analyzed, including the location, number, type and production history of each well, eliminating possible production hazards. Although no specific screening criteria is established, priority is given to reservoirs with fewer wells drilled.

3.3.2 Well age

Older wells have a higher risk of failure and potential leakage and they need to be analyzed for the economics of converting an underground storage reservoir by learning the quality of cementing of old wells, plugging of abandoned wells, underground information, infrastructure (water, electricity, transportation, etc.), and planning for new wells to be drilled. If more underground information and surface infrastructure are available, there will be lower number of old wells to be rehabilitated and new wells to be drilled, and it will be more economical to build the reservoir (Jia et al. 2016).

3.4 History of abandonment

The abandonment history of each well needs to be evaluated to ensure that potential hazards such as leaks do not occur. Many wells located within a target reservoir have been abandoned at the time of drilling or after a period of production. The following records of abandoned wells need to be evaluated: the geographic location of the abandoned well, the type and quantity of cement or other waste materials, the abandonment process, the time the well was abandoned and mined and the presence of foreign material in the abandoned well.

3.5 Economic benefit factors

As shown in Table 12, the construction cost of the three domestic gas storage tanks is the lowest in Jintan, which is mainly due to the use of existing caverns to reduce the construction cost, and has a large volume so that the cost per unit volume is the lowest.

As shown in Table 13, the main factors affecting the economic efficiency include, geographical location of the site, investment cost, scale of energy storage and economic loss due to wellbore corrosion in four evaluation indicators.

4 Mechanism of reservoir dynamic seal evolution

The engineering background of multi-cycle intensive injection and extraction in the lower reservoir makes the dynamic sealing capability and stability of trap caps and columns

Table 12 Comparison of construction costs of different gas storage (Wang et al. 2022)

Name	Unit capacity (MW)	Gas storage form	Volume (m^3)	Total cost (CNY)	Unit cost (CNY/m^3)
Jintan	60	Salt cavern	2.2×10^5	5.3×10^7	227
Yungang	60	Expansion of abandoned roadways	5.34×10^4 (Before the expansion) 9.37×10^4 (After the expansion)	1.03×10^8	1100
Zhangbei	100	Hard rock gas storage	3×10^4	6.95×10^7	2300

Table 13 Economic evaluation indicators and their selection principles (Dong and Li 2021)

Evaluation indicators	Selection principle
Geographical location	Good wind energy resources and electricity demand Within 150 km from major cities or user centers Far away from areas such as nature reserves, military zones, mineral resources protection zones, etc
Investment costs	Low cost of exploration investment and surveying of regional facilities Cementing and plugging of old and abandoned wells Surface infrastructure and regional planning, etc
Energy storage scale	Increase gas storage pressure to increase the capacity of the entire reservoir Improve the energy storage effect of a single well and enhance the regulating capacity of the gas storage reservoir Select a gas storage reservoir with high upper layer pressure
Wellbore corrosion	Test and analyze the chemical composition of formation water and types of biological flora Evaluate and analyze and take appropriate measures to prevent corrosion and reduce equipment maintenance costs

under alternating loads a critical issue that cannot be ignored (Wen et al. 2021). When the gas breakthrough enters the cap layer, the gas replaces the water in the voids or fissures, and at the same time, the mechanical effect of the cap rock will be changed with the gas breakthrough. If the conditions of microcrack expansion of the cap rock are reached, the length and tensile degree of microcracks will be increased, and the permeability will rise sharply (Peng et al. 2014). The capping layer is depicted in different time scales as shown in Fig. 10.

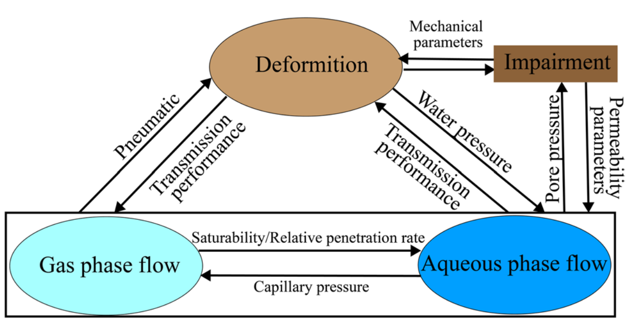


Fig. 10 Schematic diagram of the multi-field coupling process inside the cap layer

4.1 Capillary sealing of capping layer under alternating stresses

4.1.1 Capillary closure mechanism

There are many parameters for evaluating the capillary closure capacity of the cap layer, mainly the replacement pressure, permeability, porosity, surface area ratio and microporous structure of the cap layer. However, according to statistics, it is found that there is an obvious functional relationship between the parameters of cap porosity, permeability, specific surface area, microporous structure and median radius of voids and replacement pressure, which indicates that the role played by these parameters in the evaluation of the capillary closure can be replaced by the replacement pressure (Davies 1991).

At present, the breakthrough pressure is mainly used to quantitatively evaluate the capillary closure, which is the most fundamental and direct evaluation parameter of capillary sealing ability of the cover layer. It comprehensively reflects the influence of lithology, mud content, porosity, permeability, microscopic pore throat distribution on the capillary closure (Wen 2021).

