International Journal of Greenhouse Gas Control 133 (2024) 104109

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

Recent advances on carbon dioxide sequestration potentiality in salt caverns: A review

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ARTICLE INFO

Keywords:
Greenhouse gases
Global climatic changes
Salt caverns
CO_2 sequestration

ABSTRACT

Permanent CO_2 sequestration in the salt caverns seems to be one of the best geological storage options that can be used to reduce anthropogenic greenhouse gases emissions (GHGs) from the atmosphere. However, salt caverns are rarely used because other geological options are more available; hence, they are used for energy source storage for future use due to their high deliverability and ability to quickly switch an injection well to a production well. Nevertheless, salt caverns seem to have low leakage risk compared to other geological storage options due to low permeability, high ductility, and self-healing ability after deformation. In this review, recent advances in CO_2 sequestration in salt caverns have been presented. It has been revealed that salt caverns have great potential to store CO_2 permanently to help to mitigate global climatic change. Salt caverns built offshore in ultra-deep water in Brazil and Lotsberg salt formation, Alberta and Saskatchewan, Canada, have a great potential to store ~108 million tons of CO_2 and 3500 megatons, respectively. Furthermore, from geochemical Modelling and simulation, it has been revealed that these caverns can store a substantial amount of CO_2, specifically 4 billion sm^3 or 7.2 million tons, under conditions of 45 MPa pressure and a temperature of 42 °C. The identified research gaps in this study will motivate researchers and stakeholders to conduct more research on developing technology to sequestrate CO_2 into salt caverns as a reliable geological option to mitigate global climate change in places where other storage options are not available.

1. Introduction

Global energy demand is increasing fast due to the growing population and rising prosperity led by Asian developing countries (Guan et al., 2023; Shalaeva et al., 2020). From the World Energy Outlook report in 2022, the International Energy Agency IEA (2022) predicted that energy demand will increase by 47 % in 2050, with oil remaining the top source over renewables (Meghan and Maya, 2021; Mwakipunda et al., 2023c) which is associated with great greenhouse gases (GHGs) emissions with carbon dioxide (CO_2) contributing 76 % of total global emissions (Ritchie et al., 2020). China is the leading country in global CO_2 emissions, with 30.9 % expecting to reach a peak in 2030 with 14.4 billion tons and neutrality in 2060 (Zhang et al., 2022c), followed by the USA with 13.49 %, India with 7.3 %, Russia with 4.73 %, and Iran with 2.02 % (Ritchie et al., 2020). This CO_2 emission has caused global climatic changes, especially global warming, with an increase in the global average temperature rate of 1.7 °C per century (Guo et al., 2023).

Electricity generation contributes more than 70 % of CO_2 emissions. Coal still dominates as a major source of electricity around the world, producing 35.8 % of global electricity, followed by natural gas 22.2 %, hydropower 15.2 %, nuclear 9.2 %, wind 7.5 %, solar 4.5 %, other fossils like oil 3 %, bioenergy 2.4 %, and other renewables 0.2 %. China, India, and the USA produce 19.5 % of their electricity from coal. Coal has 14.98 billion tons of CO_2 per year, oil 11.84 billion tons of CO_2 per year, gas 7.92 billion tons of CO_2 per year, cement 1.67 billion tons of CO_2 per year, flaring 416.53 million tons of CO_2 per year, and other industry 296.15 million tons of CO_2 per year (Ritchie et al., 2020; Shen et al., 2023). In 2022, it was reported that CO_2 concentration in the atmosphere reached 421 ppm, almost 50 % more compared to the pre-industrial level in the 1700s (280 ppm) (Luo et al., 2023). To mitigate global climate change, it is proposed that the worldwide increase in temperature should be kept below 2 °C by 2100 (Aminu et al., 2017; Mwakipunda et al., 2023a; Ngata et al., 2023)

As a result, decarbonization has emerged as a research focus area to

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https://doi.org/10.1016/j.ijggc.2024.104109
Received 10 November 2023; Received in revised form 29 February 2024; Accepted 3 March 2024

minimize CO_2 emissions and ameliorate global climate change. Hence, Carbon Capture and Storage (CCS) (Fig. 1) have become the main technologies to reduce CO_2 emission in the atmosphere, which involves capturing CO_2 from the sources and store permanently in different geological options and has a success rate of 50 to 68 % with some projects achieved 95 % efficiency (Moseman and Herzog, 2021). Carbon capture technologies have been well discussed by Tan et al. (2016). As discussed by Zheng et al. (2020a), different ways of CO_2 storage can be classified as geological, biological, or oceanic. The geological CO_2 storage options include salt caverns, methane hydrate reservoirs, depleted oil and gas reservoirs, basaltic rocks, unmineable coal seams, oil reservoirs with residual oil saturation through enhanced oil recovery (EOR), deep saline aquifer, etc., (Aminu et al., 2017). Deep saline aquifer is the most preferred and implemented at the field scale level globally and earlier implemented at Sleipner saline aquifer in 1996 by injecting 1 million tons of CO_2 per year (Zhang et al., 2022a).

To achieve the primary mitigation strategy for the Paris Climate Summit agreement to achieve net zero greenhouse gases (GHGs) emissions by 2050 and a maximum global temperature increase of 1.5 °C (Mwakipunda et al., 2023b), more research on different CO_2 options is recommended. However, salt caverns storage option has been given little attention because of the high associated costs, instead used to store industrial waste materials (nuclear materials)(Shi et al., 2021) and energy gases such as hydrogen (Caglayan et al., 2020), compressed air energy storage (CAES)(Chen et al., 2017; Han et al., 2021), oil (Zhang et al., 2017), etc. due to its high deliverability and ability to quickly switching an injection well to production well. However, salt caverns can be used to store CO_2 permanently in areas where there are no other storage options, like Alberta and Saskatchewan in Canada, salt Caverns built offshore in ultra-deep water in Brazil or other places where the salt deposits are high (Zhang et al., 2022b). In addition, salt formations are found in almost every part of the world, providing a high chance of constructing salt caverns for CO_2 sequestration near the carbon source to reduce the transportation cost to storage sites(Dusseault et al., 2004). Furthermore, salt cavern has high sequestration efficiency compared to other geological storage options with low leakage risk (Bachu and Dusseault, 2005a). For this reason(s), this mini review provides recent advances on using salt caverns for permanent CO_2 sequestration. To the best of the authors' knowledge, this is the first review on CO_2 sequestration in salt caverns. The findings of this review paper will pave the way and motivate researchers and stakeholders to consider salt caverns as another storage options which need to be considered for their researches to be utilized for CO_2 sequestration globally in near future to meet Paris climate summit agreement. This review paper consists of several sections includes, introduction, theory, potentiality towards field applications, CO_2 leakages and monitoring, research works and future works, advantages of CO_2 sequestration in salt caverns, and conclusions and recommendations.

