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Characterizing Hydrogen Storage Potential in U.S. Underground Gas Storage Facilities

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Key Points:

- The total hydrogen working-gas energy of underground gas storage facilities in the United States is estimated to be 327 TW-hours
- Most (73.2%) underground gas storage facilities can store hydrogen blends up to 20% and continue to meet their current energy demand
- Hydrogen storage in existing underground gas storage facilities can sufficiently buffer the hydrogen demand projected for 2050

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Underground hydrogen storage is a long-duration energy storage option for a low-carbon economy. Although research into the technical feasibility of underground hydrogen storage is ongoing, existing underground gas storage (UGS) facilities are appealing candidates for the technology because of their ability to store and deliver natural gas. We estimate that UGS facilities in the United States (U.S.) can store 327 TWh (9.8 MMT) of pure hydrogen. A complete transition to hydrogen storage would reduce the collective working-gas energy of UGS facilities by ~75%; however, most (73.2%) UGS facilities could maintain current energy demand using a 20% hydrogen-natural gas blend. U.S. UGS facilities can buffer 23.9%–44.6% of the high and low hydrogen demand projected for 2050, respectively, which exceeds the current percentage of natural gas demand buffered by storage. Thus, transitioning UGS infrastructure to hydrogen could substantially reduce the number of new hydrogen storage facilities needed to support a hydrogen economy.

Plain Language Summary

Hydrogen is a high energy content fuel that can be produced with low or zero greenhouse gas emissions from water and other chemicals. Creating hydrogen during periods of energy surplus and storing it underground is one long-duration, low-emission, energy storage option that can balance supply and demand for an entire electric grid. In the United States (U.S.), existing underground gas storage (UGS) facilities are a logical first place to consider subsurface hydrogen storage, because their geology has proven favorable for storing natural gas. We estimated that existing UGS facilities can store 327 TW-h (9.8 million metric tons) of pure hydrogen. Transitioning from natural gas to pure hydrogen storage would reduce the total energy stored in existing UGS facilities by ~75%. Storing hydrogen-natural gas mixtures also reduces energy storage potential, but most (73.2%) UGS facilities can meet current energy demands with a 20% hydrogen blend. U.S. UGS facilities can store 23.9%–44.6% of the projected high and low hydrogen demand for 2050, respectively, suggesting that a partial transition of UGS infrastructure could reduce the need for new hydrogen storage facilities. These findings motivate research that explores the technical feasibility of underground hydrogen storage in natural gas storage reservoirs.

1. Introduction

Hydrogen (H_2) is gaining commercial interest as a carbon-free energy carrier that offers cost-effective energy transport and storage versatility at the gigawatt scale (Andrews & Shabani, 2012; DOE, 2020; Dolan, 2020; Dopffel et al., 2021; Ennis-King et al., 2021; Heinemann et al., 2021; Peng et al., 2016; Zivar et al., 2021). While H_2 is generated through various methods, some of which emit carbon dioxide, it can be produced without emissions through water electrolysis with renewable or nuclear energy sources (DOE, 2020; Dolan, 2020; Peng et al., 2016; Tarkowski, 2019; Zivar et al., 2021). To advance the role of H_2 in the economy, its availability across the United States (U.S.) needs to expand to ensure price stability, energy security, and independence (Shuster et al., 2021; Tarkowski, 2019). Large-scale, long-duration H_2 storage will be an essential component of the supply chain necessary to balance the mismatches between energy supply and demand and to remedy intermittent disconnects in energy generation in the same way that seasonal underground storage of natural gas currently operates (DOE, 2020; Goodman et al., 2022; Heinemann et al., 2021; Muhammed et al., 2022; Shuster et al., 2021; Tarkowski, 2019; Zivar et al., 2021).

Underground hydrogen storage (UHS) is an attractive option when compared to above-ground storage because underground storage has a smaller surface footprint and is ultimately less expensive (Tarkowski, 2017, 2019; Tarkowski & Czapowski, 2018). UHS also reduces safety risk factors associated with above-ground gas ignition

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and natural and manmade events such as floods, fire, and weather issues. UHS has been successfully demonstrated at scale in underground salt caverns such as Teesside, UK, Clemens Dome, U.S., Moss Bluff, U.S., and Beaumont, U.S (Mouli-Castillo et al., 2021). Evidence suggests that UHS is also feasible in porous and permeable reservoirs (Bauer et al., 2015; Pudlo et al., 2013). However, research into the storage feasibility of UHS in salt caverns, depleted hydrocarbon reservoirs, brine aquifers, and hard rock caverns is ongoing (Heinemann et al., 2021; Muhammed et al., 2022; Pudlo et al., 2013; Tarkowski, 2019; Wallace et al., 2021; Zivar et al., 2021) (Figure S1 of Supporting Information S1).

