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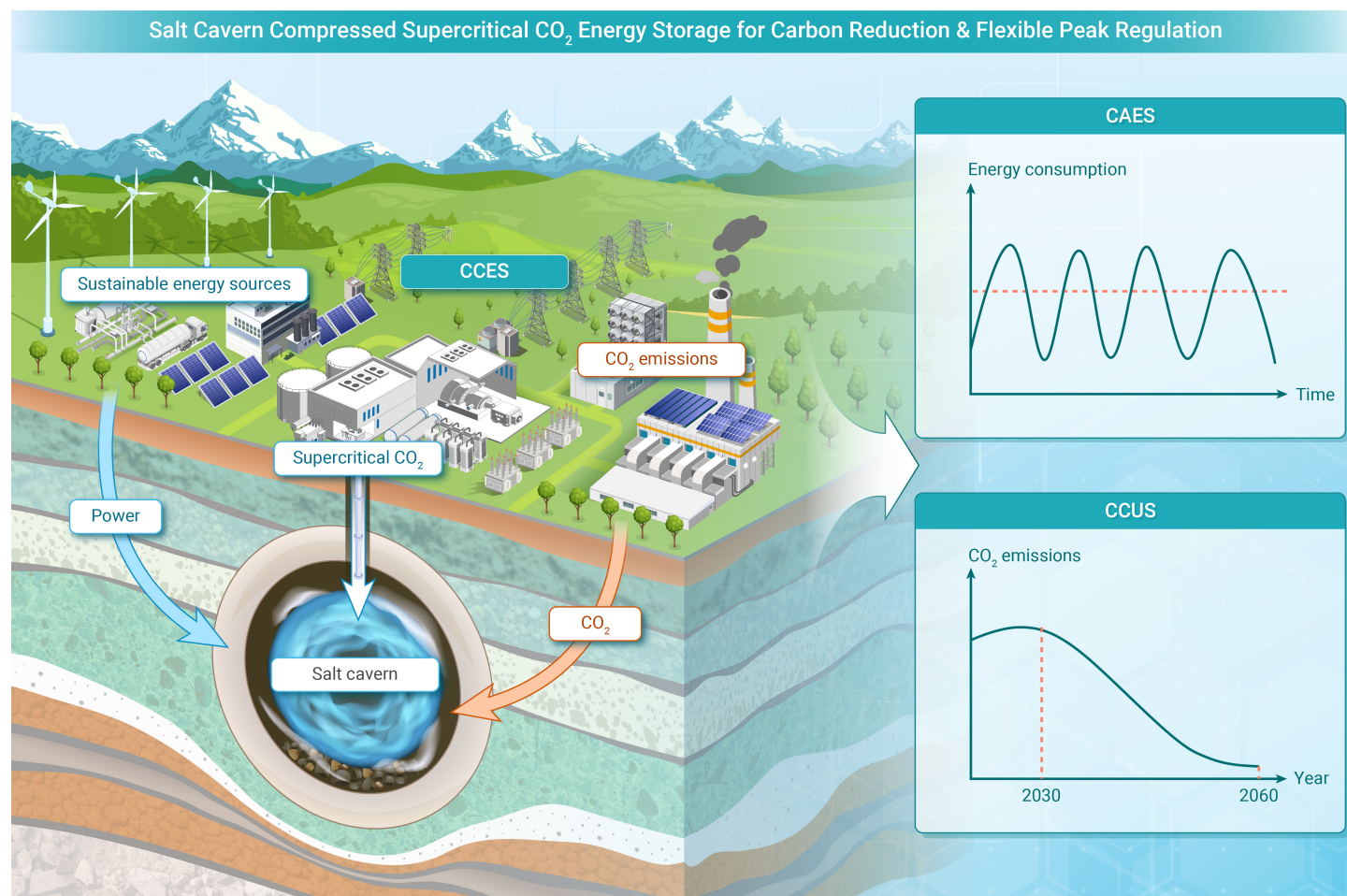
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- The concept of CCES is proposed by combining CCUS and CAES.
- The feasibility of CCES was evaluated, including stability and tightness.
- Site selection criteria and suggestions for CCES are proposed.
- The installed capacity of CCES salt caverns in China can reach 46.62-69.93 GW.

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Compressed Air Energy Storage (CAES) is an effective technology for grid-scale peak shaving, while Carbon Capture Utilization and Storage (CCUS) plays a crucial role in carbon reduction. As China strives to peaking carbon emissions by 2030 and achieve carbon neutrality by 2060 faces significant challenges, especially for the hard-to-abate sectors pose significant challenges. Building on the principles of CAES and CCUS, this paper introduces a novel approach: Compressed Carbon Energy Storage (CCES), which integrates CAES and CCUS. CCES uses salt caverns to store compressed supercritical CO₂ instead of air. This study explores the feasibility of CCES in salt caverns, addressing stability, tightness, containment, site selection, and capacity potential in China. Key findings include: 1) CCES, an advanced version of CAES, offers doubles the installed capacity compared to traditional CAES by combining the benefits of both CAES and CCUS benefits. 2) CCES salt caverns in typical bedded salt formations can maintain stability and integrity for 100 years. 3) Optimal cavern depths for supercritical CO₂ storage range 800-1500 m, with a minimum cavern volume of $25 \times 10^4 \text{ m}^3$ for a capacity of at least 300 MW. 4) CO₂ storage in salt caverns offers better tightness compared to air, methane (CH₄), and hydrogen (H₂), with an interlayer permeability threshold of $\leq 1.0 \times 10^{-18} \text{ m}^2$ for adequate tightness. 5) Potential CCES sites in China have been identified, with preliminary estimates suggesting a total capacity of 46.62-69.93 GW and theoretical capacity of up to 280 million tons of CO₂ for China's hard-to-abate sectors.

INTRODUCTION

Escalating global environmental pollution and climate change are posing severe threats to ecosystems and human societies¹, particularly in China, contributing about one-quarter of the world's carbon emissions. China's rapid economic growth and heavy reliance on fossil fuels have made it the largest carbon emitter globally (Figure 1A, Figure 1B and Figure 1E).^{2,12,13,37} To confront this challenge, China has committed to peaking carbon emissions by 2030 and achieve carbon neutrality by 2060,³ reflecting the urgency and determination in combating climate change. However, achieving these goals requires more than just a reduction in fossil fuel consumption; it necessitates the large-scale implement of advanced technologies such as compressed air energy storage (CAES) (Figure 2A)⁴ and carbon capture, utilization, and storage (CCUS) (Figure 2C).^{5b}

Both the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) emphasize the critical role of CCUS and CAES in the global energy transition. CCUS has the potential to significantly reduce large-scale emissions and, when combined with bio-energy, can even achieve negative emissions. Despite the international recognition, China still faces significant challenges in scaling these technologies. Most CCUS projects in China remain limited in scale, capturing only about 3 million tons of CO₂ annually^{-7b} far below the levels required to meet national carbon reduction targets (Figure 1D). Similarly, while CAES presents a promising solution for storing and converting excess renewable energy, it faces chal-

lenges, such as high costs and limited capacity (Figure 1C and Figure 1F). The early concept of CCES referred to Compressed CO₂ Energy Storage,⁹ primarily focusing on using man-made containers for CO₂ compression and storage,¹⁰ with corresponding energy storage models proposed.¹¹ While the early concept of CCES offered promising insights into compressed CO₂ storage, it had limitations in terms of functionality and capacity. Moreover, it did not consider the potential integration of CAES and CCUS, which offers more comprehensive energy solutions. This paper introduces an innovative concept of CCES by combining CAES and CCUS within underground salt caverns, expanding its potential applications (Figure 2B and Figure 2D). Salt caverns,¹² known for their excellent tightness properties, stability, and capacity,^{13,14} have been widely used for storing oil^{15,16} and natural gas^{17,18} since the 1940s. Currently, approximately 30 billion m³ of natural gas and two-thirds of the world's strategic oil reserves are stored in these formations. They are also ideal for advanced energy storage solutions like CAES and CCUS. Internationally, prominent examples of CAES include the Huntorf (Germany)¹⁹ and McIntosh (USA)²⁰ projects. China has plans similar projects^{21,22} with a combined installed capacity of around 6,210 MW.¹³ In China, there are currently six operational salt cavern gas storage projects, with over ten additional projects either under construction or planned, expected to exceed 20 billion m³ in total capacity.²³ As China's demand for renewable energy continues to grow, the potential of salt cavern storage becomes increasingly significant. Projections suggest that by 2060, China will develop approximately 400 million m³ of underground salt cavern space. If these caverns are utilized for CCES purposes, they could theoretically store up to 280 million tons of CO₂ from hard-to-abate sectors, supporting for China's 2060 carbon neutrality goal and highlighting the critical role of CCES in the future energy transition.