1.1. *Possible CO_2 trapping mechanisms in salt caverns*

Salt caverns have proved to be one of the geological options which can store CO_2 permanently because of their significant storage capacity, found almost in every part of the world, geological stability (impermeable caprocks), depth, etc. The possible CO_2 trapping mechanisms in salt caverns include 1) Structural trapping mechanism, 2) Solubility trapping mechanism, 3) Residual trapping mechanism, and 4) Mineral trapping mechanism. The structural trapping mechanism is the primary trapping mechanism in which injected CO_2 rises upward due to buoyancy forces and is trapped in structural impermeable salt caverns' caprock. The pressure of injected CO_2 helps strengthen the caprock's sealing capacity (Pajonpai et al., 2022; Ramos et al., 2023). In the solubility trapping mechanism, the injected CO_2 dissolves in brine found in the salt caverns, which reduces the CO_2 mobility and becomes less likely to escape to the surface. For residual trapping mechanisms, a certain amount of injected CO_2 is trapped in salt pore spaces as residual gas. This mechanism contributes to less storage in salt caverns than other trapping mechanisms (Pajonpai et al., 2022; Zhang et al., 2022b). In the mineral trapping mechanism, some of the CO_2 in the solution reacts with salt cavern minerals to form stable carbonate minerals over a long period. This trapping mechanism takes a long time to form carbonate minerals but is the safest with low CO2 risk leakage compared to other trapping mechanisms. Possible reactions which can occur during CO_2 sequestration in salt caverns are shown in Table 1. These interactions must be

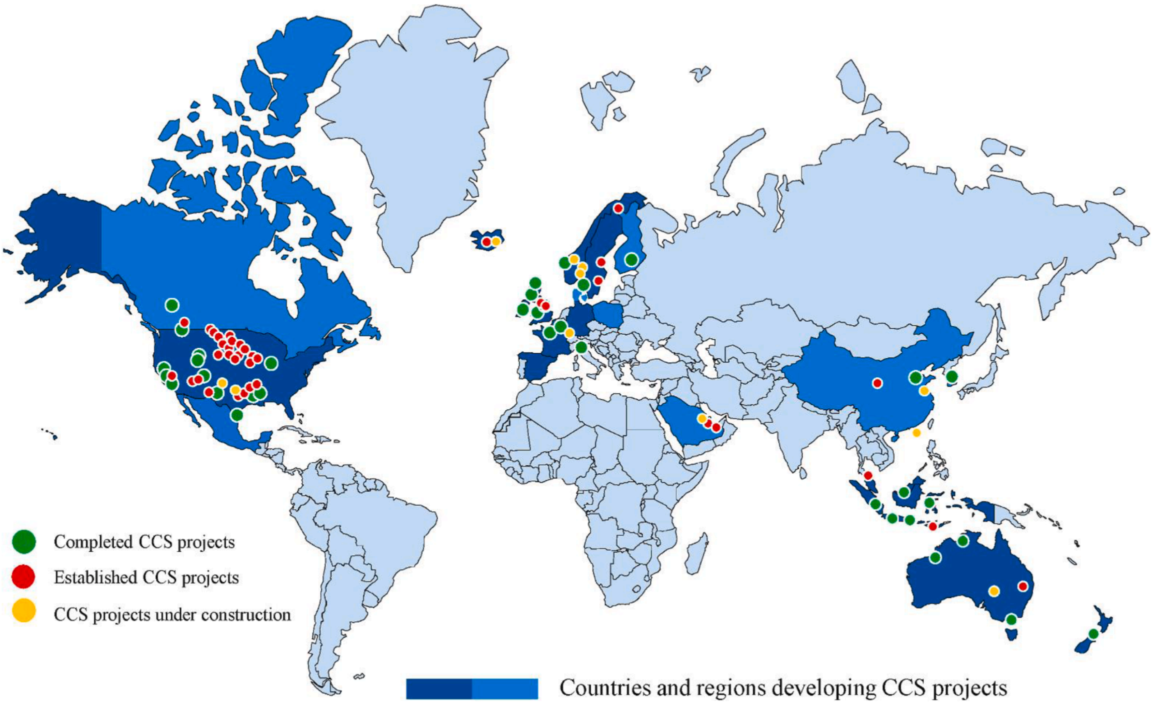


Fig. 1. Global CCS projects distribution (Wei et al., 2023a).

Table 1
Possible reactions which occur during CO_2 sequestration in salt caverns.

Reaction process	Reaction equations	Descriptions
1. Dissolution of salts in brine	$NaCl_{(s)} + H_2O_{(l)} \rightleftharpoons Na^{+}{}_{(aq)} + Cl^{-}_{(aq)}$	Brine is a corrosive solvent capable of dissolving salt (sodium chloride) found in the cavern walls. Salt dissolving can cause cavern growth over time, which may be advantageous for storage. However, a severe breakdown can jeopardize the cavern's structural stability, resulting in subsidence or collapse.
2. Formation of carbonic acid	$CO_{2\,(g)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3\,(aq)}$	The reaction between CO_2 and water H_2O results in the formation of carbonic acid H_2 CO_3, which subsequently causes a reduction in the pH level of the brine. Salt dissolving can be enhanced under acidic circumstances, leading to an increase in the storage capacity of the cavern.
3.Mineral precipitation	1.$CO_{2(g)} + Ca^{2+}_{(aq)} + 2HCO^{-}_{3(aq)} \rightarrow CaCO_{3(s)} + H_2O_{(aq)} + CO_3^{2-}(aq)$ 2.$CO_{2(g)} + Mg^{2+}_{(aq)} + 2HCO^{-}_{3(aq)} \rightarrow MgCO_{3(s)} + H_2O_{(aq)} + CO_3^{2-}(aq)$	Introducing CO2 into the brine can initiate reactions with metal cations dissolved in the solution, such as Ca^{2+} and magnesium Mg^{2+}. These reactions form carbonate minerals, specifically calcite ($CaCO_3$) and magnesite ($MgCO_3$). The procedure above is commonly referred to as mineral carbonation. The deposition of these minerals has the potential to effectively sequester (CO_2) by impeding its re-entry into the atmosphere.
4.Metals corrosion	$CO_{2(g)} + H_2O_{(l)} + Metalsurface_{(s)} \rightleftharpoons Metalions_{(aq)} + H_2CO_{3(aq)}$	If the storage facility has metallic components like well casings or pipelines, brine and carbonic acid can cause the metal to rust. Corrosion can weaken the structure of the equipment and make it more likely to leak or collapse.

considered while planning and operating salt caverns for gas storage. Careful monitoring and management of storage conditions can assist in reducing possible risks connected with these reactions while also ensuring the facility's safe and efficient operation. Additionally, it is important to note that the specific reactions and their rates depend on the CO_2 concentrations, brine composition, temperature, pressure, and other impurities in the cavern system.

CO_2 storage in salt caverns requires the selection of suitable geological formations and careful site characterization to ensure the presence of a secure caprock to prevent CO_2 leakage back to the surface or into underground drinking water sources.

