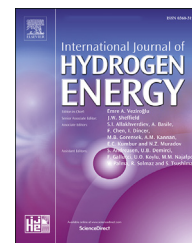


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Optimizing underground hydrogen storage in aquifers: The impact of cushion gas type

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HIGHLIGHTS

- Compositional numerical simulation of underground hydrogen storage in a North Sea aquifer utilising CMG-GEM.
- Hydrogen recovery efficiency improves with the utilisation of cushion gas.
- CO₂ exhibits highest storage capacity; N₂ and CH₄ improve recovery efficiency.
- CH₄ as cushion gas leads to 80% recovery efficiency, minimizing lateral spreading and viscous fingering.
- Cushion gas density dictates the efficiency of the underground hydrogen storage scheme.

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ABSTRACT

This study investigated the impact of cushion gas type and presence on the performance of underground hydrogen storage (UHS) in an offshore North Sea aquifer. Using numerical simulation, the relationship between cushion gas type and UHS performance was comprehensively evaluated, providing valuable insights for designing an efficient UHS project delivery.

Results indicated that cushion gas type can significantly impact the process's recovery efficiency and hydrogen purity. CO₂ was found to have the highest storage capacity, while lighter gases like N₂ and CH₄ exhibited better recovery efficiency. Utilising CH₄ as a cushion gas can lead to a higher recovery efficiency of 80%. It was also determined that utilising either of these cushion gases was always more beneficial than hydrogen storage alone, leading to an incremental hydrogen recovery up to 7%. Additionally, hydrogen purity degraded as each cycle progressed, but improved over time. This study contributes to a better understanding of factors affecting UHS performance and can inform the selection of cushion gas type and optimal operational strategies.

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1. Background

The Paris Agreement, signed in 2015, is a landmark international accord aimed at reducing greenhouse gas emissions [1]. One of the key strategies for achieving this goal is the energy

transition, which involves shifting from traditional, fossil fuel-based sources of energy to cleaner, renewable sources. Renewable energy offers several advantages over traditional sources of energy, including lower emissions, reduced air pollution, and better energy security [2,3]. The energy

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transition is a complex process that requires collaboration between governments, industry, and society [4]. Hydrogen is increasingly being viewed as a key component in the transition towards a low-carbon economy. Its potential as a clean energy source is well-known, and its ability to store energy offers a way to address the intermittent nature of renewable energy sources such as wind and solar [5].

Hydrogen's utilisation in fuel cells epitomizes a paradigm shift in clean energy conversion, where the chemical reaction of hydrogen and oxygen generates electricity, emitting only water vapor. This innovative technology offers high efficiency, zero-emission power generation, and diverse applications in transport and stationary power systems [5–8]. Moreover, hydrogen energy has garnered substantial attention within the industrial domain due to its burgeoning applications, notably within the spheres of steel and chemical industries. In the context of steel production, hydrogen exhibits remarkable potential as a surrogate for traditional coal and fossil fuels, assuming the role of an efficient reducing agent [9–11]. Projections indicate that by effecting this transition, the global steel sector stands to achieve a momentous reduction of up to 50% in carbon emissions, underscoring the profound impact of hydrogen integration [12]. This orchestrated inclusion of hydrogen in industrial frameworks is poised to yield discernible ecological dividends, primarily through the marked attenuation of greenhouse gas emissions.

Most of the learnings for underground hydrogen injection and storage were adopted from CO₂ storage in geological formations experiences. CO₂ has been injected as part of various schemes; coupled with enhanced oil recovery [13], long-term storage and sequestration [14], and extraction of natural gas from methane hydrates through CO₂–CH₄ replacement [15]. However, a major challenge lies in finding suitable storage solutions that can accommodate the large-scale and long-term storage requirements of hydrogen value chains [16,17]. One promising option for hydrogen storage is in aquifers that offer the potential for large-scale, long-term storage solutions [18–20]. There have been several successful hydrogen and natural gas or hydrogen and CO₂ mixture storage projects, including Ketzin in Germany, Beynes in France, and Lobodice in the Czech Republic [21,22].

A generic scheme of underground hydrogen storage in an aquifer coupled with cushion gas support is presented in see Fig. 1. For this storage scheme to be effective various factors play an important role. Aquifer must have a trapping mechanism to prevent hydrogen leakage such as a sealing cap rock, along with sufficient porosity and permeability to hold a significant amount of hydrogen [23,24]. Additionally, subsurface movements such as geological faults, earthquakes, or mining activities, however, may create hydrogen pathways risking its leakage to the atmosphere. The storage reservoir must be located in a stable geological formation that is unlikely to experience such movements [25–27]. Moreover, the physical mixing between the injected hydrogen and the surrounding formation fluids can result in a decrease in the storage capacity and potential contamination of the storage reservoir [28,29]. Geochemical reactions between hydrogen, reservoir fluids and rock may also lead to losses in the stored hydrogen gas, reduction in produced hydrogen's purity, and possible geomechanical alterations in reservoir rock properties [30].

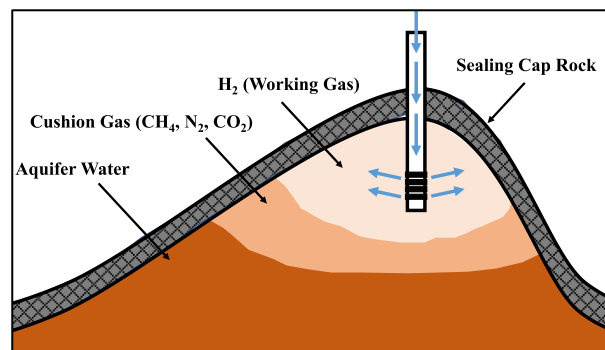


Fig. 1 – Schematic of underground hydrogen storage in an aquifer.

Other reservoir mechanisms that dictate the underground hydrogen storage performance include the reservoir rock heterogeneity, relative permeability hysteresis, and hydrogen dissolution [31–36].

Hydrogen plume migration or dissipation may also occur due to its lateral spreading or hydrogen viscous fingering resulting from high mobility compared to resident reservoir fluids. This can result in the loss of the stored hydrogen in the storage reservoir, making it less effective as a storage option [37,38]. One of the factors that can be utilised to control the hydrogen lateral spreading and gas fingering is the operational injection rate. It was reported that higher injection rates of hydrogen gas amplify the viscous forces compared to the gravitational forces resulting in the unstable displacement of the resident reservoir fluid by the injected hydrogen. Subsequently, the hydrogen gas bypasses the resident reservoir fluid and migrates deeper into the reservoir away from the storage area [37,39–41]. Another element in controlling the unstable displacement phenomena is through the injection of a cushion gas or a base gas.

As depicted in Fig. 1, the Cushion gas, or base gas, is a gas that is injected in the first cycle (prior to the injection of working gas) to provide a stable environment in underground hydrogen storage formations by achieving two primary functions. The first function is to maintain the pressure in the aquifer, or geological storage formations, by filling the void space left while hydrogen is being withdrawn. The second function is to act as a barrier between the hydrogen and surrounding resident water (or reservoir fluids) to isolate the hydrogen and reduce its escape from its plume through lateral spreading or viscous fingering. This is achieved by the lower-density contrast between hydrogen and the fluids surrounding it inside the aquifer [42–44].

