LA-UR-22-29249
Accepted Manuscript

Capacity assessment and cost analysis of geologic storage of hydrogen: A case study in Intermountain-West Region USA

Mehana, Mohamed Zakaria Saad
Ma, Zhiwei
Nasrabadi, Hadi
Chen, Bailian
Chen, Fangxuan
Van Wijk, Jolante Wieke

To be published in: International Journal of Hydrogen Energy

DOI to publisher's version: 10.1016/j.ijhydene.2022.11.292

Permalink to record:
http://permalink.lanl.gov/object/view?what=info:lanl-repo/lareport/LA-UR-22-29249

ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (XXXX) XXX

Available online at www.sciencedirect.com

ScienceDirect

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

ELSEVIER

Capacity assessment and cost analysis of geologic storage of hydrogen: A case study in Intermountain-West Region USA

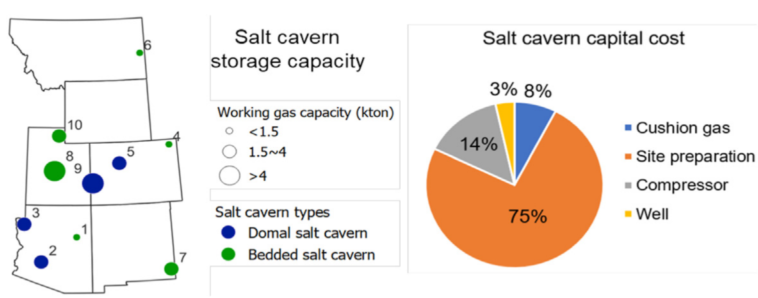
*Fangxuan Chen [a,b,**], Zhiwei Ma [a], Hadi Nasrabadi [b], Bailian Chen [a], Mohamed Zakaria Saad Mehana [a,*], Jolante Van Wijk [a]*

[a] *Los Alamos National Laboratory, Los Alamos, United States*
[b] *Texas A&M University, College Station, United States*

HIGHLIGHTS

- Techno-economic analysis of hydrogen geologic storage in the Intermountain-West, US.
- Promising sites for geologic hydrogen storage are identified.
- The hydrogen storage capacity and energy demand are estimated.
- H_2 storage costs in different geologic formations are estimated and optimized.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 September 2022
Received in revised form
31 October 2022
Accepted 26 November 2022
Available online xxx

Keywords:
Geologic hydrogen storage
Intermountain-West (I-WEST) region

ABSTRACT

Hydrogen is an integral component of the current energy transition roadmap to decarbonize the economy and create an environmentally-sustainable future. However, surface storage options (e.g., tanks) do not provide the required capacity or durability to deploy a regional or nationwide hydrogen economy. In this study, we have analyzed the techno-economic feasibility of the geologic storage of hydrogen in depleted gas reservoirs, salt caverns, and saline aquifers in the Intermountain-West (I-WEST) region. We have identified the most favorable candidate sites for hydrogen storage and estimated the volumetric storage capacity. Our results show that the geologic storage of hydrogen can provide at least 72% of total energy consumption of the I-WEST region in 2020. We also calculated the capital and levelized costs of each storage option. We found that a depleted gas reservoir is the most cost-effective candidate among the three geologic storage options. Interestingly, the cushion gas type plays a significant role in the storage cost when we consider hydrogen

* *Corresponding author.*
** *Corresponding author.*
E-mail addresses: fangxuanche@lanl.gov (F. Chen), mzm@lanl.gov (M.Z. Saad Mehana).
https://doi.org/10.1016/j.ijhydene.2022.11.292
0360-3199/Published by Elsevier Ltd on behalf of Hydrogen Energy Publications LLC.

Cost analysis
Storage capacity

storage in saline aquifers. The levelized costs of hydrogen storage in depleted gas reservoirs, salt caverns, and saline aquifers with large-scale storage capacity are approximately \$1.15, \$2.50, and \$3.27 per kg of H_2, respectively. This work provides essential guidance for the geologic hydrogen storage in the I-WEST region.

Introduction

Greenhouse gas emission is a major cause of climate change, which has largely affected the earth's ecology and environment [1,2]. It is estimated that fossil fuel combustion leads to 74% of total greenhouse gas emissions [2]. Therefore, cleaner energy alternatives are utilized to reduce carbon emissions, including solar, wind, hydropower, bioenergy, and geothermal energy [3]. However, renewable energy sources are often seasonal and/or location-dependent and cannot provide constant and reliable energy to meet the energy requirements. To solve this problem, excess energy should be stored for future use [4,5]. Hydrogen (H_2) serves as a clean energy carrier, which can be stored both into surface tanks and into subsurface sites geologically [6–8]. Fig. 1 compares the current H_2 storage options in terms of discharge duration and power [9]. It is of great significance to assess the feasibility of H_2 geologic storage [10].

Recently, the feasibility assessment of H_2 geologic storage has drawn the attention of various research institutes around the world [11–13]. Scafidi et al. [14] quantified the H_2 storage capacity of gas fields and saline aquifers on the UK continental shelf. They estimated that, assuming 50% of cushion gas, the working gas capacities were 6900 TWh and 2200 TWh for gas fields and saline aquifers, respectively. Liu et al. [13] investigated the feasibility of H_2 storage in salt caverns in Jiangsu province, China. They used numerical simulation models to evaluate salt cavities' stability and tightness. The simulation results demonstrated that the gas permeability of interlayers should be less than 10^{-3} mD to ensure wall tightness. Veshareh et al. [15] investigated the chemical and biochemical reactions in chalk hydrocarbon reservoirs to assess their feasibility as H_2 storage sites. Danish North Sea chalk hydrocarbon reservoirs were selected as targeted sites, and four principal reactions (e.g., abiotic calcite dissolution and biological souring) were considered. Their results proved that chalk reservoirs were not affected by the chemical or biochemical risks and are good candidates for H_2 storage. Zeng et al. [16] analyzed the effects of carbonate dissolution on H_2 loss for the H_2 storage in carbonate reservoirs. Their results suggested that 6.5% of H_2 would be consumed for six-month storage. In addition, the H_2-brine-rock interactions would generate a large amount of methane, leading to reduced H_2 purity.

The conventional H_2 storage options include salt caverns, saline aquifers, and depleted gas reservoirs [17]. Different storage sites have different characteristics and can be used for various purposes [18,19]. For instance, salt caverns are created by solution mining in salt-rich formations [20]. Based on the geologic structure, two types of salt caverns can be utilized: domal salt caverns and bedded salt caverns. A domal salt cavern has an integrated cavity created in a thick rock salt layer. In bedded salt caverns where rock salt layers are discontinuous, the cavity is built only in rock salt layers, which leads to a disconnected cavity [21]. The schematic

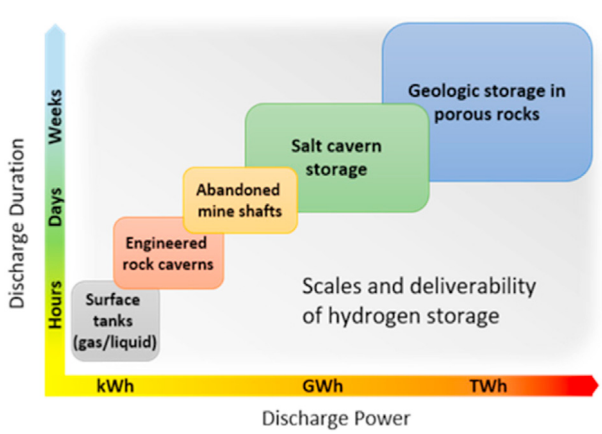


Fig. 1 – Scales and deliverability of hydrogen storage.

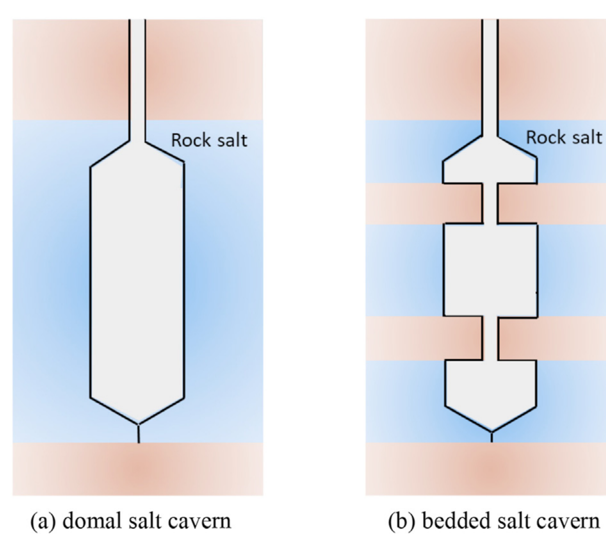


Fig. 2 – Schematic figure of (a) domal salt cavern and (b) bedded salt cavern. The blue region represents the rock salt layer. The white region is the salt cavern. A domal salt cavern has an integrated cavity created in a thick rock salt layer, while a bedded salt cavern has a compartmental cavity due to the discontinuous rock salt layers. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Please cite this article as: Chen F et al., Capacity assessment and cost analysis of geologic storage of hydrogen: A case study in Intermountain-West Region USA, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.11.292

figure of domal salt caverns and bedded salt caverns is shown in Fig. 2. Salt caverns have the advantages of long-term structural stability, good seal integrity, and low cushion gas requirement [22,23]. In addition, the high salinity nature strongly restrains the microbiological activities, which are detrimental to the storage operations [24]. However, salt cavern construction requires a large amount of water during the leaching process, which might be challenging in water scarcity regions. Consequently, water injection and disposal are needed during the cavern creation stage [5]. It is worth noting that several salt caverns have been built in the United States and the United Kingdom [25].