4.1.2 Changing law of permeability of cover layer under alternating loading

Rock permeability is controlled by the pore and fissure structure of the rock itself, and during the deformation process, the pore and fissure of the rock changes, and therefore its permeability also changes. Rock damage itself is an extremely complex problem, and it is difficult to study the seepage-stress coupling in the damage process theoretically, and the main way to study it is to conduct experimental research.

At present, there are more experimental studies on the permeability of mudstone before the peak, and the conclusions are basically the same: in the elastic deformation stage, the mudstone micropores and fissures are compressed, and the permeability decreases; with the further increase of stress, the rock micro-fissures begin to expand, and the permeability begins to increase; the peripheral pressure restricts the lateral deformation of the mudstone, which reduces the porosity, and restricts the fissure expansion and width. With the increase of the peripheral pressure, the permeability decreases (Han et al. 2011).

4.2 Mechanical integrity of the formation under variable stresses

Those factors including the tensile damage of reservoir and cap layer caused by local high pressure under alternating stress, and the risk of cap layer shear and long-term fatigue damage caused by local stress concentration due to complex geological structure, lithological changes, and laminar development, etc. are the focuses of formation mechanical integrity evaluation.

4.2.1 Mechanical closure mechanism of the cap layer

The capping layer must be thick enough to prevent rupture, and it needs to have low permeability and large capillary forces to prevent air migration through the capping layer. According to experience, the injection pressure in excess of the original formation pressure should not exceed 0.16 bar/m depth of burial to avoid cracking of the capping layer (Succar and Williams 2008; Liu et al. 2021).

4.2.2 Damage mechanism of rock deformation under alternating loads

In situ rocks are essentially subjected to monotonic and cyclic or dynamic loads. Correct and detailed knowledge of how the mechanical properties of rocks change under different loading scenarios is necessary for the safe and correct design and construction of civil, mining and geotechnical structures (underground openings, tunnels, rock columns, foundations), as well as for a better understanding of other related operations (Vaneghi et al. 2018; Chen et al. 2023; Zhang et al. 2023).

Liang et al. (2019) conducted a study on acoustic emission-based damage and fractal evolution trend of sandstone under loading and unloading conditions of isotropic layered cycling. The damage variable increased sharply in the cycling phase, and the increment of layered cycling was higher than that of isotropic cycling by 0.07. Sandstone showed greater damage under the action of layered cycling loading and unloading.

Zhang et al. (2021) established the damage ontology model of reservoir and cap layer through triaxial cyclic loading and unloading synchronized permeability test experiment, and studied the strength, permeability changing law and damage law of rocks under cyclic loading. The research results show that: under the action of external force, sandstone is easier to form connecting cracks and be damaged, while mudstone is not easy to produce connecting cracks due to the reduction of permeability by hydration and expansion.

(1) Risk of tensile damage

High-rate injection and extraction during reservoir operation can exacerbate the effects of reservoir non-homogeneity. Especially during gas injection, the bottomhole pressures may exceed the upper limit of reservoir design pressure. The local pressure may be higher than the minimum horizontal stress, causing tensile damage to the cap layer. In particular, the risk of tensile damage is much higher than the risk of shear damage in gas storage reservoirs modified by shallow buried reservoirs. Therefore, when evaluating the risk of tensile damage to the cap layer, it is important to accurately test the captive ground stress, especially in DGR. The reservoir and cap geos-tresses can be tested by hydraulic fracturing or ground leakage tests and AE Kaiser effect experiments to evaluate the risk of tensile damage (Zheng et al. 2017).

(2) Risk of shear damage

Evaluating the shear damage of the cap layer is mainly based on indoor rock mechanics experiments. Numerical simulation is carried out by establishing a three-dimensional dynamic geologic force model, and data are obtained by inversion (Teatini et al. 2014). On this basis, according to the shear damage criterion (e.g., Moore-Cullen criterion), with the shear damage safety index and other quantitative indexes, the cover shear damage safety index of the reservoir under any formation pressure during the injection and extraction process is calculated, so as to quantitatively evaluate the risk of the shear damage of the reservoir under the local high-pressure gas injection and the long-term alternating loads (Sun et al. 2017).

(3) Risk of fatigue damage

The ground stress field in a gas storage reservoir varies cyclically with the injection and extraction cycles. In addition to varying degrees of elastic–plastic deformation, localized stress concentrations may be induced, and such stress concentrations can accumulate in the rock and form fatigue damage. Fatigue damage begins where the stresses are higher and will eventually lead to fatigue damage once microscopic deformation of the tissue begins to accumulate (Ren et al. 2019).

The fatigue damage risk evaluation is to carry out indoor core triaxial loading and unloading alternating stress experiments to study the deformation and damage characteristics of the cap rock under simulated gas storage reservoir injection and extraction working conditions. It quantitatively evaluates the fatigue damage risk of the cap layer under the long-term alternating loads of the gas storage reservoir by using the accumulated plastic strain (Tenthorey et al. 2013). Ma et al. (2018) established a method to carry out triaxial loading and unloading alternating stress experiments by using constant circumferential pressure and variable axial pressure, and recommended the use of 0.1 Hz as the loading frequency of alternating stress for core experiments.