Several types of cushion gases have been investigated in underground hydrogen storage such as CH₄, CO₂ and N₂ [43,45,46]. The choice of a suitable cushion gas hinges on its intrinsic physical attributes, particularly density, while also factoring in its accessibility and associated expenses [26]. A low-density contrast is desirable to minimize mixing and ensure optimal recovery of the working gas. The utilisation of cushion gas contributes to an increased capital expenditure (CAPEX) for the underground hydrogen storage (UHS) project [43,47]. The availability of the cushion gas may depend on the location of the storage formation. Another important

consideration is the chemical stability of the cushion gas. Another important requirement is the chemical stability of the cushion gas, as any reactivity with the working gas or the reservoir matrix under prevailing conditions could give rise to undesirable by-products or compromise the integrity of the rock formation [27,47].

Heinemann et al. [43] analysed the role of cushion gas in underground hydrogen storage in saline aquifer anticlines using the commercial compositional simulator, CMG-GEM. Their findings showed that cushion gas does not grow storage capacity but rather increases the efficiency of exploiting the existing capacity. The amount of cushion gas required depends on the amount of working gas needed, and early studies should be conducted to determine cushion gas requirements and avoid potential losses. Additionally, they reported that hydrogen storage in deeper geological structures with higher reservoir permeabilities requires less cushion gas. Kanaani et al. [44] that without cushion gas, up to 15.5% of stored hydrogen was lost in UHS in a depleted oil reservoir. Moreover, CH₄ was the most effective cushion gas due to its low molecular weight and smaller density contrast to hydrogen in comparison with the other cushion gases CO₂ and N₂, resulting in higher hydrogen recovery of 89.7%. Similar to the findings of Kanaani et al. [44], Chai et al. [48] reported that the utilisation of N₂ as a cushion gas resulted in higher hydrogen recovery, 85%, compared to CO₂, 47%. They attributed the poor performance of CO₂ as a cushion gas to the methanation reaction that converts the H₂ and CO₂ gas to CH₄ gas under certain conditions therefore reducing the recoverable H₂ gas. Delshad et al. [49] reported that the cushion gas requirements for aquifers are higher than that for depleted hydrocarbon reservoirs. The Norne hydrocarbon field in Norway was investigated by Lysy et al. [50] using the black oil simulator Eclipse 100 to model the storage of hydrogen gas. Their modelling analysis demonstrated that UHS in the gas zone was the most desirable alternative, resulting in a higher hydrogen recovery rate of 87% compared to 77% and 49% hydrogen recovery from the oil and water zones, respectively. While the injection of formation gas as cushion gas improved hydrogen recovery, it also had an impact on the purity of the produced hydrogen gas due to gas mixing [50]. Zamehrian and Sedaee [51] reported that utilising N₂ as a cushion gas for underground hydrogen storage in a partially depleted gas condensate reservoir was more favourable than CH₄ and CO₂ due to the improved initial pressurization achieved by the N₂ gas. Their results showed that using N₂ as the base or cushion gas led to 66.9% hydrogen recovery compared to 65.8% and 64.9% using CH₄ and CO₂ as cushion gases, respectively. Wang et al. [52] studied the flow behaviour of hydrogen (H₂) storage in subsurface porous media using carbon dioxide (CO₂) as the cushion gas utilising numerical simulation. Their findings indicated that CO₂ solubility can have both positive and negative effects on H₂ recovery, depending on the flow conditions. In gravity-dominated scenarios, around 58% of H₂ can be recovered at a purity level above 98% (meeting ISO combustion requirements). However, they found that considering CO₂ solubility slightly reduces H₂ recovery performance due to gradual CO₂ vaporization during H₂ injection, resulting in a wider CO₂–H₂ mixing zone and decreased high H₂ purity

levels during back-production. Zhao et al. [53] examined the effects of various cushion gases (CO₂, CH₄, N₂) on an underground hydrogen storage (UHS) system in a subsurface aquifer. To achieve this, a two-phase three-component reservoir simulator was developed, calculating fluid properties with GERG-2008 EoS and simulating hydrogen/cushion gas distribution over 20,000 days. They reported that CH₄ and N₂ retained hydrogen in the top aquifer, favouring production rate but hindering purity. In contrast, CO₂ induced hydrogen-rich aqueous fingers, enhancing purity but hampering mobility [53].

The utilisation of cushion gas has been found to be advantageous in underground hydrogen storage when compared to the absence of cushion gas, as reported by various studies [39,43,44,53,54]. The efficacy of hydrogen storage is largely influenced by the type of cushion gas employed, with CH₄ and N₂ being identified as the most effective due to their lower density contrast with hydrogen gas [39,44]. This attribute reduces the occurrence of undesirable fluid behaviour such as viscous fingering and lateral spreading, which can arise between hydrogen gas and resident reservoir fluids like water when cushion gas is absent. Thus, the significance of cushion gas in underground hydrogen storage cannot be overstated, and the assessment of cushion gas volume requirements is critical prior to embarking on any UHS project.

This study aims to investigate the impact of cushion gas type and their presence on the performance of underground hydrogen storage in an aquifer model situated offshore in the North Sea. The investigation goes beyond evaluating the effectiveness of each cushion gas and delves deeper into the physical properties of the cushion gases utilised. Through the advanced numerical modelling, this study seeks to provide a more comprehensive understanding of the relationship between cushion gas type and UHS performance, offering valuable insights in designing underground hydrogen storage projects.

2. Methodology

This study investigates the impact of cushion gas type on the performance of underground hydrogen storage in an offshore North Sea aquifer. To achieve this objective, we employed numerical simulation using the compositional reservoir simulator CMG-GEM™ [55].

2.1. Model description

2.1.1. Aquifer

The aquifer model (see Fig. 2) used in this study is located in a North Sea depleted oil reservoir at a depth of 10,000 feet. Due to the pressure support provided by the aquifer being lost gradually over the last 26 years when oil production increased significantly to 200,000 STB of oil, the oil field and its associated aquifer underwent depressurization. Our study evaluated underground hydrogen storage under assumed conditions of 2030 psi pressure and 110 °C temperature, the same as the depleted oil reservoir. A summary of aquifer properties is provided in Table 1.