Existing underground gas storage (UGS) facilities are appealing to early candidates for large-scale UHS. While the ability of these storage reservoirs to contain hydrogen still needs to be understood, they have demonstrated the ability to seal and prevent unwanted migration of natural gas while delivering the large quantities of gas needed for the energy supply chain. UGS reservoirs are comprised of wells that inject and withdraw gas, layers of porous and permeable rock that contains the injected gas, and an overlying caprock that prevents its vertical migration. In the U.S., UGS facilities are frequently located within short transmission distances of population centers where energy demand is greatest (Figure S2 of Supporting Information S1) (Goodman et al., 2022). Conversion of these facilities to UHS could provide continuity of regional energy supplies, flexibility to meet peak energy demand, and suppression of energy-price volatility. As conversion proceeds, H_2 may be blended with natural gas or replaced entirely in existing UGS reservoirs (Melaina et al., 2013). Where possible, this conversion would take advantage of existing energy-transportation systems via pipelines and well networks, perhaps significantly reducing initial capital investment and accelerating early adoption. Demand for widely available H_2 sources and opportunities to use H_2 blended with natural gas will require UHS reservoirs to be distributed across the U.S.

The U.S. currently lacks nationwide estimates of the amount of H_2 that could be potentially stored underground, either as a pure gas or mixed with natural gas, that use methods consistent with the current state of academic literature. These estimates are needed to help guide policymakers in the development of strategies for expanding H_2 technologies at a regional and national scale and to aid the industry in assessing UHS potential in relation to the H_2 supply chain (Dolan, 2020). In this work, we consider natural gas storage volume data for existing UGS facilities published by the Pipeline and Hazardous Materials Safety Administration (PHMSA). We use a simple volumetric approach to characterize H_2 storage volumes for a variety of pure and blended gas scenarios and estimate their H_2 energy-storage potential. Finally, we compare our H_2 energy-storage estimates with current seasonal energy demands and projections of annual H_2 demand to assess the degree to which conversion of existing UGS facilities to hydrogen storage could assist a widespread transition to an H_2 economy.

2. Data and Methods

2.1. Underground Gas Storage Facility Data

U.S. UGS facility data were obtained from the 2019–2021 PHMSA *Underground Natural Gas Storage Facility Annual Report* (PHMSA Form 7100.4-1) (PHMSA, 2022). Annual PHMSA report data were aggregated into a unified dataset using the ID (unit ID) of each UGS facility assigned by PHMSA. PHMSA Form 7100.4-1 contains facility metadata (ID, operator name, facility name, and facility location), gas-volume information (working gas, base gas, total gas, gas injected, and gas withdrawn), and reservoir information (reservoir name, type, depth, and maximum recorded wellhead pressure in a shut-in indicator well) for each UGS facility. Gas-volume data were reported at the facility level for all UGS facilities except for three—Ellisburg, Tioga, and Bethel—which consisted of two reservoirs operated by different companies. Despite having a shared facility name and location, we considered these facilities to be distinct for this study. Information for multiple reservoirs was reported for 32 UGS facilities. The maximum of calculated reservoir midpoint depths and the maximum wellhead surface pressure were used to approximate subsurface conditions in facilities with multiple reservoirs. The combined PHMSA dataset contained information for 404 UGS facilities. Of these facilities, the 399 that reported a non-zero working-gas volume between 2019 and 2021 were considered in this study. In 2021, the U.S. Energy Information Agency (EIA) reported 412 active natural gas storage fields in the U.S., which does not align with the number reported by PHMSA (EIA, 2021). Despite this difference, we relied on the PHMSA data because only their reports contain the reservoir information necessary to perform the calculations in this study. Most (79.4%) of the 399 UGS facilities are considered operated in a depleted hydrocarbon reservoir, with smaller subsets of facilities operating in aquifers (11.5%) and salt caverns (9.0%). The maximum reported volumes of working gas and gas withdrawn were used to make a high-end estimate of the operational characteristics of each facility. Estimates of working-gas energy (WGE) by the facility were aggregated to the U.S. Energy Information Agency's (EIA) storage regions (East, Midwest, South Central, Mountain, Pacific, and Alaska) and the reservoir type (depleted hydrocarbon reservoir, salt dome, and aquifer) to simplify the presentation of results (EIA, 2015).