Also depleted gas reservoirs are favorable storage sites for various gases. As previous geologic hydrocarbon traps, these reservoirs have a large-scale porous media and impermeable seal [25,26]. In addition, the geologic characteristics of these reservoirs have been described in detail, and existing infrastructures reduce the initial capital investment. Moreover, the residual gas in the reservoir can serve as the cushion gas, reducing the amount of cushion gas required. However, many factors must be carefully considered to design H_2 geologic storage. The heterogeneity of reservoir rock mineralogy and the wettability of rocks have significant effects on the whole H_2 storage process, including injectivity, withdrawal rate, and storage durability [27–29]. In addition, the existence of microorganisms may consume H_2 and generate other gases, which reduces the stored amount and lowers the H_2 purity. For example, the sulfate-reducing bacteria can use sulfate and hydrogen to generate hydrogen sulfide [30]. The methanogens convert CO_2 and H_2 to methane and water [31]. The consumption efficiency depends on many factors, including temperature, pressure, reaction types, brine salinity, nutrients, pH, and inhibitors [32], which makes it hard to quantify the amount of H_2 consumption.

Aquifers are abundant in sedimentary basins and can also be used for H_2 storage if salt caverns and depleted gas reservoirs are unavailable in the region. Generally, an ideal aquifer for H_2 storage should have two characteristics: 1) water-bearing sand with high porosity and permeability; 2) both vertical and lateral seals. An impermeable cap rock with an anticline shape is preferred because it helps form a gas cap, reducing the amount of water produced during H_2 extraction [33]. It is worth noting that the reservoir temperature, pressure, and organic surface concentration could alter the H_2 wettability of caprock, which affects the trapping capacity and sealing integrity [34–36]. In the same vein, the higher diffusion coefficient of H_2 might detrimentally impact the sealing integrity of caprock [37]. Apart from H_2 leakage potential, possible H_2 reactivities with saline water should be carefully assessed. Currently, no pure H_2 storage in a saline aquifer is reported worldwide [38]. However, reservoir simulations have been conducted to investigate the feasibility of H_2 storage in saline aquifers [39].

Cost analysis is an important aspect of large-scale H_2 geologic storage [40,41]. Taylor et al. [42] divided the total cost of H_2 storage into three parts: capital cost, operating cost, and additional investment. The capital cost includes the storage site development, equipment purchase, general working system (heating, lighting, monitoring, and alarm system), well, and surface pipeline network. The operating cost includes H_2 production, water cooling, power, and labor costs. The additional investment involves the costs of land usage and plant construction. Ugarte and Salehi [43] mentioned that the materials used in H_2 storage should be resistant to corrosion and rusting, which leads to an extra embrittlement cost. Lord et al. [44] analyzed the total capital cost and levelized cost of H_2 storage in salt caverns, depleted oil and gas reservoirs, hard rocks, and aquifers. Their results showed that depleted oil and gas reservoirs have the lowest levelized cost of H_2 storage, which are the most economical storage candidates. The significant cost of H_2 storage in salt caverns and hard rocks is due to the high mining cost, while the cost of cushion gas accounts for most of the expenditure in depleted gas reservoirs and saline aquifers.

The I-WEST region consists of Arizona, Colorado, New Mexico, Montana, Utah, and Wyoming, which account for 6% of the population and 18% of the total area of the United States [45]. The six states share similar energy challenges: water scarcity and economic dependency on fossil fuels. The net CO_2 emissions from fossil fuels in the I-WEST region in 2019 are shown in Fig. 3. To reduce the carbon emissions and alleviate the dependency on fossil fuels, various initiatives and projects have been started to design an energy transition roadmap in the I-WEST region. Such a roadmap includes CO_2 capture and storage, H_2 production, storage and transportation, biomass utilization, and conversion components. Due to the legacy of the oil and gas industry in the region, many depleted gas fields are potential geological sites for H_2 storage. In addition, the widely deposited rock salts are ideal places for salt caverns of H_2 storage.

Energy transition in the I-WEST region entails wide adoption of clean energy alternatives to replace conventional fossil fuels [47]. With the rapid development of H_2 production techniques, the cost of H_2 production has been largely reduced, which makes it a good alternative to fossil fuels [48,49]. As a result, the techno-economic analysis of H_2 storage in the I-WEST region becomes an urgent challenge that needs to be addressed.

In this work, we analyzed the H_2 storage capacity in potential geologic sites and estimated the cost of H_2 storage of different types of geologic sites in the I-WEST region. The promising candidates for H_2 storage sites in the I-WEST region

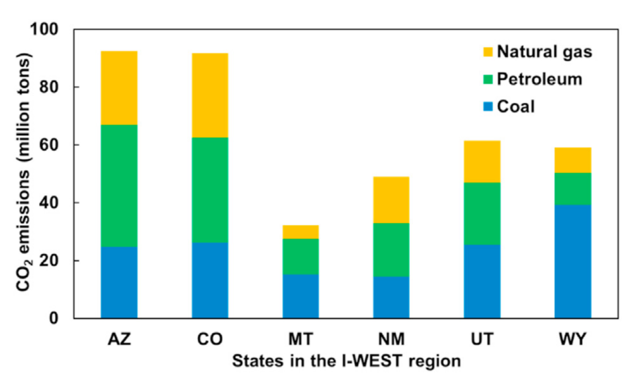


Fig. 3 – CO_2 emissions in I-WEST region in 2019. AZ: Arizona, CO: Colorado, MT: Montana, NM: New Mexico, UT: Utah, WY: Wyoming. The data were obtained from Energy Information Administration [46].

are identified, together with the H_2 storage capacity of each site. The capital and levelized costs of H_2 storage in three specific geological sites are estimated. In addition, the effects of storage volume and cushion gas type on capital and levelized costs of H_2 storage are analyzed. This work will provide essential guidance for the geologic H_2 storage in the I-WEST region.

The remaining of our paper is organized as follows: Section Methodology discusses the methodology of estimating H_2 storage capacity and cost. Section Results and analysis presents the energy consumption in each state to determine the required storage capacity. We summarize the H_2 storage capacity in potential geological sites. The cost of various geologic H_2 storage options is presented to assess the economic feasibility. Section Conclusion reports this work's main conclusions and findings.

Methodology

This section discusses the assumptions and methods for estimating the capacity and cost of H_2 storage in depleted gas reservoirs, salt caverns, and saline aquifers. Based on these methods, we evaluate the potential H_2 storage capacity and cost in geological sites in the I-WEST region.

Hydrogen storage capacity

Depleted gas reservoir

In the estimation of H_2 storage capacity in depleted gas fields, several assumptions are made:

(1) The pressure and temperature gradients are 0.433 psi/ft and 15 °F/1000 ft, respectively [20];
(2) The cumulative production amount of natural gas under reservoir conditions is equal to the volume of stored H_2 in reservoir conditions;
(3) The cushion gas is H_2, and the volume percentage of cushion gas is 50% of the total storage volume [50].
(4) The H_2 consumption due to the existence of microorganisms is not included during the calculations because it is hard to quantify the consumption amount considering the various types of microorganisms and different reservoir conditions.

The methodology in this section is modified from the methods of H_2 storage estimation in the reference [2] by assuming the remaining gas is not considered as cushion gas. The natural gas cumulative production amount under standard conditions is obtained from the state databases. For the given average depth of a field, we can estimate the average pressure and temperature of the field with the pressure gradient (0.433 psi/ft) and temperature gradient (1.5 °F/100 ft) [20]. With the average pressure and temperature of the field, we can calculate the compressibility factor (z) of natural gas using the Dranchuk and Abou-Kassem equation of state (DAK - EOS) [51]. The formation volume factor (B_g) can be calculated using the equation shown below:

$$B_g = \frac{V}{V_{sc}} = 0.0283\frac{zT}{P} \quad (1)$$

where the unit of B_g is ft^3/SCF, P in psia, and T in °R. Then, we can convert the natural gas cumulative production amount under standard conditions into reservoir conditions using B_g. Based on the assumption (2), we can obtain the volume of H_2 that can be stored underground. The underground H_2 storage volume can then be converted into the volume under standard conditions using Eq. (1). The z factor of H_2 is obtained from NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP) [52]. Assuming the volume percentage of cushion gas (H_2) is 50%, we can determine the volume of cushion gas and working gas (50%). The workflow is shown in Fig. 4.

Salt cavern

Several assumptions are made to model the salt caverns and estimate the volume of salt caverns based on the work of Lankof and Tarkowski [53] and Pierce et al. [54]:

(1) A salt cavern has a cylindrical shape with a specific diameter (D). The upper part of a cavern is a cone-shaped dome, with a height of 1/3 D. The lower part of a cavern is a conical incision, with a height of 1/6 D;
(2) Pressure gradient of fracture breakdown (g_f): 0.016 MPa/m;
(3) Minimum pressure gradient (g_{min}): 0.00835 MPa/m;
(4) Fraction of gas working capacity from the total volume: 80%;
(5) Temperature gradient: 0.027 °C/m.

The methodology of estimating single salt cavern storage capacity follows the work of Lankof and Tarkowski [53]. A schematic figure is presented in their work to explain the physical meaning of different parameters. The volume of the

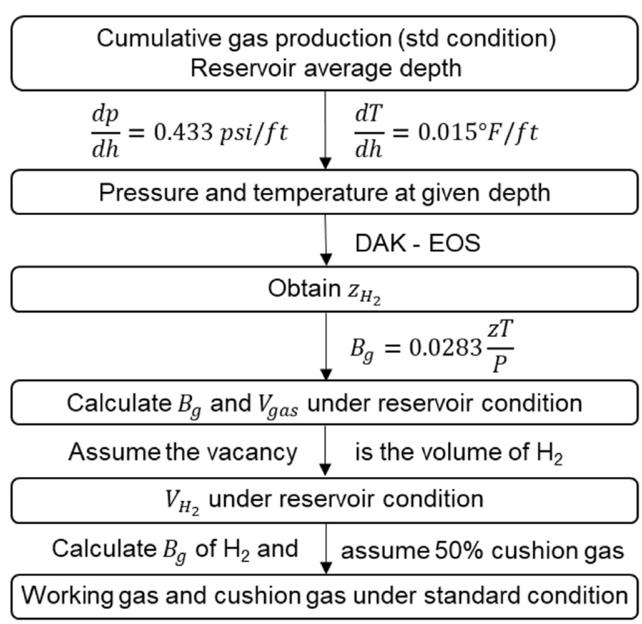


Fig. 4 – Workflow of the calculation of hydrogen storage volume in depleted gas reservoirs.