This study presents the operational concept of CCES, assesses its stability and tightness performance in salt formations, proposes site selection criteria, and forecasts its potential for power generation and carbon reduction in China (Figure 2E). By providing new insights into large-scale energy storage and carbon disposal, this research contributes to advancing both in China's and global efforts in sustainable energy solutions and carbon mitigation strategies.

MATERIALS AND METHODS

Energy efficiency calculation

The concept of CCES proposed in this paper uses CO₂ as the main energy storage medium to replace air in traditional CAES, aiming at combining CCUS carbon reduction technology with energy storage technology to achieve CCUS. As shown in Table S1, compared with air, CO₂ has a similar specific heat capacity and similar compressibility, which makes it easier to be compressed under the same conditions.

In the compression stage, assuming that the energy consumption during compression is considered only from the perspective of the compressor, there is no other energy loss and no gas leakage, the compressor power can be calculated as:

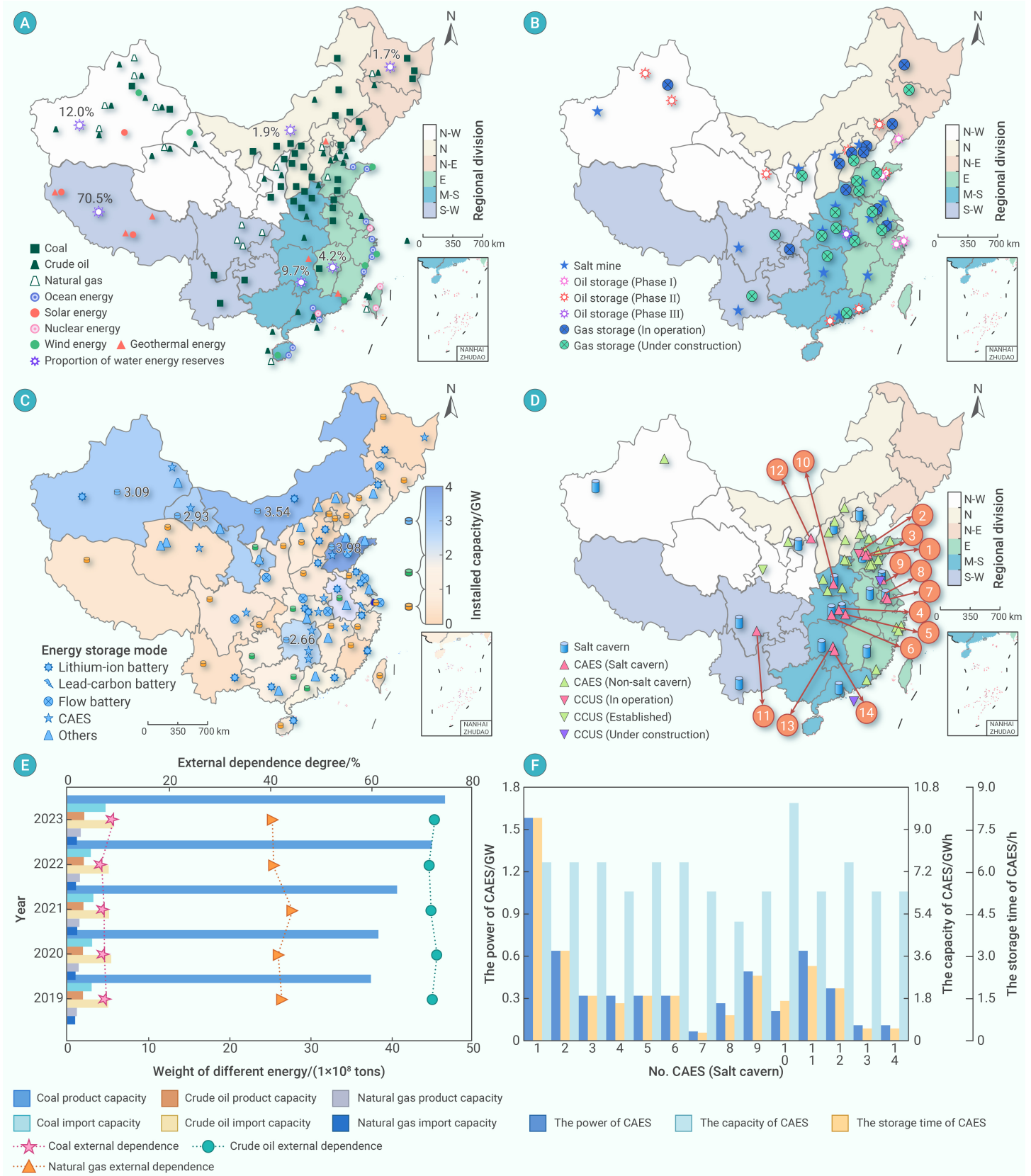


Figure 1. Energy, CAES and CCUS distribution in China (2023) (A) Distribution of energy sources in China. (B) Distribution of salt cavern storage in China. (C) Distribution of energy storage modes in China. (D) Distribution of CAES and CCUS plants in China. (E) China's energy share over the years. (F) China salt CAES operation specifications.

$$P = \frac{W}{t} = \frac{W_1}{\eta} = \frac{m_1 \times c_p \times (T_{out} - T_{in})}{\eta}, \quad (1)$$

where, P is the compressor power, W ; W is the work consumed in the

compression stage, J ; t is the compressed time, s ; W_1 is the power rate, W ; η is the efficiency of the compressor, the default is 0.8; m_1 is the mass flow in the compression process, kg/s ; c_p is the specific heat capacity of the medium, $J/(kg \cdot K)$; T_{out} and T_{in} are respectively the compressor outlet and