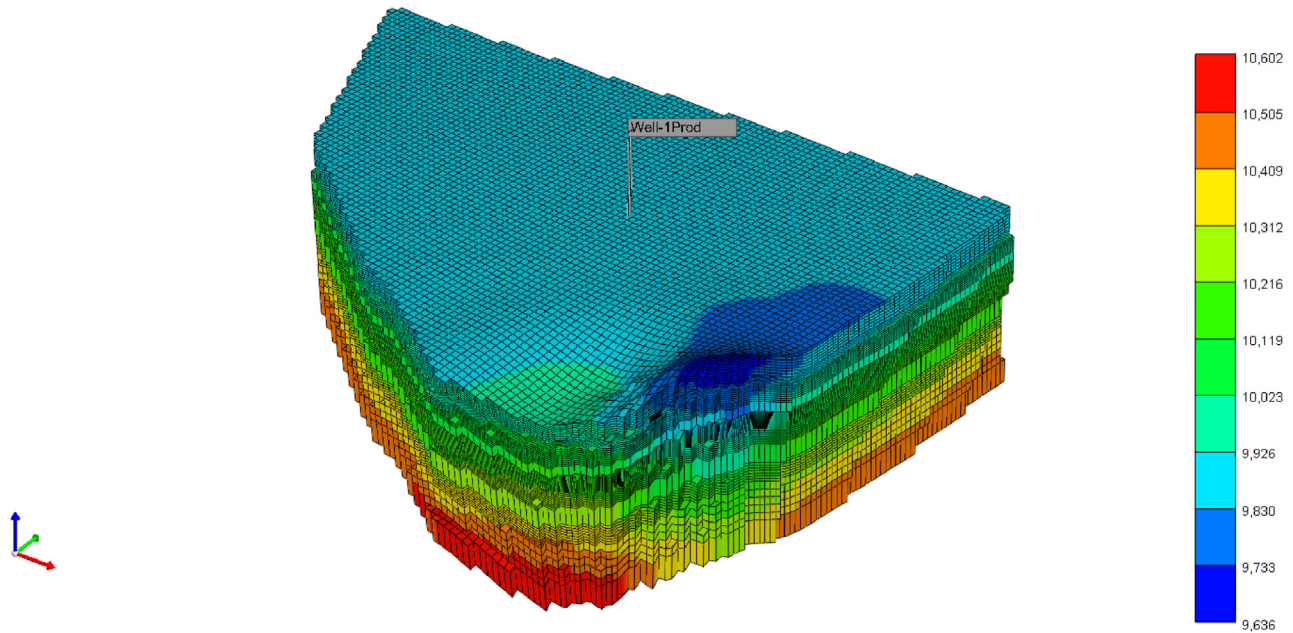


Fig. 2 – A 3D aquifer model showing grid tops and position of operating well.

2.1.2. Fluid model

The fluid compositional model consists of water and hydrogen gas, with the Peng-Robinson Equation of State employed to calculate the fluid properties. The Peng Robinson model utilised in the study was modified to account for binary gaseous mixtures. Henry's Law was utilised to incorporate the effects of hydrogen gas solubility in water, assuming thermodynamic equilibrium between the hydrogen gas and the aqueous phase. The hydrogen diffusion coefficient in water was assumed to be $8.5 \times 10^{-5} \text{ cm}^2/\text{s}$.

2.1.3. Rock and rock-fluid properties

The reservoir's dependence of rock compressibility on pressure and rock compressibility are $6.12 \times 10^{-12} \text{ psi}^{-2}$ and $3.5 \times 10^{-6} \text{ psi}^{-1}$, respectively. The aquifer has an average porosity of 0.19% and a permeability of 490 mD. The H_2 -water relative permeability curves (depicted in Fig. 3) were adapted from experimental investigations conducted by Yekta et al. [56].

2.2. Case studies

In this work, effects of CH_4 , N_2 , and CO_2 as cushion gases on the performance of underground hydrogen storage and

capacity in a deep North Sea aquifer is investigated. Four cases were run, three being for each cushion gas type and fourth one with only hydrogen injection. To act as a base case for comparison. The simulated cases consisted of six cycles of hydrogen gas injection and production stages. Each hydrogen injection stage lasted for 5 months, and the production stage continued for 7 months. The production stage of the sixth and final cycle was followed by an extended production period of hydrogen production for 3 years to recover the maximum quantity of hydrogen possible and deplete the aquifer pressure. The hydrogen injection was performed at a maximum surface rate of 35 MMscf/d (million standard cubic feet per day) and production was operated at a maximum rate of 20 MMscf/d. In the three cushion gases scenarios, the cushion gas was injected for 1 year and 2 months at a maximum rate of 40 MMscf/d prior to the six cycles of hydrogen storage. A summary of the simulated underground hydrogen storage process schedule is illustrated in Fig. 4.

The simulation study was conducted using a single well in the middle of the aquifer as shown in Fig. 2. The hydrogen injection is constrained by the maximum injection rate and a maximum bottomhole pressure of 4500 psi, the 600 psi lower than the fracture pressure (5100 psi). Correspondingly, to avoid issues with lifting the aquifer fluids to the surface, the production rate is curtailed by the maximum production rate and a minimum bottomhole pressure of 1900 psi.

Table 1 – Aquifer conditions and rock properties.

Property	Value
Depth (ft)	10,000
Temperature ($^{\circ}\text{C}$)	110
Initial Pressure (psi)	6000
Current Pressure (psi)	2000
Salinity (ppm)	24,000
Water initially in place (Billion ft^3)	2.1
Average porosity (%)	19
Aquifer gross thickness (depth 10,000 ft to 10,500 ft)	500

3. Results and discussion

Results of four cases to evaluate the effects of cushion gas type (CH_4 , N_2 , CO_2 , no cushion gas) on underground hydrogen storage in an aquifer are presented in this section, focussing on the cumulative hydrogen volumes, recovery efficiency, purity, saturation, and average aquifer pressure parameters.

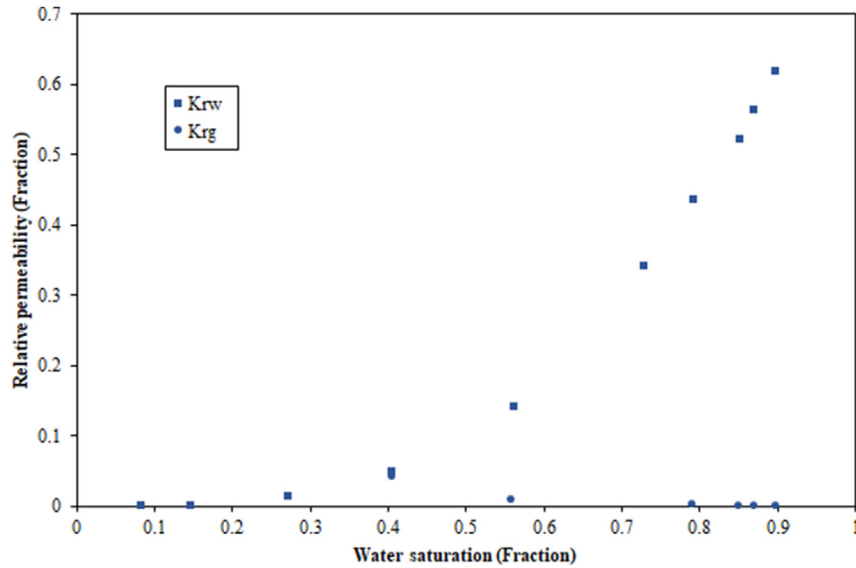


Fig. 3 – H₂-water relative permeability curves for drainage and imbibition deployed in the model [56].

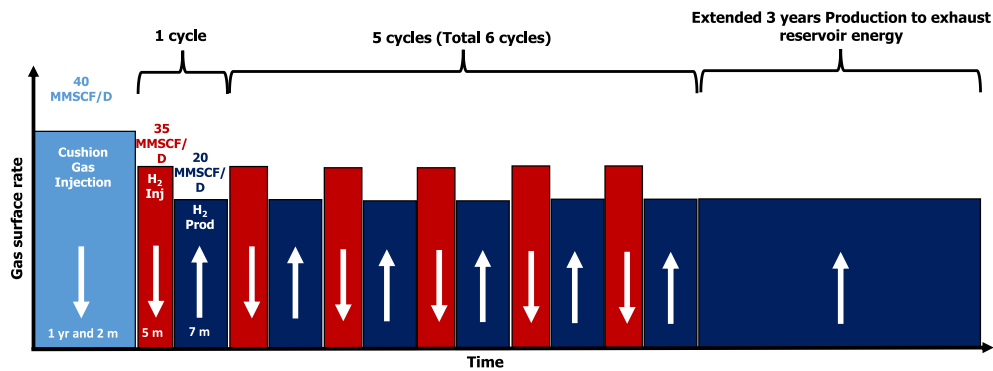


Fig. 4 – The injection and storage cycles schedule implemented in this study.