Please cite this article as: Chen F et al., Capacity assessment and cost analysis of geologic storage of hydrogen: A case study in Intermountain-West Region USA, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.11.292

cavity is calculated by assuming a cylindrical shape. The maximum and minimum pressure are computed using the equations shown below:

$$p_{max} = g_f h_n \tag{2}$$

$$p_{min} = g_{min}(h_c - h_0) \tag{3}$$

where h_n, h_c, and h_0 represent the depth to the top of the cavern neck, depth of the cavern center and depth of the cavern that can be emptied to zero pressure value. The values of g_f and g_{min} are 0.016 and 0.00835 MPa/m, respectively. The amount of H_2 stored in a single salt cavern at pressure p is calculated by the equation:

$$m = f\frac{pV}{R^{*}Tz} \tag{4}$$

where m is the amount of H_2 in the cavern, f denotes the percentage of working gas, T is the temperature, R^* means the individual gas constant of H_2, which is 4121.73 $J/\ kg \bullet K$, and z is the compressibility factor of H_2. The z factor of H_2 is obtained from NIST REFPROP Database [52]. The working capacity of H_2 can be obtained by calculating the difference of $m(p_{max})$ and $m(p_{min})$. The workflow is summarized in Fig. 5.

The maximum number of salt caverns built in a specific region is estimated based on the potential area of rock salt layers. We assume that each salt cavern is built at the same depth with the same storage volume. To ensure the stability of the salt caverns, the distance between two adjacent salt caverns is four times the diameters of a single salt cavern [55]. Therefore, we can estimate the maximum number of salt caverns using the total area of the rock salt layer divided by the square area occupied by a single salt cavern ($16D^2$).

Saline aquifer

Due to the similar characteristics of depleted gas reservoirs and saline aquifers, the assumptions and methodology of aquifer storage capacity estimation are similar to the ones of depleted gas reservoirs. One important parameter is the storage efficiency, which means the percentage of pore volume occupied by H_2. However, due to the limited research on pure H_2 storage in saline aquifers, the H_2 storage efficiency has not been analyzed. Based on the experimental and simulation data of CO_2 and natural gas storage in saline aquifers, the storage efficiency ranges from 5 to 20% [55,56], which depends on the saline aquifer properties. Herein, we assume the H_2 storage efficiency is 10%. The assumptions are shown below:

(1) The pressure and temperature gradients are 0.433 psi/ft and 15 °F/1000 ft, respectively [20];
(2) The H_2 storage efficiency is 10%;
(3) The cushion gas is H_2, and the volume percentage of cushion gas is 80% [50].

For a given depth of the aquifer, the average pressure and temperature of the aquifer can be estimated with the pressure and temperature gradients. With the assumption of 10% H_2 storage efficiency, the underground H_2 storage volume is obtained using the equation shown below:

$$V = Ah\varphi \bullet 10\% \tag{5}$$

where A is the area of the aquifer, h is the thickness of the aquifer, φ represents the porosity of the aquifer. By calculating B_g using Eq. (1), we can convert the underground H_2 storage volume to the H_2 storage volume under standard conditions. Assuming the cushion gas accounts for 80% of the total stored gas, the working gas capacity (20%) of aquifers can be determined. The workflow is shown in Fig. 6.

Hydrogen storage cost

The economic feasibility of H_2 storage is generally based on the Hydrogen Geological Storage Model (H2GSM) proposed by Kobos et al. [57]. The cost estimation of each geological site

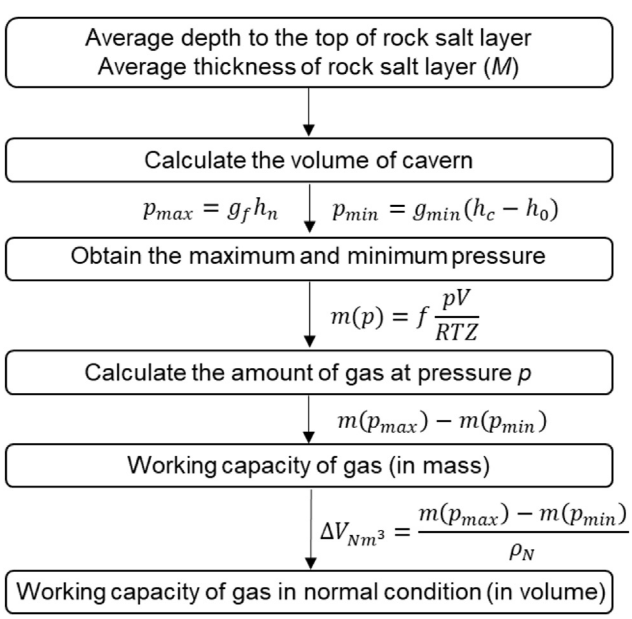


Fig. 5 – Workflow of the calculation of hydrogen storage volume in a single salt cavern.

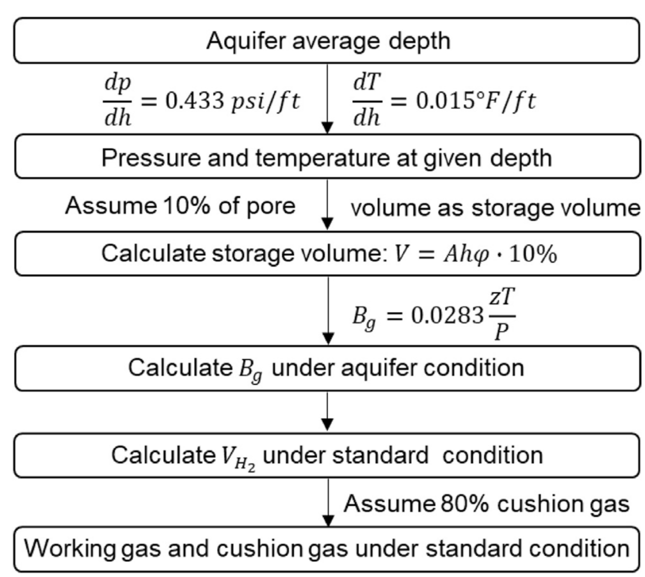


Fig. 6 – Workflow of the calculation of hydrogen storage volume in an aquifer.

Please cite this article as: Chen F et al., Capacity assessment and cost analysis of geologic storage of hydrogen: A case study in Intermountain-West Region USA, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.11.292

includes two parts: the capital cost and the levelized cost of H_2 storage. The capital cost is a one-time expenditure, which includes the cost of well construction, equipment purchase, cushion gas, and potential site preparation. The levelized cost of H_2 storage estimates the average net present cost over its lifetime. It includes the cost of equipment operation and maintenance, and resource consumption, together with the capital cost converted to each kilogram of H_2 over the lifetime.

The cost of H_2 production varies due to the production methods and regions. The European Commission's July 2020 H_2 strategy shows that the green H_2 production cost is between \$3/kg and \$6.55/kg [58]. Herein, the H_2 cost is considered as \$5/kg.

To the best of the author's knowledge, the latest cost data of H_2 storage is from Lord et al. [44], which cannot reflect current conditions. To make the data more reliable, we consider the inflation/deflation factors using the Consumer Price Index (CPI). To be consistent with the H_2 price, the cost data of H_2 storage is converted to 2020. According to the CPI from US Bureau of Labor Statistics, \$1 in 2014 has the same buying power as \$1.11 in 2020 [59]. Therefore, the cost data from Lord et al. [44] is converted to the cost in 2020 using the conversion factor of 1.11.

Capital cost

The capital cost has four parts: 1) cushion gas cost; 2) geologic site preparation cost; 3) compressor capital cost and 4) well capital cost. The detailed values are modified from Lord et al. (2014) by considering the inflation/deflation factors and summarized in Table 1.

The cost of geologic site preparation is highly dependent on the type of geologic site. Both depleted gas reservoirs and saline aquifers have natural porous media to store H_2. Due to the previous exploration and development experience, no extra effort is needed for depleted gas reservoirs. However, further analysis is required for saline aquifers to better understand the geologic structures to ensure a domal shape storage space and an impermeable rock on the top. For the salt cavern, the main capital cost is related to cavity erection and geologic survey, which includes the mining cost, the leaching plant cost, site characterization cost, and mechanical integrity test cost.

The capital cost of a compressor includes two parts: the purchase of compressors and the cost of compressing cushion gas. We assume that two-thirds of the year is considered for injection while one-third of the year is used for extraction [50]. Therefore, the total hours of operation are 5600 h. The compressor size is assumed to be 2000 kg/h, which means that one compressor can compress 2000 kg of H_2 to given pressure in 1 h. The required compressors can be calculated based on the working gas capacity (WGC). The cost of cushion gas compression involves electricity cost [60] and water and cooling cost (WCC), which can be calculated by the equations below:

$$EC = WGC \times CP \times UPE \tag{6}$$

$$WCC = WGC \times WR \times UPWC \tag{7}$$

where CP represents compressor power (kWh/kg H_2), UPE denotes the unit price of electricity (\$/kWh), WR is water requirement (L/kg H_2), and UPWC means the unit price of water and cooling (\$/100L H_2O).

For depleted gas reservoirs and saline aquifers, we assume each well is in charge of 3000 tons of H_2 injection. The number of wells can be calculated based on the H_2 storage amount. For salt caverns, we assume one well is drilled for one salt cavern. For all three geologic sites, the same well is used for both H_2 injection and extraction. Compared with other geologic sites, the cost of wells in depleted gas reservoirs is lower because the previously drilled wells may be reused for H_2 injection and extraction after some repairing procedures.