2.2. Surface and Reservoir Conditions

Gas volume measurements for each UGS facility are reported to PHMSA in standard cubic feet. Thus, we assumed surface pressure and temperature to be 14.73 psi (101.56 kPa) and 60 ˚F (15.56°C), respectively. Reservoir temperatures for each facility were estimated by assuming a geothermal gradient of 27.5 ˚C/km. The maximum reported wellhead surface pressure (P_{wh}) was used to calculate the bottom hole pressure (P_{bh}) in a shut-in dry gas well with

$$P_{bh} = P_{wh} e^{\frac{\left(\frac{S_g}{R_e}\right) H}{T_{avg}}}, \tag{1}$$

where S_g is the specific gravity of natural gas (assumed to be 0.7), R_e is the engineering-gas constant for air (29.28 N-m/N K), H is the depth of the reservoir, and T_{avg} is the average temperature in the wellbore (Lyons et al., 2015).

2.3. Hydrogen and Mixed Gas Working-Gas Energy Estimates

The working gas of a UGS facility is the total quantity of gas stored within the field that can be injected and withdrawn from the reservoir. In a typical UGS facility, the working gas is accompanied by cushion gas which remains in the reservoir indefinitely, improves deliverability, and limits liquid-phase flow (e.g., formation brine) into the storage space (Tarkowski, 2019). Operators are required to report their designed working-gas volume in standard cubic feet on PHMSA Form 7100.4-1 (PHMSA, 2022). We used the reported working-gas volume ($WGV_{CH_{4,a}}$) at surface conditions to calculate the energy of H_2 that can be stored in existing U.S. UGS facilities, $WGE_{H_{2,a}}$, with the following relationship:

$$WGE_{H_{2,a}} = LHV_{H_2} \rho_{H_2,r} \left(\frac{\rho_{CH_4,a}}{\rho_{CH_4,r}} \right) WGV_{CH_{4,a}} \tag{2}$$

where LHV_{H_2} is the lower heating value of H_2, $\rho_{H_2,r}$ is the density of H_2 in the storage reservoir at storage conditions, $\rho_{CH_4,a}$ is the density of methane (CH_4) at ground surface conditions, and $\rho_{CH_4,r}$ is the density of CH_4 in the storage reservoir at storage conditions. For simplicity, the working-gas volumes reported in the PHMSA dataset were assumed to be pure (i.e.,100%) CH_4, rather than natural gas, which typically consists of a mixture of CH_4 with small amounts of other hydrocarbons and gases. We used the Peng–Robinson equation to calculate gas densities at the surface (101.56 kPa, 288.7 K) and reservoir conditions (estimated for each facility) (Peng & Robinson, 1976). The lower heating value was used to calculate the WGE because it is likely that the latent heat contained in the water vapor generated by the combustion of H_2 in a boiler or engine will be released through an exhaust stream and not recaptured through secondary condensers, which is required to achieve the higher heating value of the fuel (McAllister et al., 2011). We also consider blended H_2–CH_4 storage scenarios and estimate the WGE of these mixtures in existing U.S. UGS facilities. The WGE of blended H_2–CH_4 mixtures, WGE_{mix}, was calculated with

$$\begin{aligned} WGE_{mix} = {} & LHV_{H_2} \rho_{H_2,r} \left[VF_{H_2,r} \left(\frac{\rho_{CH_4,a}}{\rho_{CH_4,r}} \right) WGV_{CH4,a,mix} \right] \\ & + LHV_{CH_4} \rho_{CH_4,r} \left[VF_{CH_4,r} \left(\frac{\rho_{CH_4,a}}{\rho_{CH_4,r}} \right) WGV_{CH4,a,mix} \right], \end{aligned} \tag{3}$$

where $VF_{H_2,r}$ is the volume fraction of H_2 in the mixture at storage conditions, $VF_{CH_4,r}$ is the volume fraction of CH_4 in the mixture at storage conditions, and LHV_{CH_4} is the lower heating value of CH_4. $VF_{H2,r}$ was calculated using

