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

Greg Lackey[1], Gerad M Freeman[2], Thomas A Buscheck[3], Foad Haeri[4], Joshua White[5], Nicolas John Huerta[6], and Angela Lea Goodman[7]

[1]National Energy Technology Laboratory
[2]Pacific Northwest National Laboratory
[3]Lawrence Livermore National Laboratory (DOE)
[4]The National Energy Technology Laboratory
[5]Lawrence Livermore National Laboratory
[6]PNNL
[7]U.S. Department of Energy; National Energy Technology Laboratory

November 24, 2022

Abstract

Underground hydrogen storage is a potential long-duration energy storage option for a low-carbon economy. While research into the technical feasibility of hydrogen storage in various geologic formations is ongoing, existing underground gas storage (UGS) facilities are appealing candidates because of their demonstrated ability to store and deliver gas. We estimate that transitioning U.S. UGS facilities from natural gas to pure hydrogen storage would reduce their collective working-gas energy by 75%, from 1,282 TWh to 327 TWh. However, withdrawals from most (73%) UGS facilities could be increased to maintain current energy demands with a 20% hydrogen-natural gas blend. Hydrogen demand projections for the U.S. suggest that hundreds of new underground hydrogen storage facilities may be needed by 2050. Storing pure hydrogen or 20-60% hydrogen blends in UGS facilities can sufficiently buffer this demand demonstrating that partial transitions of UGS infrastructure to hydrogen storage could substantially reduce the need for new facilities.

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

Greg Lackey[1,2*], Gerad M. Freeman[3], Thomas A. Buscheck[4], Foad Haeri[1,2], Joshua A. White[4], Nicolas Huerta[3] and Angela Goodman[1*]

[1]National Energy Technology Laboratory, 626 Cochran Mill Road, Pittsburgh, PA 15236-0940, USA

[2]NETL Support Contractor, 626 Cochran Mill Road, Pittsburgh, PA 15236-0940, USA

[3]Pacific Northwest National Laboratory, 902 Battelle Boulevard, Richland, WA 99354, USA

[4]Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550, USA

*Corresponding author: Angela Goodman (angela.goodman@netl.doe.gov), Greg Lackey (gregory.lackey@netl.doe.gov)

†Additional author notes should be indicated with symbols (current addresses, for example).

Key Points:

- The total hydrogen working-gas energy of underground gas storage facilities in the United States is estimated to be 327 terawatt-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 substantially reduce the number of new facilities needed in the U.S.

Abstract

Underground hydrogen storage is a potential long-duration energy storage option for a low-carbon economy. While research into the technical feasibility of hydrogen storage in various geologic formations is ongoing, existing underground gas storage (UGS) facilities are appealing candidates because of their demonstrated ability to store and deliver gas. We estimate that transitioning U.S. UGS facilities from natural gas to pure hydrogen storage would reduce their collective working-gas energy by 75%, from 1,282 TWh to 327 TWh. However, withdrawals from most (73%) UGS facilities could be increased to maintain current energy demands with a 20% hydrogen-natural gas blend. Hydrogen demand projections for the U.S. suggest that hundreds of new underground hydrogen storage facilities may be needed by 2050. Storing pure hydrogen or 20-60% hydrogen blends in UGS facilities can sufficiently buffer this demand demonstrating that partial transitions of UGS infrastructure to hydrogen storage could substantially reduce the need for new facilities.

Plain Language Summary

Long-duration, low-emission energy storage at the utility scale is one of the major challenges to address during the clean energy transition. Hydrogen is a high energy content fuel that is produced with low or zero emissions from a variety of feedstocks. Underground hydrogen storage is an option for long-duration energy storage that could be used to increase output from low-carbon power generators and balance energy supply and demand variations. Existing underground gas storage (UGS) facilities in the United States (U.S.) are a logical first place to consider storing hydrogen, because their geology has proven favorable for natural gas storage. We estimate that the hydrogen energy storage potential in existing U.S UGS facilities is 327 terawatt-hours. While transitioning to hydrogen storage will reduce the energy-storage potential of existing UGS facilities by 75%, 73% of current facilities can continue to meet current energy demands using a 20% hydrogen-natural gas mixture. Storing enough hydrogen to buffer anticipated energy supply and demand variations could require a substantial increase in U.S. UGS capacity. However, we demonstrate that U.S. UGS facilities can sufficiently buffer prospective hydrogen demand. Thus, a partial transition of UGS infrastructure to hydrogen storage could substantially reduce the need for new facilities.

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 utility scale (Andrews and Shabani 2012, Peng, Fowler et al. 2016, DOE 2020, Dolan 2020, Dopffel, Jansen et al. 2021, Ennis-King, Michael et al. 2021, Heinemann, Alcalde et al. 2021, Zivar, Kumar 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 (Peng, Fowler et al. 2016, Tarkowski 2019, DOE 2020, Dolan 2020, Zivar, Kumar 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 (Tarkowski 2019, Shuster 2021). 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 (Tarkowski 2019, DOE 2020, Heinemann, Alcalde et al. 2021, Shuster 2021, Zivar, Kumar et al. 2021, Goodman, Kutchko et al. 2022, Muhammed, Haq et al. 2022).

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, Tarkowski and Czapowski 2018, Tarkowski 2019). UHS also reduces safety risk factors associated with above-ground gas-ignition 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, Heinemann et al. 2021). Evidence suggests that UHS is also feasible in porous and permeable reservoirs (Pudlo, Ganzer et al. 2013, Bauer, Pfeiffer et al. 2015). However, research into the storage feasibility of UHS in salt caverns, depleted hydrocarbon reservoirs, brine aquifers, and hard rock caverns is ongoing (Pudlo, Ganzer et al. 2013, Tarkowski 2019, Heinemann, Alcalde et al. 2021, Wallace, Cai et al. 2021, Zivar, Kumar et al. 2021, Muhammed, Haq et al. 2022) (Figure S1).

Existing underground gas storage (UGS) facilities are appealing early candidates for large-scale UHS as these reservoirs 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 contain 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) (Goodman, Kutchko 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 replace it entirely in existing UGS reservoirs (Melaina 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 policy makers in the development of strategies for expanding H_2 technologies at a regional and national scale and to aid 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 volumetric approach to calculate 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 potential estimates with current seasonal energy demands and projections of annual H_2 demand to characterize the degree to which conversion of existing UGS facilities to hydrogen storage could assist a widespread transition to a 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 indictor 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 the purpose of 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, 399 that reported a non-zero working-gas volume between 2019 and 2021 were considered in this study. Most (79.4%) of the 399 UGS facilities 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 by 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 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 psia (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

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

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 2015).

2.3 Hydrogen and mixed gas working-gas energy estimates

The working gas of a UGS facility is 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

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

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 surface (101.56 kPa, 288.7 K) and reservoir conditions (estimated for each facility) (Peng and Robinson 1976). The lower heating value was used to calculate the working-gas energy 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, Chen et al. 2011). We also consider blended H_2-CH_4 storage scenarios and estimate the working-gas energy of these mixtures in existing U.S. UGS facilities. The working-gas energy of blended H_2-CH_4 mixtures, WGE_{mix}, was calculated with

$$WGE_{mix} = LHV_{H_2}\rho_{H_{2},r}\left[VF_{H_{2},r}\left(\frac{\rho_{CH_{4},a}}{\rho_{CH_{4},r}}\right)WGV_{CH4,a,mix}\right] +$$

$$LHV_{CH_4}\rho_{CH_{4},r}\left[VF_{CH_{4},r}\left(\frac{\rho_{CH_{4},a}}{\rho_{CH_{4},r}}\right)WGV_{CH4,a,mix}\right], \quad (3)$$

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

$$VF_{H_2,r} = \frac{\frac{\rho_{H_2,a}}{\rho_{H_2,r}} VF_{H_2,a}}{\frac{\rho_{H_2,a}}{\rho_{H_2,r}} VF_{H_2,a} + \frac{\rho_{CH_4,a}}{\rho_{CH_4,r}} VF_{CH_4,a}}, \quad (4)$$

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 (4), $VF_{CH4,r} = 1 - VF_{H_2,r}$.

The volumetric approach used in this study (2 and 3) is relatively simple and assumes the pore-space volume available for gas storage in the storage reservoir is the same for all gases, regardless of the properties of the gas. Also implicit to this approach is the assumption that the fraction of the total reservoir volume available for the working gas is the same for natural gas and H_2. Physics-based numerical simulations are needed to provide more accurate working-gas volume estimates of H_2 and H_2-CH_4 mixtures in UGS reservoirs. However, volumetric approaches like (equations 2 and 3) are valuable for characterizing regional storage estimates and have recently been used by other H_2 storage characterization studies (Mouli-Castillo, Heinemann et al. 2021). This storage assessment methodology to determine the H_2-storage potential is made available to the public as a tool on GitHub (https://github.com/NETL-RIC/WGV_Calculation).

