**Feasibility of Hydrogen Storage**

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**Abstract**

There is a growing demand for cleaner energy in the United States and across the globe, i.e. moving away from a reliance on fossil fuels. According to U.S. Energy Information Administration (EIA) our sources of energy include petroleum (35%), Natural Gas (34%), renewable energy (12%), coal (10%), and nuclear (9%). While Natural Gas is relatively clean burning, it still will need to be replaced in an effort to meet the increasingly net-zero carbon demands. This discussion has been the catalyst for Energy Providers to understand if Hydrogen can be the energy source of the future. This project compared Natural Gas to Hydrogen in terms of storage medium availability and gas properties. This analysis provided the data needed to quantitatively model the gases to show technical and economic feasibility.

Currently, Natural Gas is stored underground in domal salt, bedded salt, depleted reservoirs and depleted aquifers; infrastructure and business model are in place for the transmission and use of Natural Gas. Because the thermodynamic properties of Natural Gas and Hydrogen differ, it takes three times the amount of Hydrogen to provide the same amount of energy as Natural Gas. This means a greater cost for the Operator and thus the end consumer.

Simulation modeling of gas properties, expert interviews, qualitative and quantitative analyses revealed that an initial return on investment is estimated to be 160.8%/year for Hydrogen Gas Storage. It was recommended to continue storing Natural Gas but to invest in research and development of Hydrogen, which include technical feasibility in storage mediums other than domal salt along with infrastructure and transmission needs and cost to move from Natural Gas to Hydrogen. The expertise in the fossil fuel industry paves the way for a cleaner future for the Energy Industry.

**Definition of Terms**

Cavern net size is expressed in units of million barrels (mmbbls). The net size defines the amount of void space inside the cavern.

Total capacity is defined as the total volume of gas needed to fill the cavern to maximum pressure. Total capacity is equal to the sum of base gas plus working gas.

Base gas is defined as the volume of gas that must remain in the cavern to maintain minimum pressure gradients.

Working gas is defined as the volume of gas within a cavern that can be withdrawn or injected into the cavern. Working gas is profitable. It is sold in units of energy (million btu per standard cubic feet, MMbtu/scf).

**Background/Introduction**

## Storage

The storage of energy is a crucial factor in the business of selling energy. The fossil fuel portion of the energy industry provides the most power to consumers. According to the Energy Information Agency (EIA), fossil fuels make up 60% of energy provided. Currently Natural Gas is the most environmentally friendly fossil fuel and is used to power electrical plants, homes and various other industries. Natural Gas Storage has provided, on average, 3,464 bcf of gas between 2016-2020 (EIA). This is what helps to supply the energy demand in the United States; 34% of which is provided by Natural Gas (EIA). This is done by storing Natural Gas in domal salt, bedded salt, depleted reservoirs and depleted aquifers.

## Underground Storage

Underground storage has been a business for many years. Today, depleted reservoirs, depleted aquifers, bedded salt and domal salt are used to store Natural Gas. Domal salt, however, is also used to store other energy carriers including oil, liquid Natural Gas (LNG) and Hydrogen. Prior to storing each energy carrier, a cavern must be created within the salt dome. This is done by drilling a well into the salt formation then a cavern is leached using freshwater which reacts with the salt to create brine. The brine is withdrawn by injecting the energy carrier into the cavern, forcing the brine to surface which is stored in brine ponds and/or saltwater disposal wells. The result of this process is the creation of a void space in which the energy carrier (oil, Natural Gas, LNG, Hydrogen) can be stored.

## Hydrogen Properties

Hydrogen is the lightest element on the periodic table. It has a density is 1/8 that of Natural Gas. On a molecular level, Hydrogen is 4 times smaller than a Natural Gas molecule. Additionally, Hydrogen has a higher compressibility factor compared to Natural Gas (greater than 1). This means that as Hydrogen is compressed it will occupy space less efficiently than Natural Gas. This is important because pressure increases with depth. Thus, Hydrogen will store less efficiently than Natural Gas. In other words, three times more Hydrogen is needed to provide the same amount of energy as Natural Gas. The thermodynamic properties of each gas define these major differences and help to determine how each gas will behave. These properties are show in Table 1, from Minas et al. (2013). The compositions of each gas were assumed to be 100% methane for Natural Gas and 100% Hydrogen for Hydrogen gas. This table is integral to the understanding of Natural Gas and Hydrogen Gas behaviors.