1.2. *Properties of supercritical carbon dioxide*

Supercritical carbon dioxide (sCO2) is utilized in various applications, including carbon capture and storage (CCS), where it is injected into geological formations such as saline aquifers, depleted oil and gas reservoirs, and salt caverns for long-term storage. Salt caverns offer advantages for CO_2 storage due to their relatively impermeable nature and large storage capacities. Here are some key properties of supercritical CO_2 relevant to its storage in salt caverns:

- High density and viscosity: When compressed and heated beyond its critical point (around 31 °C and 7.4 MPa), CO_2 transitions into a supercritical state, particularly at typical storage depths ($>$ 800 m). In this state, it combines the properties of gases and liquids: it flows like a gas but has a density (700 kg/m^3) more comparable to a liquid. This high density allows for greater CO_2 storage capacity within the cavern compared to gaseous CO_2. Additionally, the high viscosity helps prevent leakage through fractures or rock formations(IEA, 2015; Popescu et al., 2021; Stepanek et al., 2024; Wei et al., 2023a; Zheng et al., 2022).
- Solubility in brine: Brine, a salty water solution commonly present in salt caverns, readily dissolves sCO_2. This dissolution further increases the amount of CO_2 that can be stored in the cavern and enhances the long-term trapping mechanism (Bachu and Dusseault, 2005a; IEA, 2015; Luan et al., 2024; Popescu et al., 2021; Prasad et al., 2023).
- Low reactivity with salt: Salt formations exhibit minimal chemical reactions with sCO_2, ensuring the structural integrity of the cavern over extended periods(IEA, 2015; Zheng et al., 2022).
- Thermodynamic stability: As a dense fluid, sCO_2 readily sinks to the bottom of the cavern, minimizing buoyant forces that could potentially lead to leakage(IEA, 2015; Liu et al., 2023a; Zhang et al., 2022b).
- Reduced mobility: Compared to gaseous CO_2, sCO_2 exhibits lower mobility within the cavern due to its higher viscosity and interaction with brine. This reduced mobility further contributes to containment and lowers the risk of migration outside the formation (Bachu and Dusseault, 2005a; IEA, 2015; Zhang et al., 2022b).
- Interfacial tension: The interfacial tension between sCO_2 and the surrounding brine or rock matrix influences the capillary trapping of CO_2 within the storage formation. Understanding and controlling interfacial tension is crucial for assessing storage integrity and minimizing CO_2 migration(IEA, 2015; Stepanek et al., 2024; Xie et al., 2009).

However, it's important to consider some limitations:

- High pressure and temperature requirements: Maintaining sCO_2 in its supercritical state requires specific pressure and temperature conditions, which can add complexity and cost to the injection and storage process(IEA, 2015; Popescu et al., 2021; Soubeyran et al., 2019).
- Monitoring and leakage detection: Effective monitoring and leakage detection systems are crucial due to the potential environmental consequences of CO_2 release(IEA, 2015; Soubeyran et al., 2019; Stepanek et al., 2024).
- Long-term stability: Although considered stable, understanding the long-term behaviour of sCO_2 in deep saline formations over geologic timescales requires ongoing research(IEA, 2015; Soubeyran et al., 2019; Zhang et al., 2022b).

In general, the unique properties of sCO_2 make it a promising candidate for safe and secure storage of captured CO_2 in salt caverns, contributing to efforts to reduce greenhouse gas emissions and combat climate change. However, careful consideration and mitigation of potential challenges are crucial for successful implementation.

2. Theory

2.1. *Salt caverns*

Salt caverns are formed through salt dissolution within extensive salt beds and domes, facilitated by the circulation of heated water through wells drilled into the salt formation (Li et al., 2023). Salt caverns are regularly 1000–2000 m underground distance after the dissolution process, increasing with temperature and brine concentration. Drilled deviated and direct wells alternate water injection and brine discharge during salt cavern constructions, as shown in Fig. 2. Two injection and discharge tubes in a borehole create a vertical cavern with a high height-to-width ratio. In bedded rock salt with several insoluble interlayers, an alternate injection and discharge approach through two boreholes creates a horizontal cavern with a narrow height-to-width ratio (Ling et al., 2023). Salt caverns exhibit several key characteristics, including low permeability, plasticity, high ductility, creeping properties, and the capacity to self-heal following damage (Wang et al.,

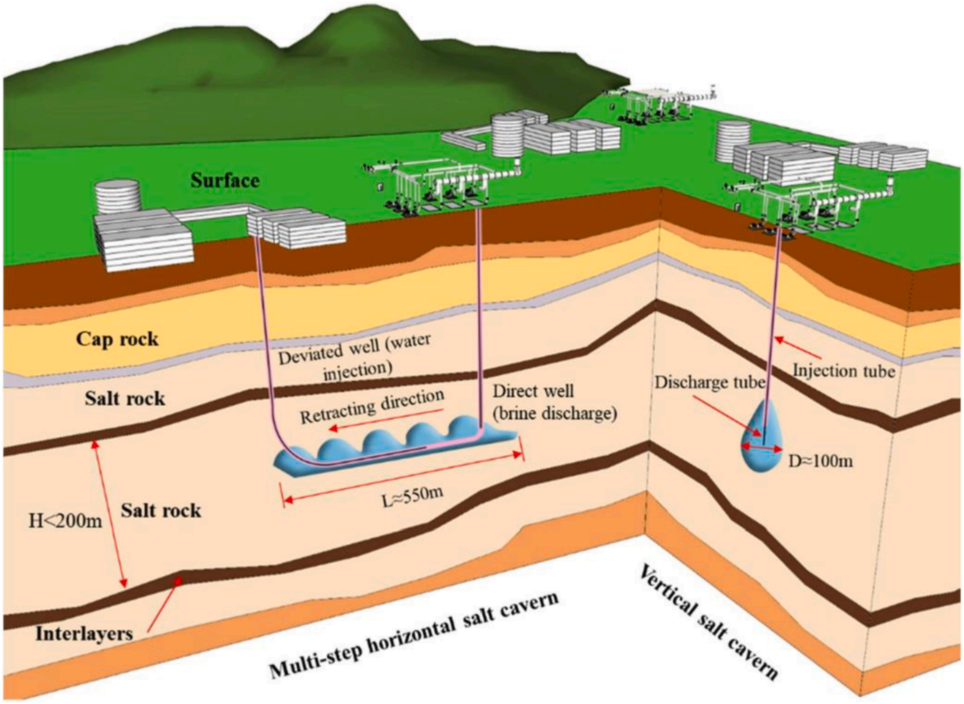
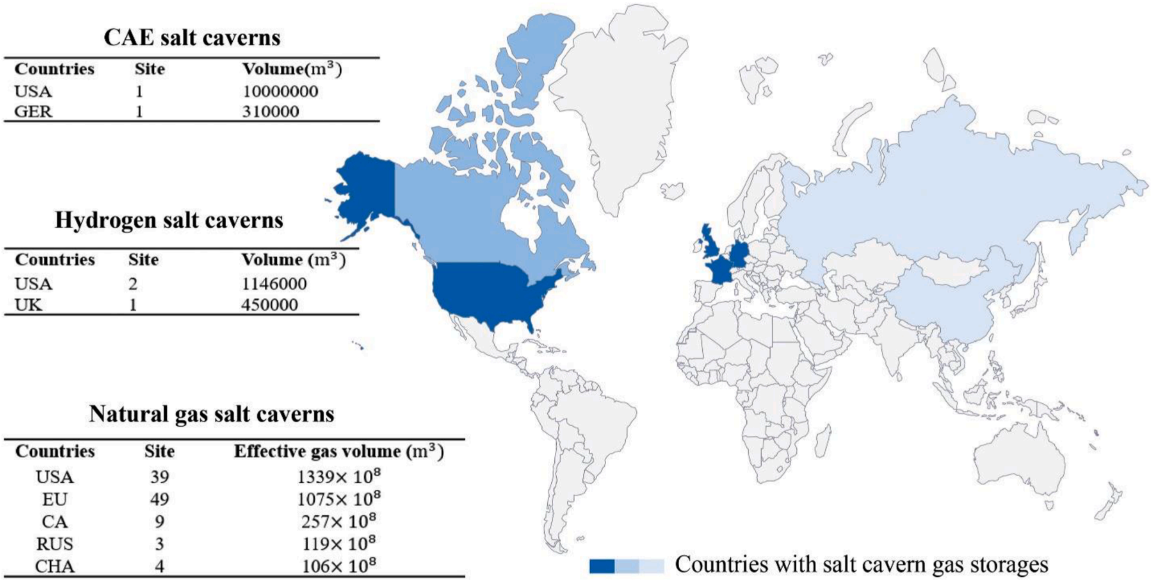