3.1. Injection and production volumes

Four scenarios were investigated where different types of cushion gases were used, CH₄, N₂, CO₂, and in one scenario no cushion gas was injected. The cushion gas was injected at a rate of 40 MMscf/d for 1 year and 2 months, followed by the injection of hydrogen gas at a maximum rate of 30 MMscf/d. Hydrogen production (withdrawal) rate was constrained at a maximum rate of 20 MMscf/d for 6 cycles. Simulation results presented in Fig. 5 show that the injection of different types of cushion gases influenced the cumulative volumes of hydrogen gas injected and produced. By the end of the storage period, the cumulative injected volume of hydrogen gas was the highest in the case of no cushion gas injection, 31.8 Bscf (Billion standard cubic feet). This is due to the higher capacity of the aquifer available as a result of the absence of the cushion gas. In the other cases, 29.2 Bscf, 27.5 Bscf, and 27.2 Bscf of hydrogen gas was injected cumulatively in the cases of CO₂, N₂ and CH₄, respectively for cushion gas utilisation. The higher volume of hydrogen gas stored in the CO₂ case can be partially explained by the higher solubility of CO₂ (1.7 gCO₂/kgH₂O @ 20 °C and 14.7 psi) in water compared to N₂ and CH₄ (0.019 gN₂/kgH₂O and

0.023 gCH₄/kgH₂O @ 20 °C and 14.7 psi, respectively). The high solubility of CO₂ water reflects a higher aquifer volume available to be occupied by the injected hydrogen gas allowing for more hydrogen to be stored in the aquifer.

Most importantly the cumulative hydrogen gas injected was directly correlated with the cushion gas density. Higher the cushion gas density the higher is the injected hydrogen gas volume. This observation is depicted in Fig. 6, where it can be seen that the cumulative hydrogen gas injected at the end of the simulation period, was higher in case of CO₂ (29.2 Bscf) followed by N₂ (27.5 Bscf) and CH₄ (27.2 Bscf). In a similar order, the gas density (at standard conditions) of CO₂ is 1.98 g/L which is higher than that of N₂, 1.25 g/L, which is higher than CH₄ gas's density, 0.657 g/L. This correlation can be explained by the fact that CO₂ due to its higher density occupies less volume inside the aquifer allowing for more hydrogen gas to be stored compared to the other cushion gases, N₂ and CH₄.

The cumulative hydrogen gas produced varied in the four simulated scenarios, where it was highest in the case in which no cushion gas was utilised, 23.3 Bscf. This can be directly explained by the significantly higher hydrogen gas stored compared to the other cases. The second highest hydrogen

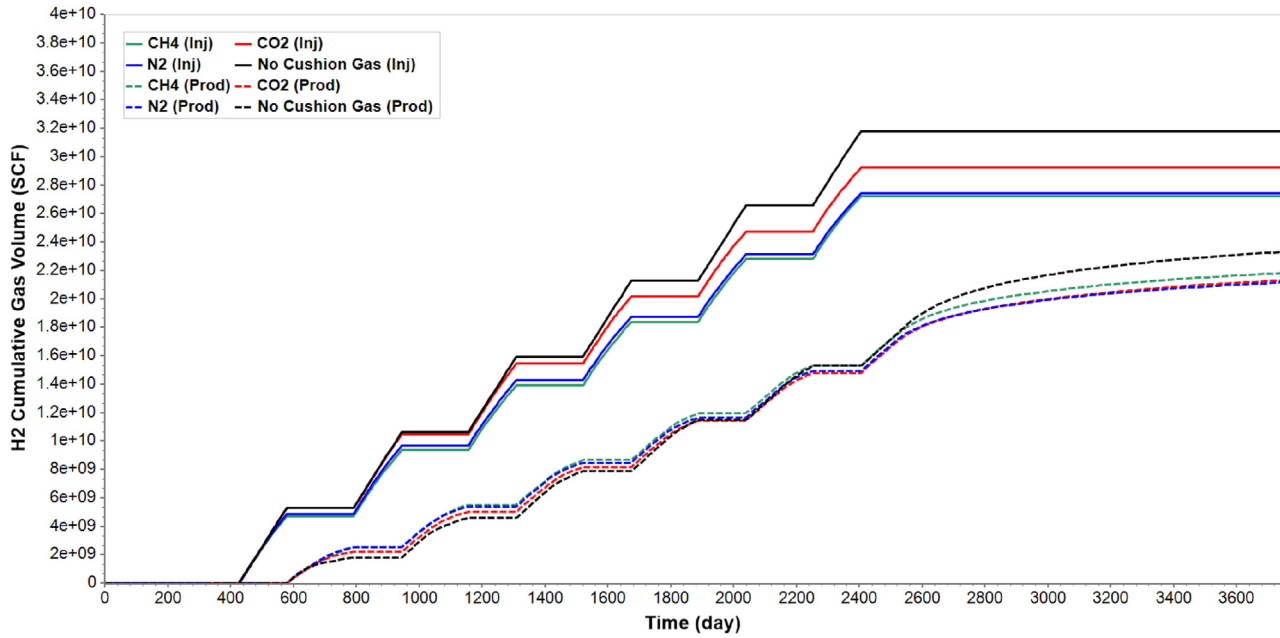


Fig. 5 – Cumulative injected and produced hydrogen volumes profiles over a 10-year period for the four studied scenarios (no-cushion gas, CH₄ as cushion gas, CO₂ as cushion gas, N₂ as cushion gas).

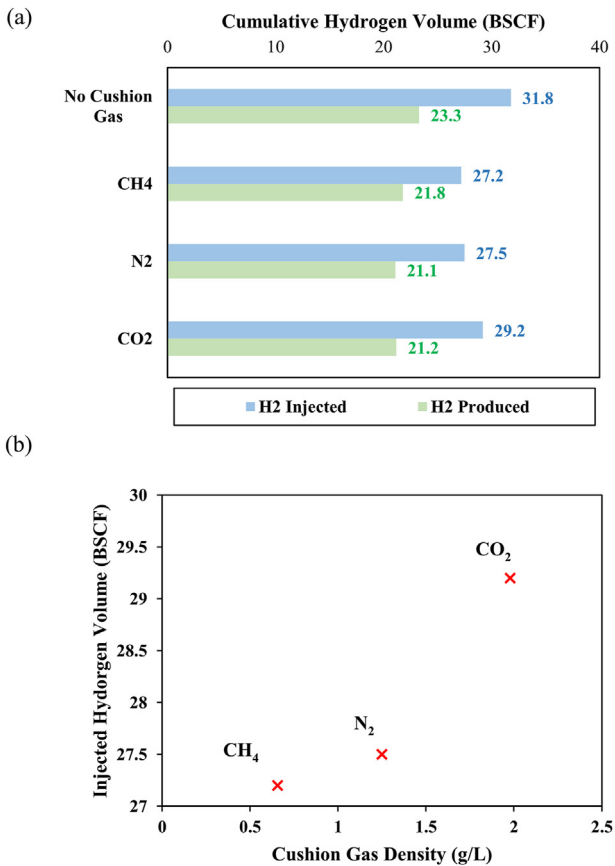


Fig. 6 – (a) Final cumulative injected and produced hydrogen volumes and (b) relationship between injected hydrogen gas volume and cushion gas density.

production was observed in the CH₄ scenario, which was 21.8 Bscf followed by CO₂, 21.2 Bscf and N₂, 21.1Bscf. The variation of the cumulative hydrogen gas produced with the type of cushion gas utilised can be attributed to the different physical properties of the utilised cushion gases. However, to properly compare the effect of cushion gas type on the hydrogen production, it is necessary to make the comparison based on the hydrogen recovery efficiency rather than the cumulatively produced volumes, which is discussed in the next section.