The total capital cost (TCC) is the sum of cushion gas cost, geological site preparation cost, compressor capital cost, and well capital cost.

Levelized cost

The levelized cost of H_2 storage consists of three main parts: 1) levelized total capital cost; 2) compressor operation and maintenance cost (COMC); and 3) well operation and maintenance cost (WOMC). The detailed values are modified from

Table 1 – The capital cost of hydrogen storage.

Capital cost type	Name of capital cost	Depleted gas reservoir	Salt cavern	Saline aquifer
Cushion gas cost	Cushion gas percentage (%)	50	20	80
	H_2 cost (\$/kg H_2)	5	5	5
Geologic site preparation cost	Mining cost (\$/m^3)	0	25.53	0
	Leaching plant cost (\$/kg H_2)	0	5.55	0
	Site characterization (\$)	0	127,650	11,433,000
	Mechanical integrity cost (\$/kg)	0	2.553	0
Compressor capital cost	Total hours of operation (h/year)	5600	5600	5600
	Compressor size (H_2 kg/h)	2000	2000	2000
	Compressor capacity (kton H_2)	11.2	11.2	11.2
	Capital cost per compressor (\$)	10,189,467	10,189,467	10,189,467
	Compressor power (kWh/kg H_2)	2.2	2.2	2.2
	Cost of electricity (\$/kWh)	0.1421	0.1421	0.1421
	Water requirement (L/kg H_2)	50	50	50
	Water & cooling cost (\$/100L H_2O)	0.0222	0.0222	0.0222
Well capital cost	Well cost (\$/per well)	288,600	1,276,500	1,276,500

Table 2 – Levelized cost of hydrogen storage.

Levelized cost type	Name of levelized cost	Depleted gas reservoir	Salt cavern	Saline aquifer
Levelized total capital cost	Discount rate	0.1	0.1	0.1
	Well lifetime (year)	40	40	40
	Capacity factor	0.8	0.8	0.8
Compressor operation and maintenance cost	Electricity cost ($/kg H_2)	0.3126	0.3126	0.3126
	Water and cooling cost ($/kg H_2)	0.0111	0.0111	0.0111
Well operation and maintenance cost	H_2 well cost ($/kg H_2)	0.0117	0.0514	0.0514
	H_2 surface pipeline cost ($/kg H_2)	0.0045	0.0045	0.0045

Lord et al. [44] by considering the inflation/deflation factors and summarized in Table 2. The values of three different geologic sites are similar. The only difference is the levelized H_2 well cost due to the previously erected infrastructure in the depleted gas reservoir.

The equation of levelized total capital cost (LTCC) is shown below:

$$LTCC = (TCC \times CRF) / CF \quad (8)$$

TCC is calculated as the sum of all capital costs. The capacity factor (CF) is assumed to be 0.8. The capital recovery factor (CRF) is obtained with the equation shown below:

$$CRF = \frac{r(1+r)^t}{(1+r)^t - 1} \quad (9)$$

where r denotes the discount rate, and t represents the economic lifetime. The levelized cost of hydrogen storage (LCHS) is calculated based on the equation shown below:

$$LCHS = \frac{LTCC}{WGC} + COMC + WOMC \quad (10)$$

Results and analysis

In this section, the energy demand in the I-WEST region is estimated based on the population and energy consumption per capita. The capacity and cost of H_2 storage are calculated based on the aforementioned methods. Finally, the energy demand, H_2 storage capacity and cost are summarized by states.

Hydrogen storage capacity

In this subsection, we will discuss the H_2 storage capacity in depleted gas reservoirs, salt caverns, and saline aquifers.

Depleted gas reservoirs

We selected depleted gas reservoirs with high cumulative production in the I-WEST region to ensure the large storage capacity. We calculate the working gas capacity of H_2 storage based on the methodology mentioned in Section Depleted gas reservoir. The results are presented in Fig. 7. The sizes of dots represent the working gas capacity of depleted gas reservoirs, while the colors of dots represent the major types of formations in depleted gas reservoirs. We can observe that the numbers of depleted gas fields with working gas capacity less than 200 kton, between 200 and 600 kton, and higher than 600 kton are 14, 9, and 4, respectively. In our calculation, we consider the H_2 as cushion gas to ensure the high purity of produced H_2. If the cushion gas is the remaining natural gas in the field, the working gas capacity of H_2 storage should be much higher.

Salt cavern

Firstly, the sites with large-scale rock salt deposits in the I-WEST region are considered the potential locations for the erection of salt caverns. Then, the selection of ideal locations for salt caverns includes the top depth of the rock salt layer and the thickness of the rock salt layers. Considering the stability of salt caverns and their possible effect on underground water, the suitable top depth of the rock salt layer ranges from 500 to 1800 m [53,54]. The minimum thickness of the rock salt layer is considered to be 122 m (400 ft) to ensure a large storage capacity and cost-effectiveness.

Following the aforementioned methods, we select ten potential locations to build salt caverns for H_2 storage. The results are shown in Fig. 8. The sizes of dots represent the working gas capacity of a single salt cavern, while the colors of dots represent the type of salt caverns. We can observe that a single salt cavern has a storage capacity of several thousand tons. Most of the salt caverns are built in Arizona, Colorado and Utah. Since Arizona does not have any depleted gas reservoirs for H_2 storage as shown in Fig. 7, salt caverns can be the alternative geologic sites for H_2 storage in Arizona.

The total working capacity of salt caverns in the desired region is summarized in Fig. 9. The total working capacity is calculated based on the working capacity of a single salt cavern and the potential number of salt caverns built in that region. Based on our estimation, the number of salt caverns in a basin ranges from several hundreds to several thousands. The total working gas capacity of salt caverns is at the scale of million tons. The sizes of dots represent the total working gas capacity of salt caverns, while the colors of dots represent the type of salt caverns.

Saline aquifer

Generally, a saline aquifer suitable for storage has a similar geologic requirement as a depleted gas reservoir, including the high porosity and permeability of porous media with impermeable cap rocks overlaid [38]. The aquifers with large drainage areas are selected to ensure a large storage volume. Additionally, high porosity and permeability aquifers are preferred due to their better storage capability and deliverability. Following these criteria, 12 saline aquifers are selected as the potential storage sites in the I-WEST region.

Based on the aforementioned methods, the working gas capacity of H_2 storage in saline aquifers is shown in Fig. 10. The sizes of dots represent the working gas capacity of saline

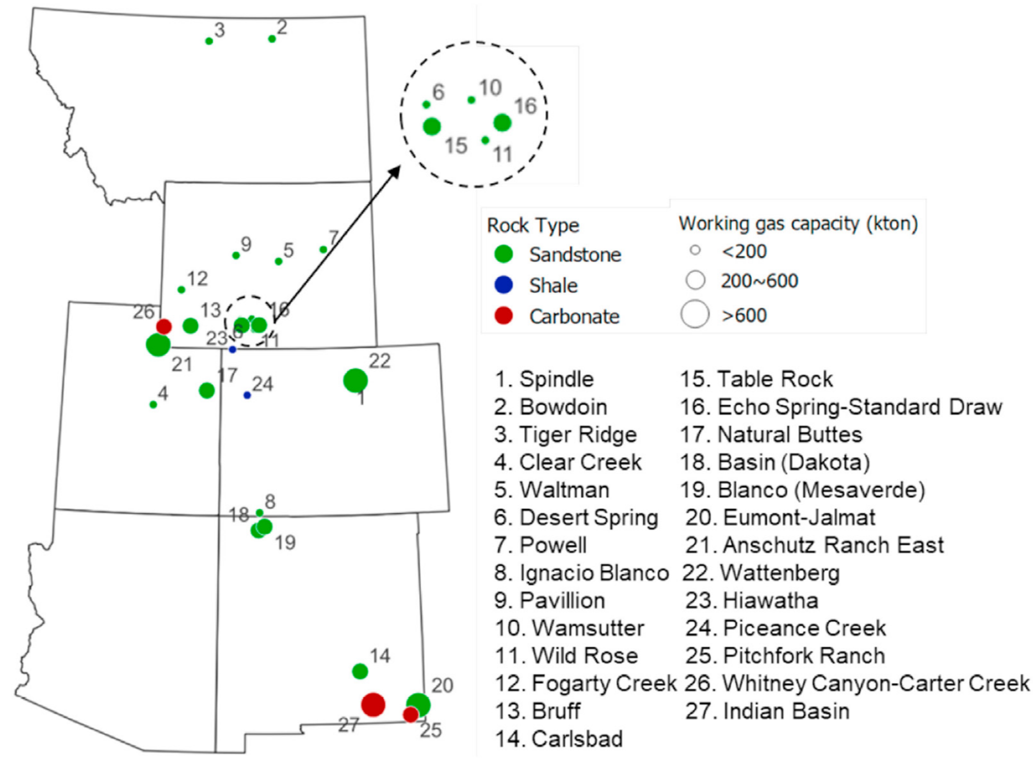


Fig. 7 – Working gas capacity of H_2 storage in depleted gas reservoirs in the I-WEST region. The labels in the figure represent the names of fields. The name in the parenthesis is the formation of the field.

aquifers, while the colors of dots represent the lithology of saline aquifers. The storage capacity of saline aquifers includes several formations in the basins. We can observe that the working gas capacity in many regions is more than 1000 million tons due to the wide distribution of underground water. However, site characterization is necessary to narrow down the potential area and determine the final storage sites to ensure the sealing strength.

To give a rough estimation of the storage capacity of a saline aquifer site, the Baker dome in Four Corners Platform, San Juan Basin, is selected as the target H_2 storage site [61]. The tectonic trap of the dome allows the formation of a gas cap, which contributes to the recovery of H_2 [62]. The detailed information [63] on H_2 storage in the Baker dome is shown in Table 3.