(4) Fault shear-slip instability

Fault shear slip instability is similar to the principle of cap shear damage, but the fault is a geologically fractured zone, which is the largest mechanically weak surface, and cohesion is generally ignored. Geomechanical studies show that in the process of ground stress disturbance caused by gas storage reservoir injection and extraction, when the shear stress acting on the fault surface is greater than the product of the friction coefficient and the effective positive stress, the fault slips and loses its sealing ability. Slip and destabilization of far-field faults can cause substantial deformation of the formation, which in turn affects the integrity of the wellbore (Zheng et al. 2017).

5 Current status of high-flow rate CAES injection and production operation technology

The primary focus of high-flow pressurized gas storage is on pipe column safety and the study of injection and extraction schemes. Currently, international research on utilizing depleted oil and gas reservoirs for gas storage is still in the exploratory and theoretical analysis stage. The Pacific Gas and Electric Company (PG&E) in California, USA, has developed a mature technology research program for a 300MW-10h scale CAES plant located in the King Island depleted gas field in San Joaquin County (U. S. Department of Energy 2013; Wu 2019).

5.1 Safety evaluation of high-frequency injection pipe column

During high-frequency injection and extraction, the injection and extraction pipe column is affected by corrosion and stress, and is prone to fatigue damage and fracture failure, which has a greater impact on the safety and stability of the gas storage reservoir (Wan et al. 2023b). In the design of the injection process and completion pipe column, it mainly relies on optimization and design software. It can comprehensively consider the factors such as load change, temperature and pressure alternating influence and corrosion, which have a great influence on the safety of the tubular column in the design process. The current research on column corrosion is more mature, and relevant corrosion prediction models have also been established. However, due to the dominant CO_2 and sulfide corrosion in the field, the study of oxygen corrosion is more focused on the study of the process of oil drive with the injection of air. There is less study on the separate injection of air, the corrosive influence of different flow rates, temperatures and pressures on the entire injection column.

Oliveira et al. (2021) introduced an additional module in the MATLAB reservoir simulation toolbox and described a new quadratic method, defined as the derivative of a stratigraph-modified Lorentz diagram, which is based on the flow unit velocity at these depths. The depth range in the reservoir is divided into barrier, strong baffle, weak baffle and normal unit, and the ability of the analysis module in observing well geology is verified by case study.

Yao (2021) evaluated the risk of gas storage pipe columns by fuzzy comprehensive evaluation method. For the establishment of the evaluation index system and the calculation of the index weights in the evaluation process, they chose the fishbone diagram and the hierarchical analysis method respectively, and set up the fishbone diagram-fuzzy hierarchical comprehensive evaluation model to judge the risk level of the pipeline columns, deriving the relative importance of the influencing factors for the damage of pipeline columns.

5.2 Research and optimization of efficient injection and production scheme

At present, most of the domestic and international studies on CAES projects in DGR are at the stage of theory and field test, and there are fewer studies on efficient injection and extraction programs. In the CAES operation process, the safety of injection and extraction column of reservoir can be evaluated by using methods including software and indoor experiments. DGR storage can meet the flow rate and pressure required for system operation, but proper system management and operation must be performed. During the initial gas top formation phase, additional boreholes are required to extract raw formation water while air is being injected in order to meet a reasonable construction time without exceeding the allowable borehole pressure.

6 Developments and suggestions

Based on the conclusions of relevant domestic and international studies and field tests on CAES projects for the conversion of DGR, the following points are proposed:

(1) The domestic prospects for the development of CAES in DGR are promising. However, there is a need to enhance the localization of key equipment for CAES. This equipment primarily consists of compressors, heat exchangers, and expanders. While some related equipment is available in the industry, it currently holds a small market share globally, and there is still a performance gap compared to major manufacturers.
(2) At the CAES site selection stage, it is possible to drill sufficient core samples for surface testing to acquire data on permeability, mineral types, and potential sediment distribution. For testing purposes, injection and extraction wells can be positioned at different locations within the reservoir to analyze the composition and chemical properties of the extracted gas and water. This helps prevent issues such as scaling, corrosion, and oxidation, thereby reducing the impact on the porosity and permeability of the reservoir.
(3) The nature of the reservoir, geologic safety, history of depleted reservoirs, and economics need to be evaluated in advance of the project. A comparative analysis of the feasibility of the block can be made based on PG&E's evaluation of the CAES project in depleted reservoirs in KingIsland, USA, as compared to other commercial energy storage technologies.
(4) The dynamic sealing evolution mechanism of the reservoir is more complex. The numerical simulation studies of gas storage reservoir primarily focus on the reservoir itself, and there is less emphasis on the numerical simulation of the geomechanics of the cap layer. Therefore, it is necessary to combine the analysis of both the reservoir and the cap layer to conduct dynamic mechanical analysis and enhance system stability.
(5) High-flow compressed gas storage energy injection and production technology is a key technology for improving work efficiency. There are fewer studies on the safety evaluation and program of high-frequency injection and production pipe column, and further research in this area is needed to strengthen this aspect.