3.2. Hydrogen recovery efficiency

The hydrogen recovery efficiency refers to the ratio of the volume of hydrogen produced to the volume of hydrogen injected. From a technical point of view, the hydrogen recovery efficiency can be used to decide which cushion gas is more favourable for underground hydrogen storage. During the storage cycles, the injection and production stages result in decreasing and increasing the hydrogen recovery efficiency, respectively, with an overall upward trend as depicted in Fig. 7. This upward trend is attributed to the improved hydrogen gas phase continuity inside the reservoir as the injection continues with the progressing cycles, resulting in improved hydrogen gas mobility and recovery. The hydrogen recovery efficiency varied significantly depending on the type of cushion gas utilised. The highest recovery was observed in the case of injecting CH₄ as a cushion gas where H₂ recovery of 0.8 or 80% of the initial H₂ injected was achieved by the end of the simulation period. N₂ cushion resulted in the second highest hydrogen recovery efficiency, 0.77 or 77%, followed by CO₂ and the case where no cushion gas was utilised with a hydrogen recovery efficiency of 0.734 or 73.4% was achieved.

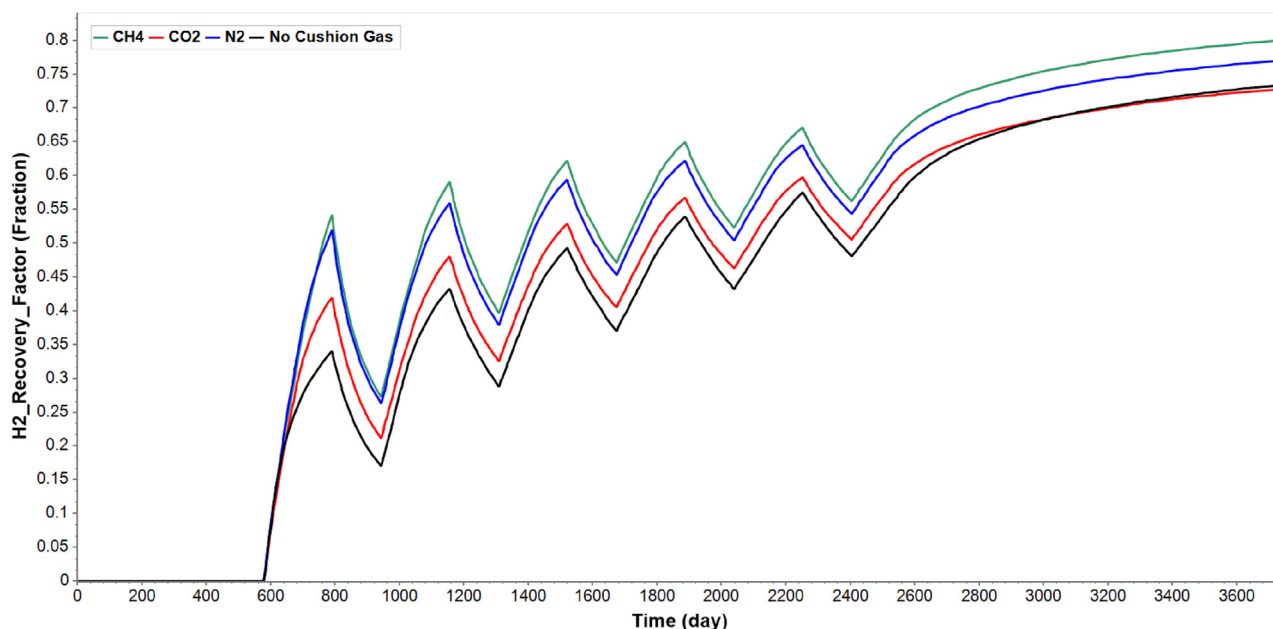


Fig. 7 – H₂ recovery efficiency profiles over a 10-year period for the four studied scenarios (no-cushion gas, CH₄ as cushion gas, CO₂ as cushion gas, N₂ as cushion gas).

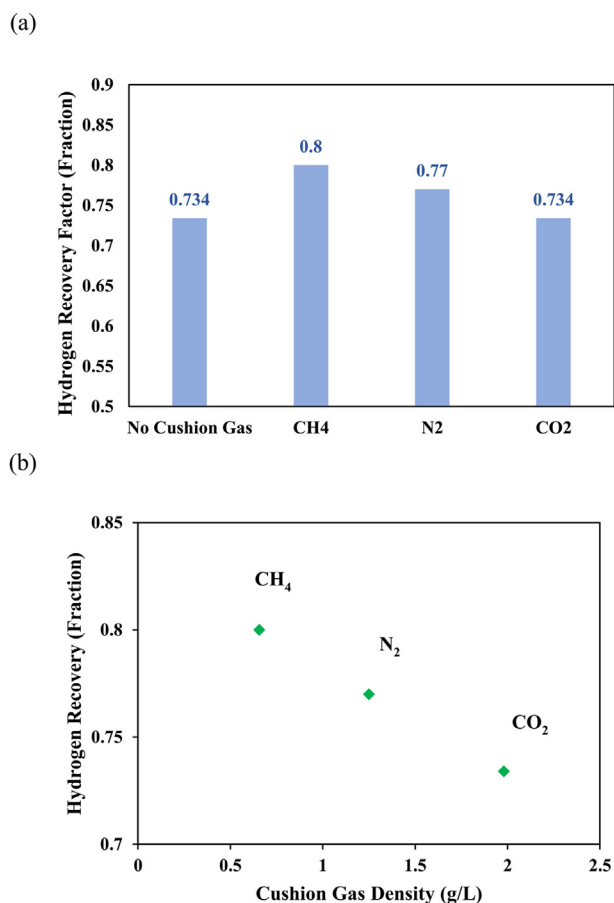


Fig. 8 – (a) Final hydrogen recovery efficiency for each case and (b) relationship between recovery efficiency and cushion gas density.

A comparison between the hydrogen recovery efficiency and cushion gas density (see Fig. 8) reveals a remarkable trend which indicates that lighter cushion gases result in an improved hydrogen recovery efficiency compared to heavier gases. The hydrogen recovery efficiency was highest in CH₄ with a density of 0.657 g/L which is lighter than both N₂, 1.25 g/L and CO₂, 1.98 g/L. The improved recovery efficiency can be explained by the higher ability of lighter cushion gases in reducing the hydrogen gas's gravity-overriding and viscous fingering which are amplified by the higher gas density contrast between the hydrogen gas and cushion gas. This invites to analyse the gas saturation profiles inside the aquifer in each case to understand H₂ gas movement.