$$VF_{H_2,r} = \frac{\frac{\rho_{H_2,a}}{\rho_{H_2,r}} VF_{H_2,a}}{\frac{\rho_{H_2,a}}{\rho_{H_2,r}} VF_{H_2,a} + \frac{\rho_{CH_4,a}}{\rho_{CH_4,r}} VF_{CH_4,a}}, \tag{4}$$

where $VF_{H_2,a}$ and $VF_{CH_4,a}$ are the volume fractions of H_2 and CH_4 in the mixture at surface conditions and $\rho_{H_2,a}$ and $\rho_{CH_4,a}$ are the densities of H_2 and CH_4 at surface conditions. In Equation (4), $VF_{CH4,r} = 1 - VF_{H_2,r}$.

Table 1
Summary of Estimated Working-Gas Energy (TWh) in U.S

	N Facilities (% total)	Cumulative working-gas energy, TWh (M; IQR)				
		Pure CH_4	5/95 H_2/CH_4 mix	20/80 H_2/CH_4 mix	80/20 H_2/CH_4 mix	Pure H_2
Regions						
East	131 (32.8%)	291 (1.0; 0.3–2.3)	278 (0.9; 0.3–2.2)	242 (0.8; 0.3–1.9)	113 (0.4; 0.1–0.9)	75 (0.3; 0.1–0.6)
Midwest	127 (31.8%)	327 (0.8; 0.3–3.0)	313 (0.8; 0.3–2.9)	271 (0.7; 0.2–2.5)	126 (0.3; 0.1–1.2)	83 (0.2; 0.1–0.8)
South Central	93 (23.3%)	418 (2.6; 1.1–5.8)	400 (2.5; 1.0–5.6)	346 (2.2; 0.9–4.8)	159 (1.1; 0.4–2.1)	105 (0.7; 0.3–1.4)
Mountain	28 (7.0%)	126 (1.7; 0.4–4.4)	121 (1.7; 0.4–4.2)	106 (1.4; 0.4–3.7)	51 (0.7; 0.2–1.7)	34 (0.4; 0.1–1.2)
Pacific	16 (4.0%)	112 (5.0; 1.8–6.7)	107 (4.8; 1.8–6.4)	92 (4.2; 1.5–5.6)	43 (1.9; 0.7–2.6)	28 (1.3; 0.5–1.7)
Alaska	4 (1.0%)	8 (1.6; 0.3–3.4)	8 (1.6; 0.3–3.2)	7 (1.4; 0.3–2.8)	3 (0.6; 0.1–1.3)	2 (0.4; 0.1–0.9)
Storage-Formation Type						
Depleted Reservoir	317 (79.4%)	1,054 (1.2; 0.4–3.9)	1,008 (1.1; 0.3–3.7)	876 (1.0; 0.3–3.2)	408 (0.5; 0.1–1.5)	270 (0.3; 0.1–1.0)
Aquifer	46 (11.5%)	107 (1.0; 0.3–2.2)	102 (0.9; 0.3–2.1)	89 (0.8; 0.3–1.8)	41 (0.4; 0.1–0.8)	27 (0.2; 0.1–0.5)
Salt Cavern	36 (9.0%)	122 (2.6; 1.1–5.4)	116 (2.5; 1.1–5.2)	100 (2.1; 0.9–4.5)	45 (1.0; 0.4–2.)	30 (0.6; 0.3–1.3)
Total	399	1,282 (1.2; 0.4–3.7)	1,226 (1.1; 0.4–3.6)	1,064 (1.0; 0.3–3.1)	494 (0.5; 0.2–1.4)	327 (0.3; 0.1–1.0)

Note. UGS facilities are categorized by region and storage-formation type. Estimates for pure methane (CH_4) and pure hydrogen (H_2) working gases are shown along with three H_2/CH_4 gas mixture scenarios (5/95, 20/80, and 80/20). The median (M) and interquartile range (IQR) of UGS facility working-gas energy distributions are also shown along with projected H_2 demands for each region and the entire U.S. Estimates of working-gas mass (MMT) are provided in Table S1 of Supporting Information S1.