3. Results & 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 working-gas energy (WGE) for all U.S. UGS facilities to be 327 TWh. 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 and Figure S3). 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 in the South Central region and 2.2 TWh in Alaska (Table 1 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 and Figure S4).

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). Total H_2 WGEs for salt cavern and aquifer UGS facilities were smaller – 29.5 TWh and 27.4 TWh, respectively. The distributions of H_2 WGE for UGS facilities operating in each storage formation were also right-skewed. Salt cavern UGS facilities were larger and had greater H_2 WGEs than depleted reservoir and aquifer facilities (Table 1 and Figure S5).

H_2 blends between 5% and 20% by volume are generally considered acceptable for most downstream end-use systems (Melaina 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 TWh, 1,064 TWh, 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 working-gas energy (WGE) of UGS facilities in the U.S. is 1,282 TWh. Transitioning working gas from CH_4 to pure (i.e., 100%) H_2 nationwide would reduce the cumulative WGE by 75% to 327 TWh (Table 1). This reduction in the energy-storage potential is expected. 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. The degree to which WGE will be reduced by a H_2 transition is dependent on the density ratio of H_2 to CH_4 in the storage reservoir, with a lower H_2-to-CH_4 density ratio resulting in a greater reduction in WGE. The H_2-to-CH_4 density ratio is lowest at 18,000 kPa (increasing at lower and higher pressures) and decreases at higher temperatures (Goodman, Kutchko 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). UGS facilities in the dataset with reservoirs located between 1,201-1,400 m had pressure and temperature conditions that resulted in the greatest reduction in WGE (M, 75.7%) (Figure S7 and Table S1).

Table 1. Summary of estimated working-gas energy (TWh) in U.S. UGS facilities 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.

		Cumulative Working-Gas Energy (M; IQR), TWh				
	N Facilities (% Total)	**Pure CH_4**	**5/95 H_2/CH_4 Mix**	**20/80 H2/CH4 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)

Blending H_2 into working gas also reduces the energy-storage potential of UGS facilities. Using our 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).

3.2 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 9,294 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 – 10% 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 14% of the

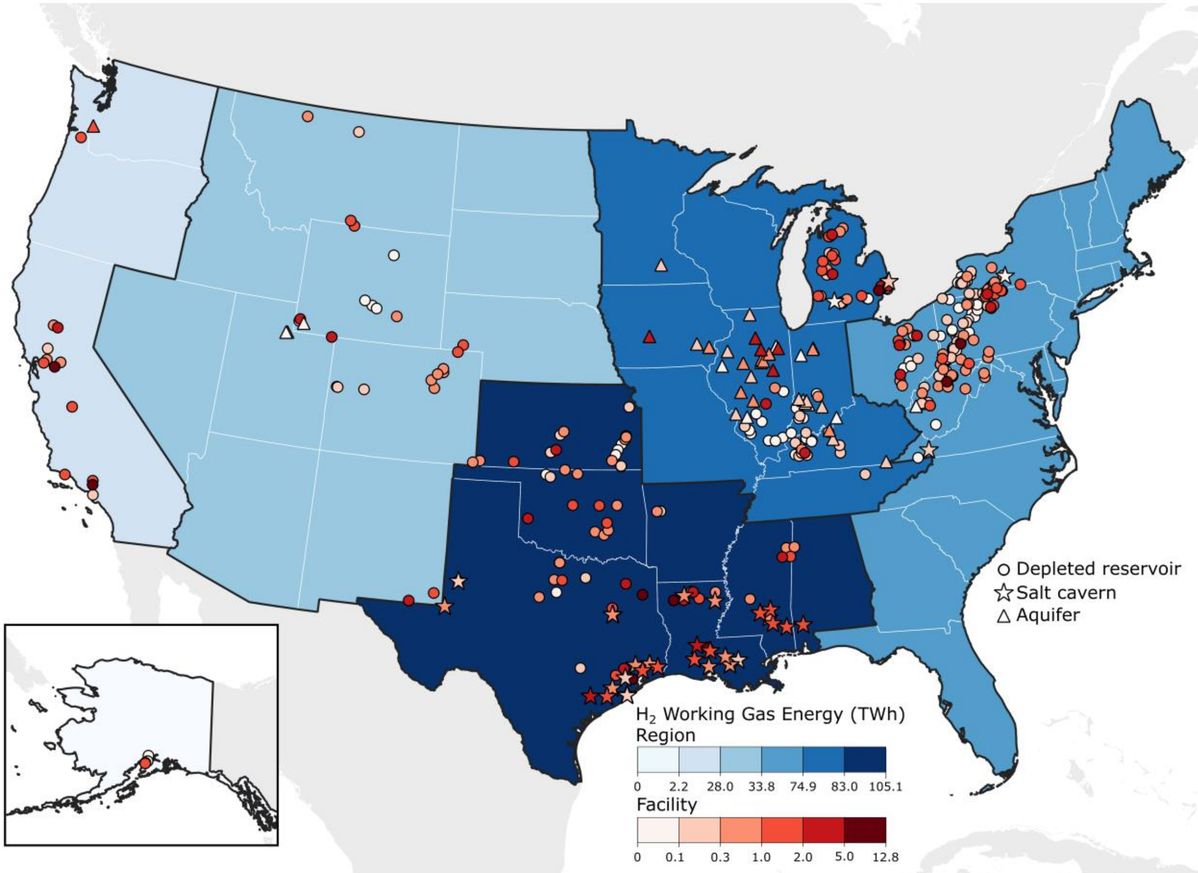

Figure 1. Estimated working-gas energy (TWh) of pure (i.e., 100%) H_2 in U.S. UGS facilities (light to dark red). UGS facility storage-formation types are designated by symbol shape. Shaded regions (light to dark blue) represent total working-gas energy (TWh) of 100% H_2 storage by the natural gas storage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

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 2019-2021. 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 S2). While variations in the percentage of WGE used were observed between regions (Figure S10 and Table S3), 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 S4). 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 S2). Of the 399 UGS facilities considered, we estimated that 322 and 292 will use less than 100% of their WGE and can continue to meet seasonal energy demand if they switch to a 5% H_2 or 20% H_2 working gas, respectively. 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 S5). 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 S5).

3.3 Buffering prospective H_2 energy demand

Current demand for H_2 in the U.S. is 333 TWh (10 million metric tons, MT) (Gilroy 2022). There are three active U.S. UHS facilities: Moss Bluff, Spindletop, and Clemens Dome that store 0.4 TWh (0.013 MT) 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 MT) by 2050 (Oleson 2022). Right now, UHS primarily supports industrial petrochemical processing (Shuster 2021). 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 (14%). If this were the case, the U.S. UHS capacity would need to increase by 102.6-191.2 TWh by 2050 to sufficiently buffer H_2 demand projections. Assuming that new UHS facilities would have a H_2 WGE of 0.3 TWh (the median H_2 WGE calculated for existing UGS facilities), 342-637 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 would buffer 44.6-23.9% (327 TWh) of the H_2

Table 2. Estimated percentage of H_2 demand buffered by H_2 storage in existing UGS facilities. Scenarios in which the cumulative WGE of UGS facilities is below 14% (the current estimated buffered percentage of natural gas energy demand) are highlighted.

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%

demand scenarios considered (Table 2), which exceeds the 14% 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 40-60% would buffer 14% 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 deliver more than 100% of their WGE, it is 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 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 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 storage of H_2-natural gas mixtures (20-60% H_2) 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, Kutchko et al. 2022, Muhammed, Haq 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 (Miyazaki 2009, Henkel, Pudlo et al. 2014, Michanowicz, Buonocore et al. 2017, Muhammed, Haq et al. 2022) (Flesch, Pudlo et al. 2018, Yekta, Pichavant et al. 2018, Gregory, Barnett et al. 2019). The mobility of H_2 in the subsurface also increases leakage concerns through the caprock, a fault zone, or a compromised wellbore (Kutchko, Strazisar et al. 2007, Miyazaki 2009, Michanowicz, Buonocore et al. 2017). 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.

Development of H_2 infrastructure is a major transformation that will require support from key stakeholders and regulatory agencies (Amid, Mignard et al. 2016, Tarkowski 2019, Goodman, Kutchko et al. 2022). 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, Wong-Parodi 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, Mignard et al. 2016, Tarkowski 2019, Goodman, Kutchko et al. 2022).