Table 1. Gas Properties

|  |  |  |
| --- | --- | --- |
| **Properties** | **Hydrogen** | **Natural Gas** |
| Gas Density (lbm/ft³) | 0.00531 | 0.0424 |
| Atomic Radius (pm) | 25 | 95 |
| Dynamic Viscosity (lbm/ft \* 3) | 5.86E-06 | 7.24E-06 |
| Compressibility Factor | 1.001 | 0.998 |
| Net Heating Value (Btu/lbm) | 51586.212 | 21525.407 |
| Net Heating Value (Btu/ft³) | 273.943 | 912.034 |
| Joule-Thompson Coefficient (°F/psia) | -0.00349 | 0.058 |
| Thermal Conductivity (Btu/h \* ft \* °F) | 0.101 | 0.0189 |
| Isobaric Heat Capacity (Btu/lbm \* °F) | 3.411 | 0.528 |
| Flammability Rangy by Volume (%) | 4 - 74 | 5 - 15 |

*\*Table 1 Properties of Hydrogen and Natural Gas Compared*   
\*Note: pm = 1 x 10-12 m.

## Hydrogen Production

Hydrogen does not exist freely in the atmosphere; it is always found with other elements such as water, H2O and methane, CH4. Hydrogen production is the process of separating Hydrogen from other elements. Each type of production is given a color. The color represents the method used to produce the Hydrogen as well as the environmental impact. The most common method is steam methane reforming, SMR coupled with a water-gas shift reaction, WGS. While the least common method is the utilization of electrolysis. The term grey Hydrogen indicates SMR plus WGS with a release of CO2 to atmosphere. Blue Hydrogen indicates SMR plus WGS with the sequestration and storage of CO2. Green Hydrogen indicates the use of electrolysis powered by renewable resources to produce Hydrogen which has no harmful byproduct, see Figure 1. Table 2 and Figure 2 show the differences among the types of Hydrogen production

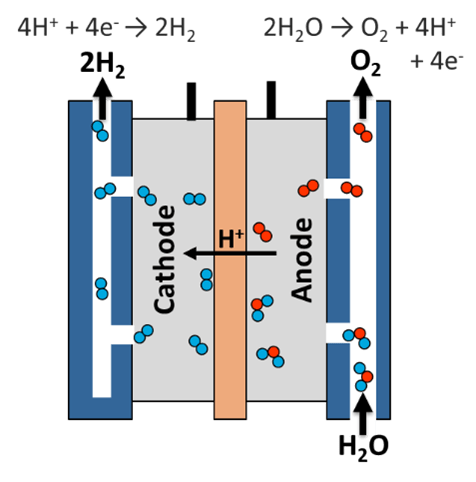


Figure.Electrolysis.

Table 2. Types of Hydrogen Production



Timeline

Description automatically generated

Figure . Hydrogen production graphic.

## Hydrogen Economics

They type of Hydrogen production correlates to profitability as each has a different cost. According to Earth.org (Shin, 2020), green Hydrogen cost USD $3 to $7.50 per kg while grey Hydrogen cost $0.90 to $3.20 per kg. The aspect of cost also must consider the cost to develop a salt cavern for storage. According to Lord et al. (2014), the cost of developing a salt cavern is just over 60 million USD which translates to $1.60 per kg. The cost of Hydrogen and cost of storage development explain why the most widely used Hydrogen production method is grey followed by blue with green as the least used method.

**Literature Review**

## Underground Storage Considerations for Hydrogen

The storage of gases underground has been researched extensively. The interest in underground Hydrogen storage has increased as the discussion around cleaner energy takes hold. There have been various publications that detail the design and transport criteria, risks and design considerations.

Tarkowski (2019) publication details the various types of storage mediums to consider for Hydrogen storage and details the **pro et contra** (pros and cons) for each type of storage. This publication proposes salt cavern storage as the dominant storage medium since it is proven for Hydrogen. The use of depleted reservoirs, aquifers and bedded salt pose much greater risk given the properties of Hydrogen. The risk associated with hydrocarbon storage in bedded salt is discussed at length in the Daemen et al. (2013) publication. It is concluded that there is increased leakage risk with bedded salt as compared to domal salt or other storage mediums. In the Amid et al. (2016] publication, storage of Hydrogen in depleted reservoirs and depleted aquifers is evaluated in comparison to Natural Gas storage in terms of working gas, base gas and technical considerations. The Ozarslan (2012) publication discusses the proven ability to store Hydrogen in domal salt caverns.