The volumetric approach used in this study is relatively simple and typically used for site characterization and screening (Mouli-Castillo et al., 2021). The code used to perform the calculations in this study is available to the public as a tool on GitHub (https://github.com/NETL-RIC/WGV_Calculation). The findings of this study rely on the assumption that the caprock overlying the— natural gas storage reservoirs considered will be impermeable to H_2—a subject of ongoing research. Also implicit in this approach are the assumptions that (a) the pore-space volume available for gas storage in the reservoir is the same for all gases, regardless of the properties of the gas, (b) the fraction of the total reservoir volume available for the working gas is the same for natural gas and H_2, and (c) the sites considered would operate at the same pressures for hydrogen storage as they would for natural gas storage. Physics-based numerical simulations that consider the multiphase flow of H_2 and other fluids in the reservoir, heterogeneous reservoir properties, and realistic H_2 injection and withdrawal schedules are needed to provide more accurate working-gas volume estimates of H_2 and H_2–CH_4 mixtures in UGS reservoirs.

3. Results and Discussion

3.1. Hydrogen Energy-Storage Potential in Existing UGS Facilities

Assuming a pure (i.e., 100%) H_2 working gas, we estimated the total WGE for all U.S. UGS facilities to be 327 TW-hours (TWh). In terms of mass, we estimate that U.S. UGS facilities have a hydrogen storage potential of 9.8 million metric tons (MMT). The distribution of H_2 WGE for individual UGS facilities was skewed heavily to the right, with a median (M) and interquartile range (IQR) of 0.3 TWh and 0.1 to 1.0 TWh, respectively (Table 1, Table S1 and Figure S3 of Supporting Information S1). The minimum H_2 WGE estimated for a UGS facility was <0.1 TWh and the maximum was 12.8 TWh. The regional H_2 energy-storage potential varied substantially between 105 TWh (3.2 MMT) in the South Central region and 2.2 TWh (0.1 MMT) in Alaska (Table 1, Table S1 of Supporting Information S1, and Figure 1). Regional distributions of H_2 WGE for individual UGS facilities were also right-skewed, with the largest UGS facilities located in the Pacific and South Central regions and smaller UGS facilities located in the Mountain, Alaska, East, and Midwest regions (Table 1, Table S1 and Figure S4 of Supporting Information S1).

When grouped by reservoir type, the total H_2 energy-storage potential logically aligned with the number of UGS facilities operating in those reservoirs. Depleted hydrocarbon reservoirs had the greatest total H_2 energy-storage potential in the U.S. (270 TWh; 8.1 MMT). Total H_2 WGEs for salt cavern and aquifer UGS facilities were