Acknowledgments

The authors would like to thank Bob Smith, Blaine Keener, and Catherine Washabaugh from the Pipeline and Hazardous Materials Safety Administration for their assistance with accessing and interpreting the dataset. This work was supported by the U.S. Department of Energy, Office of Fossil Energy and Carbon Management (FECM) through the Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA) project. Portions of this research were executed through the NETL Research and Innovation Center's Carbon Storage Program. This project was funded by the United States Department of Energy, National Energy Technology Laboratory, in part, through a site support contract. Neither the United States Government nor any agency thereof, nor any of their employees, nor the support contractor, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Open Research

All data created for this study are available in Table S6 and can also be downloaded from a data repository on NETL's Energy Data Exchange (EDX) (Lackey, Freeman et al. 2022). 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).

5. References

Amid, A., et al. (2016). "Seasonal storage of hydrogen in a depleted natural gas reservoir." International Journal of Hydrogen Energy **41**(12): 5549-5558.

Andrews, J. and B. Shabani (2012). Where does hydrogen fit in a sustainable energy economy? Evolving Energy - International-Energy-Foundation International Energy Congress (IEF-IEC), Australia.

Bauer, S., et al. (2015). Quantifying induced effects of subsurface renewable energy storage. European Geosciences Union General Assembly 2015 - Division Energy, Resources and Environment, Egu 2015. M. Ask, S. Hangx, V. Bruckman and M. Kuhn. **76:** 633-641.

DOE (2020). Department of Energy Hydrogen Program Plan. https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf, U.S. Department of Energy.

Dolan, C. (2020). Road Map to a US Hydrogen Economy. Reducing Emissions and Driving Growth Across the Nation. http://www.ushydrogenstudy.org/.

Dopffel, N., et al. (2021). "Microbial side effects of underground hydrogen storage - Knowledge gaps, risks and opportunities for successful implementation." International Journal of Hydrogen Energy **46**(12): 8594-8606.

EIA (2015). Natural Gas Storage Regions. U.S. Energy Information Administration (EIA.gov).

EIA (2017, 2017). "Annual Energy Outlook 2017 with projections to 2050." from https://www.eia.gov/pressroom/presentations/sieminski_01052017.pdf.

Ennis-King, J., et al. (2021). Underground storage of hydrogen: mapping out the options for Australia, CSIRO Energy.

Flesch, S., et al. (2018). "Hydrogen underground storage-Petrographic and petrophysical variations in reservoir sandstones from laboratory experiments under simulated reservoir conditions." International Journal of Hydrogen Energy **43**(45): 20822-20835.

Gilroy, N. (2022). "H2@Scale Concept Hydrogen Demand and Resources [data set]." Retrieved 6/2/2022, from https://dx.doi.org/10.25984/1845000.

Goodman, A., et al. (2022). Subsurface Hydrogen and Natural Gas Storage: State of Knowledge and Research Recommendations Report NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2022; p 77. National Energy Technology Laboratory: Morgantown, WV**:** 77.

Gregory, S. P., et al. (2019). "Subsurface Microbial Hydrogen Cycling: Natural Occurrence and Implications for Industry." Microorganisms **7**(2).

Heinemann, N., et al. (2021). "Enabling large-scale hydrogen storage in porous media - the scientific challenges." Energy & Environmental Science **14**(2): 853-864.

Henkel, S., et al. (2014). Mineral reactions in the geological underground induced by H-2 and CO2 injections. 12th International Conference on Greenhouse Gas Control Technologies (GHGT), Austin, TX.

INGAA (2021). How are pipelines regulated? . Interstate Natural Gas Association of America. .

Israel, A. L., et al. (2015). "Eliciting Public Concerns about an Emerging Energy Technology: The Case of Unconventional Shale Gas Development in the United States." Energy Research & Social Science **8** 139-150.

Kutchko, B. G., et al. (2007). "Degradation of well cement by CO2 under geologic sequestration conditions." Environmental Science and Technology **41**(13): 4787-4792.

Lackey, G., et al. (2022). "Hydrogen Storage Potential in U.S. Underground Gas Storage Facilities." Retrieved 9/26/2022, 2022, from https://edx.netl.doe.gov/dataset/hydrogen-storage-potential-in-u-s-underground-gas-storage-facilities.

Lyons, W. C., Carter, T., & Lapeyrouse, N. J. (2015). Formulas and calculations for drilling, production, and workover: All the formulas you need to solve drilling and production problems. Elsevier, Gulf Professional Publishing.

McAllister, S., et al. (2011). Fundamentals of combustion processes, Springer.

Melaina, M. W., Antonia, O., Penev, M. (2013). Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. 15013 Denver West Parkway
Golden, Colorado 80401
National Renewable Energy Laboratory.

Michanowicz, D. R., et al. (2017). "A national assessment of underground natural gas storage: identifying wells with designs likely vulnerable to a single-point-of-failure." Environmental Research Letters **12**(6).

Miyazaki, B. (2009). Well integrity: An overlooked source of risk and liability for underground natural gas storage. Lessons learned from incidents in the USA. Geological Society. London, Special Publications. **313:** 163-172.

Mouli-Castillo, J., et al. (2021). "Mapping geological hydrogen storage capacity and regional heating demands: An applied UK case study." Applied Energy **283**.

Muhammed, N. S., et al. (2022). "A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook." Energy Reports **8**: 461-499.

NEA (2017). The effects of hydrogen injection in natural gas networks for the Dutch underground storages. Netherlands Enterprise Agency

Oleson, D. (2022). "How Not To Short-Circuit the Clean Energy Transition; Video and Report Explain Why Fault Protection Should Be on Grid Planners' Radar." from https://www.nrel.gov/news/program/2022/how-not-to-short-circuit-the-clean-energy-transition.html.

Peng, D. D., et al. (2016). "Enabling utility-scale electrical energy storage by a power-to-gas energy hub and underground storage of hydrogen and natural gas." Journal of Natural Gas Science and Engineering **35**: 1180-1199.

Peng, D. Y. and D. B. Robinson (1976). "A new two-constant equation of state." Industrial & Engineering Chemistry Fundamentals, **15**(1): 59-64.

PHMSA (2022). "Underground Natural Gas Storage Annual Report Form F 7100.4-1." Friday, March 4, 2022, from https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/data_statistics/pipeline/annual_underground_natural_gas_storage_2017_present.zip.

Pudlo, D., et al. (2013). The H2STORE Project: Hydrogen Underground Storage – A Feasible Way in Storing Electrical Power in Geological Media? Clean Energy Systems in the Subsurface: Production, Storage and Conversion. X. H. Hou M., Were P. Springer, Berlin, Heidelberg, Springer Series in Geomechanics and Geoengineering.

Shuster, M. W. B., Shuvajit; Duncan, Ian J.; Eichhubl, Peter; Hosseini, Seyyed A.; Javadpour, Farzam; Kipper, Jay P.; Lin, Ning; Nicot, Jean-Philippe; Ren, Bo (2021). Hydrogen Infrastructure expansion requires realistic framework. Oil & Gas Journal. Austin, Texas, Bureau of Economic Geology**:** 50-59.

Tarkowski, R. (2017). "Perspectives of using the geological subsurface for hydrogen storage in Poland." International Journal of Hydrogen Energy **42**(1): 347-355.

Tarkowski, R. (2019). "Underground hydrogen storage: Characteristics and prospects." Renewable & Sustainable Energy Reviews **105**: 86-94.

Tarkowski, R. and G. Czapowski (2018). "Salt domes in Poland - Potential sites for hydrogen storage in caverns." International Journal of Hydrogen Energy **43**(46): 21414-21427.

Wallace, R. L., et al. (2021). "Utility-scale subsurface hydrogen storage: UK perspectives and technology." International Journal of Hydrogen Energy **46**: 25137-25159.

Yekta, A. E., et al. (2018). "Evaluation of geochemical reactivity of hydrogen in sandstone: Application to geological storage." Applied Geochemistry **95**: 182-194.

Zivar, D., et al. (2021). "Underground hydrogen storage: A comprehensive review." International Journal of Hydrogen Energy **46**(45): 23436-23462.