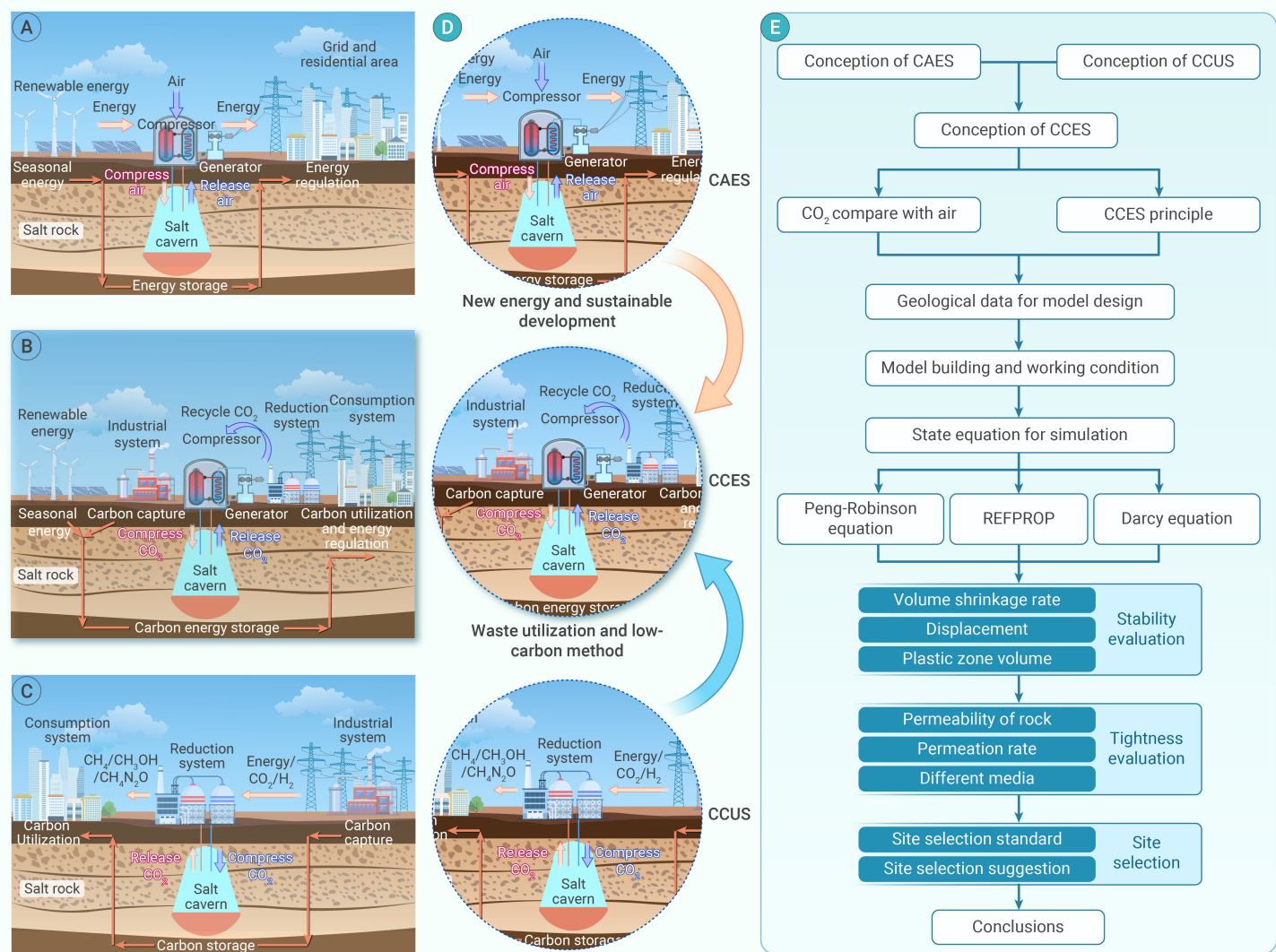


Figure 2. CAES, CCUS and CCES related concept (A) Working principle of salt cavern CAES power station. (B) Working principle of salt cavern CCES power station. (C) Working principle of salt cavern CCUS power station. (D) Schematic of salt cavern CAES and CCUS combined with CCES. (E) Research frame.

inlet temperature, K.

In the energy release stage, the Brayton cycle²⁴ can serve as a simplified model for calculating the output power of turbine, based on the non-secondary combustion turbine's release mechanism. The output power of turbine can be calculated according to the following equation:

$$P_1 = \frac{m \times (h_1 - h_2)}{\eta}, \quad (2)$$

where, P_1 is the turbine power, W; m is the mass flow of the release process, kg/s; η is the efficiency of the turbine, the default is 0.8; h_1 and h_2 are the enthalpy of the medium in the input and output states, kJ/kg, respectively.

Geological model construction

A salt cavern with a depth of 1000 m, a height of 130 m and a maximum radius of 50 m is established according to the formation conditions. Interlayers are evenly distributed in the salt rock layer around the cavern. There are a total of 17 mudstone interlayers with a thickness of 2 m uniformly distributed. The top and bottom of the cavern are 200 m thick mudstone. At the same time, with reference to the seepage storage of sediment and surrounding rock^{25,26} the effective volume of the whole cavern is as high as $40 \times 10^4 \text{ m}^3$, as shown in Figure 3B. This model can well fit the conditions of bedded salt rock formation with "thin single layer, many interlayers and high impurities", and also facilitate the subsequent creep simulation.

It is necessary to set specific operating conditions, including upper and lower limits of injection and production pressure, injection and production

frequency, etc. According to the buried depth of the model 1000 m, the stress of the raw rock at the top of the cavern is 23 MPa. With reference to the design experience of the existing gas storage reservoir in China's bedded salt rock, the critical pressure of supercritical CO_2 , and previous relevant studies,²⁷ the upper limit of the pressure can be set as $0.8 \sigma_0 = 18.4 \text{ MPa}$. The lower pressure limit is set to 16.1 MPa when the condition of 7.38 MPa of supercritical CO_2 and the safe pressure of gas storage exceeds $0.2 \sigma_0 = 4.6 \text{ MPa}$. To meet the daily demand for power supply peak regulation, the injection and production frequency is set to 1 time/d, which can meet the daily 8 h charge and 5 h discharge from the perspective of CAES, and far exceed the considerable economic flow from the perspective of CCUS.²⁸ As shown in Figure 3C, under this operating condition, according to previous studies,²⁹ the stability of the cavern is relatively good.

Creep model construction

The creep constitutive model of Flac3D and Norton-power constitutive model have been widely used to study the creep of combined formations of salt rock and mudstone.^{30,31} The creep equation is as follows:

$$\dot{\epsilon}_s = A \times \left(\frac{\sigma_1 - \sigma_3}{\sigma'} \right)^n, \quad (3)$$

where, A is the creep constant of the material, $\text{MPa}^{-n} \cdot \text{yr}^{-1}$; n is the stress index parameter, determined by the material; $\dot{\epsilon}_s$ is the steady state creep rate; σ_1 and σ_3 are the first and the third principal stress respectively, MPa; σ' is the unit stress, take 1 MPa. Detailed constitutive parameters set are shown in

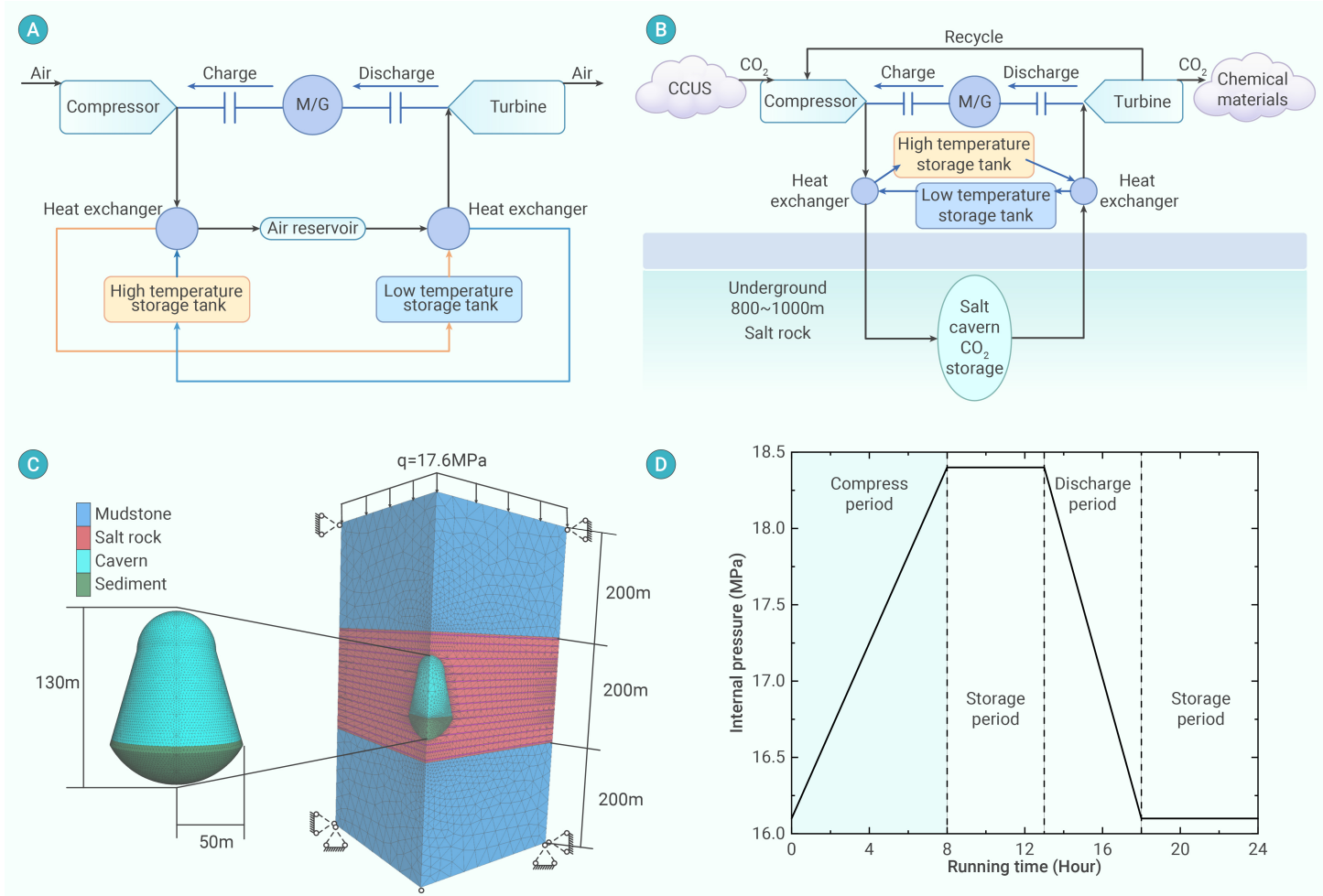


Figure 3. CCES principle, model and working condition design (A) Schematic diagram of non-secondary combustion CAES technology. (B) Salt cavern non-secondary combustion CCES schematic diagram. (C) Geological model. (D) Injection and production pressure circulation diagram.