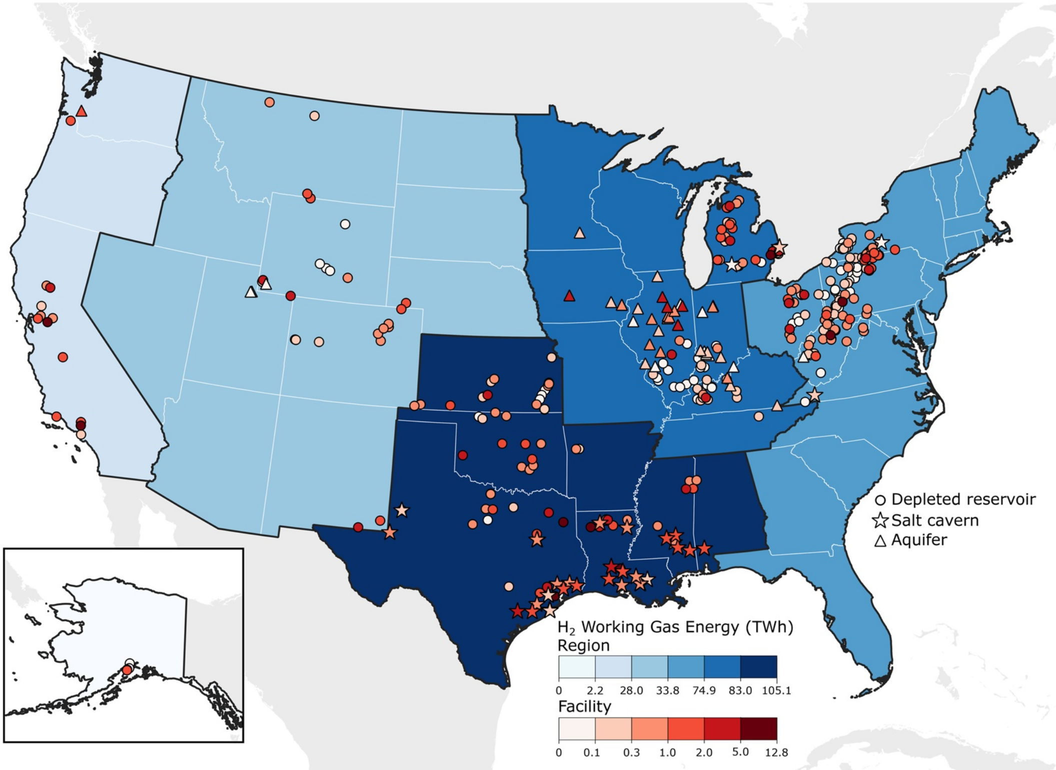

Figure 1. Estimated working-gas energy (TWh) of pure (i.e., 100%) H_2 in U.S. underground gas storage (UGS) facilities (light to dark red). UGS facility storage-formation types are designated by symbol shape. Shaded regions (light to dark blue) represent total working-gas energy (TWh) of 100% H_2 storage by the natural gas storage reporting regions used by the U.S. Energy Information Agency (South Central, Midwest, East, Mountain, Pacific, and Alaska).

smaller—29.6 TWh (0.9 MMT) and 27.4 TWh (0.8 MMT), respectively. The distributions of H_2 WGE for UGS facilities operating in each storage formation were also right-skewed. Salt cavern UGS facilities had larger gas storage volumes and subsequently greater H_2 WGEs than depleted reservoir and aquifer facilities (Table 1, Table S1 and Figure S5 of Supporting Information S1).

H_2 blends between 5% and 15% by volume are not believed to increase the risk of gas use in end-use systems and while there is variability among studies, most suggest that blends between 5% and 20% are acceptable (Melaina et al., 2013). To characterize the impact of mixing H_2 with U.S. subsurface energy-storage reserves, we estimated the energy-storage potential of U.S. UGS facilities assuming three H_2-CH_4 working-gas blends (Table 1). The total WGE of U.S. UGS facilities was 1,226, 1,064, and 494 TWh for H_2–CH_4 mixtures of 5%, 20%, and 80% H_2 by volume, respectively. As expected, the estimated WGE decreased as the H_2 blend % increased for each reservoir type and region considered.

3.2. Impact of Hydrogen Transition on Underground Energy-Storage Reserves

Assuming pure CH_4 storage, the current cumulative WGE of UGS facilities in the U.S. is 1,282 TWh. We estimate that transitioning working gas from CH_4 to pure (i.e., 100%) H_2 nationwide would reduce the cumulative WGE by 75%–327 TWh (Table 1). A reduction in energy-storage potential is expected if UGS facilities that transition to hydrogen storage maintain their current operational conditions. Despite having a higher energy content by mass than CH_4, the relatively low density of H_2 will result in lower H_2 working-gas volumes in UGS facilities and subsequently a reduction in energy-storage potential. With the considered approach, the degree to which WGE will be reduced by an H_2 transition was dependent on the density ratio of H_2 to CH_4 in the storage reservoir. A lower H_2-to-CH_4 density ratio resulted in a greater reduction in WGE. The H_2-to-CH_4 density ratio was lowest at 18,000 kPa (increasing at lower and higher pressures) and decreased at higher temperatures (Goodman et al., 2022). Estimated WGE reductions for all U.S. UGS facilities ranged between 71% and 76%

and formed a left-skewed distribution (M, 74%; IQR, 73%–75%) (Figure S6 of Supporting Information S1). UGS facilities in the dataset with reservoirs located between 1,201 and 1,400 m had pressure and temperature conditions that resulted in the greatest reduction in WGE (M, 75.7%) (Figure S7 and Table S2 of Supporting Information S1).Blending H_2 into working gas also reduces the energy-storage potential of UGS facilities. Using our volumetric approach, a 1% increase in working-gas H_2 concentration corresponded to a 0.8% reduction in the U.S. UGS facility WGE (Table 1 and Figure S8 of Supporting Information S1).

3.3. Buffering Current Seasonal Energy Storage Demands With Hydrogen-Natural Gas Blends

The average annual natural gas energy consumption in the U.S. between 2019 and 2021 was 8,214 TWh (EIA, 2017). Averaging gas extraction volumes for each UGS facility over the study period, we estimated that the total annual energy withdrawn from UGS facilities was 911 TWh—11% of the average U.S. natural gas demand. If all available working gas in UGS facilities (1,282 TWh) were used (Table 1), underground storage could buffer up to 16% of the U.S. natural gas demand. This excess energy storage could help ease the transition to blended H_2–CH_4 working gases, which will ultimately reduce the energy content of the stored gas.