7 Conclusions

Based on the current situation and development of CAES technology in China, the characteristics of CAES siting in DGR, the evolution mechanism of reservoir dynamic sealing, and the high-flow pressurized gas storage and injection technology are analyzed.

The current research status of capillary confinement mechanism under alternating load, change rule of cap permeability, mechanical confinement mechanism of cap, as well as the risk of tensile, shear, fatigue and fault shear-slip damage under alternating load are summarized. Taking the project of 300 MW-10 h CAES power plant in the depleted gas reservoir of Golden Island, San Joaquin County, California, USA, as an example, this paper analyzed the safety evaluation of the pipe columns and the study of efficient injection and extraction schemes, which can provide a reference for the study of CAES engineering in DGR.

Acknowledgements The authors would gratefully like to acknowledge the financial support from the Scientific Research and Technology Development Project of China Energy Engineering Corporation Limited (CEEC-KJZX-04).

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Ackerman G, Pacheco F (2020) Renewable energy push boosts bets on wind, solar in Israel. Environment & Energy Report

Agrawal R, Kumar Y, Sarkhel R, Damdhar MS, Sangwai JS (2023) Enhancing the CO_2 sequestration potential in subsea terrain by hydrate formation from liquid CO_2. Energy Fuels 37(19):14961–14976

Allen RD, Doherty TJ, Kannberg LD (1985) Summary of selected compressed air energy storage studies. United States N. p

Allen RD, Gutknecht PJ (1980) Porous media experience applicable to field evaluation for compressed air energy storage. United States N. p

Al-Yaseri A, Fatah A, Amao A, Wolff-Boenisch D (2023) Basalt–hydrogen–water interactions at geo-storage conditions. Energy Fuels 37(19):15138–15152

Bai B (2008) Flow-geomechanics theory and numerical simulation method of site stability for CO_2 sequestration in coalbeds. University of Chinese Academy of Sciences (Chinese Academy of Sciences, Wuhan Institute of Geotechnical Mechanics)

Berrada A, Loudiyi K, Zorkani I (2017) Toward an improvement of gravity energy storage using compressed air. Energy Procedia 134:855–864

Borri E, Tafone A, Comodi G, Romagnoli A, Cabeza LF (2022) Compressed air energy storage—an overview of research trends and gaps through a bibliometric analysis. Energies 15(20):7692

Brahim H, Ilinca A, Perron J (2008) Energy storage systems—characteristics and comparisons. Renew Sustain Energy Rev 12(5):1221–1250

Budt M, Wolf D, Span R, Yan J (2016) Compressed air energy storage: an option for medium to large scale electrical-energy storage. Energy Procedia 88:698–702

Buhagiar D, Sant T (2017) Modelling of a novel hydro–pneumatic accumulator for large-scale offshore energy storage applications. J Energy Stor 14(2):283–294

Carneiro JF, Matos CR, Gessel SV (2019) Opportunities for large-scale energy storage in geological formations in mainland Portugal. Renew Sustain Energy Rev 99:201–211

Chen LJ, Zheng TW, Mei SW, Xue XD, Liu BH, Lu Q (2016) Review and prospect of compressed air energy storage system. J Mod Power Syst Clean Energy 4:529–541

Chen YL, Hao XJ, Xue DJ, Li Z, Ma XR (2023) Creep behavior and permeability evolution of coal pillar dam for underground water reservoir. Int J Coal Sci Technol 10(1):136–141

Chino K, Araki H (2000) Evaluation of energy storage method using liquid air. Heat Transf Asian Res 29(5):347–357

Cooper PW, Grubelich MC, Bauer SJ (2011) Potential hazards of compressed air energy storage in depleted natural gas reservoirs. Office of scientific & technical information technical reports

Duhan J (2018) Compressed air energy storage in salt caverns: geomechanical design workflow, CAES siting study from a geomechanics perspective, and deep brine disposal. UW Space

Dolatabadi A, Fabris D, Samara-Rubio D (2013) Isothermal efficiency of liquid piston compressors employed in compressed air energy storage systems. Fluids Eng Div Summer Meet 9(13):7–11

Dib G, Haberschill P, Rullière R, Revellin R (2021) Thermodynamic investigation of quasi-isothermal air compression/expansion for energy storage. Energy Convers Manag 235:114027

Dong JW, Li Y (2021) Study of the site evaluation of compressed air energy storage in aquifers. Saf Environ Eng 28(03):228–239

Donadei S, Schneider GS (2016) Chapter 6-Compressed air energy storage in underground formations. Storing Energy 113–133

Davies PB (1991) Evaluation of the role of threshold pressure in controlling flow of waste–generated gas into bedded salt at the waste isolation pilot plant. United States: N. p

Diao YJ, Zhang SQ, Guo JQ, Li XF, Zhang H (2011) Geological safety evaluation method for CO_2 geological storage in deep saline aquifer. Geol China 38(3):786–792