SUPPORTING INFORMATION

FOR

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

Greg Lackey[1,2*], Gerad M. Freeman[3], Thomas A. Buscheck[4], Foad Haeri[1,2], Joshua A. White[4], Nicolas Huerta[3] and Angela Goodman[1*]

[1]National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA 15236-0940, USA

[2]NETL Support Contractor, 626 Cochrans Mill Road, Pittsburgh, PA 15236-0940, USA

[3]Pacific Northwest National Laboratory, 902 Battelle Boulevard, Richland, WA 99354, USA

[4]Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550, USA

*Corresponding author: Angela Goodman (angela.goodman@netl.doe.gov), Greg Lackey (gregory.lackey@netl.doe.gov)

Contents of this file

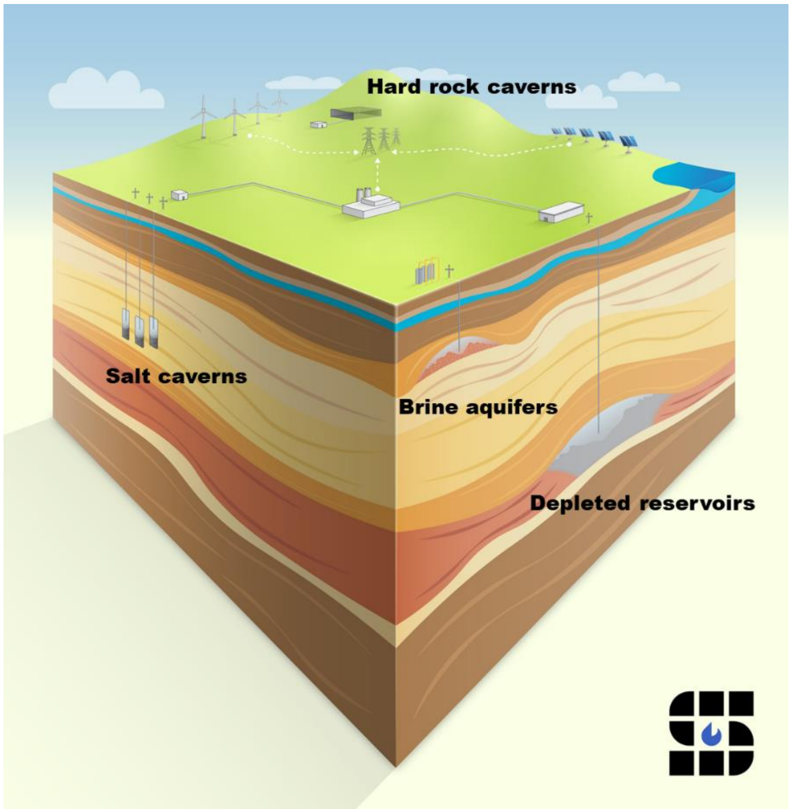

Figure S1. Schematic showing underground storage of H_2 in depleted reservoirs, brine aquifers, salt caverns, and hard rock caverns in association with power generation and H_2 production (modified from [1]).

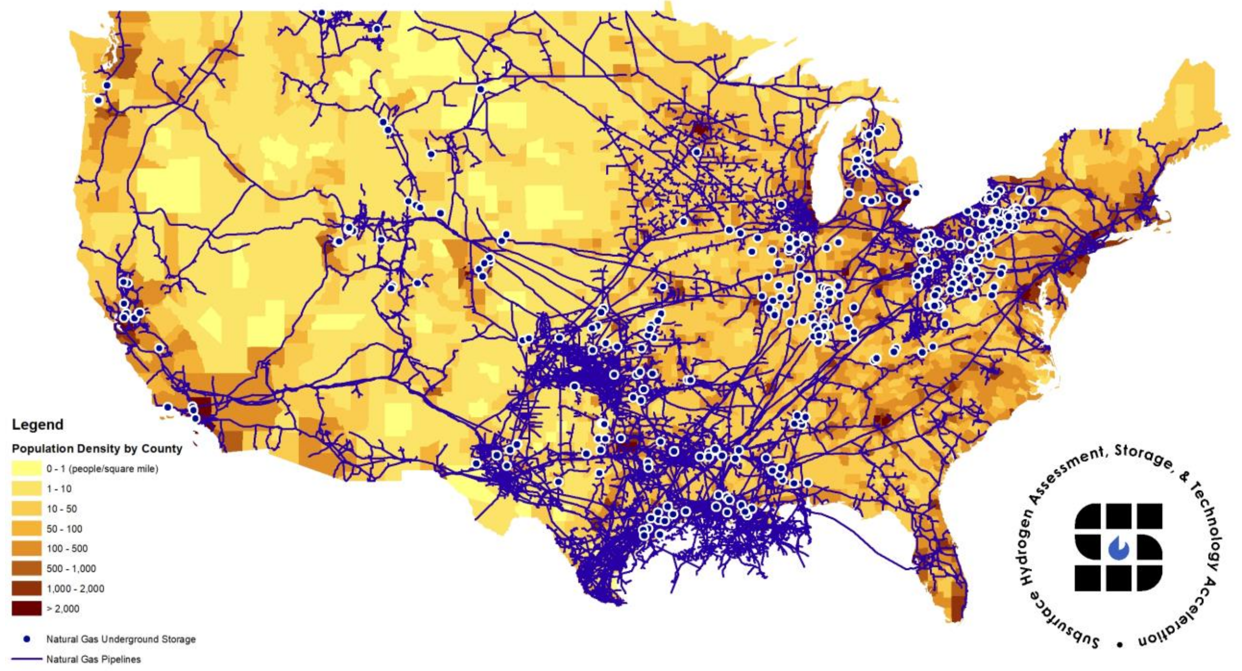

Figure S2. Distribution of existing UGS storage fields (blue circles with white outlines), NG distribution pipelines (blue lines), and proximity to major population densities (shaded from yellow to orange). (modified from [1]).

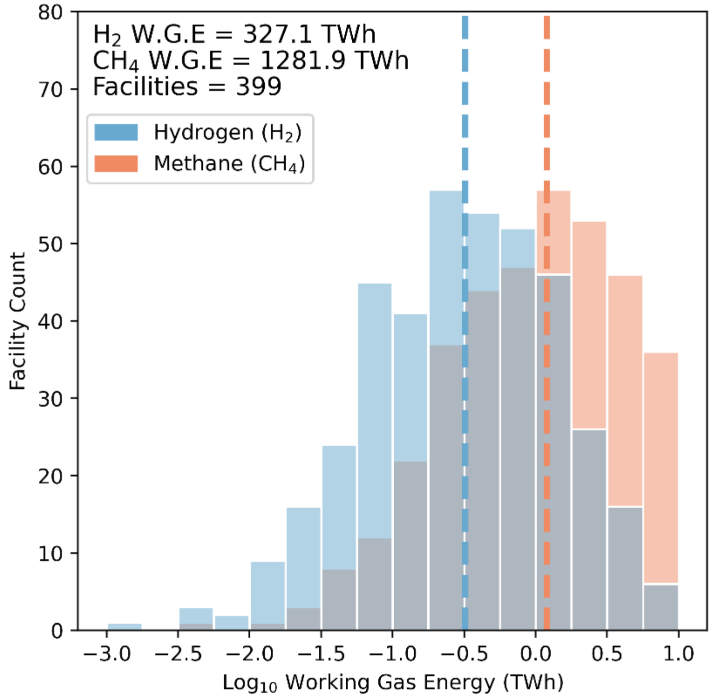

Figure S3. Histograms comparing the working gas energy (W.G.E) of individual U.S. UGS facilities for pure methane (CH_4) and pure hydrogen (H_2) storage scenarios. The median of each histogram is also shown as a dashed line. Overlap between the two histograms is shown in gray. A log base 10 scale is used for clarity of presentation.