Energy demand

We estimate the total amount of energy required per year in each state based on the data from EIA [46]. Considering the

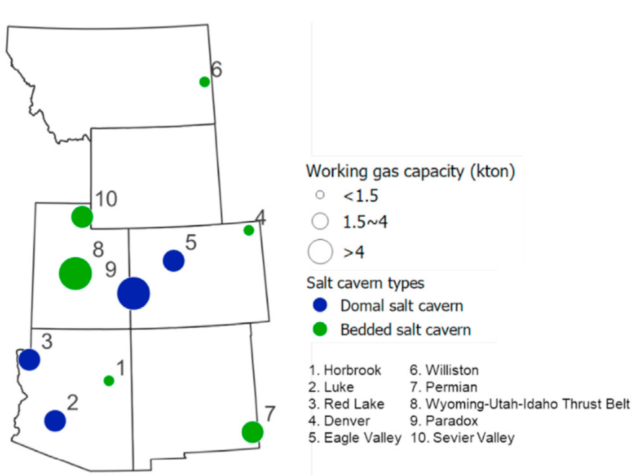


Fig. 8 – Working gas capacity of H_2 storage in a single salt cavern in the I-WEST region. The labels in the figure represent the names of basins.

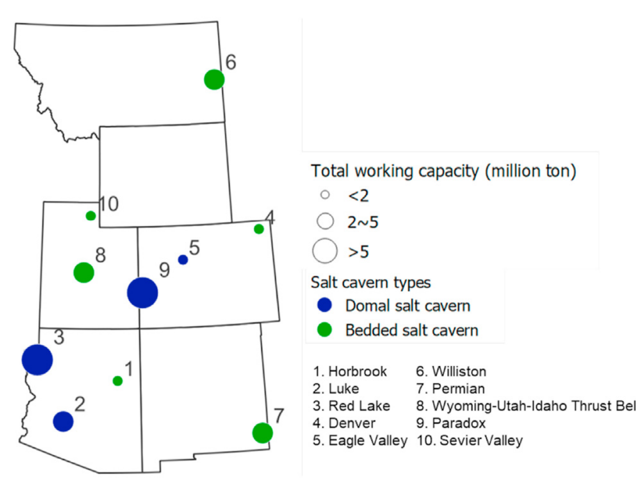


Fig. 9 – Total working gas capacity of hydrogen storage in salt caverns in the I-WEST region. The labels in the figure represent the names of basins.

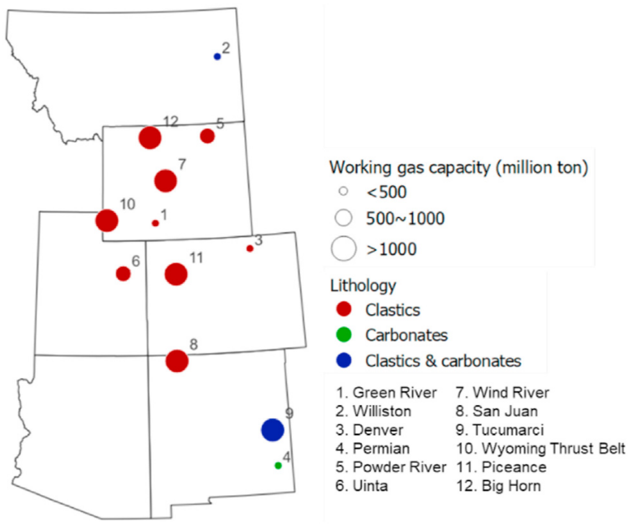


Fig. 10 – Working gas capacity of H_2 storage in saline aquifers in the I-WEST region. The labels are the names of the basins where the saline aquifers are located in.

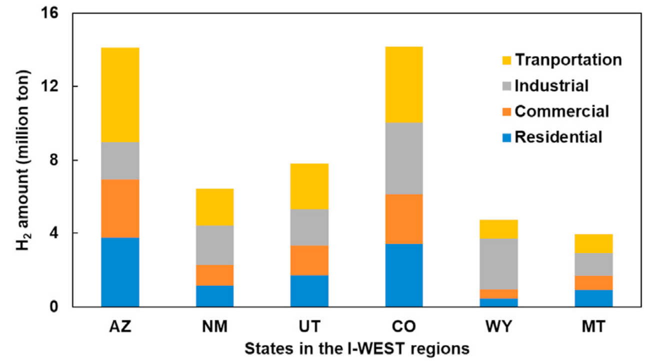


Fig. 11 – Energy consumption per year in I-WEST region.

energy value of H_2 is 3 kWh/m^3 [53], we converted the energy consumption in the I-WEST region to the amount of H_2 required, as shown in Fig. 11. We can observe that Arizona and Colorado have higher energy demands than other states in the I-WEST region. The major energy consumption sectors in the I-WEST region are the industrial and transportation sectors.

To analyze if the H_2 storage capacity meets the energy demand in the I-WEST region, we summarize each state's energy demand and H_2 storage capacity in Fig. 12. It is worth noting that, due to the limited site characterization and high cost of saline aquifer storage, only the H_2 storage capacities in depleted gas reservoirs and salt caverns are considered. Comparing the energy demand and storage capacity, the H_2 storage capacities in depleted gas reservoirs and salt caverns can meet 72% of the total energy demand in the I-WEST region in 2020. According to the International Energy Agency (IEA) prediction, H_2 will account for about 10% of total energy consumption in 2050 [64]. Fig. 12 suggests that H_2 storage capacity of the depleted gas reservoirs and salt caverns meet at least 30% of energy demand in each state in the I-WEST region, which is higher than the percentage of H_2 in energy consumption predicted by IEA. However, the estimation is made at the state level. Considering the different energy consumptions and geologic structures in a city, detailed plans should be made. For example, for the regions away from depleted gas reservoirs and unsuitable for the erection of salt caverns, a saline aquifer (if available nearby) should be considered as the first choice of the H_2 storage site.

Hydrogen storage cost

We calculated the capital and levelized costs of H_2 storage in three typical case studies for depleted gas reservoirs, salt caverns and saline aquifers based on Tables 1 and 2 The characterizations of three geologic sites are shown in Table 3.

The capital and levelized costs of H_2 storage of the three geologic sites are shown in Tables 4 and 5. The proportion of each cost type is shown in Figs. 13 and 14. The H_2 recovery is not considered in the cost estimation due to the lack of data. A general trend of H_2 recovery of different geologic sites from high to low is salt cavern [65] > saline aquifer [38] > depleted reservoir [66]. As shown in Fig. 13, the cushion gas cost accounts for more than 80% of the capital cost of depleted gas reservoir or saline aquifer, while the geologic site preparation cost is the major cost of H_2 storage in salt cavern. For the levelized cost of H_2 storage, the levelized total capital cost is the major part regardless of the type of geologic site, which is due to the high value of total capital cost. For salt caverns, the total capital cost is mainly affected by the mining and leaching cost, which is determined by the cavity volume. However, for depleted gas reservoirs or aquifers, the total capital cost can be significantly reduced if we lower the cushion gas cost, which is possible by changing the type of cushion gas.

Table 3 – Geological site characterization.

	Depleted gas reservoir	Salt deposits per cavern	Saline aquifer
Geologic site	Wattenberg field (CO)	Red Lake (AZ)	Baker dome (CO)
Storage volume underground (million ft^3)	8200	15.5	5602
Average depth (ft)	8000	4000	4717
Average Pressure (psi)	3479	1732	2057
Average temperature (F)	180	122	128
Total H_2 storage amount (kton)	3546	4.2	1613
Working gas percentage (%)	50	80	20
Working gas capacity (kton)	1773	3.4	323
Cushion gas amount (kton)	1773	0.8	1290

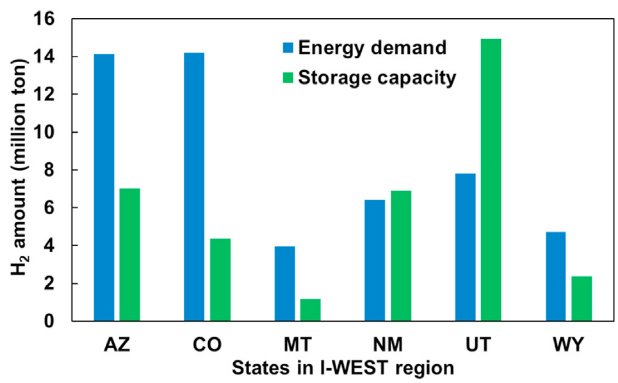


Fig. 12 – Energy demand and hydrogen storage capacity in the I-WEST regions in 2020. The hydrogen storage capacity only includes the storage capacities in depleted gas reservoirs and salt caverns. AZ: Arizona, CO: Colorado, MT: Montana, NM: New Mexico, UT: Utah, WY: Wyoming.

The cushion gas types may affect the H_2 recovery and the economic issue. According to previous works [67,68], we find two general trends of the effect of cushion gas on H_2 recovery. Firstly, the cushion gas type has little effect on H_2 recovery (generally less than 5%) [67,68]. Secondly, with the increasing cycles of H_2 production, the effect of cushion gas types on H_2 recovery becomes less significant [67,68]. Based on these two trends, we ignore the H_2 recovery part and only focus on the economic issue of cushion gas types.

To evaluate the effect of cushion gas types on H_2 storage cost, we consider natural gas and nitrogen (N_2) as alternative cushion gases. Due to the contamination of cushion gas, the extra cost should be considered in H_2 purification. According to previous analysis [60,69], the cost of H_2 purification ranges from $1 to $8.3/kg H_2, which depends on the initial H_2 percentage, target H_2 purity, and types of mixed gases. Herein, we perform the sensitivity analysis on the purification cost in depleted gas reservoirs and saline aquifers. The results of the sensitivity analysis are summarized in Figs. 15 and 16. As the purification cost increases, the capital cost and levelized cost of H_2 storage using N_2 or natural gas as cushion gas increase. The purification cost threshold is the intersection point with the line using H_2 as cushion gas. For H_2 storage in depleted gas reservoirs (take Wattenberg field as an example), the purification cost thresholds for the capital cost of natural gas and N_2 are $2.51 and $2.55/kg H_2, respectively, indicating that it is cost-effective to change cushion gas type when the purification cost is less than $2.50/kg H_2. For saline aquifers (take Baker dome as an example), the purification cost thresholds for the capital cost of natural gas and N_2 are $9.84 and $9.86/kg H_2, respectively. The purification cost threshold is beyond the purification cost range, meaning using another type of gas as cushion gas for H_2 storage in saline aquifers is economical.