Fig. 2. Salt caverns (Li et al., 2023).

2021). NaCl is the main component in salt caverns. Salt cavern volume is 10×10^4-100×10^4 m^3 with a depth range of 500–2000 m (Wei et al., 2023a, 2023b; Zhao et al., 2021). Global salt cavern distribution for storage is shown in Fig. 3. Advantages and disadvantages of rock salt as host rock for CO_2 sequestration are shown in Table 2.

2.2. Procedures for constructing salt caverns

Constructing salt caverns is a complicated process. Due to its durability and impermeability, salt caverns store natural gas, petroleum, and other industrial materials. Salt cavern construction can take 4 to 5 years. The advantages of constructed salt caverns over other geological storage options for storage purposes have been discussed by Merey (2019). Salt cavern construction follows these steps: 1) Site selection: find a location with a salt formation that is thick and largely pure. At this point, geological surveys and analysis are essential to assess the feasibility of the location. Site selection criteria have been discussed by Liu et al. (2020) and Zheng et al. (2020b). Also, the sequestration facilities must be located near the CO_2 source to reduce transportation costs. Further, the depth of the salt layer should be > 800 m, Temperature > 31.1 °C and pressure > 7.39 MPa to accommodate storage for supercritical conditions. One advantage of storing CO_2 in a supercritical state is that it increases the capacity for CO_2 sequestration resulting from its greater density (Pajonpai et al., 2019). 2) Drilling the well; after selecting the site, a borehole is created within the salt formation. This well is the entry point for introducing water to form the cavern. The normal drilling procedures in oil or gas wells are followed.3) Solution mining involves introducing water into the well, which leads to the dissolution of the salt



CAE salt caverns

Countries	Site	Volume(m^3)
USA	1	10000000
GER	1	310000

Hydrogen salt caverns

Countries	Site	Volume (m^3)
USA	2	1146000
UK	1	450000

Natural gas salt caverns

Countries	Site	Effective gas volume (m^3)
USA	39	1339×10^8
EU	49	1075×10^8
CA	9	257×10^8
RUS	3	119×10^8
CHA	4	106×10^8

Fig. 3. Global salt caverns distributions (Liu et al., 2021).

Table 2
Advantages and disadvantages of rock salt as host rock (Habibi, 2019).

Aspect	Advantages	Disadvantages
Geomechanical	-Without considerable crack generation at low and average compression stresses -Low porosity and permeability -Self healing	-Low tensile strength -Dissolution, especially for low-depth caverns
Economical	-Economical justifiable of solution mining -Low working gas -High deliverability -Low investment -Low maintenance and operational cost -Low energy required during injection and production cycles -Accessibility of salt throughout the word	-High creep closure rate at deep caverns
Environmental	-No chemical reaction with stored material -Low required surface facility -Not affected or low affected by catastrophes	-Extruding of salt produced by solution mining is challenging
Strategic	-Passive defence -Controlling energy programs	-Not enough -Accessibility of salt caverns to market

and the subsequent formation of a brine solution. The brine is subsequently retrieved to the surface to undergo additional processing. Three steps for solution mining are shown in Fig. 40.4) Cavern enlargement; following the initial dissolution, the cavern undergoes a gradual expansion through the ongoing process of injecting and withdrawing brine. The procedure above is commonly iterated multiple times within several months or years until the desired dimensions of the cavern are attained. The dimensions of the cavern are determined by various factors, including but not limited to pressure, temperature, and the rate at which dissolution occurs. Continuous monitoring and geological assessments are carried out during the enlargement period to ensure the cavern's integrity and stability. If any problems are discovered, remedial measures may be executed.5) Casing and completion: once the desired cavern size is attained, the well is cased with cement or steel to prevent leakage and ensure structural integrity. After casing and completion operations, the salt cavern is ready for injection operation. Natural gas, petroleum, or other materials can be injected into the cavern, displacing the brine. The cavern's impermeable nature ensures the stored material remains isolated and secure. Safety measures and regulations must be followed during all salt cavern construction and operation phases. This involves monitoring for possible incidents, ensuring structural integrity, and adhering to industry standards. The procedures for constructing salt caverns are summarized in Fig. 5.

The construction of salt caverns requires the expertise of geologists, engineers, and other professionals with expertise in solution mining and underground storage. The process can be complicated and must be meticulously planned and carried out to ensure the cavern's security and efficiency for its intended purpose.