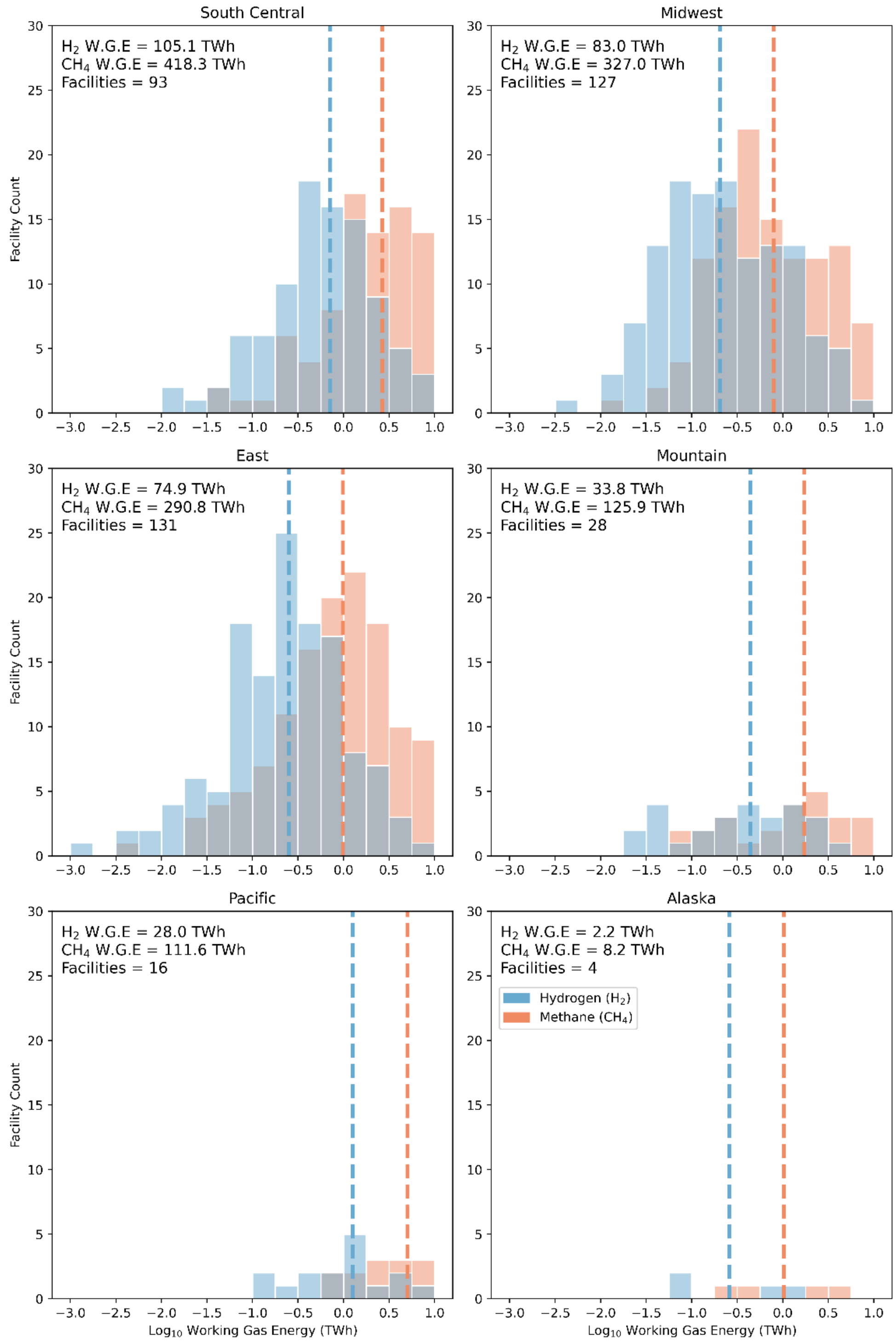

Figure S4. Histograms comparing the working gas energy (W.G.E) of individual U.S. UGS facilities for pure methane (CH_4) and pure hydrogen (H_2) storage scenarios categorized by U.S. Energy Information natural gas storage region. Overlaps between the histograms are shown in gray. The median of each histogram is also shown as a dashed line. A log base 10 scale is used for clarity of presentation.

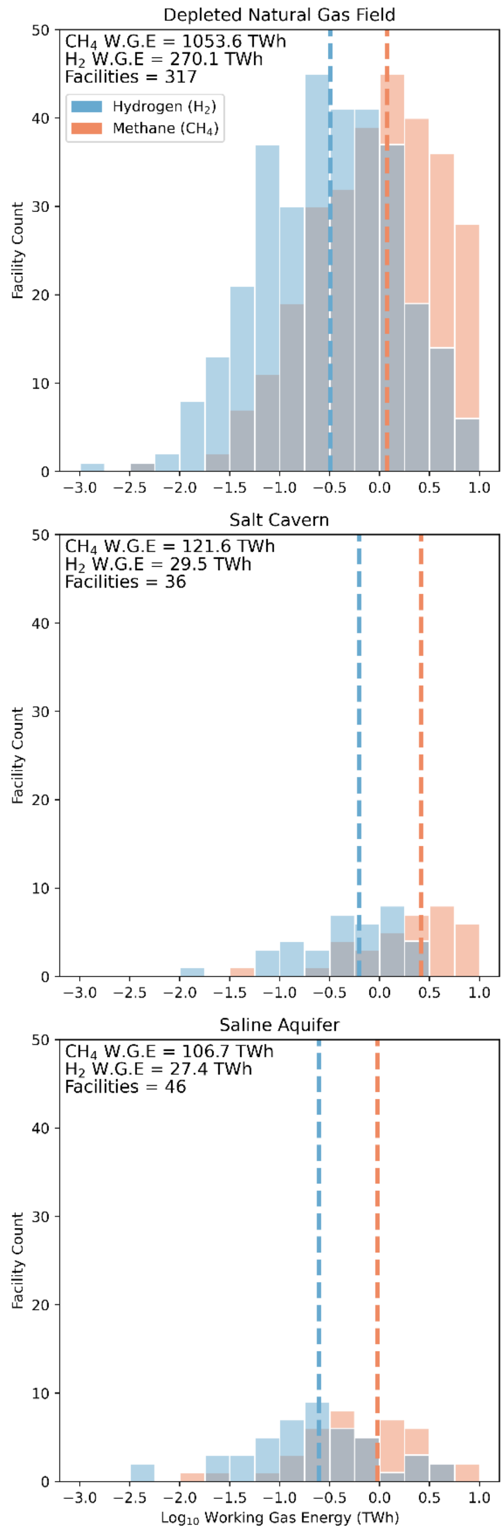

Figure S5. Histograms comparing the working gas energy (W.G.E) of individual U.S. UGS facilities for pure methane (CH_4) and pure hydrogen (H_2) storage scenarios categorized by storage reservoir type. Overlaps between the histograms are shown in gray. The median of each histogram is also shown as a dashed line. A log base 10 scale is used for clarity of presentation.

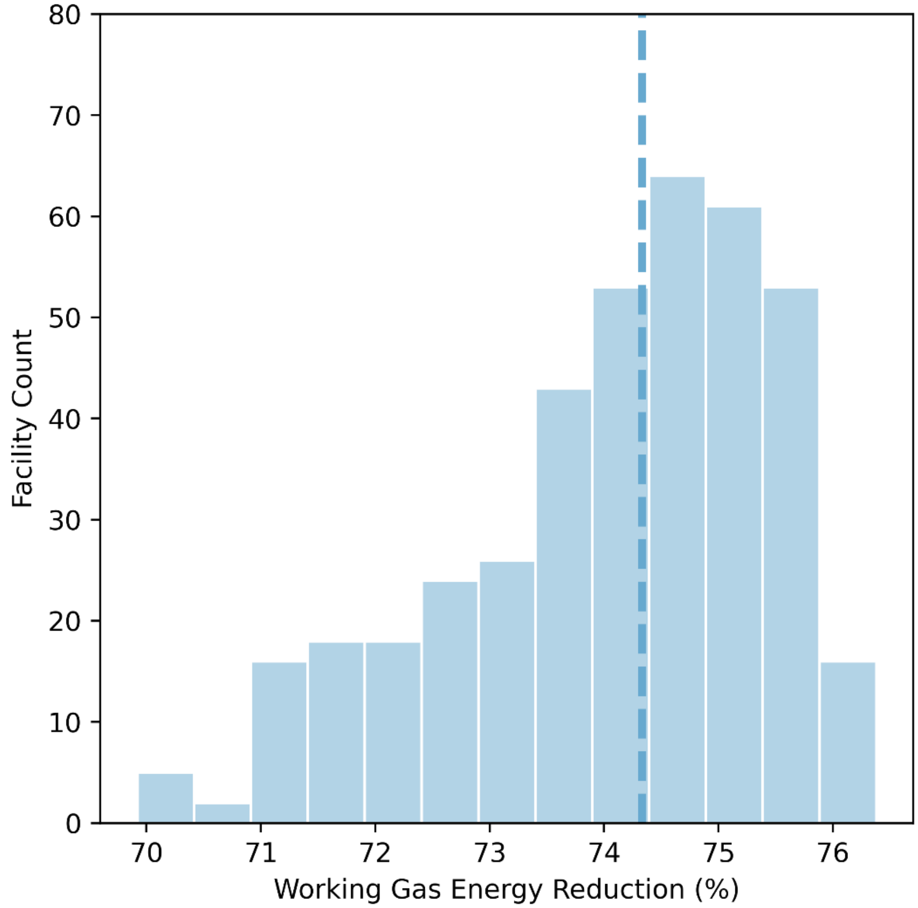

Figure S6. Histogram showing the percent reduction in working gas energy of individual U.S. UGS facilities that results from a transition to pure hydrogen (H_2) storage. The median of the population is shown as a dashed line.