Table S3.

Since CO_2 is stored in a supercritical state under this formation condition, the most widely used CO_2 gas equation is the Peng-Robinson equation of state (EOS).³²

$$P_2 = \frac{RT}{V_m - b} - \frac{a(T)}{V_m(V_m + b) + b(V_m - b)} \quad (4)$$

$$a(T) = 0.45723553 \times \frac{R^2 T_c^2 a(T)}{P_c} \quad (5)$$

$$b = 0.077796074 \times \frac{RT_c}{P_c} \quad (6)$$

$$a(T) = [1 + (0.37464 + 1.54226w - 0.26992w^2) \times (1 - T_r^{0.5})]^2 \quad (7)$$

Here, P is gas pressure, Pa; V_m is the molar volume of the gas, that is, the volume of 1 mole of gas, m^3/mol ; T is the temperature of the gas, K; R is the gas constant, $R = 8.314 \text{ Pa} \cdot \text{m}^3 \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$; b is the constant calculated according to the above equation; $T_r = T/T_c$ is the reduction temperature defined by the ratio of temperature to the critical temperature. T_c , P_c , and w represent the critical temperature, critical pressure, and centrifugal factor, respectively. Correspondingly, for CO_2 , the relevant parameters $T_c = 304.19 \text{ K}$, $P_c = 7.3815 \times 106 \text{ Pa}$, and $w = 0.22746$.

Volume shrinkage, deformation displacement and plastic region distribution are often used to evaluate cavern stability. Volume shrinkage rate refers to the ratio of the current effective volume reduction of the cavern to the initial effective volume of the cavern.³³

$$n = \frac{V_i - V_0}{V_0} \times 100\%, \quad (8)$$

where, n is the volume shrinkage rate, %; V_i is the effective volume of the cavern running to year i , m^3 ; V_0 is the effective volume of the initial cavern, m^3 .

The plastic zone in salt cavern is often judged by the failure criterion of Mohr-Coulomb strength.^{34,35}

$$\tau = c + \sigma \tan \phi, \quad (9)$$

where, τ is the shear stress on the shear failure surface, MPa; σ is the normal stress on the shear failure surface, MPa; c is the cohesion of rock mass, MPa; ϕ is the internal friction angle of rock mass, $^\circ$.

Infiltration model construction

To determine whether CO_2 penetration into the surrounding rock, it is essential to set and monitor the pore pressure. The pore pressure of the surrounding rock increases as the pressurized CO_2 permeates into it. In our model, CO_2 is stored in a supercritical state in the formation of 1000 m depth and 323.15 K temperature. REFPROP software³⁶ is used to compute the density, viscosity and compression coefficient of CO_2 under as the pressure varies.

The CO_2 density varies with pressure as:

$$\rho_{50^\circ\text{C}} = -1.5041P(t)^2 + 71.327P(t) - 66.47. \quad (10)$$

The CO_2 viscosity varies with pressure as:

$$\mu_{50^\circ\text{C}} = -0.1314P(t)^2 + 7.1083P(t) - 24.68. \quad (11)$$

The CO_2 compression coefficient varies with pressure as:

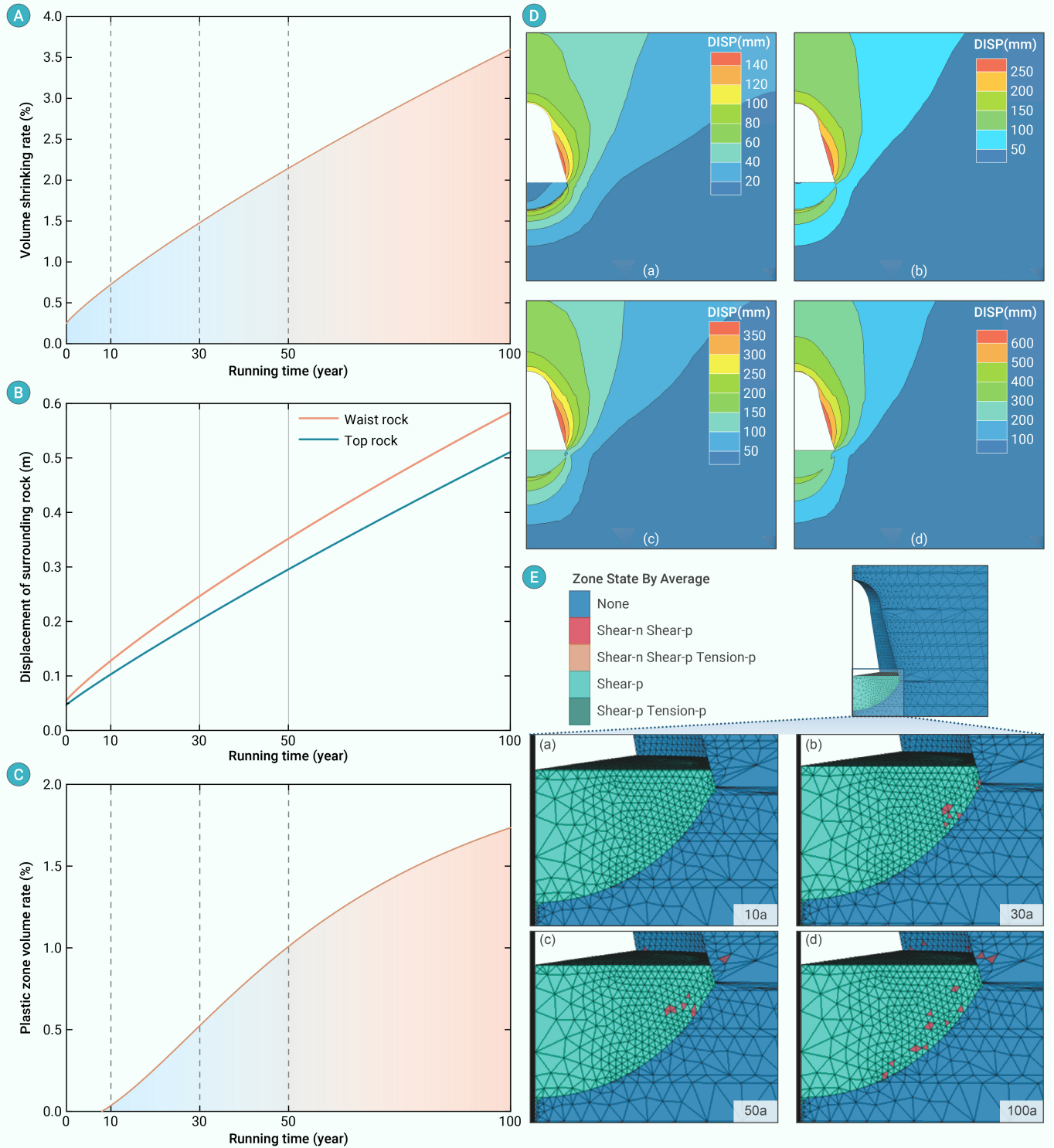


Figure 4. Stability evaluation diagram (A) Volume shrinkage diagram. (B) Displacement diagram of cavern surrounding rock. (C) Volume proportion diagram of cavern plastic zone. (D) Cavern morphology diagram: (a) 10a, (b) 30a, (c) 50a, (d) 100a. (E) Cavern plastic zone distribution: (a) 10a, (b) 30a, (c) 50a, (d) 100a.

$$\beta_{50^{\circ}\text{C}} = 2E - 4P(t)^{-3.153}. \quad (12)$$

Here, $P(t)$ is the pressure of CO_2 , MPa; $\rho_{50^{\circ}\text{C}}$ is the density of CO_2 , kg/m^3 ; $\mu_{50^{\circ}\text{C}}$ is the dynamic viscosity of CO_2 , $1/\text{Pa}$; $\beta_{50^{\circ}\text{C}}$ is the compression coefficient of CO_2 , $1/\text{Pa}$.

