IIT GUWAHATI

MTP Phase-I: Hydrogen Storage Potential in Salt Caverns of Western Part of India

GUIDED BY:

Dr. Karuna Kalita

Professor

PRESENTED BY:

HARDIK DAVE

Roll No. 234103324

Outline

1. Introduction

- The widespread use of fossil fuels causes carbon emissions, leading to global warming and climate change. We must transition to renewable energy to reduce carbon emissions and limit global temperature rises to 1.5°C.
- However, the intermittent nature of solar and wind power limits large-scale renewable energy use.
- Converting renewable energy into hydrogen and storing it can address the intermittent nature of solar and wind power, enabling large-scale use

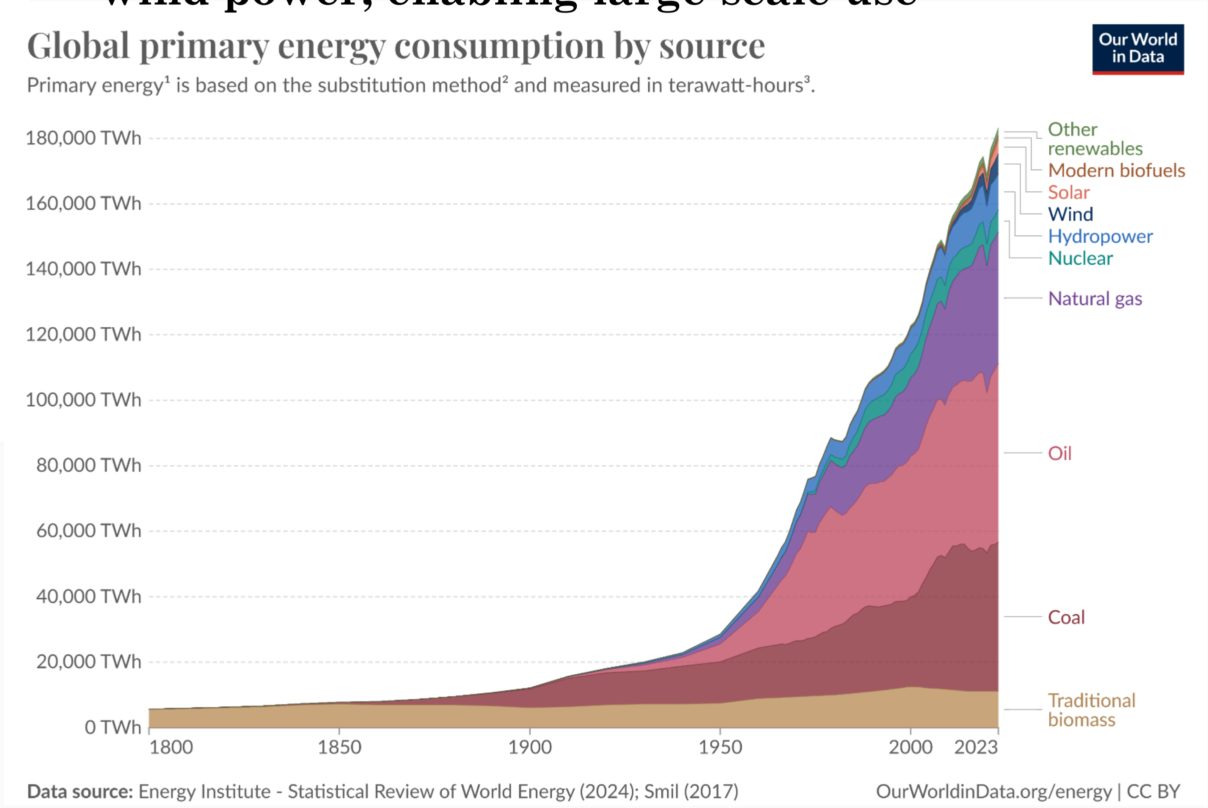


Fig 1: Global energy consumption [1]