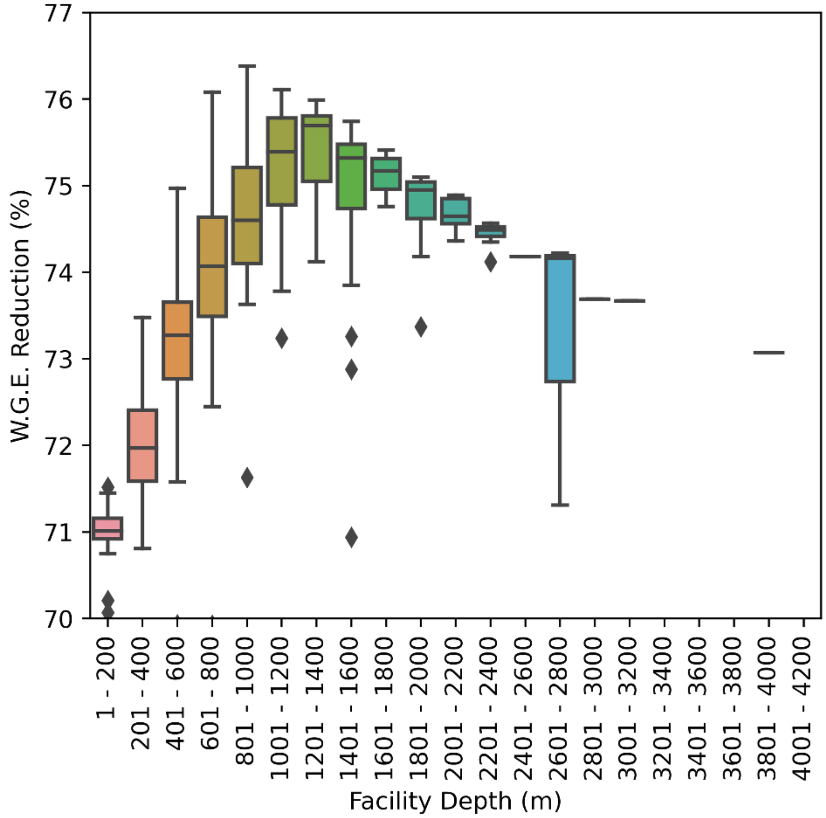

Figure S7. Box plots showing the distribution of the percent reduction in working gas energy of U.S. UGS facilities that results from a transition to pure hydrogen (H_2) storage grouped by reservoir depth.

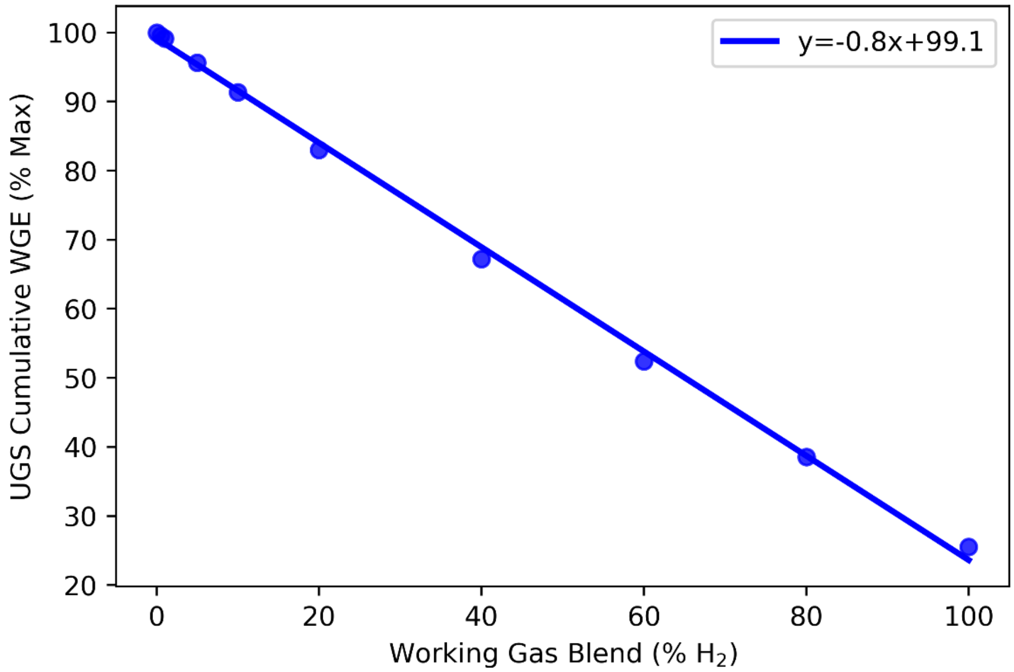

Figure S8. Total U.S. UGS Facility working gas energy (WGE) as a percentage of the maximum U.S. UGS facility WGE vs. the % H_2 in working gas.

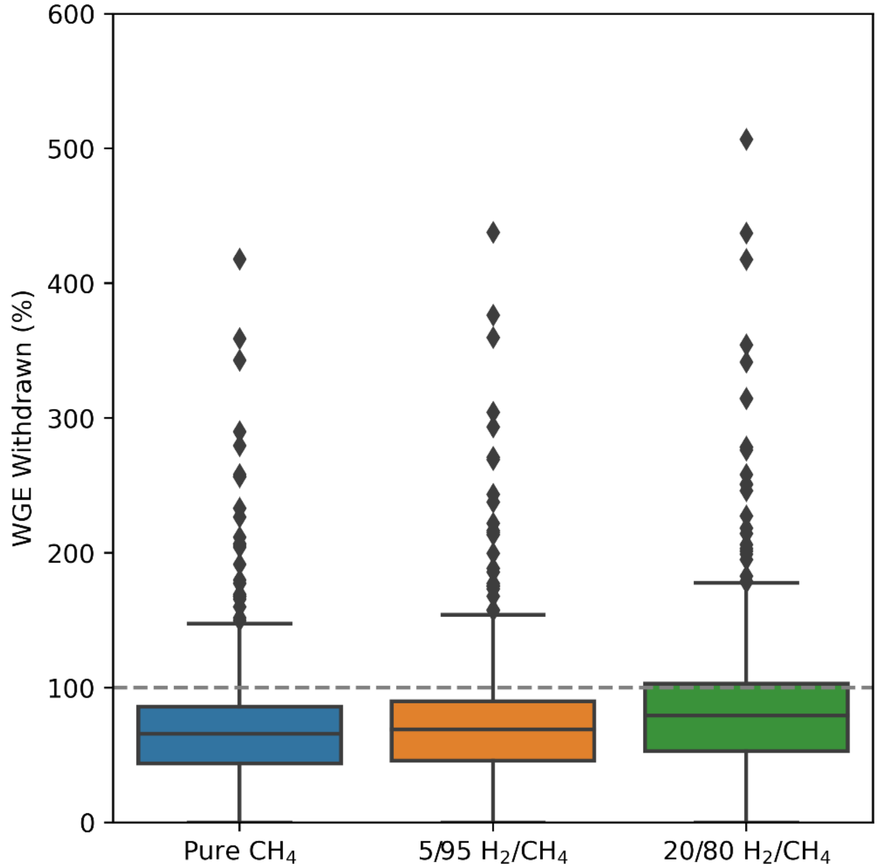

Figure S9. Box plots showing the distribution of the percentage of working gas energy (WGE) withdrawn from individual UGS facilities for pure CH_4, 5/95 H_2/CH_4, and 20/80 H_2/CH_4 working gas scenarios.