Fang ZW (2023) Optimization of heat transfer performance of medium-deep casing type buried pipe in severe cold region. Northeast Petroleum University

Feng YJ (2023) China's energy security under the drastic changes of international energy system. Int Econ Rev 163(1):38–52

Fu H (2019) Research on principle and operation strategy of hydraulic compressed air energy storage system. Beijing: North China Electric Power University 01:45–56

Fu H, Jiang T, Cui Y, Quan C (2019) An operation control strategy for a virtual pumped storage system based on a linear motor. Energy Stor Sci Technol 8(1):98–107

Fushimi C (2021) Valorization of biomass power generation system: noble use of combustion and integration with energy storage. Energy Fuels 35(5):3715–3730

Gao D, Yang JX, Qi YW, Guo C, Zhang H (2023a) Review and perspectives on CO_2 bubble dynamic characteristics in different liquids during carbon capture, utilization, and storage process. Energy Fuels 37(1):58–73

Gao XY, Yang SL, Shen B, Tian L, Li S, Zhang X, Wang JT (2023b) Influence of reservoir spatial heterogeneity on a multicoupling process of CO_2 geological storage. Energy Fuels 37(19):14991–15005

Guo C, Wang Z, Liu K, Li C (2019) The application and research progress of special underground space. Geol China 46(3):482–492

Guo CB, Li C, Yang LC, Liu K, Ruan YJ, He Y (2021) Research review and engineering case analysis of geological compressed air energy storage. Geol Surv China 8(4):109–119

Guo H (2013) Performance study on novel compressed air energy storage systems. Graduate School of Chinese Academy of Sciences (Institute of Engineering Thermophysics)

Guo WP, Zhang B, Liang YT, Qiu R, Wei XM, Niu PT, Zhang HR, Li ZC (2022) Improved method and practice for site selection of underground gas storage under complex geological conditions. J Nat Gas Sci Eng 108:104813

Han GF, Wang EZ, Liu XL (2011) Seepage characteristics of rock during damage process. J Civ Environ Eng 33(5):41–50

Hassanpouryouzband A, Joonaki E, Edlmann K, Haszelidine RS (2021) Offshore geological storage of hydrogen: is this our best option to achieve net-zero? ACS Energy Lett 6(6):2181–2186

He Q, Liu H, Hao YP, Liu YN, Liu W (2018) Thermodynamic analysis of a novel supercritical compressed carbon dioxide energy storage system through advanced exergy analysis. Renew Energy 127:835–849

He Q, Wang K (2022) Research progress of isothermal compressed air energy storage technology. Therm Power Gener 51(8):11–19

He ZQ, He T, Yin WK, Sun P, Ai S (2020) Development suggestions and production technologies and development of Sinopec's gas storage of depleted gas reservoir type. Geol Explor 56(3):0605–0613

Holden P, Moen D, DeCorso M, Howard J (2000) Alabama electric cooperative compressed air energy storage (CAES) plant improvements. In GT2000; Volume 3: Heat Transfer; Electric Power; Industrial and Cogeneration-alabama electric cooperative compressed air energy storage (CAES) plant improvements

Holst K, Huff G, Schulte RH, Critelli N (2012) Lessons from Iowa: development of a 270 megawatt compressed air energy storage project in midwest independent system operator: a study for the DOE energy storage systems program. Transmission & Distribution World Exclusive Insight

Hostetler DD, Childs SW, Phillips SJ (1983) Subsurface monitoring of reservoir pressure, temperature, relative humidity, and water content at the CAES field experiment, Pittsfield, Illinois: system design. United States N. p

Hou JG (2024) New Year Message in 2024. In: Proceedings of the Chinese Academy of Sciences, vol 39, issue no 01, pp 2

Hu SW, Xu WQ, Jia GW, Cai ML, Li JD, Lu YK, Ren T (2023) Efficiency analysis of an arrayed liquid piston isothermal air compression system for compressed air energy storage. J Therm Sci 32:17–29

Iglauer S (2022) Optimum geological storage depths for structural H_2 geo-storage. J Petrol Sci Eng 212:109498

Jarvis AS (2015) Feasibility study of porous media compressed air energy storage in South Carolina, United States of America. All Theses:2256

Jia SP, Jin FM, Zheng DW, Meng QC, Zhang H, Lin JP, Wei Q (2015) Evaluation indices and classification criterion of aquifer site for gas storage. Chin J Rock Mech Eng 34(08):1628–1640

Jia SP, Zheng DW, Jin FM, Zhang H, Meng QC, Lin JP, Wei Q (2016) Evaluation system of selected target sites for aquifer underground gas storage. J Cent South Univ 47(3):857–868

Kalam S, Abu-Khamsin SA, Kamal MS, Abbasi GR, Lashari N, Patil S, Abdurrahman M (2023) A mini-review on underground hydrogen storage: production to field studies. Energy Fuels 37(12):8128–8141

King M, Apps J (2013) Compressed air energy storage: matching the earth to the turbo-machinery-no small task. Sandia National Laboratories