2.3. Key characteristics of salt caverns for CO_2 sequestration

CO_2 sequestration in salt caverns is still in the infancy stage. Few researchers and stakeholders are investigating the possibility of sequestrating CO_2 in salt caverns. Salt caverns have several essential characteristics that render them suitable for CO_2 sequestration. 1) Impermeable: salt formations exhibit a significantly low level of permeability (10^{-19} m^2), thereby impeding the fluid flow, including that of CO_2, through their structure. This characteristic guarantees the containment of the stored carbon dioxide within the cavern, minimizing the occurrence of substantial leakage or migration (Peng et al., 2023).2) Self-sealing: salt can facilitate the mending of fractures and effectively seal minor leaks that may develop gradually. The inherent ability of the cavern to seal itself provides an extra level of security in terms of containing CO_2(Liang et al., 2023).3) Natural caprock: the caprock formations in the vicinity, commonly referred to as caprock, generally serve as an additional means of confining the CO_2 within the salt cavern. The caprock is a physical barrier, mitigating the potential for CO_2 leakage (Bain et al., 2023).4) Rapid injection and withdrawal rates; salt caverns facilitate the expeditious injection and extraction of fluids. The attribute above confers a notable benefit in the context of CO_2 sequestration, as it enables the effective and adaptable control of the injection and storage procedures (Liao et al., 2023).5) Geological stability: salt formations exhibit a high degree of geological stability, a crucial characteristic that plays a pivotal role in guaranteeing the enduring confinement of stored CO_2. The inherent stability of these structures mitigates the likelihood of cavern collapse or structural failure, thereby minimizing the potential for CO_2 leakage (Rogers III, 2023).6) Salt caverns have excellent ductility, i.e., when subjected to the high pressures and temperatures found deep underground, slowly deforming and flowing over millions of

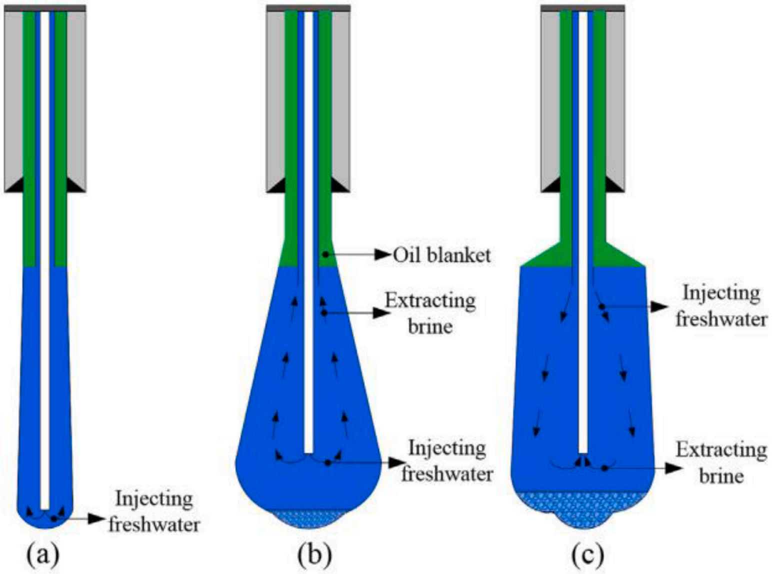


Fig. 4. Three steps involved in solution mining: a) Initial phase, b) Intermediate phase, and c) Complete phase (Li et al., 2022).

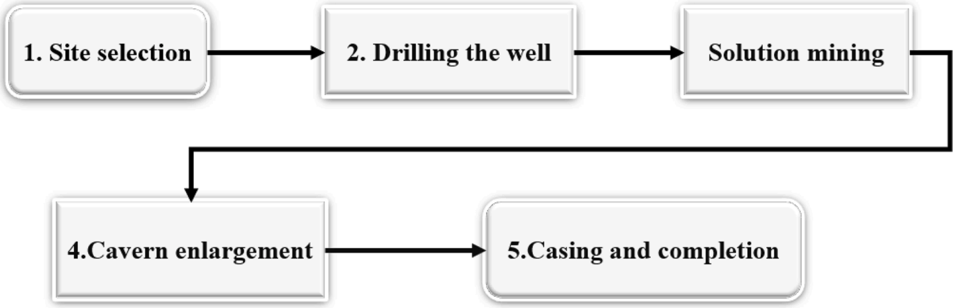


Fig. 5. Procedures for constructing salt caverns.

years (Dong et al., 2023).

2.4. Factors affecting gas storage efficiency in salt caverns

Every salt cavern storage project exhibits unique features. It is crucial to thoroughly evaluate these factors to maximize storage efficiency and maintain a reliable and safe operational environment. These factors include: 1) Mechanical properties; structural flaws, such as cracks or deformations in the cavern's walls, can potentially result in gas leakage or collapse. These outcomes may significantly reduce the efficiency of storage operations and give rise to safety hazards (Liu et al., 2021; Luan et al., 2024; Senseny et al., 1992; Wang et al., 2021).2) Tightness and stability; tight caverns minimize gas leakage risk, retaining stored gas. Maintaining inventory and cavern storage capacity needs a tight cavern. Stable salt caverns prevent roof collapses and wall deformations (Li et al., 2019; Liu et al., 2021; Wang et al., 2018). 3) Volume shrinkage: The cavern's available storage capacity decreases directly due to cavern volume reduction. As the gas volume decreases, the cavern's capacity to hold gas decreases, thereby reducing the quantity of gas that can be stored. The creeping ability of salt caverns is the major factor which can cause cavern volume shrinkage (Bérest et al., 2001; Liu et al., 2021). The reduction in size resulting from elastoplasticity and initial creep deformation will be predominantly observed during the initial phase of cavern construction and operation, which typically lasts less than 5–10 a. Subsequently, the salt cavern will primarily experience steady-state creep during periods of stable operation, lasting longer than 10 a (Ma et al., 2021).4) Cavern pressure: gas storage efficiency in a cavern is influenced by the pressure at which it is stored. Increased pressure facilitates higher gas density, optimizing storage capacity (Liu et al., 2021).5) Cavern temperature: the thermal conditions within the cavern can potentially impact the behaviour of gases, including their density and compressibility. Consequently, these factors play a significant role in determining the performance of gas storage operations (Liu et al., 2021). Salt caverns possess a notable benefit in their remarkably high volumetric capacity, which typically ranges from 600 to 900 kg CO_2/m^3 of cavern and depends on the pressure and temperature of caverns only. In comparison, solubility or mineral trapping in rock formations often yields a significantly lower capacity of 2 to 15 kg CO_2/m^3 of rock. In addition, for salt caverns, this capability is promptly attained, whereas the procedures of dissolution and mineralization require varying durations ranging from tens to thousands of years (Bachu and Dusseault, 2005a; Zheng et al., 2022).

2.5. Carbon dioxide sequestration phases in salt caverns

CO_2 sequestration in salt caverns is aimed at mitigating climate change by capturing CO_2 emissions from industrial sources and storing them underground. It involves three phases: 1) Injection (short) phase: In this phase, captured CO_2 is transported from its source, such as industrial facilities or power plants, to the selected salt cavern storage site. The CO_2 is then injected into the salt cavern under high pressure. Salt caverns are preferred storage sites due to their impermeable nature and large storage capacity compared to other geological formations like depleted oil and gas reservoirs or saline aquifers (Canle, 2023; da Costa et al., 2019; Liu et al., 2023b; Zheng et al., 2022). 2) Storage (medium) Phase: Once injected into the salt cavern, the CO_2 is stored securely underground. Salt caverns offer favourable geological conditions for CO_2 storage due to their low permeability and high porosity, which reduce the risk of CO_2 leakage. Over time, the CO_2 is expected to undergo mineralization and dissolution processes, becoming trapped within the salt formation (Cihan et al., 2015; da Costa et al., 2019; Liu et al., 2023b; Stepanek et al., 2024).3) post-storage monitoring phase/long-term phase: Monitoring the stored CO_2 is essential to ensure the integrity of the storage site and to detect any potential leakage or migration of CO_2. Monitoring techniques include surface monitoring using remote sensing technologies, subsurface monitoring such as seismic surveys and well logging, and direct measurement of CO_2 concentrations in soil and groundwater. Continuous monitoring allows for early detection of any issues and enables corrective actions to be taken promptly. Post-storage monitoring may continue for decades or even centuries to ensure the effectiveness and safety of CO_2 sequestration in salt caverns(Bachu and Dusseault, 2005b; da Costa et al., 2019; Liu et al., 2023b; Wei et al., 2023a; Zhang et al., 2022b).