Fig. 9 depicts the hydrogen saturation inside the aquifer at the end of the extended production period for each scenario. The absence of cushion gas (Fig. 9a) resulted in the excessive lateral spreading of the injected hydrogen gas as a result of gravity overriding which is more pronounced because the hydrogen gas is in direct contact with the resident aquifer water. The hydrogen gas is much lighter than the water and hence has higher mobility, resulting in the observed excessive lateral spreading. The utilisation of CO₂ as a cushion gas (Fig. 9b) resulted in a limited H₂ lateral spreading compared to the absence of a cushion gas scenario. However, the density contrast between H₂ and CO₂ led to viscous fingering phenomena in which the higher mobility of H₂ caused it to penetrate through the CO₂ gas phase. Consequently, the hydrogen recovery efficiency degrades due to the increased disconnected hydrogen gas phase. Both hydrogen lateral spreading and viscous fingering for N₂ as a cushion gas (Fig. 9c) are better controlled compared to the CO₂ and no-cushion scenarios, due to the lower density of N₂ compared to CO₂. Lateral spreading and viscous fingering phenomena are

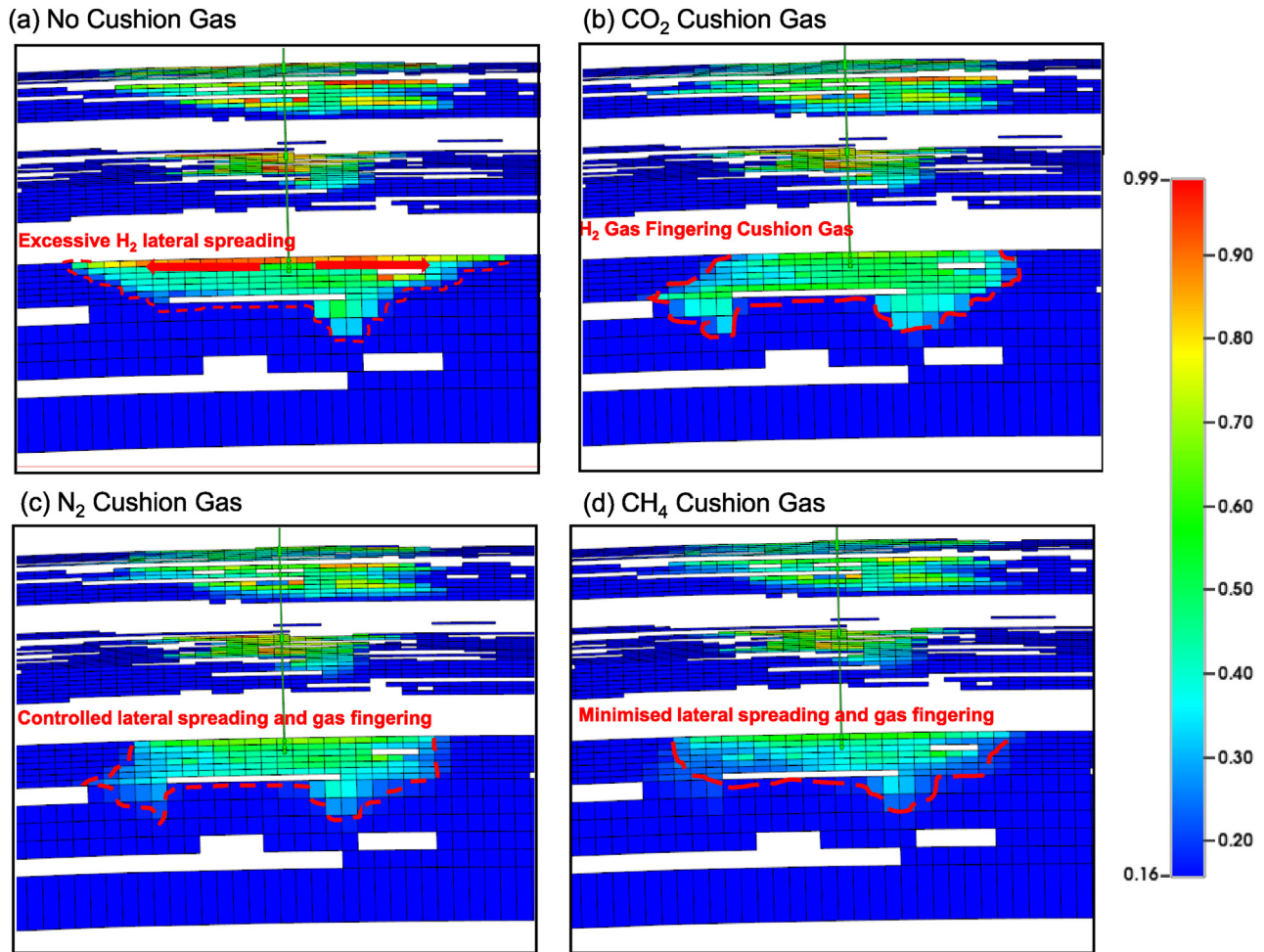


Fig. 9 – H₂ saturation profiles at the end of the final production period for each simulated case (a) no-cushion gas, (b) CO₂ cushion gas, (c) N₂ cushion gas, and (d) CH₄ cushion gas.

further minimised through the deployment of CH₄ as a cushion gas as depicted in Fig. 9d. This improved control of the stored hydrogen gas is the result of the lower density contrast between H₂ and CH₄ which led to a higher recovery efficiency of 0.8 or 80% compared to the other cushion gases.

These important observations indicate the importance of the cushion gas density and consequently type on the overall performance of the underground hydrogen storage process. In addition to the controlling hydrogen gas movement, the second important function of cushion gas during underground hydrogen storage is to provide pressure support during the hydrogen withdrawal process and therefore affecting the overall hydrogen recovery. The effect of cushion gas type on the aquifer pressure is discussed next.

3.3. Pressure

Aquifer pressure depends on the amount and density of injected gas. Response of average aquifer pressure to the type of cushion gas utilised is presented in Fig. 10 for the four studied cases over the storage period. It can be observed that the pressure remains constant at 2030 psi during the first 1 year

and 2 months in the no-cushion gas case (only hydrogen gas injection) compared to later phase of injection. Pressure behaviour in the other three cushion gas cases demonstrate that the pressure distribution in the six storage cycles (starting from March 2024) depends on the initial aquifer pressurization owing to the injection of cushion gas and respective type of the cushion gas injected. The aquifer pressure increases from 2030 psi to 2373 psi due to the injection of CO₂ as a cushion gas, to 2687 psi in the N₂ scenario and to 2723 psi in the CH₄ scenario.

Upon analysing the pressure trends in tandem with the cushion gas density it was found that the pressure at the end of the cushion gas injection stage was higher when the cushion gas was lighter as depicted in Fig. 11. Hence, in this study, we observed that the aquifer pressurization due to CH₄ injection was better compared to N₂ and CO₂ injection. This can be attributed to the fact that lighter gases such as CH₄ and N₂ require higher pressure compared to denser gases such as CO₂ to maintain similar amounts of the gases. Therefore, CH₄ is the best cushion gas option in terms of controlling H₂ spreading inside the aquifer and also initial stage pressurization maximising the hydrogen recovery efficiency compared to N₂ and CO₂.