Kumar T, Eswari JS (2023) Review and perspectives of emerging green technology for the sequestration of carbon dioxide into value-added products: an intensifying development. Energy Fuels 37(5):3570–3589

Li HY, Xu WB, Zhang B, Zhang JS, Yang T, Zhang L, Lu LY (2022) Compressed air energy storage technology and its application. Hubei Electr Power 46(04):1–7

Li NY, Feng WT, Yu JJ, Chen F, Zhang Q, Zhu SJ, Hu Y, Li Y (2023) Recent advances in geological storage: trapping mechanisms, storage sites, projects, and application of machine learning. Energy Fuels 37(14):10087–10111

Liang DX, Zhang N, Xie LX, Zhao GM, Qian DY (2019) Damage and fractal evolution trends of sandstones under constant-amplitude and tiered cyclic loading and unloading based on acoustic emission. Int J Distrib Sens Netw 15(7):1477–1550

Liu J (2012) Numerical and experimental study on heat and cold energy storage using supercritical air. Graduate School of Chinese Academy of Sciences (Institute of Engineering Thermophysics)

Liu JC, Xu YJ, Chen ZY, Zhang XJ, Chen HS, Tan CQ (2014) The development status and energy storage characteristic of gas storage device of compressed air energy storage system. Sci Technol Eng 14(35):148–156

Liu LY, Mu WM, Zhai YJ (2021) Study on the fatigue failure law of gas storage caprock under periodic injection and production. E3S Web Conf 290:1–4

Liu MC (2022) Logging evaluation technology and further development of tight reservoirs. Spec Oil Gas Reservoirs 29(4):12–20

Luo X, Wang JH, Krupke C, Wang Y, Sheng Y, Li J, Xu YJ, Wang D, Miao SH, Chen HS (2016) Modelling study, efficiency analysis and optimisation of large-scale adiabatic compressed air energy storage systems with low-temperature thermal storage. Appl Energy 162:589–600

Ma XH, Zheng DW, Shen RC, Wang CY, Luo JH, Sun JC (2018) Key technologies and practice for gas field storage facility construction of complex geological conditions in China. Pet Explor Dev 45(3):507–520

Maisonnave O, Moreau L, Aubrée R, Benkhoris M-F, Neu T, Guyomarc'h D (2018) Optimal energy management of an underwater compressed air energy storage station using pumping systems. Energy Convers Manag 165:771–782

Morgan R, Nelmes S, Gibson E, Brett G (2015) Liquid air energy storage-analysis and first results from a pilot scale demonstration plant. Appl Energy 137:845–853

Mouli-Castillo J, Wilkinson M, Mignard D, McDermott C, Haszeldine RS, Shipton ZK (2019) Inter-seasonal compressed-air energy storage using saline aquifers. Nat Energy 4:131–139

Ngata MR, Yang B, Khalid W, Ochilov E, Mwakipunda GC, Aminu MD (2023) Review on experimental investigation into formation damage during geologic carbon sequestration: advances and outlook. Energy Fuels 37(9):6382–6400

Nguyen NN (2023) Prospect and challenges of hydrate-based hydrogen storage in the low-carbon future. Energy Fuels 37(14):9771–9789

Odukomaiya A, Abu-Heiba A, Gluesenkamp KR, Abdelaziz O, Jackson RK, Daniel C, Graham S, Momen AM (2016) Thermal analysis of near-isothermal compressed gas energy storage system. Appl Energy 179(10):948–960

Okoroafor ER, Saltzer SD, Kovscek AR (2022) Toward underground hydrogen storage in porous media: reservoir engineering insights. Int J Hydrog Energy 47(79):33781–33802

Oliveira GP, Rodrigues TNE, Lie K-A (2021) GAWPS: a MRST-based module for wellbore profiling and graphical analysis of flow units. Adv Geo-Energy Res 6(1):38–53

Ozarslan A (2012) Large-scale hydrogen energy storage in salt caverns. In J Hydrog Energy 37(19):14265–14277

Peng G (2023) Fracture propagation laws of staged hydraulic fracture in fractured geothermal reservoir based on phase field model. Int J Coal Sci Technol 10(1):52. https://doi.org/10.1007/s40789-023-00636-y

Peng Y, Liu JS, Pan ZJ, Connell L, Chen ZW (2014) A fully coupled model for caprock sealing efficiency. US rock mechanics/geomechanics symposium. American Rock Mechanics Association

Perkins G (2019) A 0-dimensional cavity growth submodel for use in reactor models of underground coal gasification. Int J Coal Sci Technol 6:334–353

Quoilin S, Declaye S, Legros A, Guillaume L, Lemort V (2012) Working fluid selection and operating maps for organic rankine cycle expansion machines. IEEE Power Eng Rev 1(3):37–37

Rabi AM, Radulovic J, Buick JM (2023) Comprehensive review of compressed air energy storage (CAES) technologies. Thermo 3(1):104–126

Raimi D, Krupnick AJ, Shah J-S, Thompson A (2021) Decommissioning orphaned and abandoned oil and gas wells: new estimates and cost drivers. Environ Sci Technol 55(15):10224–10230