Generally, CO_2 sequestration in salt caverns offers a promising solution for reducing greenhouse gas emissions and combating climate change. However, it is essential to conduct thorough site characterization, risk assessment, and long-term monitoring to ensure the safety and effectiveness of this technology. However, it's important to note that these phases are not strictly linear, and some activities may overlap. The duration of each phase can vary depending on the project scale, regulatory requirements, and monitoring needs.

2.6. Feasibility evaluation of salt caverns for underground gas storage (UGS)

Evaluating salt caverns viability for UGS is comprehensive research which consists mainly of three aspects, namely serviceability, safety and design, and economics, as shown in Fig. 6. Serviceability involves the standard and desirable characteristics of UGS salt caverns to be met, such as cavern shape, cavern volume, and flexibility in use. Cavern shape: The shape of the cavern can affect its ability to be serviced. For example, a long, thin cavern may be more challenging to access and maintain than a shorter, wider cavern. For cavern volume: The volume of the Cavern will determine how much CO_2 can be stored. However, a larger cavern may also be more expensive to construct and maintain. Flexibility in use: The flexibility of the cavern refers to its ability to be used for multiple purposes. For example, a cavern that can be used for both CO_2 storage and natural gas storage may be more feasible than a cavern that can only be used for one purpose. There are several criteria used to evaluate the serviceability, safety and design of salt caverns for UGS, as discussed by DeVries et al. (2005),Brouard et al. (2012),Yang et al., (2009), and Ma et al., (2015). These criteria include: 1) The cavern

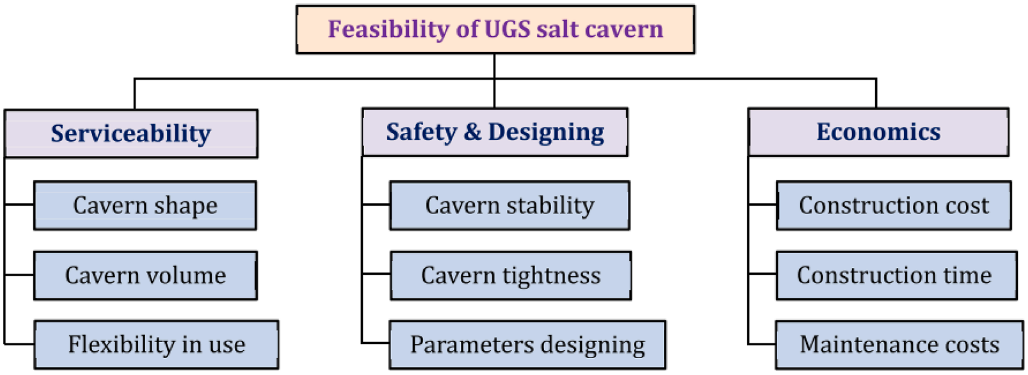


Fig. 6. Feasibility evaluation of salt caverns for UGS (Liu et al., 2018).

should have a regular shape and be large enough in volume. 2) In the first year, the volume loss rate should be <1 %,5 % for the first five years, and 30 % for 30 years. 3) The stress states should be inside the compression-dilatancy boundary (CDB) at critical locations around the cavern wall, such as the roof centre, intermediate side wall, and floor centre.4) At the point where the interbed and salt layer meet, there should be no dislocation or slippage.5) The integrity, lifespan, and resistance to corrosion of the well system should be of an outstanding standard(Liu et al., 2023a; Shi and Durucan, 2005).

Safety and designing involve mainly three aspects to be considered: cavern stability, cavern tightness, and parameter design. For cavern stability: The stability of the cavern is critical for safety. The cavern must be able to withstand the pressure of the injected CO_2 without collapsing. For cavern tightness: The Cavern must be tight enough to prevent CO_2 from leaking out. This is important for both environmental and safety reasons. For parameters designing: This refers to the specific design parameters that must be considered when constructing a salt cavern for CO_2 storage. These parameters include the thickness of the salt walls, the depth of the cavern, and the injection pressure. However, serviceability, safety and design are executed together. For instance, the stability of a typical cavern tends to be extremely high, and the construction of a cavern relies heavily on tightness and stability. Thus, to assess the feasibility of a UGS, it is necessary to investigate its serviceability, safety and design(Dusseault et al., 2004; Wei et al., 2023a).

Economics involves evaluating construction costs, construction time, and maintenance costs(Liu et al., 2018). Construction cost: The cost of constructing a salt cavern for CO_2 storage can vary depending on the size, shape, and location of the cavern. Construction time: The time it takes to construct a salt cavern for CO_2 storage can also vary depending on the size and complexity of the project. Maintenance costs: The cost of maintaining a salt cavern for CO_2 storage will depend on the size, shape, and condition of the Cavern (Stepanek et al., 2024).

Overall, the feasibility of a UGS salt cavern for CO_2 storage will depend on a number of factors, including the serviceability, safety, and economics of the project. Carefully considering all of these factors is essential for ensuring the success of a CO_2 storage project.

3. Potentiality towards field applications

There are no reported pilot tests or field applications on CO_2 sequestration in salt caverns because most salt caverns worldwide are used for energy storage (oil and gases) for future energy security. In addition, salt caverns are used for waste disposal. However, there are two areas in which there are large salt deposits which can be used for CO_2 sequestration due to large emissions, and salt caverns remain the only storage options. Hence, this section provides the recent progress of these two areas.

3.1. *Salt caverns built offshore in ultra-deep water in Brazil*

Brazil discovered tremendous oil reserves in 2006 in a water depth of ~2200 m under a caprock of 2000 m of pre-salt rock over the reservoirs. These reservoirs produce 50 % of Brazil's oil and gas. The production in these oil fields has a high oil and gas ratio associated with a high content of CO_2 (~80 %). It has been used for enhanced oil recovery purposes in the same field, which leads to increased CO_2 contamination in produced oil and increased the separation cost during refinery, which is mixed with other gases such as methane and ethane. Recently, research has been carried out to evaluate the feasibility and development of technology for storing CO_2 and associated gas mixtures (CH_4) in thick layers of salt rock by building huge salt caverns. The technology is in the proof stage. Before constructing the system at full scale, it was decided to make a smaller experimental cavern to determine its final design's field parameters (da Costa et al., 2020b; Maia da Costa et al., 2019). The examined salt dome can facilitate the construction of 15 caverns that contain roughly 108 million tons of CO_2. The geomechanical modelling and simulation findings conducted in this study provide evidence of the technical viability of constructing offshore salt caverns with significant dimensions, measuring 450 metres in height and 150 metres in diameter. These caverns can store a substantial amount of CO_2, specifically 4 billion sm^3 or 7.2 million tons, under conditions of 450 bar pressure and a temperature of 42 °C (da Costa et al., 2020a). The risk assessment of the offshore salt caverns has been analysed, as discussed by Pestana et al., (2019). It has been found that if the project is economically feasible, it will be the largest CCS project in the world (da Costa et al., 2020b; Goulart et al., 2020).