When storing CO_2 in salt caverns, its migration behavior, as well as the diffusion and slippage effects, must be considered. The flow regime of CO_2 in surrounding rocks can be determined using the Reynolds number of CO_2 flow:

$$R_e = u\rho\sqrt{K}/1750\mu\phi^{1.5}, \quad (13)$$

where, R_e is the permeability Reynolds number and has no dimension; u is the flow rate of the fluid, cm/s ; K is the permeability of rock, m^2 ; ρ is the fluid density, g/cm^3 ; μ is the fluid viscosity, $\text{mPa} \cdot \text{s}$; ϕ is the porosity of the rock, no dimension. The calculation shows the Reynolds number far less than 0.1 in each layer, indicating the penetration of CO_2 in surrounding rocks follows Darcy's law.

The Darcy seepage module³⁷ in COMSOL is used to simulate the infiltration process of CO_2 into the surrounding rock of salt cavern, initially satu-

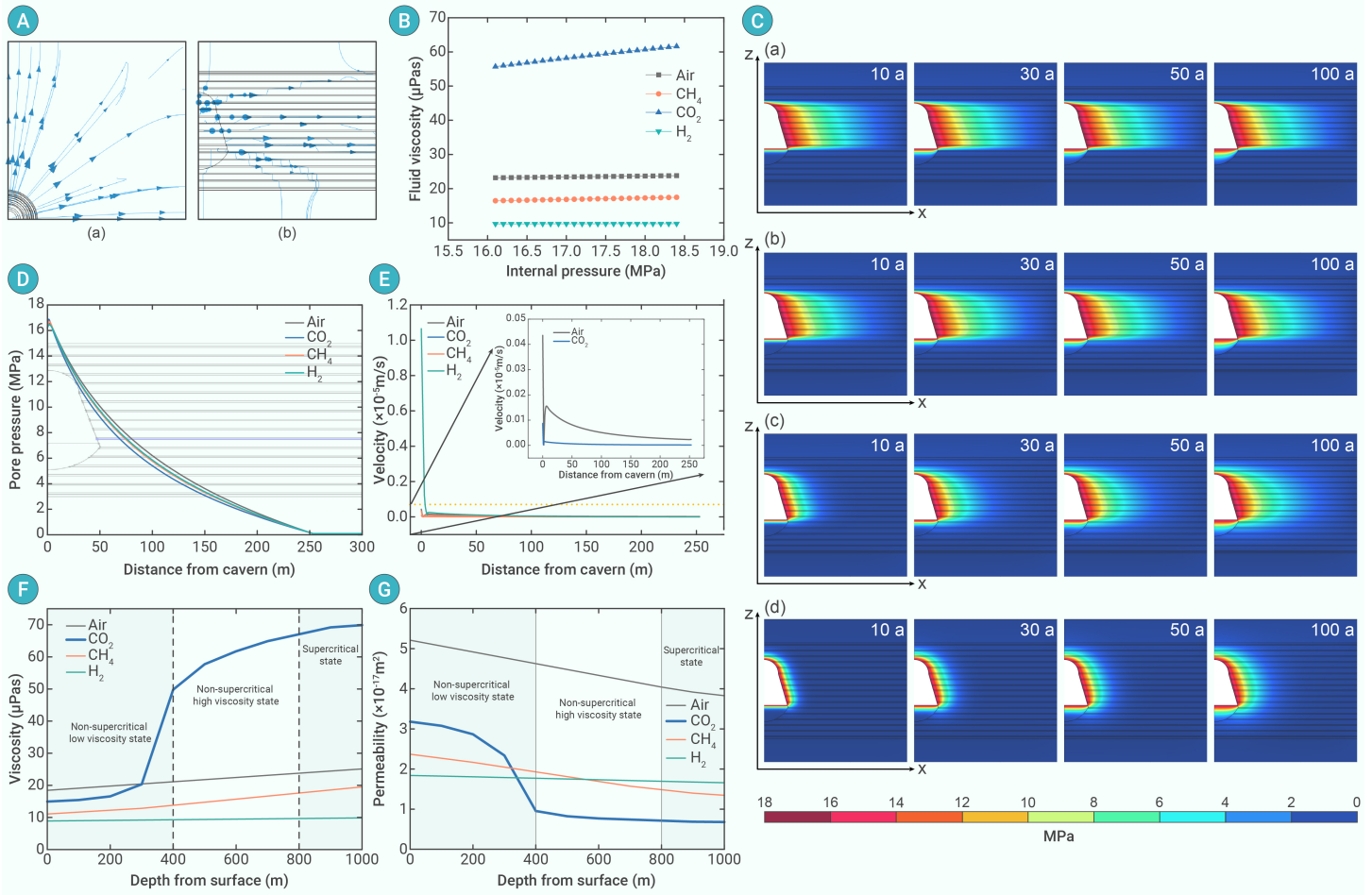


Figure 5. Tightness evaluation diagram (A) Permeation flow diagram. (B) Viscosity diagram of different storage media. ($T = 323.13$ K) (C) Pore pressure diagram of interlayer with different permeability of cavern (Unit: MPa). (a) Interlayer-1, (b) Interlayer-2, (c) Interlayer-3, (d) Interlayer-4. (D) Pore pressure distribution of different storage media in cavern. (100a) (E) velocity distribution of different media. (F) Changes of gas viscosity at different burial depths. (G) Changes of gas permeability at different burial depths.

rated with water. The governing equations of the model are as follows:

$$\frac{\partial}{\partial t}(\phi\rho) + \nabla(\rho u) = Q_m \quad (14)$$

$$\frac{\partial}{\partial t}(\phi\rho) = \rho S \frac{\partial P}{\partial t} \quad (15)$$

$$S = \phi\beta_g + (1 - \phi)\beta_s \quad (16)$$

$$u = -K \frac{\nabla P + \rho g \nabla Z}{\mu} \quad (17)$$

where, Q_m is the mass flow; Z is the hydraulic water head; g is the gravitational acceleration; S is the water storage coefficient; β_g is the fluid compression coefficient, and β_s is the rock skeleton compression coefficient.

Key parameters of layered salt rock mainly include porosity, permeability, and compressibility. According to the established model and the geological conditions of layered salt rock in China, the porosity and permeability parameters of salt rock and mudstone interlayer are shown in Table S4.³⁸

Permeation tests using different gases (Air, CH_4 , CO_2 , H_2) are conducted on the same sandwich rock of mudstone interlayer under identical conditions: room temperature 25°C and confining pressure 5 MPa. Table S5 summarizes the values of the measured permeability.

Definition of permeability coefficient

To better evaluate the tightness of salt caverns for CO_2 , the permeability coefficient of fluid stored in salt cavern, α ,³⁸ can be calculated by the following equation:

$$\alpha = \frac{A_i \phi_i K_i}{A_{\text{cavern}}} \quad (18)$$

where, A_i is the interlayer area of salt cavern, m^2 ; ϕ_i is the porosity of interlayer in the formation, %; K_i is the permeability of interlayer of salt cavern, m^2 ; A_{cavern} is the total surface area of the salt cavern, m^2 .