Ren S, Wang XS, Gao SX, Ouyang X, Xie KN (2019) Experimental study on fatigue damage of sandstone based on NMR and acoustic emission. Trans Beijing Inst Technol 39(8):792–799

Stottlemyre JA (1978) Preliminary stability criteria for compressed air energy storage in porous media reservoirs. United States N. p

Su Y, Sun Q, Wang W, Guo X, Xu J, Li G, Pu X, Han W, Shi Zh (2022) Spontaneous imbibition characteristics of shale oil reservoir under the influence of osmosis. Int J Coal Sci Technol 9(1):69. https://doi.org/10.1007/s40789-022-00546-5

Succar S, Williams RH (2008) Compressed air energy storage: theory, resources, and applications for wind power. Report prepared by the energy systems analysis group. Princeton Environmental Institute, Princeton University

Sun JC, Wang JM, Zheng DW, Xu HC, Li C, Zhao K, Zhong R (2017) Regional scale 3D geomechanical modeling for evaluating caprock integrity and fault leakage potential during underground gas storage operations in a produced field. SPE:186053

Sun LT, Liu YY, Cheng ZC, Jiang LL, Lv PF, Song YC (2023a) Review on multiscale CO_2 mineralization and geological storage: mechanisms, characterization, modeling, applications and perspectives. Energy Fuels 37(19):14512–14537

Sun Q, Zhang WQ, Geng JS, Hu JJ, Zhang YL, Lv C, Ge ZL, Li PF, Jia HL, Liu YB, Li YX (2023b) Technological path and geological guarantee for energy storage in underground space formed by coal mining. Coal Geol Explor 51(2):229–242

Teatini P, Castelletto N, Gambolati G (2014) 3D geomechanical modeling for CO_2 geological storage in faulted formations. a case study in an offshore northern Adriatic reservoir, Italy. Int J Greenh Gas Control 22:63–76

Tenthorey E, Vidal-Gilbert S, Backé G, Puspitasari R, Pallikathekathil Z, Maney B, Dewhurst D (2013) Modelling the geomechanics of gas storage: a case study from the Iona gas field, Australia. Int J Greenh Gas Control 13:138–148

U. S. Department of Energy (2013) Pacific gas and electric company (PG&E) compressed air energy storage (CAES) compression testing phase project, San Joaquin Country, California

Vandeginste V, Ji YK, Buysschaert F, Anoyatis G (2023) Mineralogy, microstructures and geomechanics of rock salt for underground gas storage. Deep Undergr Sci Eng 2(2):129–147

Vaneghi RG, Ferdosi B, Okoth AD, Kuek B (2018) Strength degradation of sandstone and granodiorite under uniaxial cyclic loading. J Rock Mech Geotech 10(1):117–126

Wan JF, Meng T, Li JL, Liu W (2023a) Energy storage salt cavern construction and evaluation technology. Adv Geo-Energy Res 9(3):141–145

Wan MZ, Ji WD, Wan JF, He YX, Li JC, Liu W, Jurado MJ (2023b) Compressed air energy storage in salt caverns in China: development and outlook. Adv Geo-Energy Res 9(1):54–67

Wang TT, Yang CH, Wang HM, Ding SL, Daemen JJK (2018) Debrining prediction of a salt cavern used for compressed air energy storage. Energy 147(15):464–476

Wang J, Xi Z, Lu DH (2021) Pore structure of shale gas reservoirs revealed by constant speed mercury injection experiments: a case study of Wufeng formation shale from northwestern Hunan province. Geol Explor 57(2):450–456

Wang FQ, Wang HB, Wu MX, Zong WB, Wang H, Li P (2022) Compressed air energy storage technology and development. Water Pover 48(11):10–15

Wang JG, Wang HM, Wang XL, Yang SQ, Wu HT, Leung CF, Tian JL (2023a) A multiphysical-geochemical coupling model for caprock sealing efficiency in CO_2 geosequestration. Deep Undergr Sci Eng 2(2):188–203

Wang JY, Kong YL, Duan ZF, Zhang JX, Luo XL, Huang YH, Luo NN, Cheng ZY, Zhou N, Zhang WZ, Pang ZH (2023b) Geothermal energy exploitation and storage in coal field under the dual carbon goal. Coal Geol Explor 51(2):1–11

Wen CX (2021) Damage characteristics and permeability evolution mechanism of mudstone under multi-cycle alternating stress. School of Urban Construction Yangtze University

Wen CX, Jia SP, Zhao ZY, Wang JJ, Chen ZL, Zhang GY, Chang YS (2021) Experimental study on the evolution of rock strength and sealing properties under multi-cycles alternating loading. IOP Conf Ser Earth Environ Sci 861:062063

Wiles LE, Mccann RA (1983) Reservoir characterization and final pre-test analysis in support of the compressed-air-energy-storage Pittsfield aquifer field test in Pike County, Illinois. Technical report

Wu ZY (2019) CAES cavern wellbore tubular string preferably. China University of Petroleum, Beijing