The impact of working gas capacity on capital cost and levelized cost of H_2 storage is analyzed in Figs. 17 and 18. We assume the average depth of the storage site is 1000 m. In Fig. 17, H_2 storage in saline aquifers has the highest cost whereas H_2 storage in depleted gas reservoirs is the most cost-effective choice. In Fig. 18, the levelized cost of H_2 storage first decreases sharply with the increased working gas capacity. Then the curves become flat, indicating that the levelized cost is not significantly affected by the working gas capacity for a large storage volume. The levelized cost of H_2 storage in the depleted gas reservoir, salt cavern, and saline aquifer at high working gas capacity (100 kton) is about $1.15, $2.50, and $3.27/kg H_2, respectively. From Eq. (10), the working gas capacity primarily affects the first term of levelized cost of H_2 storage (LCHS). For the fixed capital cost which is not calculated in the unit price ($/kg H_2), the increase in storage capacity will lead to a decrease in the first term of LCHS and therefore reduces the value of LCHS. With the continuous growth of working gas capacity, the fixed capital cost becomes relatively low compared with the capital cost that is proportional to the working gas capacity. Thus, an increasing linear trend exists in capital cost curves while the levelized cost curves become flat at high working gas capacity.

Based on IEA prediction, H_2 will account for about 10% of total energy consumption in 2050 [64]. Therefore, the capital

Table 4 – The capital cost of hydrogen storage of three geological sites.

	Depleted gas reservoir	Salt cavern	Saline aquifer
Geological site	Wattenberg field (CO)	Red Lake (AZ)	Baker dome (CO)
Cushion gas cost (million $)	8864	4.2	6452
Geologic site preparation cost (million $)	0	45.4	11
Compressor capital cost (million $)	2194	10.5	713
Well capital cost (million $)	171	2.6	138
Total capital cost (million $)	11,229	63	7314

Table 5 – Levelized cost of hydrogen storage of three geologic sites.

	Depleted gas reservoir	Salt cavern	Saline aquifer
Geologic site	Wattenberg field (CO)	Red Lake (AZ)	Baker dome (CO)
Levelized total capital cost ($/kg)	0.8096	2.3785	2.8982
Compressor levelized cost ($/kg)	0.3237	0.3237	0.3237
Well and surface pipeline levelized cost ($/kg)	0.0162	0.0558	0.0558
Levelized cost of H_2 storage ($/kg)	1.1495	2.7580	3.2777

Please cite this article as: Chen F et al., Capacity assessment and cost analysis of geologic storage of hydrogen: A case study in Intermountain-West Region USA, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.11.292

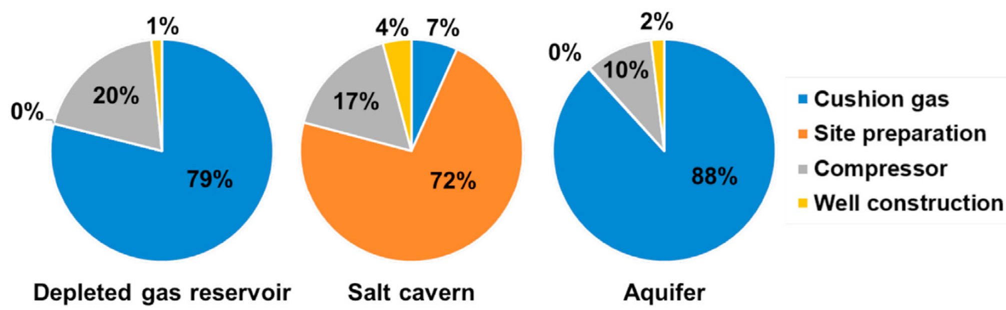


Fig. 13 – **Pie charts of the capital cost of hydrogen storage in the depleted gas reservoir, salt cavern, and saline aquifer.**

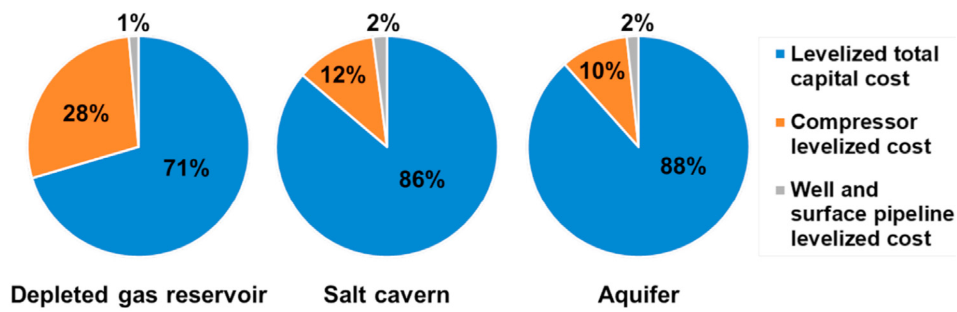


Fig. 14 – **Pie charts of levelized cost of hydrogen storage in the depleted gas reservoir, salt cavern, and aquifer.**

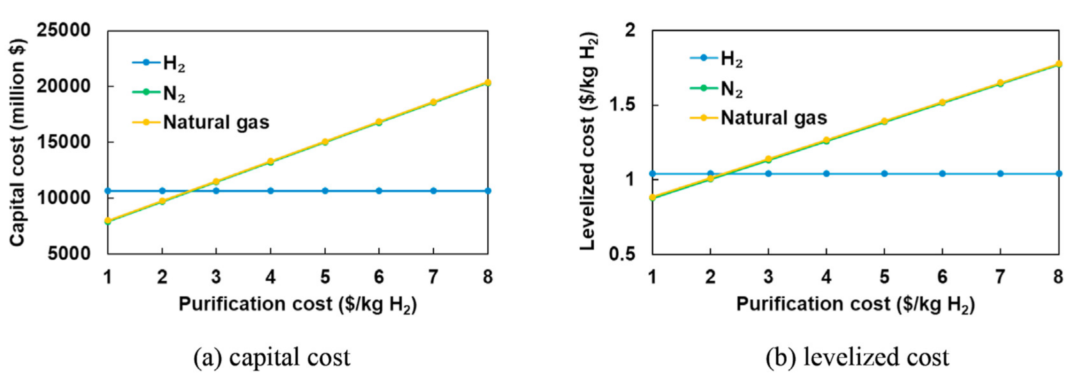


Fig. 15 – **Sensitivity analysis on purification cost of H_2 storage in depleted gas reservoirs (Wattenberg field) with cushion gas types of H_2, N_2 and natural gas: a) capital cost; b) levelized cost.**

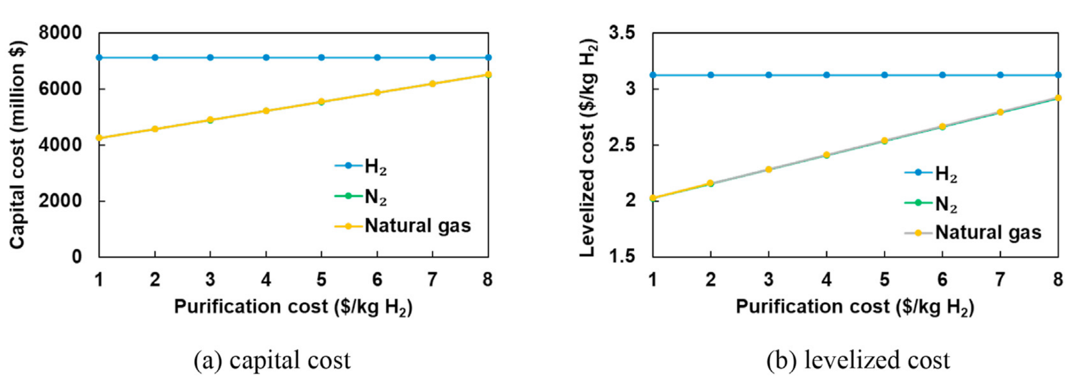


Fig. 16 – **Sensitivity analysis on purification cost of H_2 storage in saline aquifers (Baker dome) with cushion gas types of H_2, N_2 and natural gas: a) capital cost; b) levelized cost.**

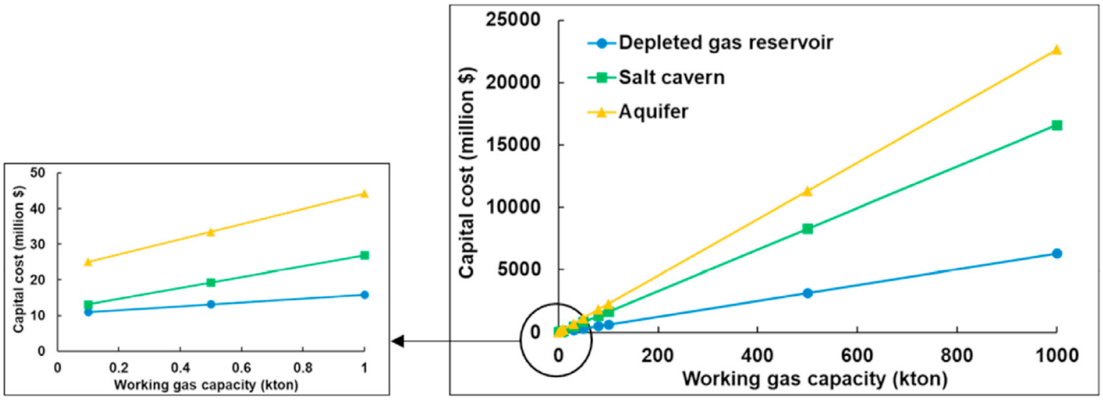


Fig. 17 — The capital cost of H_2 storage with different working gas capacities. The working gas's capital cost with a capacity of less than 1 kton is magnified for clarification.