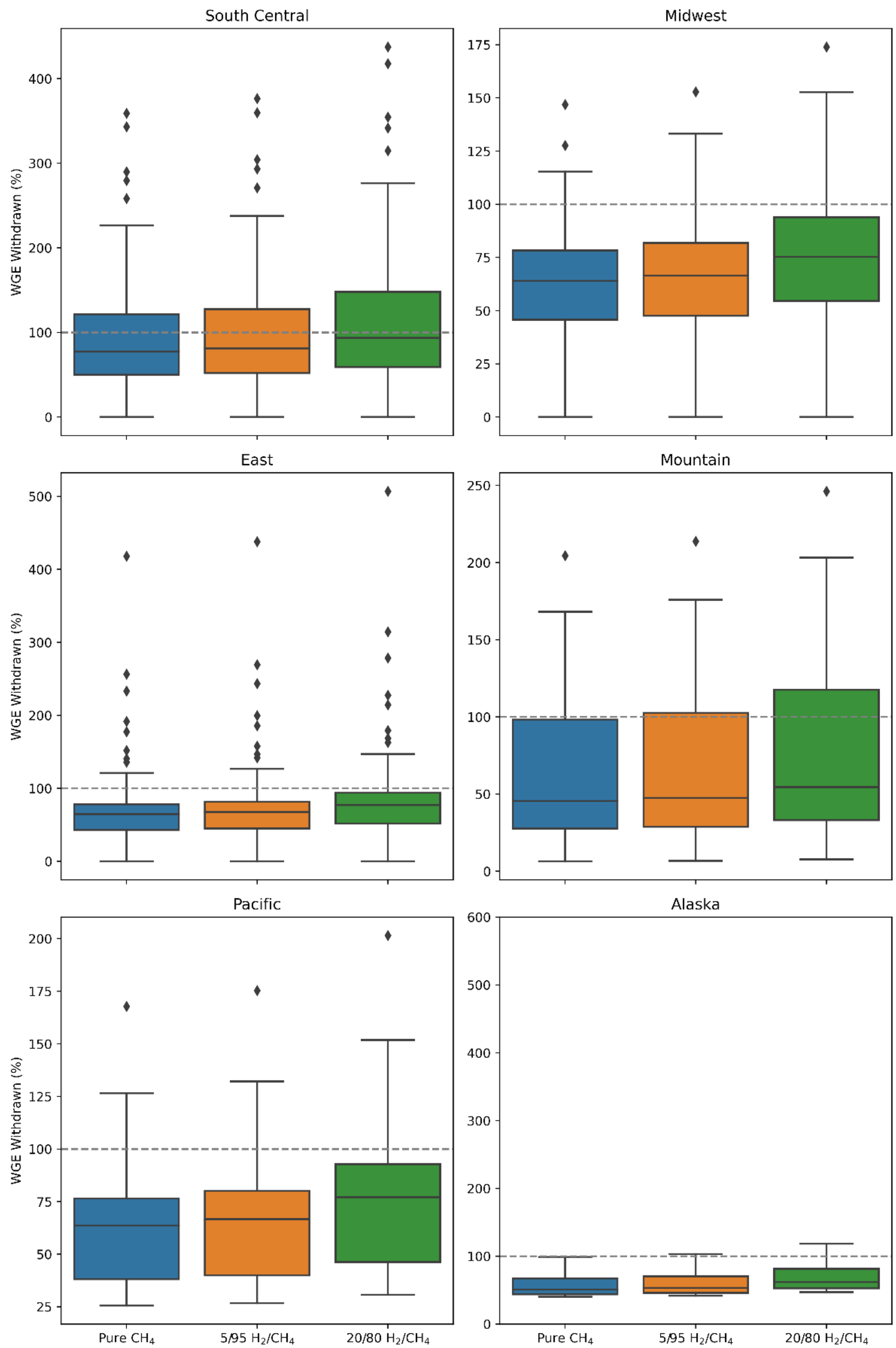

Figure S10. Box plots showing the distribution of the percentage of working gas energy (WGE) withdrawn from individual UGS facilities for pure CH_4, 5/95 H_2/CH_4, and 20/80 H_2/CH_4 working gas scenarios grouped by region.

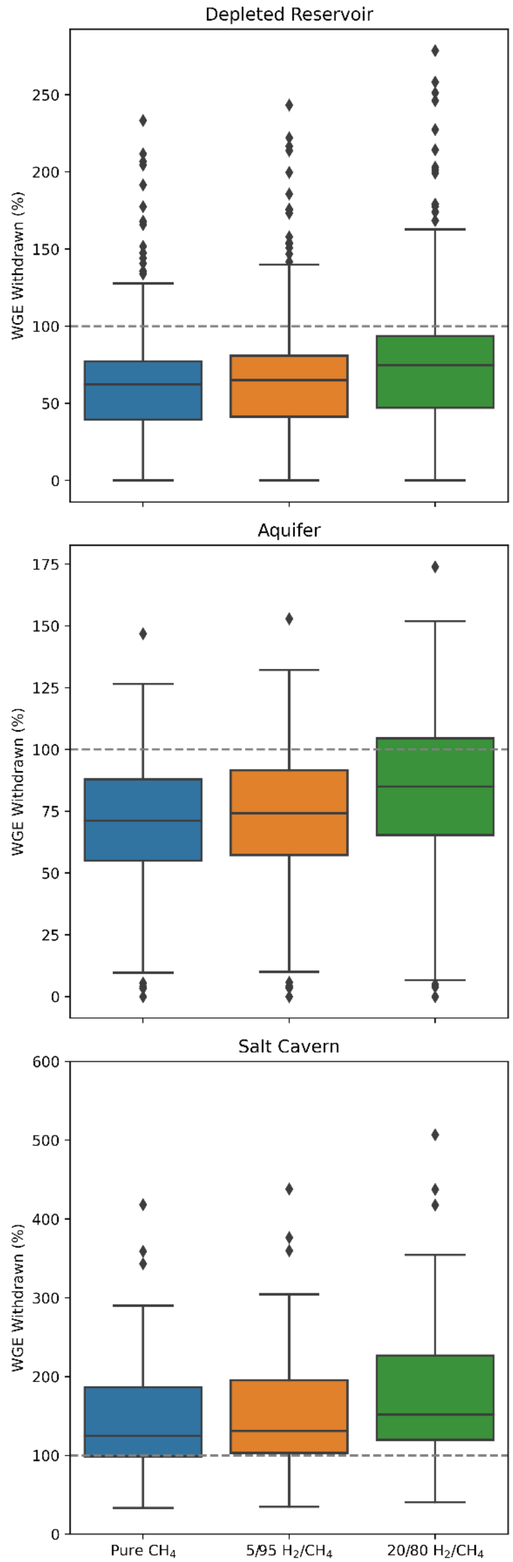

Figure S11. Box plots showing the distribution of the percentage of working gas energy (WGE) withdrawn from individual UGS facilities for pure CH_4, 5/95 H_2/CH_4, and 20/80 H_2/CH_4 working gas scenarios grouped by storage reservoir type.

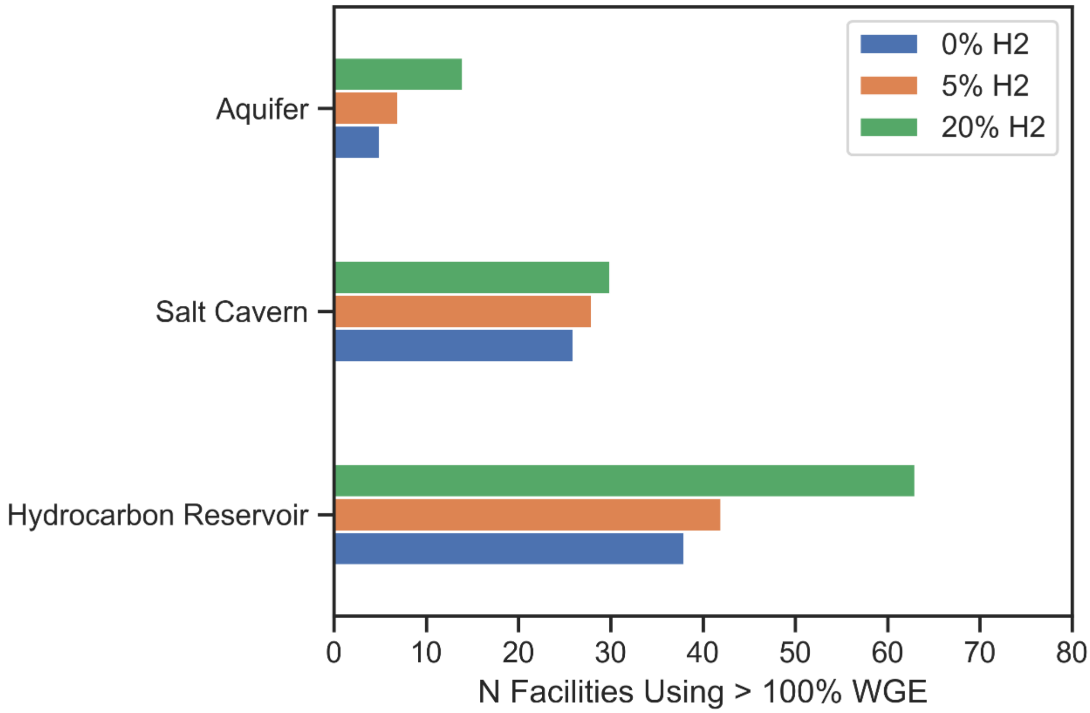

Figure S12. The number of UGS facilities with an energy demand greater than 100% of their working gas energy for pure CH_4 (0% H_2), 5/95 H_2/CH_4 (5% H_2), and 20/80 H_2/CH_4 (20% H_2) storage scenarios grouped by reservoir type.