Based on the parameters of the interlayer area in the surrounding rock, the salt cavern surface area, and the porosity and permeability of relevant interlayers in this model, the permeability coefficients for storing different gases storage under varying permeability are calculated for 4 distinct groups, as shown in Table S6 below. The permeability coefficient is influenced both indirectly by the gas viscosity and directly by the permeability of the interlayers. Because the permeability decreases exponentially, the gas penetration capacity also decreases exponentially, which indicates that the permeability characteristics of the interlayer play a major role in the process of salt cavern storage, while the gas itself has little influence.

RESULTS

CCES concept and working principle

Traditional adiabatic CAES systems,³⁹ such as those at Huntorf and McIntosh, operate with conventional combustion-gas turbines. However, these systems have several drawbacks including natural gas consumption, low energy conversion efficiency, and associated carbon emissions. To address these issues, advanced adiabatic CAES (AA-CAES) technology has been proposed.⁴⁰ Unlike traditional CAES, AA-CAES captures and re-utilizes compression heat and residual energy without relying on fossil fuels, resulting in improved efficiency and a reduced environmental impact. The development of AA-CAES offers a promising solution to the limitations of traditional adiabatic CAES systems.

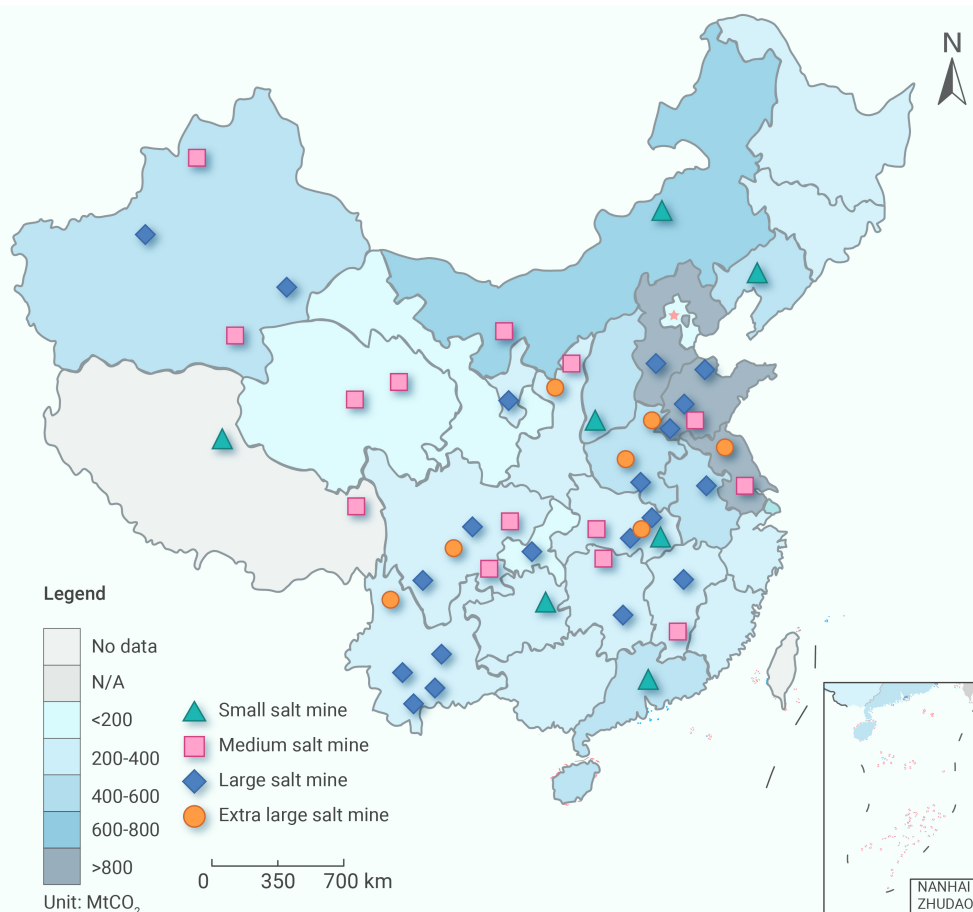


Figure 6. Spatial distribution of CO₂ emissions and salt mines in China in 2019.

(5) Recycling: The de-pressurized CO₂ is re-compressed and stored again back to the salt cavern, allowing the system to balance energy supply and demand. Additionally, the CO₂ can be reused for carbon processing or other industrial applications.

To compare the performance of CAES and CCES systems, we analyze a salt cavern at a depth of 1000 m with a volume of $50 \times 10^4 \text{ m}^3$ and an operating pressure range of 16.1 to 18.4 MPa. The gas compression phase (i.e. energy storage phase) spans 8 hours, while energy discharge occurs over 5 hours. The comparison of energy efficiency between air and CO₂ is shown in Table S2.

Notably, under these conditions, CO₂ exhibits over twice the storage density and flow rate compared to air. With these parameters, a CAES system would achieve an installed capacity of 15.42 MW. For a 300 MW air-based AA-CAES system, the required airflow is about $42.16 \times 10^3 \text{ t/h}$. In contrast, by switching to supercritical CO₂, the CCES system's capacity can be doubled to 600 MW with a reduced flow rate of about $30.76 \times 10^3 \text{ t/h}$. From the simulation and analysis, the cavern holds up to 36×10^4 tons of CO₂ under an operational pressure range of 16.1 to 18.4 MPa, storing significant amounts of

AA-CAES stores surplus electricity by compressing and storing gas, typically air, in a chamber during periods of low energy demand. During high-demand periods, the stored high-pressure gas is released through an expansion turbine to generate electricity, providing a reliable and efficient method for large-scale energy storage and conversion. Salt caverns are increasingly utilized in AA-CAES systems for their excellent sealing and structural properties, and potential storage gases¹⁶ include air, CO₂, nitrogen, or helium.

However, traditional AA-CAES faces limitations such as relatively low energy density and efficiency when using air as the storage medium. To address these challenges, supercritical CO₂ has emerged as a promising alternative due to its higher density, superior energy storage capacity,^{41,42} and favorable thermodynamic properties. Building on these advantages, this paper introduces the concept of Compressed CO₂ Energy Storage (CCES)—a novel variant of AA-CAES. CCES leverages salt caverns for storing compressed supercritical CO₂ instead of air, enhancing energy density and operational efficiency. Beyond energy storage, CCES offers the added benefit of large-scale carbon sequestration, utilizing the high mass density and gas viscosity of supercritical CO₂ to ensure secure, long-term containment. This dual functionality makes CCES an innovative solution for integrating renewable energy and addressing carbon emissions challenges. The CCES system operates through five distinct stages (Figure 3A), combining the principles of energy storage and carbon management to create a comprehensive and efficient energy solution.

(1) CO₂ Capture and Purification: CO₂ is captured from industrial sources, then purified, and conditioned for subsequent compression and storage.

(2) Compression: The purified CO₂ is compressed and injected into a salt cavern, displacing in-situ brine and achieving its supercritical pressure.

(3) Energy Storage: The compressed CO₂ is stored underground in the salt cavern, with pressure and injection-extraction cycles carefully managed to ensure safety and system stability.

(4) Energy Release: When energy is needed, the pressurized CO₂ is released from the cavern and the stored energy is converted into electricity using a turbine, with output adjustable to meet power grid demands.

compressed CO₂. During the energy discharge phase, about 30.76×10^3 tons/hour of supercritical CO₂ is released. With 5 hours of discharge per day, the total CO₂ extracted daily would be about 153,800 tons of CO₂.

The energy storage capacity of salt caverns is closely tied to the operating pressure range. Achieving a 300 MW output within the 16.1–18.4 MPa range presents a challenge, as conventional CAES systems typically operates at much lower pressures, around 1.0–7.0 MPa or 3.0–9.0 MPa for such capacities. However, the higher density and enthalpy of CO₂ under these conditions enable significantly; CO₂ has over twice the mass flow rate of air and releases more than five times the energy, making it a superior medium for energy storage and discharge under these conditions (Table S2).