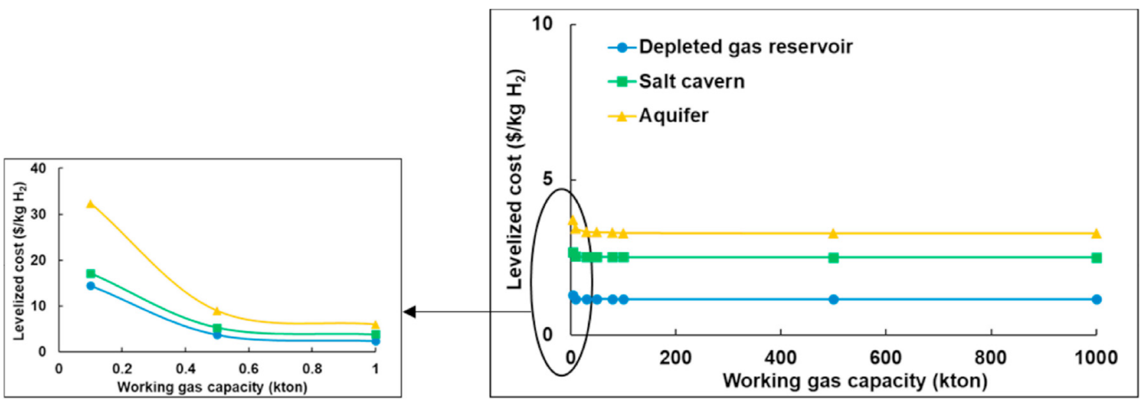


Fig. 18 — The levelized cost of H_2 storage with different working gas capacities. The working gas's levelized cost with a capacity of less than 1 kton is magnified for clarification.

cost of 10% of energy demand and levelized cost of H_2 storage are estimated in Fig. 19. The high capital cost is caused by the large storage capacity whereas the high levelized cost is due to the high percentage of H_2 storage in salt caverns.

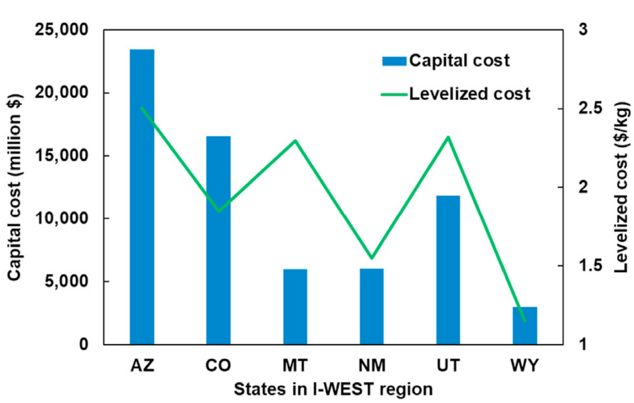


Fig. 19 — Capital cost and levelized cost of H_2 storage in the I-WEST regions. AZ: Arizona, CO: Colorado, MT: Montana, NM: New Mexico, UT: Utah, WY: Wyoming.

Conclusion

In this work, we analyzed the techno-economic feasibility of geologic H_2 storage in the I-WEST region. We developed workflows to estimate the H_2 storage capacity of the depleted gas reservoirs, salt caverns, and saline aquifers. The suitable geologic sites for H_2 storage in the I-WEST region are identified, and the working gas capacity of each site is estimated. In addition, we select three typical sites (Wattenberg field in Colorado, Red Lake in Arizona and Baker dome in Colorado) to estimate the capital and levelized costs of H_2 storage in the three sites. The main findings are summarized as follows:

- We identified 27, 10, and 12 potential candidates for H_2 storage in depleted gas reservoirs, salt caverns and saline aquifers, respectively. The selected geologic H_2 storage sites in each state can meet at least 30% of the energy consumption in each state of the I-WEST region.
- The capital costs of H_2 storage in Wattenberg field (depleted gas reservoir), Red Lake (single salt cavern) and Baker dome (saline aquifer) are estimated at 11229, 63, and 7314 million dollars, respectively. The cushion gas cost accounts for more than 80% of the capital cost of depleted

Please cite this article as: Chen F et al., Capacity assessment and cost analysis of geologic storage of hydrogen: A case study in Intermountain-West Region USA, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.11.292

gas reservoirs or saline aquifers, while the geologic site preparation cost is the major cost for H_2 storage in salt caverns.

- Due to the high cost of H_2, we evaluated the economic feasibility of using natural gas and nitrogen as alternative cushion gases. Our analysis shows that using natural gas or nitrogen as cushion gas for H_2 storage in saline aquifers is economical.
- We analyzed the effect of working gas capacity on storage cost. H_2 storage in saline aquifers has the highest cost regardless of the working gas capacity. For high storage volume, H_2 storage in depleted gas reservoirs is the cost-effective option. The levelized cost of H_2 storage in a depleted gas reservoir, salt cavern, and aquifer with large-scale storage capacity is about \$1.15, \$2.50, and \$3.27/kg H_2, respectively.

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.

Acknowledgment

This work was supported by Los Alamos National Laboratory Technology Evaluation & Demonstration funds.

Nomenclature

COMC	Compressor operation and maintenance cost
CF	Capital factor
CP	Compressor power
CRF	Capital recovery factor
EC	Electricity cost
LCHS	Levelized cost of hydrogen storage
LTCC	Levelized total capital cost
TCC	Total capital cost
UPE	Unit price of electricity
UPWC	Unit price of water and cooling
WCC	Water and cooling cost
WGC	Working gas capacity
WOMC	Well operation and maintenance cost
WR	Water requirement
A	Area of aquifer
B_g	Formation volume factor
D	Diameter of cavern
f	Percentage of working gas
g_f	Fracture breakdown pressure gradient
g_{min}	Minimum pressure gradient
h_0	Depth of the cavern with zero value of Pressure
h_c	Depth of the cavern center
h_n	Depth to the top of the cavern neck
m	Hydrogen amount in the cavern
p	Pressure
r	Discount rate
R^*	Individual gas constant of hydrogen
t	Economic lifetime
T	Temperature
V	Volume
z	Compressibility factor
φ	Porosity

REFERENCES

[1] Qiu Y, Zhou S, Wang J, Chou J, Fang Y, Pan G, et al. Feasibility analysis of utilising underground hydrogen storage facilities in integrated energy system: case studies in China. Appl Energy 2020;269:115140.
[2] Mouli-Castillo J, Heinemann N, Edlmann K. Mapping geological hydrogen storage capacity and regional heating demands: an applied UK case study. Appl Energy 2021;283:116348.
[3] Ellabban O, Abu-Rub H, Blaabjerg F. Renewable energy resources: current status, future prospects and their enabling technology. Renew Sustain Energy Rev 2014;39:748–64.
[4] Ishaq H, Dincer I, Crawford C. A review on hydrogen production and utilization: challenges and opportunities. Int J Hydrogen Energy 2022;47:26238–64.
[5] Zivar D, Kumar S, Foroozesh J. Underground hydrogen storage: a comprehensive review. Int J Hydrogen Energy 2021;46:23436–62.
[6] Abe JO, Popoola A, Ajenifuja E, Popoola O. Hydrogen energy, economy and storage: review and recommendation. Int J Hydrogen Energy 2019;44:15072–86.
[7] Kovač A, Paranos M, Marciuš D. Hydrogen in energy transition: a review. Int J Hydrogen Energy 2021;46:10016–35.
[8] Kojima Y. Hydrogen storage materials for hydrogen and energy carriers. Int J Hydrogen Energy 2019;44:18179–92.
[9] Ye Y, Lu J, Ding J, Wang W, Yan J. Performance improvement of metal hydride hydrogen storage tanks by using phase change materials. Appl Energy 2022;320:119290.
[10] Mirzaei MA, Yazdankhah AS, Mohammadi-Ivatloo B. Stochastic security-constrained operation of wind and hydrogen energy storage systems integrated with price-based demand response. Int J Hydrogen Energy 2019;44:14217–27.
[11] Le Duigou A, Bader A-G, Lanoix J-C, Nadau L. Relevance and costs of large scale underground hydrogen storage in France. Int J Hydrogen Energy 2017;42:22987–3003.
[12] Stone HB, Veldhuis I, Richardson RN. Underground hydrogen storage in the UK, 313. Geological Society, London, Special Publications; 2009. p. 217–26.
[13] Liu W, Zhang Z, Chen J, Jiang D, Wu F, Fan J, et al. Feasibility evaluation of large-scale underground hydrogen storage in bedded salt rocks of China: a case study in Jiangsu province. Energy 2020;198:117348.
[14] Scafidi J, Wilkinson M, Gilfillan SM, Heinemann N, Haszeldine RS. A quantitative assessment of the hydrogen storage capacity of the UK continental shelf. Int J Hydrogen Energy 2021;46:8629–39.
[15] Veshareh MJ, Thaysen EM, Nick HM. Feasibility of hydrogen storage in depleted hydrocarbon chalk reservoirs: assessment of biochemical and chemical effects. Appl Energy 2022;323:119575.
[16] Zeng L, Keshavarz A, Xie Q, Iglauer S. Hydrogen storage in Majiagou carbonate reservoir in China: geochemical modelling on carbonate dissolution and hydrogen loss. Int J Hydrogen Energy 2022;47:24861–70.
[17] Muhammed NS, Haq B, Al Shehri D, Al-Ahmed A, Rahman MM, Zaman E. A review on underground hydrogen