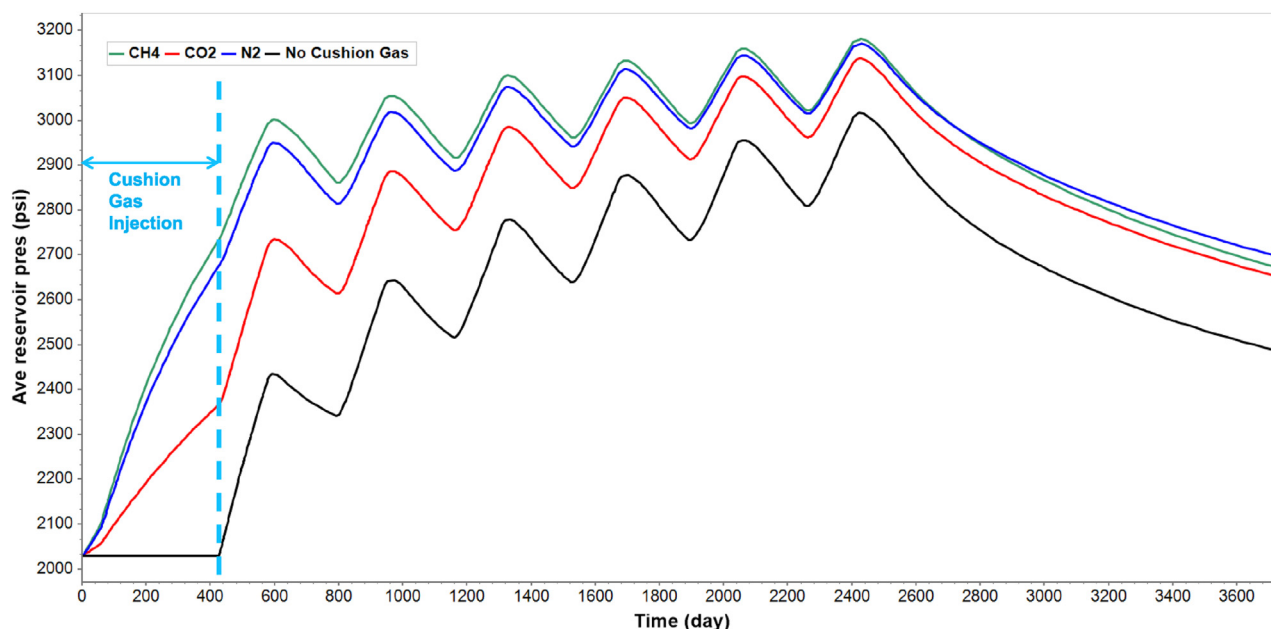


Fig. 10 – Average aquifer pressure profiles over a 10-year period for the four studied scenarios (no-cushion gas, CH₄ as cushion gas, CO₂ as cushion gas, N₂ as cushion gas).

3.4. Hydrogen purity and cushion gas recycling

Hydrogen gas purity is a critical factor in hydrogen energy applications. The purity of hydrogen gas refers to the degree to which it is free of other gases or impurities, such as oxygen, methane, nitrogen, water vapor, carbon monoxide, and carbon dioxide. It affects the efficiency and safety of fuel cells, which require pure hydrogen gas to produce electricity. Moreover, the purity of hydrogen gas is critical for hydrogen storage and transportation. Impurities may lead to corrosion or damage to storage and transport equipment increasing the risk of leakage or explosions.

Purity of the produced hydrogen gas is affected by the presence of cushion gas or native formation gases. In this work, we evaluated the purity of hydrogen in the four cases studied and the results are presented in Fig. 12a. The hydrogen purity was calculated as the ratio of the hydrogen gas

production rate to the total gas production rate. Results show that the produced hydrogen purity is dictated by the presence of cushion gas as well as the type of cushion gas utilised. In the absence of cushion gas, hydrogen purity always remained above 0.94 or 94%. The purity of hydrogen, in this case, was affected by the production of trace aquifer gases such as carbon dioxide and water vapor.

By comparing the results of the cushion gas cases shown in Fig. 12a, it is evident that deploying N₂ as a cushion gas leads to the highest hydrogen purity compared to the other cushion gases, CH₄ and CO₂. Although N₂ results in a higher hydrogen quality, the overall produced hydrogen purity remains mostly remain 0.95 or 95% for all cushion gases with purity dropping to less than 0.5 or 50% during the final production months of the first storage cycle. Another general characteristic observation is that the hydrogen purity at the start of each production stage in each cycle is relatively high and degrades as the production continues. This can be attributed to the fact that at the start of the production stage, the hydrogen gas that occupies the near wellbore region of the aquifer is produced first and as the production continues the cushion gas, which is further from the wellbore, is produced in association with hydrogen gas. Furthermore, it is noted that the hydrogen purity improves as the storage cycles progress, which can be explained by the increased hydrogen gas phase occupying the near wellbore region hindering the cushion gas production as the from regions further away from the wellbore.

Cushion gas recycling is another phenomenon that needs to be observed during underground hydrogen storage. It is the production of cushion gas in association with the produced hydrogen gas. It affects the cushion gas functions inside the geologic formation to control hydrogen escaping and pressure support. Hence, it is important to understand the amount of cushion gas recycling and determine if remedial cushion gas

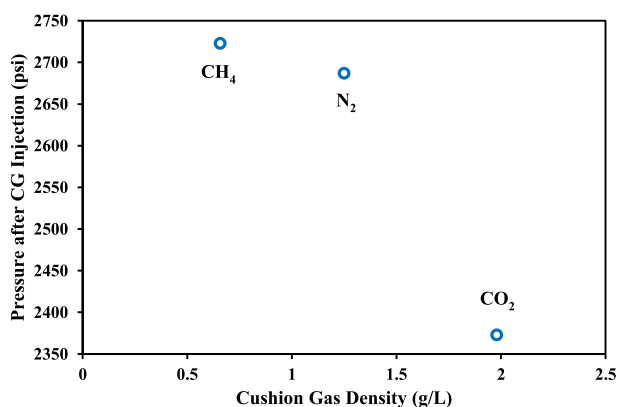
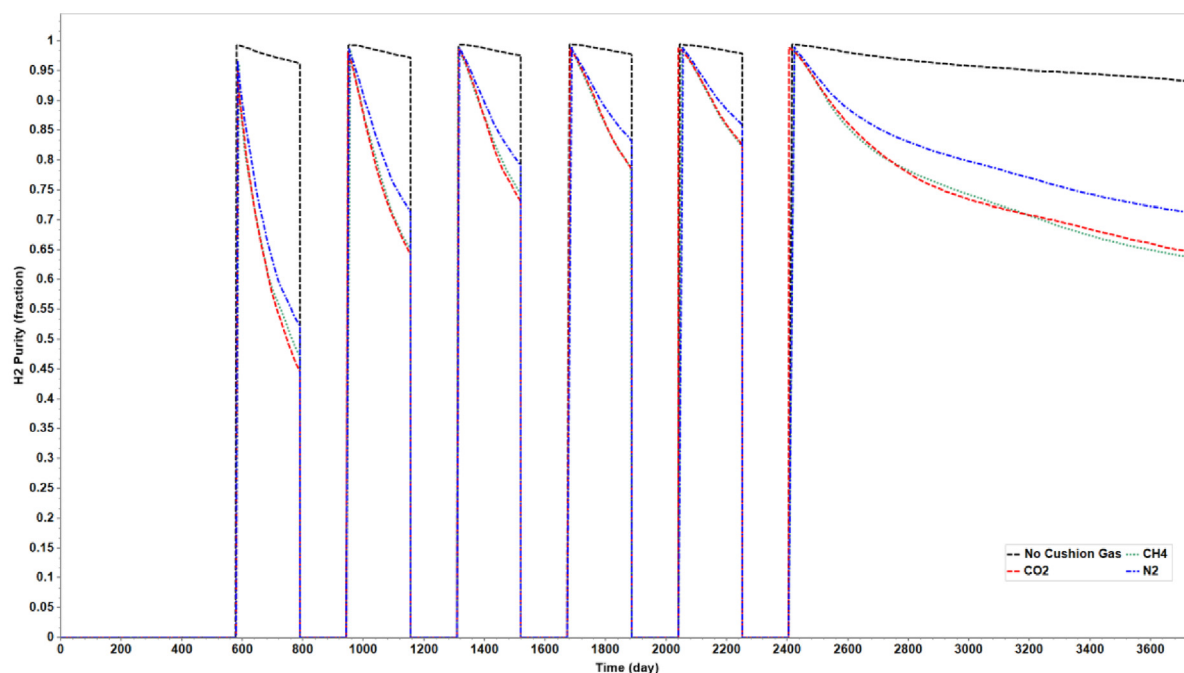


Fig. 11 – Relationship between aquifer pressure after cushion gas injection and cushion gas density.