The CCES system using CO₂ is considered to be more efficient and environmentally friendly compared to CAES, primarily due to the higher density and similar compressibility of CO₂, which significantly reduces energy loss. Furthermore, the integration of CCES with CCUS technology plays a crucial role in isolating CO₂ from industrial emissions, thereby enhancing energy efficiency and carbon reduction.⁴³ Underground salt caverns are identified as ideal for this purpose, offering a large capacity, flexible scalability, and cost-effectiveness. These caverns provide an optimal solution for energy storage and carbon management. Additionally, from an ecological perspective, CCES systems have a minimal environmental impact. The storage reservoirs are located deep underground, typically at depths around 1000 meters, and are encased by dense salt formations. This natural geological barrier ensures minimal interaction with the surrounding deep-earth environment. On the surface, the impact is also minimal, as the only infrastructure connecting the storage cavern to the surface is a small wellhead, occupying very little land. This isolation ensures that the CCES system exerts negligible influence on surface ecosystems or land use. This approach supports early deployment of CCES plants and provides a novel solution for large-scale carbon management, particularly in areas where alternative storage options are limited.⁴²

In conclusion, CCES using salt caverns provides a secure, cost-effective, and environmentally friendly option for integrating renewable energy and reducing carbon emissions. This approach reduces reliance on traditional

energy sources while incorporating CCUS technology to advance the efficiency and scalability of renewable energy systems. By combining energy storage and carbon management, CCES represents a forward-thinking strategy for advancing the global transition toward clean energy.

Stability analysis of CCES salt cavern

Considering the unique characteristics of bedded salt rocks in China, such as thin single layers, numerous interlayers, and high impurities, this study focuses on examining the salt-bearing strata in Huai'an City, Jiangsu Province. It has been determined that salt caverns at depths exceeding 800 m in this region are suitable for supercritical CO₂ storage. To explore this potential, a model salt cavern is established with a depth of 1000 m, a height of 130 m, and a maximum radius of 50 m. The model includes 17 evenly spaced mudstone interlayers, each 2 m thick, with an additional 200 m of mudstone layers at both the top and bottom. Calculations indicate the cavern's effective volume to be about $40 \times 10^4 \text{ m}^3$, which accurately represents typical bedded salt rock conditions in China, making it suitable for energy injection-extraction cycle simulations.

Based on design practices for bedded salt rocks in China,²⁹ the critical pressure for supercritical CO₂, and previous studies,²⁹ the operational pressure range for the CCES salt cavern is set at 16.1 to 18.4 MPa. The designed CCES system operates on a daily injection-production cycle of 8 hours charging and 5 hours discharging. Based on the proposed operational conditions, the simulation over a 100-year period showed that the cavern's volume shrank by a maximum of 3.61%, remaining well below the 30% threshold (Figure 4A).⁴³ Initial shrinkage results from stress balance due to excavation. Displacements of deformation show a maximum roof subsidence of 0.58 m and waist deformation of 0.51 m, both within 5% (2.5 m) of the cavern's diameter (Figure 4B).^{44,45} Deformation is primarily due to lateral convergence and surrounding rock deformation, with maximum displacement reaching 0.60 m after 100 years (Figure 4D). Plastic zone volume increases slightly from 0% to 1.65% but stabilized by the end of the simulation (Figure 4C), indicating long-term stability. Although plastic zone distribution increases near the cavern's maximum diameter, but no significant plastic failure is observed (Figure 4E).

Tightness analysis of CCES salt cavern

Under identical operating conditions, simulations are conducted with varying interlayer permeability parameters to assess cavern tightness under different salt formation conditions. Figure 5A illustrates that CO₂ primarily permeates through interlayers, which have significantly higher permeability than the surrounding salt rock, spreading outwards from the cavern wall. Figure 5C displays the pore pressure distributions for different interlayer permeabilities after 10, 30, 50, and 100 years. For interlayer permeabilities of 1×10^{-16} and $1 \times 10^{-17} \text{ m}^2$, CO₂ can penetrate up to 300 m within 30 years. In contrast, at a permeability of $1 \times 10^{-18} \text{ m}^2$ CO₂ penetration is significantly reduced and does not reach the boundary even after 100 years. Further reducing permeability to $1 \times 10^{-19} \text{ m}^2$ further limits CO₂ penetration even more. We conclude that higher permeabilities pose a risk of excessive CO₂ spread.

The performance of CO₂ compared to other gases varies under formation conditions (pressure gradient of 2.3 MPa/100 m, a surface temperature of 25°C, and a geothermal gradient of 3°C/100 m). Figure 5F and Figure 5G reveal that CO₂ viscosity and permeability change with depth: low viscosity and similar permeability to other gases up to 400 m; high viscosity with 4 to 5 times lower permeability between 400 and 800 m; and the highest viscosity and lowest permeability below 800 m. At a 1000 m depth, permeability values are: air - $3.83 \times 10^{-17} \text{ m}^2$, CH₄ - $1.34 \times 10^{-17} \text{ m}^2$, H₂ - $1.66 \times 10^{-17} \text{ m}^2$, and CO₂ - $6.79 \times 10^{-18} \text{ m}^2$. After 100 years, CO₂ consistently exhibits the lowest pore pressure, the slowest seepage velocity compared to air, CH₄, and H₂, with a seepage distance of 250 m. Figure 5E shows the corresponding seepage velocities after 100 years: H₂ at $1.06 \times 10^{-5} \text{ m/s}$, air at $4.35 \times 10^{-7} \text{ m/s}$, CH₄ at $3.25 \times 10^{-7} \text{ m/s}$, and CO₂ at $8.68 \times 10^{-8} \text{ m/s}$. The slower seepage velocity of CO₂ in salt cavern storage results in a shorter penetration range, demonstrating superior tightness compared to other gases and making it a more secure and effective option for long-term containment.

DISCUSSION

With the technical parameters established and the simulation results determined, the next crucial step is to evaluate the overall feasibility of CCES. In this context, safety is one of the top priorities, particularly the stability and tightness of salt cavern storage. Long-term stability and secure containment are crucial for ensuring the system's viability. This study analyzes simulation results to assess these factors, proposes site selection criteria for CCES salt cavern plants based on China's geological conditions, and examines the overall feasibility of CCES in terms of stability, tightness, site selection, and potential installed capacity.

Stability assessment

Despite the advancements in CO₂ storage technologies, China currently lacks specific standards for evaluating storage stability in salt caverns. To address this, we adapt the guidelines from existing gas storage or compressed air energy storage projects in bedded salt rock. A key consideration is limiting volume shrinkage, as it directly impacts storage capacity, economic viability, and cavern stability.⁴³ For a CCES plant, maintaining a stable volume shrinkage rate is crucial, it should be limited to 20% after 30 years and 30% after 100 years to ensure long-term stability. Our calculations show that operating at an average pressure of 17.25 MPa supports cavern stability and maximizes CO₂ energy density, extending system lifespan and ensuring reliable long-term storage.

Another key indicator of cavern stability is the displacement of surrounding rock. Research indicates that maximum displacement should not exceed 5% of the cavern's maximum diameter. Our calculations suggest that after 100 years of operation, displacements levels have remained stable and below this threshold, indicating strong stability. Additionally, special attention must be given to the cavern's waist, where displacement is higher than at the roof due to its pear-shaped design.⁴⁶ Moreover, the presence of a plastic zone near the maximum radius suggests potential deformation, which may require targeted reinforcement or design adjustments to maintain long-term stability.

In conclusion, over a 100-year operation period with pressures ranging from 16.1 to 18.4 MPa and daily injection-production cycles, the CCES salt cavern shows consistent stability in terms of volume shrinkage, surrounding rock displacement, and plastic zone distribution. This reliable performance suggests that salt caverns used in CCES plants will remain long-term structural integrity, reinforcing their feasibility for durable carbon storage and energy solutions.

Tightness assessment

The assessment of salt cavern tightness for gas storage focuses on the gas penetration range and seepage velocity. Our simulations indicate that as interlayer permeability decreases from $1 \times 10^{-16} \text{ m}^2$ to $1 \times 10^{-19} \text{ m}^2$, the gas penetration range also significantly reduces. Specifically, when interlayer permeability is below $1 \times 10^{-18} \text{ m}^2$, CO₂ penetration can be effectively limited to under 150 m. However, if the permeability exceeds this threshold, CO₂ penetration may exceed 150 m. Therefore, it is important to design the pillar width of CCES salt cavern based on the expected gas penetration range to ensure optimal storage safety.