storage: insight into geological sites, influencing factors and future outlook. Energy Rep 2022;8:461–99.
[18] Moradi R, Groth KM. Hydrogen storage and delivery: review of the state of the art technologies and risk and reliability analysis. Int J Hydrogen Energy 2019;44:12254–69.
[19] Acar C, Dincer I. The potential role of hydrogen as a sustainable transportation fuel to combat global warming. Int J Hydrogen Energy 2020;45:3396–406.
[20] Lemieux A, Shkarupin A, Sharp K. Geologic feasibility of underground hydrogen storage in Canada. Int J Hydrogen Energy 2020;45:32243–59.
[21] Bruno MS. Geomechanical analysis and design considerations for thin-bedded salt caverns. Terralong Technologies USA; 2005.
[22] Ramesh Kumar K, Makhmutov A, Spiers CJ, Hajibeygi H. Geomechanical simulation of energy storage in salt formations. Sci Rep 2021;11:1–24.
[23] Wallace RL, Cai Z, Zhang H, Zhang K, Guo C. Utility-scale subsurface hydrogen storage: UK perspectives and technology. Int J Hydrogen Energy 2021;46:25137–59.
[24] Dopffel N, Jansen S, Gerritse J. Microbial side effects of underground hydrogen storage–Knowledge gaps, risks and opportunities for successful implementation. Int J Hydrogen Energy 2021;46:8594–606.
[25] Tarkowski R. Underground hydrogen storage: characteristics and prospects. Renew Sustain Energy Rev 2019;105:86–94.
[26] Singh H. Hydrogen storage in inactive horizontal shale gas wells: techno-economic analysis for Haynesville shale. Appl Energy 2022;313:118862.
[27] Ali M, Jha NK, Pal N, Keshavarz A, Hoteit H, Sarmadivaleh M. Recent advances in carbon dioxide geological storage, experimental procedures, influencing parameters, and future outlook. Earth Sci Rev 2022;225:103895.
[28] Iglauer S, Ali M, Keshavarz A. Hydrogen wettability of sandstone reservoirs: implications for hydrogen geo-storage. Geophys Res Lett 2021;48:e2020GL090814.
[29] Hosseini M, Fahimpour J, Ali M, Keshavarz A, Iglauer S. Hydrogen wettability of carbonate formations: implications for hydrogen geo-storage. J Colloid Interface Sci 2022;614:256–66.
[30] Aftab A, Hassanpouryouzband A, Xie Q, Machuca LL, Sarmadivaleh M. Toward a fundamental understanding of geological hydrogen storage. Ind Eng Chem Res 2022;61:3233–53.
[31] Heinemann N, Alcalde J, Miocic JM, Hangx SJ, Kallmeyer J, Ostertag-Henning C, et al. Enabling large-scale hydrogen storage in porous media–the scientific challenges. Energy Environ Sci 2021;14:853–64.
[32] Thaysen EM, McMahon S, Strobel GJ, Butler IB, Ngwenya BT, Heinemann N, et al. Estimating microbial growth and hydrogen consumption in hydrogen storage in porous media. Renew Sustain Energy Rev 2021;151:111481.
[33] Katz DL, Tek MR. Storage of natural gas in saline aquifers. Water Resour Res 1970;6:1515–21.
[34] Ali M, Yekeen N, Pal N, Keshavarz A, Iglauer S, Hoteit H. Influence of pressure, temperature and organic surface concentration on hydrogen wettability of caprock; implications for hydrogen geo-storage. Energy Rep 2021;7:5988–96.
[35] Ali M, Jha NK, Al-Yaseri A, Zhang Y, Iglauer S, Sarmadivaleh M. Hydrogen wettability of quartz substrates exposed to organic acids; Implications for hydrogen geo-storage in sandstone reservoirs. J Petrol Sci Eng 2021;207:109081.
[36] Ali M, Yekeen N, Pal N, Keshavarz A, Iglauer S, Hoteit H. Influence of organic molecules on wetting characteristics of mica/H2/brine systems: implications for hydrogen structural trapping capacities. J Colloid Interface Sci 2022;608:1739–49.
[37] Keshavarz A, Abid H, Ali M, Iglauer S. Hydrogen diffusion in coal: implications for hydrogen geo-storage. J Colloid Interface Sci 2022;608:1457–62.
[38] Sáinz-García A, Abarca E, Rubí V, Grandia F. Assessment of feasible strategies for seasonal underground hydrogen storage in a saline aquifer. Int J Hydrogen Energy 2017;42:16657–66.
[39] Azretovna Abukova L, Nabievich Zakirov S, Pavlovich Anikeev D, Sumbatovich Zakirov E. Formation of an effective hydrogen storage in an aquifer and control of its parameters. In: SPE Russian petroleum Technology conference. OnePetro; 2020.
[40] Gorre J, Ruoss F, Karjunen H, Schaffert J, Tynjälä T. Cost benefits of optimizing hydrogen storage and methanation capacities for Power-to-Gas plants in dynamic operation. Appl Energy 2020;257:113967.
[41] Blanco H, Nijs W, Ruf J, Faaij A. Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization. Appl Energy 2018;232:617–39.
[42] Taylor J, Alderson J, Kalyanam K, Lyle A, Phillips L. Technical and economic assessment of methods for the storage of large quantities of hydrogen. Int J Hydrogen Energy 1986;11:5–22.
[43] Ugarte ER, Salehi S. A review on well integrity issues for underground hydrogen storage. J Energy Resour Technol 2022;144.
[44] Lord AS, Kobos PH, Borns DJ. Geologic storage of hydrogen: scaling up to meet city transportation demands. Int J Hydrogen Energy 2014;39:15570–82.
[45] 2022 world population by country. Accessed July 30, 2022. https://worldpopulationreview.com/.
[46] U.S. Energy Information Administration - EIA - Independent Statistics and analysis." Accessed July 30, 2022. https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_sum/html/rank_use_capita.html&sid=US.
[47] McPherson M, Johnson N, Strubegger M. The role of electricity storage and hydrogen technologies in enabling global low-carbon energy transitions. Appl Energy 2018;216:649–61.
[48] Reuß M, Grube T, Robinius M, Preuster P, Wasserscheid P, Stolten D. Seasonal storage and alternative carriers: a flexible hydrogen supply chain model. Appl Energy 2017;200:290–302.
[49] Gorre J, Ortloff F, van Leeuwen C. Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage. Appl Energy 2019;253:113594.
[50] Lord AS. Overview of geologic storage of natural gas with an emphasis on assessing the feasibility of storing hydrogen. Sandia national laboratories (SNL), albuquerque, NM, and livermore, CA …; 2009.
[51] Dranchuk P, Abou-Kassem H. Calculation of Z factors for natural gases using equations of state. J Can Petrol Technol 1975;14.
[52] Lemmon E, Huber ML, Mclinden MO. NIST standard reference database 23: reference fluid thermodynamic and transport properties-REFPROP, version 8.0. 2007.
[53] Lankof L, Tarkowski R. Assessment of the potential for underground hydrogen storage in bedded salt formation. Int J Hydrogen Energy 2020;45:19479–92.
[54] Pierce WG, Rich EI. Summary of rock salt deposits in the United States as possible storage sites for radioactive waste materials. US Government Printing Office; 1962.
[55] Bergmo P, Wessel-Berg D, Grimstad A-A. Towards maximum utilization of CO2 storage resources. Energy Proc 2014;63:5114–22.
[56] Tooseh EK, Jafari A, Teymouri A. Gas-water-rock interactions and factors affecting gas storage capacity during natural gas

Please cite this article as: Chen F et al., Capacity assessment and cost analysis of geologic storage of hydrogen: A case study in Intermountain-West Region USA, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.11.292

storage in a low permeability aquifer. Petrol Explor Dev 2018;45:1123–8.
[57] Kobos PH, Lord AS, Borns DJ, Klise GT. A life cycle cost analysis framework for geologic storage of hydrogen: a user's tool. Sandia national laboratories (SNL), albuquerque, NM, and livermore, CA …; 2011.
[58] van Renssen S. The hydrogen solution? Nat Clim Change 2020;10:799–801.
[59] US Bureau of labor Statistics, https://www.bls.gov/cpi/.
[60] Nordio M, Wassie SA, Annaland MVS, Tanaka DAP, Sole JLV, Gallucci F. Techno-economic evaluation on a hybrid technology for low hydrogen concentration separation and purification from natural gas grid. Int J Hydrogen Energy 2021;46:23417–35.
[61] Kelley VC. Tectonics of the San Juan basin and surrounding areas. 1957.
[62] Foh S, Novil M, Rockar E, Randolph P. Underground hydrogen storage. final report.[salt caverns, excavated caverns, aquifers and depleted fields]. Upton, NY (USA): Brookhaven National Lab.; 1979.
[63] Fassett JE. Oil and gas resources of the San Juan basin, New Mexico and Colorado. In: Economic geology, US: The geology of North America: Geological Society of America; 1991. p. 357–72.
[64] Bouckaert S, Pales AF, McGlade C, Remme U, Wanner B, Varro L, et al. Net zero by 2050: a roadmap for the global energy sector. 2021.
[65] San S, Karakilcik H, Karakilcik M, Erden M, Atiz A. Investigation of cushion gas/working gas ratios of underground salt caverns for hydrogen storage. Emerging trends in energy storage systems and industrial applications: Elsevier; 2023. p. 67-78.
[66] Mahdi DS, Al-Khdheeawi EA, Yuan Y, Zhang Y, Iglauer S. Hydrogen underground storage efficiency in a heterogeneous sandstone reservoir. Adv Geo-Energy Res 2021;5:437.
[67] Zamehrian M, Sedaee B. Underground hydrogen storage in a partially depleted gas condensate reservoir: influence of cushion gas. J Petrol Sci Eng 2022;212:110304.
[68] Kanaani M, Sedaee B, Asadian-Pakfar M. Role of cushion gas on underground hydrogen storage in depleted oil reservoirs. J Energy Storage 2022;45:103783.
[69] He X. Techno-economic feasibility analysis on carbon membranes for hydrogen purification. Separ Purif Technol 2017;186:117–24.

Please cite this article as: Chen F et al., Capacity assessment and cost analysis of geologic storage of hydrogen: A case study in Intermountain-West Region USA, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2022.11.292