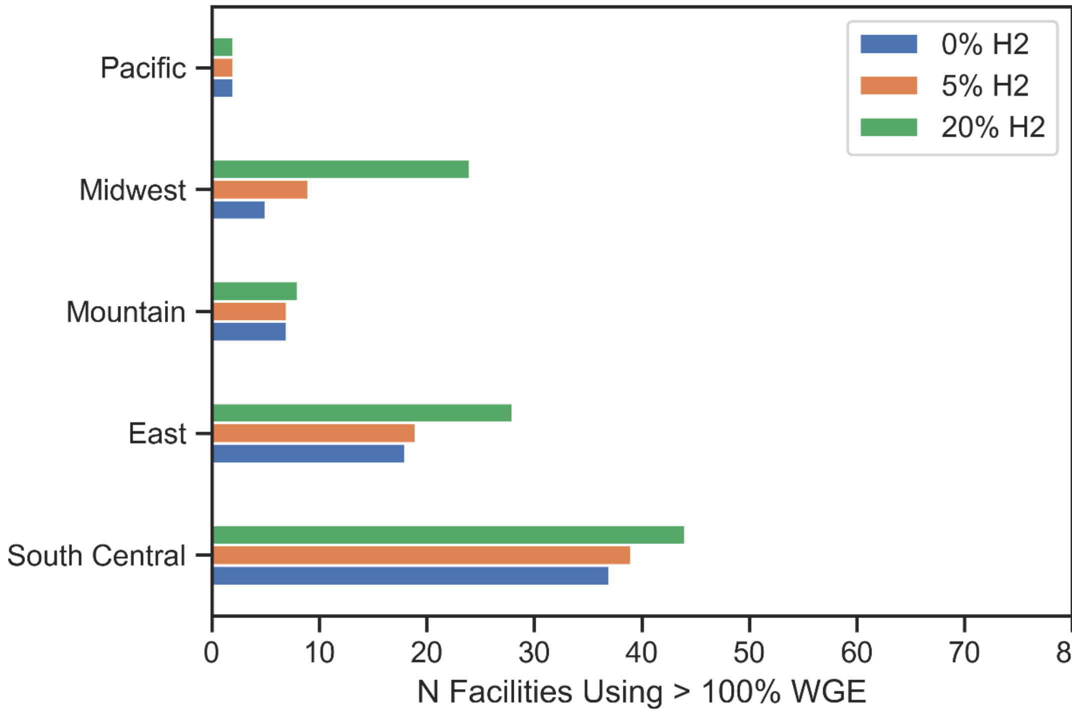

Figure S13. The number of UGS facilities with an energy demand greater than 100% of their working gas energy for pure CH_4 (0% H_2), 5/95 H_2/CH_4 (5% H_2), and 20/80 H_2/CH_4 (20% H_2) storage scenarios grouped by U.S. EIA natural gas storage region.

Table S1. Statistical summary of the percentage of working gas energy reduction from a transition to pure H_2 storage at U.S. UGS facilities grouped by depth.

Depth Range	count	mean	std	min	25%	50%	75%	max
1 - 200	13	71.0	0.4	70.1	70.9	71.0	71.2	71.5
201 - 400	43	72.0	0.6	70.8	71.6	72.0	72.4	73.5
401 - 600	56	73.1	0.9	69.9	72.8	73.3	73.7	75.0
601 - 800	75	74.0	1.0	69.9	73.5	74.1	74.6	76.1
801 - 1000	49	74.7	0.9	71.6	74.1	74.6	75.2	76.4
1001 - 1200	39	75.2	0.7	73.2	74.8	75.4	75.8	76.1
1201 - 1400	26	75.4	0.5	74.1	75.1	75.7	75.8	76.0
1401 - 1600	39	74.9	1.0	70.9	74.7	75.3	75.5	75.7
1601 - 1800	14	75.1	0.2	74.8	75.0	75.2	75.3	75.4
1801 - 2000	14	74.8	0.5	73.4	74.6	75.0	75.0	75.1
2001 - 2200	17	74.7	0.2	74.4	74.6	74.7	74.9	74.9
2201 - 2400	7	74.4	0.2	74.1	74.4	74.5	74.5	74.6
2401 - 2600	1	74.2		74.2	74.2	74.2	74.2	74.2
2601 - 2800	3	73.2	1.7	71.3	72.7	74.2	74.2	74.2
2801 - 3000	1	73.7		73.7	73.7	73.7	73.7	73.7
3001 - 3200	1	73.7		73.7	73.7	73.7	73.7	73.7
3201 - 3400	0							
3401 - 3600	0							
3601 - 3800	0							
3801 - 4000	1	73.1		73.1	73.1	73.1	73.1	73.1
4001 - 4200	0							

Table S2. Statistical summary of the percentage of working gas energy currently withdrawn at U.S. UGS facilities.

% WGE Withdrawn	N facilities	Mean	Std	min	25%	50%	75%	Max
0% H2	399	72.1	51.9	0.0	43.9	65.9	85.9	418.2
5% H2	399	75.4	54.4	0.0	45.9	69.0	89.9	438.0
20% H2	399	86.8	63.0	0.0	53.0	79.4	103.1	507.0

Table S3. Statistical summary of the percentage of working gas energy currently withdrawn at U.S. UGS facilities grouped by U.S. EIA natural gas storage region.

Region	N facilities	Mean	Std	min	25%	50%	75%	Max
WGE Used (0% H2)								
Alaska	4	60.2	26.6	40.2	43.8	50.9	67.3	98.8
East	131	68.3	50.8	0.0	43.1	64.7	78.2	418.2
Midwest	127	61.0	27.2	0.0	45.7	64.0	78.3	146.9
Mountain	28	64.6	51.8	6.4	27.6	45.5	98.2	204.5
Pacific	16	67.4	36.8	25.6	38.1	63.6	76.4	167.8
South Central	93	96.3	71.9	0.0	49.9	77.4	121.5	359.1
WGE Used (5% H2)								
Alaska	4	62.9	27.9	41.7	45.8	53.3	70.4	103.2
East	131	71.4	53.2	0.0	45.0	67.5	81.7	438.0
Midwest	127	63.7	28.4	0.0	47.6	66.5	81.9	152.9
Mountain	28	67.6	54.2	6.7	28.8	47.5	102.6	213.8
Pacific	16	70.6	38.5	26.7	39.9	66.6	80.1	175.3
South Central	93	100.8	75.4	0.0	52.0	81.0	127.4	376.5
WGE Used (20% H2)								
Alaska	4	72.3	32.2	47.1	52.7	61.8	81.4	118.6
East	131	82.1	61.4	0.0	51.8	77.2	94.0	507.0
Midwest	127	73.0	32.5	0.0	54.5	75.3	93.9	173.9
Mountain	28	77.7	62.6	7.7	33.2	54.5	117.6	246.2
Pacific	16	81.4	44.2	30.7	46.3	77.1	92.8	201.5
South Central	93	116.5	87.7	0.0	59.2	93.6	148.0	437.4

Table S4. Statistical summary of the percentage of working gas energy currently withdrawn at U.S. UGS facilities grouped by storage reservoir type.

Reservoir Type	count	mean	std	min	25%	50%	75%	max
% WGE Withdrawn (0% H2)								
Aquifer Reservoir	46	69.1	32.1	0.0	55.0	71.1	87.9	146.9
Hydrocarbon Reservoir	317	63.2	37.7	0.0	39.5	62.3	77.3	233.3
Salt Cavern	36	154.6	93.8	33.3	98.5	124.9	186.3	418.2
% WGE Withdrawn (5% H2)								
Aquifer Reservoir	46	72.2	33.5	0.0	57.3	74.2	91.6	152.9
Hydrocarbon Reservoir	317	66.0	39.4	0.0	41.4	65.0	81.0	243.4
Salt Cavern	36	162.1	98.4	34.9	103.2	131.0	195.3	438.0
% WGE Withdrawn (20% H2)								
Aquifer Reservoir	46	82.8	38.6	0.0	65.4	85.0	104.5	173.9
Hydrocarbon Reservoir	317	75.8	45.3	0.0	47.1	74.8	93.6	278.6
Salt Cavern	36	188.4	114.3	40.4	119.7	152.0	226.7	507.0

Table S5. The number of UGS facilities that will have a demand that exceeds 100% of their WGE if a 5/95 H_2/CH_4 or 20/80 H_2/CH_4 blend is used grouped by region and reservoir type.

Region	Reservoir Type	5% H2	20% H2
Alaska	Hydrocarbon Reservoir	1	1
East	Hydrocarbon Reservoir	1	10
Midwest	Aquifer Reservoir	2	9
Midwest	Hydrocarbon Reservoir	1	9
Midwest	Salt Cavern	1	1
Mountain	Hydrocarbon Reservoir	0	1
South Central	Hydrocarbon Reservoir	1	4
South Central	Salt Cavern	1	3
Total		8	38

SI References

1 Goodman, A. *et al.* Subsurface Hydrogen and Natural Gas Storage: State of Knowledge and Research Recommendations Report 77 (National Energy Technology Laboratory: Morgantown, WV, 2022).