Among various gases considered in this study, CO₂ has the smallest penetration range, which makes its storage safer compared to other gases. This enhanced safety is attributed not only to lower seepage of CO₂, influenced by formation's permeability, but also to its higher dynamic viscosity. The increased viscosity results in slower seepage velocity and reduced penetration. As shown in Figure 5B, at temperatures of 50°C and pressures between 16.1 and 18.4 MPa, the viscosity of gases considered increases with pressure. CO₂ not only starts with a higher viscosity than other gases considered but exhibits the steepest rate of viscosity increase with respect to pressure, further showing seepage velocity within the same salt formations.

In a summary, after 100 years of operation under pressures between 16.1 to 18.4 MPa with daily injection-production cycles, CO₂ storage in salt caverns demonstrates superior tightness compared to other gases considered. This suggests that bedded salt formations deemed suitable for gas storage can also be reliable for CO₂ storage. Moreover, formations that may not be ideal for other gases could still be viable for CO₂, thereby broadening the potential sites for CCES salt cavern plants.

Site selection standard

Our simulations confirm that the CCES salt cavern meets the stability and tightness requirements for a 100-year operational period. Based on these findings, the proposed site selection standards for constructing a CCES salt rock plant are as follows:

Siting Conditions: 1) Proximity to power grids: the CCES plant should be located near power grids to facilitate easy integration and effective peak load regulation; 2) Distance from sensitive area: the plan must be situated at a distance of more than 25 km from protected animal and plant areas, as well as residential zones, thus to minimize environmental impacts and disruption; 3) Geological stability: the geological formation at the site must be stable and sealed, avoiding areas with faults and folds to ensure structural integrity; 4) Cavern depth: the salt cavern should be located between 800 and 1500 m deep to maintain the supercritical state of CO₂ and achieve high energy storage capacity; 5) Cavern volume: to achieve a minimum installed capacity of 300 MW, the cavern volume should be at least $25 \times 10^4 \text{ m}^3$. These factors are crucial for ensuring the safe and efficient operation of the CCES plant.

Carbon Supply Conditions: A single salt cavern with a volume of $40 \times 10^4 \text{ m}^3$ can store between 28×10^4 and 36×10^4 ton of supercritical CO₂ under a pressure range of 16.1–18.4 MPa. The combined capacity of ten such CCES salt caverns significantly exceeds the current total capacity of all CCUS projects in China, which is 3 million t/year. However, successful CCES implementation depends on not only the storage capacity but also the carbon utilization and energy demands of the industrial and power sectors.

Tightness Conditions: Based on the calculated permeability coefficients at the evaluated conditions (air: 5.69×10^{-19} , CH₄: 1.99×10^{-19} , CO₂: 1.0×10^{-19} , H₂: 2.47×10^{-19}) (Table S7), CO₂ shows the lowest seepage capacity, indicating the best tightness for storage purposes. For CCES construction, the surrounding rock should meet the following criteria to ensure adequate tightness: permeability $\leq 10^{-18} \text{ m}^2$, porosity ≤ 0.11 , and a comprehensive permeability coefficient $\alpha \leq 1.0 \times 10^{-19} \text{ m}^2$.

Site selection recommendation

To ensure the stability and tightness of CCES salt caverns in bedded salt rock in China, several recommendations for developing CCES plants in these geological settings are proposed:

(1) Integration with Renewable Energy: High-frequency operations often result in excess CO₂, which can have negative environment impacts if released into the atmosphere. However, by integrating CCES technology, it is possible to recovery and compress the excess CO₂ for energy storage. Therefore, it is important to strategically locate CCES facilities near areas with high renewable energy potential, carbon emissions, and power consumption. As shown in Figure 6, suitable regions for CCES projects include East, Central, and Southwest China.^{47,48} Nevertheless, further studies are needed to account for complex terrain and geological conditions.

(2) Promising Locations: Statistics indicate that Huai'an, Chuzhou, Jintan, and Zhaoji salt mines in Jiangsu Province, along with Tai'an Salt Mine in Shandong Province, are highly suitable for CCES plant construction. Additionally, Henan and Hubei Provinces also show potential, however, further investigation is needed to assess the tightness and the thickness of interlayers. Supercritical CO₂, with its high viscosity, provides better tightness in salt caverns compared to other gases, making previously certified gas storage sites viable for CCES projects (Table S8).

(3) Evaluation of Existing Caverns: For existing or abandoned salt caverns, a feasibility assessment is necessary to determine their suitability for CCES projects. CO₂ storage is generally considered safer and more stable than storing air, CH₄, or H₂. Therefore, the site selection for CCES projects should not be limited to locations previously used for compressed air, natural gas, or hydrogen storage. Prior to utilizing existing caverns, a comprehensive analysis of the surrounding rock is required to assess potential risks from long-term CO₂-H₂O-mineral reactions. Additionally, an economic and social cost-benefit analysis should be conducted if necessary.

Power generation and carbon emission

Our previous research⁴² confirms that approximately 20–30% of the idle salt caverns in China can store about 51.8–77.7 million t of carbon. Most of these caverns (70%) are located at depths of 800–1500 m. If 60% of these

caverns are used for CCES, the total carbon storage capacity could reach 21.76–32.63 million t. With an average cavern depth of 1000 m and operating pressure of 16.1–18.4 MPa, the total installed capacity for CCES projects is estimated to be between 46.62 and 69.93 GW.

Assuming an 8-hour storage cycle and a 5-hour extraction cycle, approximately 153,800 tons of CO₂ can be extracted daily, further supporting carbon reduction goals and efficient energy storage. And the annual electricity generation could range from 69.93 to 104.895 TWh over 330 days. This would equate to saving 8.6–12.9 million t of standard coal annually. The implementing CCES projects in China is expected to reduce carbon emissions by 23.22–34.84 million t/year, sulfur dioxide emissions by 7,311–10,967 t/year, and nitrogen oxide emissions by 6,365–9,548 t every year, thereby significantly advancing carbon reduction and environmental protection goals.

CONCLUSION

This study presents an innovative approach, Compressed Carbon Energy Storage (CCES), by integrating Compressed Air Energy Storage (CAES) and Carbon Capture, Utilization, and Storage (CCUS) in underground salt caverns. The CCES system is demonstrated to have nearly double installed capacity of a conventional CAES system. Numerical simulations are used to assess the stability and tightness of the CCES salt cavern under specific conditions. The results confirm that bedded salt rock meets the necessary criteria for storage capacity, stability, and tightness. A cavern with a volume of $50 \times 10^4 \text{ m}^3$ can safely operate with a daily cycle for up to 100 years, demonstrating excellent performance. For optimal site selection, caverns should be located between 800 to 1500 m deep to effectively support supercritical CO₂ storage, with volumes exceeding $25 \times 10^4 \text{ m}^3$ to achieve a minimum 300 MW capacity. Interlayer permeability should be $\leq 1 \times 10^{-18} \text{ m}^2$ to ensure tightness, with even lower permeabilities ($1 \times 10^{-19} \text{ m}^2$ and $1 \times 10^{-20} \text{ m}^2$) further reducing CO₂ leakage. The high viscosity of CO₂ at its supercritical state provides better tightness compared to air, CH₄, or H₂, due to its supercritical state and higher viscosity. China's extensive salt resources, particularly in Central and East China, are well-suited for CCES plants. The potential installed capacity of CCES salt cavern projects in China is estimated to range from 46.62 to 69.93 GW, with an annual electricity output ranging from 76.92 to 115.38 TWh. These findings offer significant benefits for renewable energy storage and carbon reduction goals.

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AUTHOR CONTRIBUTIONS

Resources, Investigation, Project administration, Funding acquisition, Writing-original draft, Writing-review & editing, W.L.; Formal analysis, Investigation, Methodology, Software, Data curation, Writing-original draft, X.D.; Conceptualization, Methodology, Data curation, Formal analysis, Writing-review & editing, W.L., L.J. and J.W.; Methodology, Data curation, Investigation, Y.J. and J.W.; Resources, Formal analysis, Data curation, Investigation, K.W., N.Z., A.H. and X.K.. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND MATERIALS AVAILABILITY

Data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

Supplementary material is available at: <https://doi.org/10.59717/j.xinn-energy.2024.100065>