3.2. *Lotsberg salt formation, Alberta, Canada*

For decades, hydrocarbons (oil, natural gas, ethane, propane) and non-aqueous fluid products (e.g., ethylene glycol) have been stored in salt caverns in central Alberta's Lotsberg Salt, which has a high concentration of chemical plants. The permanent carbon sequestration and storage in caves can be achieved by utilizing materials such as coke. Significant quantities of coke are generated through heavy oil and bitumen upgrading facilities. It is possible to enhance coke production and reduce the consumption of CH_4 during the hydrogenation process by modifying the upgrading procedures. The method of grinding coke and transporting it through pipelines to salt caverns for deposition as a dense aqueous slurry is rather straightforward from a technological standpoint. The settling of coke, the potential filling of the cavern with coke, and the displacement of the aqueous phase through CO_2 injection (due to coke's strong ability to adsorb CO_2) can significantly enhance the facility's carbon storage capacity. This particular alternative may be intriguing within the current context of the ongoing and accelerated production of heavy oil and tar sands in Alberta (Bachu et al., 2000; Dusseault et al., 2005).

The Lotsberg salt is the lowest of three huge salt beds located east-northeast of Edmonton, Alberta, in Canada. There are no noteworthy faults or folds in the salt or underlying rocks in the Lotsberg Salt area. As a result, no joints or fissures have opened due to flexure, and all strata have a high degree of lateral coherence. The Lotsberg salt is typically found in the centre of the deposit as a single huge salt formation that's believed to reach a thickness of 160 meters with a height range of 80 to 100 m and a security barrier of 30 to 40 m thickness at the top and >10 m at the bottom. In most cases, it is separated into an upper Lotsberg salt and a lower Lotsberg salt by a wedge of shale that ranges in thickness from 10 to 20 meters. The salt has been recrystallized and is exceptionally pure, with almost no clay and anhydrite seams typical of bedded salt deposits. The Lotsberg salt, like all-natural salt deposits that are laterally continuous, is believed to be impermeable. This initial investigation demonstrates that storing CO_2 in salt caverns is a theoretically feasible approach for reducing anthropogenic CO_2 emissions into the atmosphere permanently (>1000 years) or temporarily (decades) until another geological sink becomes available (Dusseault et al., 2004). It is expected that 3500 Mt CO_2 might be stored in salt domes and rock caverns in Alberta and Saskatchewan, Canada (Shi and Durucan, 2005). It was found that there are currently no documented technical barriers or excessive risks that would hinder the utilization of salt caverns for permanent CO_2 sequestration(Dusseault et al., 2004; Shi and Durucan, 2005).

4. CO_2 leakages and monitoring

CO_2 is not hazardous like other natural gases stored in salt caverns, such as methane, hydrogen, and compressed air energy, though its leakage needs to be avoided. The unique characteristics of salt caverns that have low-risk leakage or almost do not exist are extremely low porosity (<1 %), extremely low permeability less than 10^{-21}–10^{-20} m^2 for halites, and creeping properties (Bachu and Dusseault, 2005a; Popescu et al., 2021; Zhao et al., 2021). Adjacent layers in salt caverns frequently contain salt-plugged pore spaces, preventing CO_2 movement. Since capillary effects and zero far-field permeability prevent CO_2 from displacing brine from micro fissures in the cavern walls and access boreholes, they will anneal over time. Due to creeping properties, salt caverns may collapse, but no fissures/fractures may develop to allow CO_2 leakage towards the underground water sources or atmosphere due to low permeability. When fracture condition is attained, a small amount of CO_2 causes pressure to drop inside salt caverns, which closes the fracture(Bordenave et al., 2013). The only believable ways for CO_2 leakage are along the casing and the well cement. A straight, vertical conduit for CO_2 flow to the surface would result from leakage along the wellbore. Since supercritical CO_2 decompresses as it flows upwards, its density decreases, buoyancy increases, and the flow accelerates due to this gradient self-improvement process. However, if the wellbore is well-cemented with low-permeability cement, the leakage risk through the wellbore is lowered (Dusseault et al., 2000; Wolterbeek and Hangx, 2023).

After the cavern is sealed, a monitoring technique is essential to observe displacement that occurs slowly due to creeping within the salt caverns. Hence, seismic monitoring techniques such as vertical seismic profile (VSP), reflection, cross-hole, and refraction are not used due to negligible strains and modest volumetric closures. Casing and annulus pressure monitoring is the only method with detection capability relevant to leakage assessment. In addition, a purely mechanical and robust pressure measuring system is also suitable for monitoring leakage in salt caverns (Bachu and Dusseault, 2005a; van Wijk et al., 2008).On the other hand, microseismic and surface subsidence surveys can be employed to monitor the rock mass reaction to salt creep, thereby providing an early warning system for detecting CO_2 leakage using overburden strata. The phenomenon of salt creep is expected to result in the closure of caverns to some extent both during and following the process of CO_2 filling(Shi and Durucan, 2005).