Of the 399 facilities considered, 330 used less than 100% of their WGE between 2019 and 2021. More than 100% of the WGE was only used in 69 facilities, which can be achieved through multiple injection and withdrawal cycles. The median percentage of the WGE used at UGS facilities was 66% (IQR, 44%–86%) (Figure S9 and Table S3 of Supporting Information S1). While variations in the percentage of WGE used were observed between regions (Figure S10 and Table S4 of Supporting Information S1), reservoir type provided the clearest distinctions in the degree to which WGE was used at each facility.

Salt cavern facilities had higher deliverability and used a higher percentage of their WGE (M, 125%; IQR, 99%–186%) than aquifers (M, 71; IQR, 55%–88%) and depleted reservoirs (M, 62%; IQR, 40%–77%) (Figure S11 and Table S5 of Supporting Information S1). Switching to 5% or 20% H_2 blends by volume and maintaining the same energy withdrawal would increase the median WGE used by facilities to 69% (IQR, 46%–90%) and 79% (IQR, 53%–103%), respectively (Figure S9 and Table S3 of Supporting Information S1). Of the 399 UGS facilities considered, we estimated that 322 will use less than 100% of their WGE and can continue to meet seasonal energy demand if they switch to a 5% H_2 working gas. Switching to a 20% H_2 blend lowers the number of facilities that can continue to meet seasonal energy demands to 292. The number of facilities that exceeded their WGE in the 5% and 20% H_2 working-gas scenarios was 77 and 107, respectively. If withdrawals from these UGS facilities cannot be increased above 100% of their WGE, their operations will need to expand or new UGS facilities will need to be constructed nearby. The majority (65.8%) of the 38 facilities pushed over the 100% WGE threshold in a 20% H_2 working-gas scenario were depleted hydrocarbon reservoirs (Figure S12 and Table S6 of Supporting Information S1). The greatest increase (18) in the number of UGS facilities that exceeded 100% of their WGE in a 20% H_2 working-gas scenario occurred in the Midwest region (Figure S13 and Table S6 of Supporting Information S1).

3.4. Buffering Prospective H_2 Energy Demand

The current demand for H_2 in the U.S. is 333 TWh (10 MMT) (Gilroy, 2022). There are three active U.S. UHS facilities: Moss Bluff, Spindletop, and Clemens Dome which store 0.4 TWh (0.013 MMT) of H_2—approximately 0.1% of the H_2 demand. It is projected that new uses for H_2 in the economy (e.g., steelmaking, synthetic fuels, fuel cell vehicles) could grow U.S. H_2 demand to 733–1,366 TWh (22–41 MMT) by 2050 (Ruth et al., 2020; Shuster et al., 2021). Right now, UHS primarily supports industrial petrochemical processing (Ruth et al., 2020). However, the role of UHS and subsequently the relative quantity of H_2 energy storage needed with respect to demand will evolve to accommodate new H_2 applications. For example, if H_2 is used to buffer mismatches between renewable (e.g., solar) energy supply and demand, the percentage of the H_2 demand that would need to be passed through storage may approach the percentage of the natural gas demand currently buffered by existing UGS facilities (16%). If this were the case, the U.S. UHS capacity would need to increase by 116.9–218.2 TWh by 2050 to sufficiently buffer H_2 demand projections. Assuming that new UHS facilities would have an H_2 WGE of 0.3 TWh (the median H_2 WGE calculated for existing UGS facilities), 390–727 new UHS facilities would need to be constructed. However, storing H_2 in existing UGS facilities has the potential to substantially reduce the number of new UHS facilities needed. If used to store pure H_2, the cumulative H_2 WGE of existing UGS facilities

Table 2
Estimated Percentage of H_2 Demand Buffered by H_2 Storage in Existing UGS Facilities

Working-gas composition (H_2 WGE)	H_2 demand buffered by storage (%) Low demand (733 TWh)	High demand (1,366 TWh)
5/95 H_2-CH_4 (19 TWh)	2.6%	1.4%
20/80 H_2-CH_4 (74 TWh)	10.1%	5.4%
40/60 H_2-CH_4 (144 TWh)	19.6%	10.5%
60/40 H_2-CH_4 (209 TWh)	28.5%	15.3%
80/20 H_2-CH_4 (270 TWh)	36.8%	19.8%
Pure H_2 (327 TWh)	44.6%	23.9%