The publication by Panfilov (2016) details the threats surrounding the behavior of Hydrogen within a storage medium and incorporates the risk discussion regarding the use of pipeline to transport Hydrogen. The determination is there is a significant difference between the Natural Gas reaction with formation compared to Hydrogen in a depleted reservoir and depleted aquifer including: chemical reactions with surrounding formation, gas loss to the formation, and potential leakage rate. In addition, pipeline infrastructure as a means of transporting Hydrogen is discussed and concludes a better understanding of metallurgical constraints and leakage potential are needed.

The salt cavern design for Hydrogen was discussed in Minas & Skaug (2021) where the emphasis was on the properties of Hydrogen and the resulting effect on metallurgical design for the construction of salt cavern wells for Hydrogen storage. The publication by Nieland (2008) compares the salt cavern design among Hydrogen, Natural Gas and compressed air in order to determine the amount of working gas versus base gas for each type of gas stored. It concludes with a comparison of which type of gas has the greatest amount of working gas per storage capacity; Natural Gas has the greatest amount of working gas followed by compressed air with Hydrogen having the least amount of working gas.

## Hydrogen Transportation Considerations

An aspect of Hydrogen storage that must be considered in the transportation of the gas. The capability to store Hydrogen is just as important as the capability to transport the Hydrogen to market. Cowell et al. (2020) provide insight into the metallurgical challenges as well as a decrease in pipeline deliverability that would occur as a result of Hydrogen being introduced into the pipeline; the greater the amount of Hydrogen, the greater the effects on metallurgy and deliverability. Additionally, Hydrogen and Fuel Cell Technologies Office (2021) reviews the current state of pure Hydrogen pipelines and determines a conversion of Natural Gas Hydrogen pipelines to pure Hydrogen pipelines would be extremely challenging. This would require more research and understanding before projects of such magnitude could become a reality.

## Applications of Hydrogen

There are multiple opportunities to grow the use of Hydrogen in the energy sector. These uses and their financial implications has been studied and published. Weeda & Ball (2016) discuss reliance on fossil fuels being unsustainable when considering predicted population growth from now to 2050. The solution for this is the increased use of renewable resources, specifically Hydrogen for fueling cars and providing power through electrolysis to enhance the overall power provided by renewable resources.

Ballotpedia (2021) reviews the history of environmental policies in the United States from the 1970s to current time. In this 50-year history there has been incremental increase of renewable resources as part of tax incentives. In more recent years, there has been a change from tax incentives being the only driver to enforceable environmental regulation driving implementation of renewable resources as well.

Nguyen& Schwartz (2021) provide a financial model of the potential market for using the excess power from wind turbines to produce Hydrogen through electrolysis and store it in salt caverns. In turn, the Hydrogen can be used for power generation during periods of inactive wind activity.

Frey et al. (2021) model the use of Hydrogen and Natural Gas blend to meet the demand for cleaner energy. This publication also compares current salt cavern storage for Natural Gas as a baseline to compare Natural Gas alone versus a blend of Hydrogen and Natural Gas. Frey et al. (2021) also discusses the transportation constraints and how this affects the use of Hydrogen and Natural Gas blend.

**Methodology**

## Research Design

This project consists of both qualitative and quantitative research to determine the feasibility of underground Hydrogen storage. The qualitative portion consists of research, conferences, workshops, interviews, and interpretive analysis. The quantitative method used was modeling. The purpose of the modeling was to demonstrate the following and use those results to complete the interpretive analysis portion of the qualitative methodology. This will be done by researching and analyzing the methods of Hydrogen production, infrastructure requirements, metallurgy considerations, storage mediums (i.e. domal cavern, bedded salt, depleted reservoir, depleted aquifer), and ability to convert Natural Gas storage to Hydrogen storage. Finally, the cost associated with Hydrogen storage will be analyzed and comparative modeling used to determine Hydrogen storage feasibility. Specifically:

1. Volume of Hydrogen that can be stored in a cavern at a given pressure and temperature.
2. Volume of Natural Gas that can be stored in a cavern at a given pressure and temperature
3. Volume of Hydrogen working gas and base gas available at given pressures and temperatures.
4. Volume of Natural Gas working gas and base gas at given pressures and temperatures
5. Amount of energy available in Natural Gas cavern versus Hydrogen gas cavern

In Figure 3 a broad view of a salt dome is shown with small schematics of leached caverns. In Figure 4, a basic cavern schematic is shown with the casing shoe labeled. The gas volume is measured by reading pressure on the casing shoe then converting that pressure to a gas volume. The integrity of the cavern depends on operating within the pressure range allowed between base gas (minimum pressure) and maximum capacity (base gas plus working gas). Salt dome caverns vary in size and shape and thus the volume of base gas and working gas will differ. However, the minimum and maximum pressure gradients are the same. The recommended pressure gradients are defined in API 1170 Section 9.1 (American Petroleum Institute).

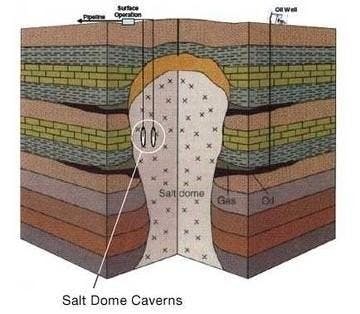


Figure . Salt dome.

Graphical user interface, application, PowerPoint

Description automatically generated

Figure . Basic salt dome cavern schematic.

Graphical user interface

Description automatically generated with medium confidence

Figure . 3D view of salt caverns.

## Participants

The participants included Subject Matter Experts via interviews as well as assistance with developing the quantitative model. These participants have a collective 70 years in the energy industry.

## Instruments

The qualitative instruments consist of research papers, interviews, workshop presentations, conference presentations and graphical data for interpretive analysis.

The quantitative instrument is a data simulation model that allows for the input of gas properties needed to calculate the amount of gas available in an underground storage cavern given various thermodynamic properties.

## Procedure

Gas properties and calculation assumptions were input into the simulation model. The model then calculated total gas capacity, working gas capacity and base gas capacity for Hydrogen gas cavern model and Natural Gas cavern model. The results were collected and input into a tables and graphs for interpretive analysis of the qualitative methodology.

This procedure was repeated for three different scenarios: shallow depth cavern, medium depth cavern and deep depth cavern. Each scenario had 3 iterations to model various cavern sizes along with the depths. The scenarios demonstrate the behavioral differences of Hydrogen and Natural Gas at different pressures. This is important for the determination of working gas volumes and thus profitability.

## Data Modeling

### Quantitative Modeling

The model is based on the formula PV = znRT

P - pressure

V – volume

z – compressibility factor for the given gas

n – amount of gas

R – ideal gas constant

T - Temperature (Fahrenheit)

There are assumptions built into the model. These assumptions are gas compositions, method for calculating z factor and method for calculating bottom hole pressure (bhp). The model used assumed AGA8 method for calculating compressibility factor, z as defined in AGA 8 of American Gas Association, 2003. The cullender smith method was used for calculating bottom hole pressure as described in Natural Gas Reservoir Engineering (Ikoku, 1992). The gas compositions assumed were:

* Hydrogen gas composition:
  + H2: 100%
* Natural Gas composition\*
  + C1: 94.920%
  + N2: 0.285%
  + CO2: 0.966%
  + C2: 3.522%
  + C3: 0.223%

(\*Note: In this gas composition the IC4, NC4, IC5, NC5, C6, C7, C8 and C9 make up 0.084% of the composition. This brings the total to 100%)

Additional assumptions are listed below. Their purpose is to have an “all else equal” baseline in order to narrow the focus on the difference in gas behavior and those affects. This means given all costs and cavern parameters equal.