5. Research gaps and future works

Salt caverns have great potential to store CO_2 for long-term storage plans to mitigate global climate change. The method has a small risk of leakage compared to other CO_2 storage options. However, salt caverns have been given little attention compared to other geological options. Several parts noted in this review paper which need more research are outlined in this section:1) Modelling and simulation, especially coupled hydrogeological-geochemical-geo-mechanical simulation tools to predict the long-term response of the rock mass to salt creep to assess its influence on cavern integrity and long-term CO_2 to be sequestrated, need to be developed for permanent storage.2) Estimation method for the amount of CO_2 sequestrated in salt caverns needs to be developed like other geological options 0.3) Exploring techniques to improve CO_2 storage capacity and efficiency in salt caverns could be a worthwhile research topic. This includes exploring ways to enhance CO_2 injection, migration, and trapping mechanisms to maximize storage capacity.4) Researchers can look for ways to minimize the overall cost of CO_2 sequestration in salt caverns. This involves improvements in drilling and injection techniques and the exploration of synergies with other industries to share infrastructure expenses.5) More research is needed to understand the long-term effects of CO_2 injection on salt deposits and the geology surrounding them. This includes researching potential geomechanical effects, seismic risks, and induced seismicity.6) Long-term monitoring and assessing CO_2 storage in salt caverns is a critical study field. Understanding the behaviour of CO_2 over long periods, potential leakage paths, and the success of the containment method are all part of this. Researchers might build enhanced monitoring tools to ensure the storage locations' integrity and safety.7) Unlike other CO_2 geological storage options, few experiments have been conducted to investigate the potentiality of salt caverns to store CO_2. Hence, more experiments are encouraged towards full-field operations. Additionally, it is crucial to focus on developing methodologies for scaling up laboratory results.8) Impurities have been proved to negatively affect the amount of stored CO_2 in other geological storage options. However, the effects of impurities on CO_2 to be stored in salt caverns have not been investigated.9) The scrutiny of the feasibility of CO_2 storage in salt caverns is hindered by a shortage of essential data and the presence of diverse mechanisms operating on different time-based scales. More research is recommended on these various mechanisms that act in distinct time scales.10) It is essential to consistently dedicate resources towards the determination of appropriate kinetic rates under storage-relevant environments, as well as the characterization of reactive surface areas.11) Machine learning (ML) has been applied accurately in predicting CO_2 storage performance, site selection, estimation of storage capacity, wettability changes, monitoring, etc., in other geological storage options such as aquifer, deep unmineable coals seams, basalts, methane hydrate reservoirs, residual oil reservoirs etc., Similarly, ML application in salt caverns need to be investigated for better storage performance.12) Additional investigation is required pertaining to the evaluation of the stability of rock salt caverns. A more comprehensive understanding of the processes of damage and cavern roof collapse requires an investigation of the impact of interactions between fluid and solid phases.13) More Modelling and experiments are needed to determine how dissolution affects global storage and mass transfer under salt cavern conditions. These CO_2-specific studies must more precisely quantify the volume of gas likely to dissolve, the time needed to attain equilibrium between both phases and the projected pressure drop, which has been observed.14) Economic analysis of CO_2 sequestration in salt caverns compared to other geological storage options is an important research area that needs more investigation.

6. Advantages of CO_2 sequestrations in salt caverns over other geological options

Compared to other CO_2 storage options, salt caverns provide CO_2

sequestration with many benefits that cannot be found elsewhere. Some of these advantages include the following: 1) Geologic stability: salt caverns are geological formations that occur naturally and have demonstrated long-term stability over geological periods. They have low permeability and are typically characterized by effective sealing properties, mitigating the potential for CO_2 leakage or migration(Fagorite et al., 2023).2) Compatibility with existing infrastructure; numerous salt caverns have historically been utilized to store natural gas and oil. Consequently, the requisite infrastructure at both surface and underground levels for CO_2 storage may already be in place, thereby reducing the overall costs associated with its implementation (Eigbe et al., 2023; Fagorite et al., 2023; Liu et al., 2023a).3) Reduced monitoring and verification requirements; compared to other storage options like basaltic rocks, depleted oil and gas reservoirs, or deep saline aquifers, salt caverns' low permeability and self-sealing characteristics help to reduce the need for intensive monitoring and verification (Bachu and Adams, 2003; Fagorite et al., 2023).4)High storage capacity; salt caverns often have a high storage capacity, making them an ideal choice for long-term storage of CO_2. Due to the increased volumetric efficiency of salt caverns, considerable volumes of CO_2 can be stored in a very small area. This helps mitigate the effects of climate change(Fagorite et al., 2023; Leung et al., 2014; Wei et al., 2023a).5) Enhanced safety: salt caverns are considered safe for storing CO_2 owing to their stable and delineated geological structures. In addition, it is worth noting that the storing process occurs at significant depths beneath the Earth's surface, mitigating possible hazards to people on the surface(Bachu, 2000; Fagorite et al., 2023).

It is imperative to acknowledge that although salt caverns present numerous benefits, the selection of CO_2 storage technique is contingent upon several aspects, such as regional geology, accessibility of infrastructure, financial implications, and environmental impact evaluations. Depending on their unique circumstances and specific requirements, various locations may use other storage options.

7. Challenges of storing CO_2 in salt caverns

Sequestering carbon dioxide (CO_2) in salt caverns is one of the potential methods for carbon capture and storage (CCS) to mitigate climate change. However, it is not without its challenges. Some of the major challenges associated with this approach includes :1) Geologic suitability: identifying suitable salt formations that can securely contain CO_2 is a significant challenge. Not all salt caverns are suitable, and thorough geological assessments are required to ensure the integrity of the storage site (Pajonpai et al., 2022).2) Induced seismicity: the injection and pressurization of CO2 into salt caverns can potentially induce seismic activity if not carefully managed, posing risks to nearby infrastructure and communities(Bordenave et al., 2013; Popescu et al., 2021).3) Long-term liability: CCS projects, including salt cavern storage, may require long-term monitoring and maintenance to ensure the safety of stored CO_2. This creates potential liability and financial responsibilities for operators and governments(da Costa et al., 2020b; Shi and Durucan, 2005).4) Cost and energy requirements: Building and maintaining the infrastructure for CO_2 capture and storage in salt caverns can be expensive. It also requires energy for compression, transportation, and injection, which may reduce the net carbon reduction benefits(Maia da Costa et al., 2019).5) Regulatory and permitting challenges: Obtaining the necessary permits and meeting regulatory requirements for CCS projects can be a complex and lengthy process, which can slow down implementation(Zhang et al., 2022b).

8. Conclusions and recommendations

This review paper investigated the recent advances in sequestrating CO_2 in salt caverns. Some of the research gaps which need more research have been outlined. It has been revealed that salt caverns can store CO_2 permanently to mitigate global climatic changes, especially in places where other CO_2 geological storage options are not available. Also, it is suggested to store CO_2 in a supercritical state in a salt cavern because it increases the capacity for CO_2 sequestration resulting from its greater density. Further, CO_2 storage leakage risk in salt caverns is low compared to other geological options due to its low permeability, self-healing capacity, and creeping ability. Furthermore, it is estimated that a single cavern with a diameter of 100 m can store approximately 500,000 tons of CO_2. This proves how salt caverns can help to store CO_2 to mitigate global climatic change. Apart from that, it has been found that CO_2 sequestration in salt caverns offers notably higher efficiency than other methods of geological CO_2 sequestration, with an increase of at least one order of magnitude in sequestration efficiency. In addition, the salt cavern has a notable benefit in their remarkably high volumetric capacity, typically ranging from 600 to 900 kg CO_2/m^3, controlled only by cavern temperature and pressure and occurring immediately. In comparison to solubility or mineral trapping in rock formations, structural trapping often yields a significantly lower capacity of 2 to 15 kg CO_2/m^3 of rock, with its durations ranging from tens to thousands of years.

CRediT authorship contribution statement

Grant Charles Mwakipunda: Writing – review & editing, Writing – original draft, Conceptualization. **Melckzedeck Michael Mgimba:** Supervision, Project administration, Formal analysis. **Mbega Ramadhani Ngata:** Writing – review & editing, Resources, Formal analysis. **Long Yu:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The Authors declare that there is no conflict of interest

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors acknowledge support from the Chinese Scholarship Council (2022GXZ005733)

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