Note. Scenarios in which the cumulative WGE of UGS facilities is below 16% (the current estimated buffered percentage of natural gas energy demand) are highlighted.

would buffer 44.6%–23.9% (327 TWh) of the H_2 demand scenarios considered (Table 2), which exceeds the 16% buffer that currently exists for natural gas. Blending H_2 with natural gas in existing UGS facilities and separating it onsite could also help meet H_2 demand projections. H_2-CH_4 blends between 20%–40% and 60%–80% would buffer 16% of the low and high H_2 demand scenarios, respectively (Table 2).

4. Summary and Future Outlook

The factors that will influence the future of natural gas and H_2 storage in the U.S. are yet to be determined. In the near term, our estimates suggest that storing H_2-natural gas mixtures of up to 20% H_2 will not impact the ability of the majority (73.2%) of U.S. UGS facilities to continue buffering current seasonal energy demands. However, H_2 working gas blends will push additional U.S. UGS facilities to use more than 100% of their WGE. While a subset of UGS facilities currently delivers more than 100% of their WGE, it is reasonable to expect that underground gas storage operations will need to be expanded in some regions to accommodate a transition to H_2 mixtures. In the long term, new UGS facilities dedicated to H_2 storage will also be needed to buffer the growing demand for pure H_2. The percentage of this H_2 demand that will need to be stored to buffer cyclical H_2 supply–demand mismatches is not currently known, but will be driven by pure-H_2 applications. If an underground storage buffer similar to what is currently provided for natural gas is required, hundreds of new UHS facilities may be needed. Existing UGS facilities currently have the capacity to sufficiently buffer prospective H_2 demand. Transitioning a portion of existing UGS facilities to the storage of H_2-natural gas mixtures or pure H_2 could substantially reduce the number of new UHS facilities needed.

It is likely that our estimates for the H_2 storage potential in existing UGS facilities are a higher bound. The volumetric approach used in this study does not account for the differences in the physical properties of H_2 and natural gas that will ultimately determine the WGE of UGS facilities storing H_2. Many factors such as H_2 diffusion, viscous fingering, and redistribution may potentially reduce the H_2 composition of working gas over storage cycles (Goodman et al., 2022; Muhammed et al., 2022). Biotic and abiotic processes such as sulfate reduction and iron-hydroxide precipitation may consume significant quantities of injected H_2 or reduce injectivity (Flesch et al., 2018; Gregory et al., 2019; Henkel et al., 2014; Michanowicz et al., 2017; Miyazaki, 2009; Muhammed et al., 2022; Yekta, Pichavant et al., 2018). The mobility of H_2 in the subsurface also increases leakage concerns through the caprock, a fault zone, or a compromised wellbore (Kutchko et al., 2007; Michanowicz et al., 2017; Miyazaki, 2009). Initial studies show that 2% of H_2 will be lost over the life cycle of a UGS storage operation (NEA, 2017). However, more research is needed to understand the physical and chemical processes that may impact the efficiency of underground H_2 storage and improve energy-storage estimates.

The development of H_2 infrastructure is a major transformation that will require support from key stakeholders and regulatory agencies (Amid et al., 2016; Goodman et al., 2022; Tarkowski, 2019). UGS facilities are currently regulated by the state public utility commissions with oversight from the Environmental Protection Agency, U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration, state oil and gas or environmental regulatory agencies, and Federal Energy Regulatory Commission (INGAA, 2021). UHS projects will also require early public education and acceptance of UHS in terms of benefits and risks (Israel et al., 2015). These technical, political, and social factors are important to consider as work to bring down costs of H_2 production, transport, storage, and use progresses across many areas of the economy to meet recent U.S. policy goals (Amid et al., 2016; Goodman et al., 2022; Tarkowski, 2019).

Data Availability Statement

All data created for this study are available in Data Set S1 and can also be downloaded from a data repository on NETL's Energy Data Exchange (EDX) (Lackey et al., 2022). Users wishing to gain access will need to register for an account. The underground gas storage facility data used for this study are available from the Pipelines and Hazardous Materials Safety Administration (PHMSA) underground gas storage report (PHMSA, 2022).

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