* Transportation
* Pipeline Infrastructure
* Surface Facility Infrastructure
* Market Availability
* Cavern Depths
* Cavern Net Size
* Casing Shoe Depth
* Cavern Roof Depths
* USD Gas Price $3.72/MMBtu (NASDAQ 2021 Natural Gas Cavern Average)

There were 3 scenarios with 3 iterations for each scenario. Scenario one is the shallowest of the caverns with a casing shoe depth of 2000 feet, the cavern roof depth was 2100 feet and a total depth of 3500 feet. In Scenario 2 the casing shoe depth what is 3000 feet, the cavern roof depth was 3100 feet and the total cavern depth of the cavern was 4500 feet. In the third scenario, the casing shoe depth was 4000 feet, cavern roof was 4100 feet and the total depth of the cavern was five 5500 feet. Each scenario had three iterations run. The iterations compared cavern size differences at the scenario depths. The net size for iteration one was a 6 million barrel cavern, iteration two was an 8 million barrel cavern and iteration three was a 10 million barrel cavern. These iterations and scenarios are found in *Table 3*.

Table 3. Quantitative Modeling Scenarios and Iterations



The parameters and assumptions were input into the model for both Natural Gas composition assumption and Hydrogen gas composition assumption. The resulting calculation gave total gas capacity, base gas capacity and working gas capacity in units of billion cubic feet (bcf). These capacities are shown in *Table 4*.

Table 4. Quantitative Modeling Scenarios and Iterations Results



The working gas capacities were then converted to million btu per standard cubic feet (MMBtu/scf) to compare the energy content between Natural Gas and Hydrogen. The results of the conversion are found in *Table 5*. The conversion formula for bcf to MMBtu is as follows:

* Natural Gas = 1030 btu/scf
* Hydrogen gas = 325 btu/scf
* Therm = 100,000 BTU
* Deka = 10
* Dekatherm = 10\* 100,000 BTU = 1 million BTU
* 1.030 million btu = MCF of Natural Gas = 1.030 Dekatherms
* Hydrogen = 0.325 million BTU or 0.325 Dekatherm

Table 5. Working Gas to Energy Content Conversion Results



The results of the model were used in the interpretive analysis of the qualitative portion of the methodology.

### Qualitative: Interpretive Analysis

The interpretive analysis used working gas capacity differences between Natural Gas and Hydrogen gas. The results of the model show there is less working gas in Hydrogen gas caverns than Natural Gas caverns for each iteration of each scenario. Additionally, Hydrogen has 1/3 less energy content than Natural Gas as shown in the energy content conversion. This means the Natural Gas profit margin is greater than Hydrogen. In *Figure 2* the assumption of equal market for Natural Gas and Hydrogen was assumed. The average 2021 market for Natural Gas was $3.72 MMBtu/scf. There is a clear difference in profit.

Figure .Natural gas vs. hydrogen profit.

In addition to this profit difference, three times more Hydrogen is needed to provide the same amount of energy as Natural Gas. Currently, there is not enough underground storage available to replace Natural Gas with Hydrogen. This is inferred because the only proven underground storage for Hydrogen is salt dome caverns as discussed in the Literature Review of this paper. While Natural Gas is stored in salt dome caverns, bedded salt caverns, depleted reservoirs, and depleted aquifers. This means, even if the profit were equal, the availability to provide the required energy that is in current demand would not be possible with Hydrogen. The underground storage of Natural Gas is still a necessity.

The results of the model require a return to the assumptions. Specifically, transportation, pipeline infrastructure and market conditions which would impact market. If Hydrogen gas were to replace Natural Gas the additional cost incurred to update current infrastructure to meet the needs of Hydrogen. It can be inferred that cost of Hydrogen would increase on the end of the consumer. This would create an even greater profit margin between Hydrogen and Natural Gas thus strengthening the results of the original model.

**Return on Investment**

The ROI investment for this project is compared between Hydrogen Gas Storage and Natural Gas Storage. There are two cases reflected for ROI. The values reflected for ROI consider a previously developed domal salt storage cavern storage facility which includes 4 storage caverns.

## Cost of Investment

The yearly maintenance cost in this project estimates the cost of one mechanical integrity test (MIT), yearly subsidence report, yearly inventory logging, yearly maintenance logging and yearly regulatory fees that total $990,000.00.

Further costs include facility maintenance and pipeline maintenance each with a yearly cost of $6,250,000 totaling $12,500,000.00.

Noble inhouse labor is estimated to be $2,000,000 per year to support the planning and overall execution of the above stated O&M work. This cost includes salary and overall benefits package.