Wu ZH (2022) Active faults and engineering applications I: definition and classification. J Earth Sci Environ 44(06):922–947

Xie LH, Zhang H, Li HL (2009) Accident analysis and risk identification of underground gas storage rebuilt upon the depleted oil and gas reservoirs. Nat Gas Ind 29(11):116–119

Xiong AL, Cheng GF, Li DT, Ding WP, Liu YX, Chen G, Yang L, Yuan YL, Zhu YS, Liu YL (2023) Study on micropore structure and micro residual oil distribution of ultra-low permeable reservoir: a case study of chang4+5 of Baibao Area. J Jilin Univ (earth Sci Ed) 53(5):1–16

Xu QQ, Song K (2021) Model predictive control of compressed air energy storage system. Control Theory Appl 38(12):1935–1946

Xu PY, Wang CQ, Zhang FC, Li XF, Ran XF, Xi YJ (2012) Study on the safety risk evaluation indexes system for CO_2 geological storage in the deep saline aquifer. Saf Environ Eng 19(4):62–65

Xu YH, Zhang HG, Yang FB, Tong L, Yan D, Yang YF, Wang Y, Wu YT (2021) Performance analysis of combined cooling power based on small–scale compressed air energy storage system. J Energy Stor 44(A):103382

Yang ZS, Wang HR, Li RX, Zhang Y, Chen H, Li ZB, Yao ER (2020) A novel combined cooling heating and power system with coupled compressed air energy storage and supercharged diesel engine. Energy Storage Sci Technol 9(6):1917–1925

Yang CH, Wang TT, Chen HS (2023a) Theoretical and technological challenges of deep underground energy storage in China. Engineering 25(6):168–181

Yao DZ (2021) Safety analysis and development of software of pipe strength of pipe string in underground gas storage. China University of Petroleum (East China)

Young DL, Johnston H, Augustine C (2021) Electrical energy storage using compressed gas in depleted hydraulically fractured wells. iScience 24(12):103459

Yang Y, Li LX, Wang X, Qin N, Zhang RH, Zhao YL, Tian Y (2023b) Simulation study of hydrogen sulfide removal in underground gas storage converted from the multilayered sour gas field. Int J Coal Sci Technol 10(1):71

Zhang H, Zhong Y, Kuru E, Kuang JC, She JP (2019a) Impacts of permeability stress sensitivity and aqueous phase trapping on the tight sandstone gas well productivity: a case study of the Daniudi gas field. J Pet Sci Eng 177(10):261–269

Zhang J, Zhou S, Li S, Song W, Feng Z (2019b) Thermodynamic analysis of compressed air energy storage system (CAES) based on Huntorf case. J Eng Thermophys Rus 40(1):118–124

Zhang GQ, Fan ZW, Zeng DQ, Zhang JF, Mao HJ, Mi LD, Jia YW, Yang XS, Jing X (2021) Damage law of reservoir and cap rock of gas storage under alternating load. Fault-Block Oil Gas Field 28(6):769–774

Zhang JD, Wang XM, Tan YF, Yu KC, Zhang TT (2022) Inversion analysis of physical parameters of low-permeability underground gas storage. J Harbin Inst Technol 54(06):105–111

Zhang C, Bai QS, Han PH, Wang L, Wang XJ, Wang FT (2023) Strength weakening and its micromechanism in water–rock interaction, a short review in laboratory tests. Int J Coal Sci Technol 10(1):18–32

Zhao TB, Liu SM, Ma HL, Mei DS, Wei ZX, Mei CW (2023) Research status and development trend of compressed air energy storage in abandoned coal mines. Coal Sci Technol 51(1):163-176

Zheng DW, Xu HC, Wang J, Sun JC, Zhao K, Li C, Shi L, Tang LG (2017) Key evaluation techniques in the process of gas reservoir being converted into underground gas storage. Petrol Explor Dev 44(5):840–849

Zheng YL, Sun JC, Qiu XS, Lai X, Liu JD, Guo ZP, Wei H, Min ZS (2020) Connotation and evaluation technique of geological integrity of UGSs in oil/gas fields. Nat Gas Ind B 7(6):594–603

Zong S, Liu S, Xu H, Wang W, Cao B, Huang F (2023) Numerical simulation of CO_2 storage in bedded salt rock storage cavern in Subei Basin. Coal Geol Explor 51(3):27–36

Authors and Affiliations

Jifang Wan[1] · Yangqing Sun[2] · Yuxian He[2] · Wendong Ji[1] · Jingcui Li[1] · Liangliang Jiang[3] · Maria Jose Jurado[4]

✉ Yangqing Sun
syq1320841591@163.com

✉ Yuxian He
heyx2022@126.com

1 China Energy Digital Technology Group Co., Ltd., Beijing 100044, China

2 School of Mechanical Engineering, Yangtze University, Jingzhou 434023, China

3 Department of Chemical and Petroleum Engineering, The University of Calgary, Calgary, Alberta, Canada

4 Geosciences Barcelona CSIC, Spanish National Research Council, 08028 Barcelona, Spain