(a)



(b)

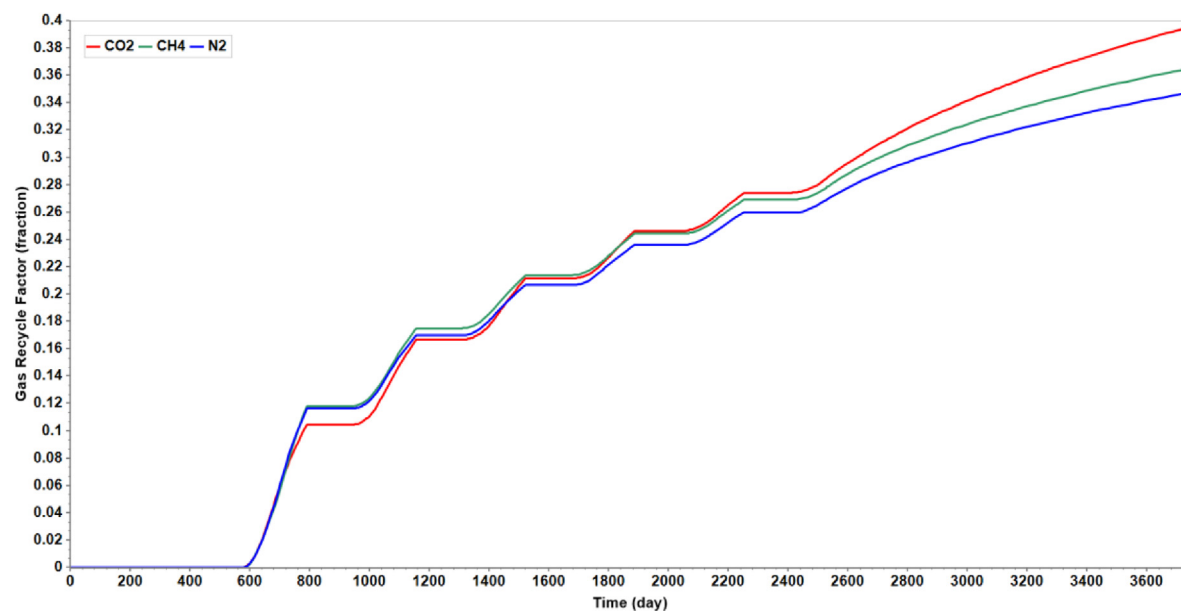


Fig. 12 – (a) H₂ purity and (b) cushion gas recycle factor for the four studied scenarios (no-cushion gas, CH₄ as cushion gas, CO₂ as cushion gas, N₂ as cushion gas).

injection is required. To investigate this phenomenon, we define the cushion gas recycle factor which is the ratio of the cumulative cushion gas produced to the cushion gas injected expressed as a fraction or percentage. The cushion gas recycle factor for the three cushion gas cases throughout the storage process is exhibited in Fig. 12b. Through examining the trend of the recycle factor, we observe that it increases reflecting the rise in the cumulative cushion gas production compared to the cushion gas initially utilised at the beginning of the

storage process. The recycle factors of N₂ and CH₄ in the first storage cycle are identical and reach 0.12 or 12% by the end of the first production stage. Meanwhile, CO₂ recycle factor by the end of the first cycle is at 0.1 or 10%. However, as the cycles progress, CO₂ recycling becomes the highest compared to the other cushion gases by the end of the storage period with a recycle factor of 0.39 or 39%. CH₄ results in the second highest cushion gas recycling with a recycle factor of 0.36 or 36% followed by N₂ with a factor 0.33 or 33% indicating that a third of

the initial N₂ injected as a cushion gas is reproduced throughout the storage process.

Further inspection of the cushion gas recycle factor curves in Fig. 12b, show that the rate of recycling decreases as the storage cycles progress. This can be described by the fact that the hydrogen purity improves with the storage cycles (Fig. 12a) which was explained by the increased volumes of hydrogen gas phase occupying the near wellbore pores inside the geologic formation limiting the cushion gas production. Hence, the rate by which the hydrogen purity changes in each curve (Fig. 12a) is in an opposite trend to the rate by which cushion recycle factor curves (Fig. 12b) change as the storage cycles progress. Hydrogen gas purity and cushion gas recycling are of great importance during underground hydrogen storage as it has a direct impact on the surface facilities design and project economics. Hence, both factors should be properly evaluated as a part of each simulation study prior to underground hydrogen storage evaluation in a target geologic formation.

4. Conclusion

The impact of cushion gas type and presence on the performance of underground hydrogen storage in an offshore North Sea aquifer has been investigated in this study. A more comprehensive understanding of the relationship between cushion gas type and UHS performance has been provided through the use of numerical simulation techniques, thus offering a valuable insight in designing efficient and reliable underground hydrogen storage projects.

Results showed that the recovery efficiency and hydrogen purity of the system can be significantly impacted by the choice of cushion gas type. CO₂ was found to have the highest storage capacity due to its higher density, while lighter gases like N₂ and CH₄ exhibited better recovery efficiency by reducing gravity overriding and viscous fingering. Furthermore, it was found that the deployment of CH₄ as a cushion gas can lead to a higher recovery efficiency of 0.8 or 80% compared to the other cushion gases by minimizing lateral spreading and viscous fingering. However, it has also been determined that utilising cushion gas, regardless of its type, is always better than not using it. The use of cushion gas led to an incremental hydrogen recovery of up to 7%, which can significantly improve the overall efficiency of underground hydrogen storage.

It was also revealed that the hydrogen purity at the start of each production cycle was relatively high and degraded as the cycle progressed but improved over time due to the increased hydrogen gas phase occupying the near wellbore region. This characteristic can help in the design and optimization of UHS systems and their operational strategies.

In conclusion, this study has contributed to a better understanding of the factors that affect UHS performance, especially in offshore environments. Our results can inform the selection of cushion gas type and aid in the design of optimal operational strategies to enhance the efficiency and reliability of underground hydrogen storage systems. Future studies can build on our findings by investigating the impact of other factors, such as injection and production rates, on UHS performance in different geological settings.

CrediT authorship contribution statement

Motaz Saeed: Writing – original draft, Visualization, Investigation, Methodology, Software, Data curation, Writing – review & editing, Formal Analysis. Prashant Jadhawar: Writing – original draft, Visualization, Investigation, Methodology, Software, Data curation, Writing – review & editing, Formal Analysis, Funding Acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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