Table 6. Cost of Investment Summary

|  |  |
| --- | --- |
| **Cost of Investment** |  |
| **Cavern Mechanical Integrity Test (MIT)** | **$120,000** |
| **Cavern Subsidence Reports** | **$50,000** |
| **Cavern Inventory Logging** | **$150,000** |
| **Regulatory Fees** | **$20,000** |
| **Cavern Maintenance Logging** | **$650,000** |
| **Facility Maintenance** | **$6,250,000** |
| **Pipeline Maintenance and Inspection** | **$6,250,000** |
| **Labor** | **$2,000,000** |
| **Total:** | **$15,490,000** |

## Net Return on Investment

For this project, the numbers reflected assume Hydrogen Gas has the same market value as Natural Gas Storage which is $3.72 MMBtu/scf according to NASDAQ 2021 average. It is also assumed that all working gas is sold for each cavern.

Table 7. Net Return on Investment Summary

|  |  |  |
| --- | --- | --- |
| **Net Return on Investment** | **Hydrogen (MMBtu/scf)** |  |
| **Cavern 1** | **0.76** | **$2,840,000** |
| **Cavern 2** | **1.27** | **$4,740,000** |
| **Cavern 3** | **2.22** | **$8,270,000** |
| **Cavern 4** | **2.43** | **$9,060,000** |
|  | **Total:** | **$24,910,000** |
| **Net Return on Investment** | **Natural Gas (MMBtu/scf)** |  |
| **Cavern 1** | **3.13** | **$11,630,000** |
| **Cavern 2** | **5.21** | **$19,390,000** |
| **Cavern 3** | **9.63** | **$35,810,000** |
| **Cavern 4** | **9.76** | **$36,310,000** |
|  | **Total:** | **$103,140,000** |

In the case of Hydrogen Gas Storage, considering a Cost of Investment of $15,490,000.00 and a Net Return on Investment of $24,910,000.00, an initial Return on Investment each year is estimated to be 160.8%.

In the case of Natural Gas Storage, considering a Cost of Investment of $15,490,000.00 and a Net Return on Investment of $103,140,000.00, an initial Return on Investment each year is estimated to be 665.8%.

**Recommendations and Conclusion**

It is shown in the results that ROI is significantly higher for Natural Gas Storage than Hydrogen Gas Storage. This ROI did come with the assumption that the market for Hydrogen and Natural Gas are equivalent as well as the infrastructure needs being equivalent. Additionally, the storage medium utilized was domal salt caverns since it is the only proven method for Hydrogen Gas.

Given the assumptions, it is recommended that Natural Gas Storage continue to be stored and sold for energy needs. It is also recommended that a percentage of revenue be dedicated to research into capital development and cost associated with

1. Facility Infrastructure
2. Pipeline Infrastructure
3. Depleted Reservoir Storage
4. Hydrogen production technology

The storage of Hydrogen gas with the purpose of replacing Natural Gas will not be feasible financially or technically until it is cheaper to produce green Hydrogen, the infrastructure needs are more thoroughly understood and there are more available methods of storage. These cumulative factors must align for Hydrogen Gas Storage to be profitable for an Operator.

This project was able to model Natural Gas and Hydrogen Gas at various depths and various cavern sizes. This modeling calculated working gas which showed to have a greater capacity with Natural Gas than Hydrogen in each scenario. In addition, the modeling showed the energy content for Hydrogen is 1/3 less than the energy content of Natural Gas. This proves that more Hydrogen is needed to provide the same amount of energy as Natural Gas. Thus, more storage space would be needed. This project concluded the only storage medium technically viable for Hydrogen Gas is domal salt. Thus, it was recommended to determine more sound storage spaces for Hydrogen. Additional recommendations were to invest in the future by taking a percentage of revenue and putting it toward research of infrastructure as well as green Hydrogen production. The funding of research is vital because there is a responsibility on the Operator to invest in the future which points toward an energy future that incorporates a higher percentage of renewable resources than is currently part of the energy business today. For the energy future to change, the cost staying as low as possible is vital to the overall feasibility.

These factors along with an estimated rate of return of 685.8% for Natural Gas compared to 160.8% for Hydrogen, lead to the recommendation that continuing to invest in the storage of Natural Gas while investing in a Hydrogen future is in the best interest of Operator and end user.

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