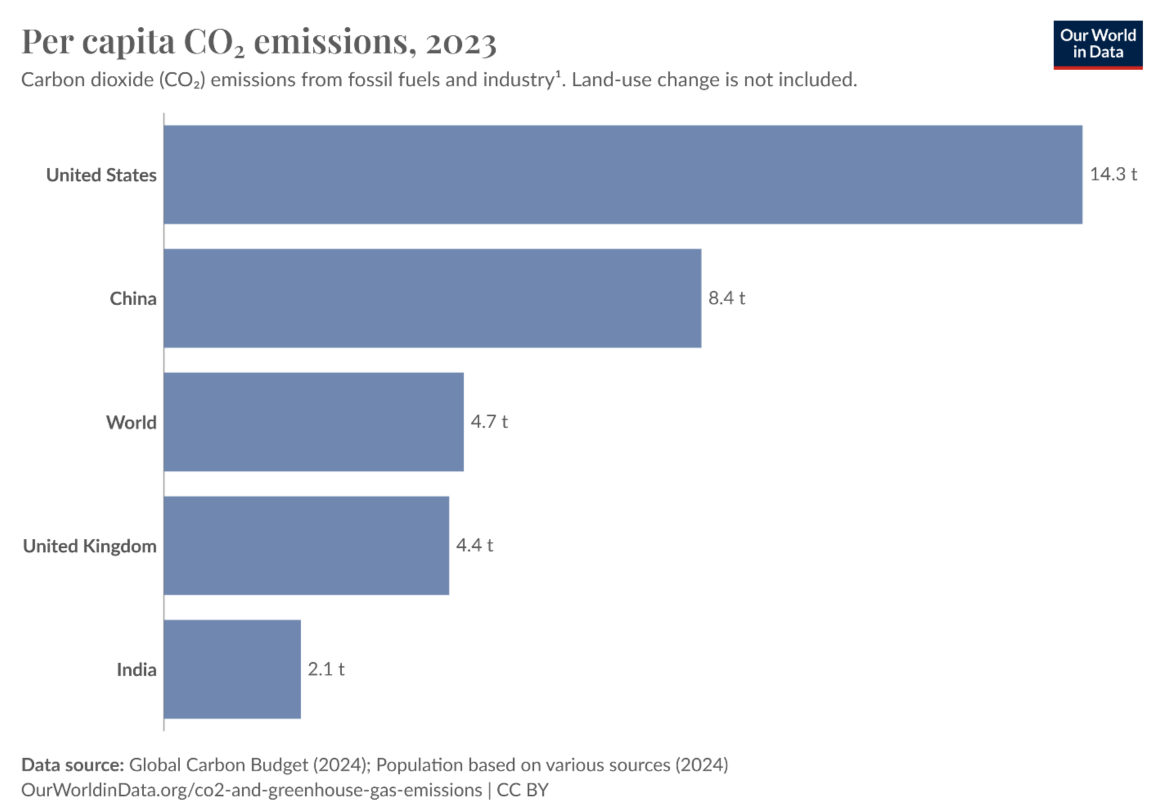


Fig 2: Global Carbon Emission [1]

i. Why Hydrogen?

Hydrogen is the richest in the energy per unit mass (LHV 120 MJ/kg).

Safer than other fuels, cleaner combustion product.

-Density: 0.08 kg/m^3 at NTP , Diffusivity 0.63 cm^{2}s^{-1}

	On Mass basis		On Volume basis
	On LHV basis	On HHV basis	Volumetric Density
Hydrogen	120 MJ/kg	142 MJ/kg	1.8 MJ/L @ 200 bar (ρ = 15 kg/m^3)
Methane	50 MJ/kg	55.6 MJ/kg	8.39 MJ/L @ 200 bar
LPG	46 MJ/kg	50 MJ/kg	26 MJ/L @ 5 bar
Gasoline	44 MJ/kg	47 MJ/kg	32 MJ/L @ NTP

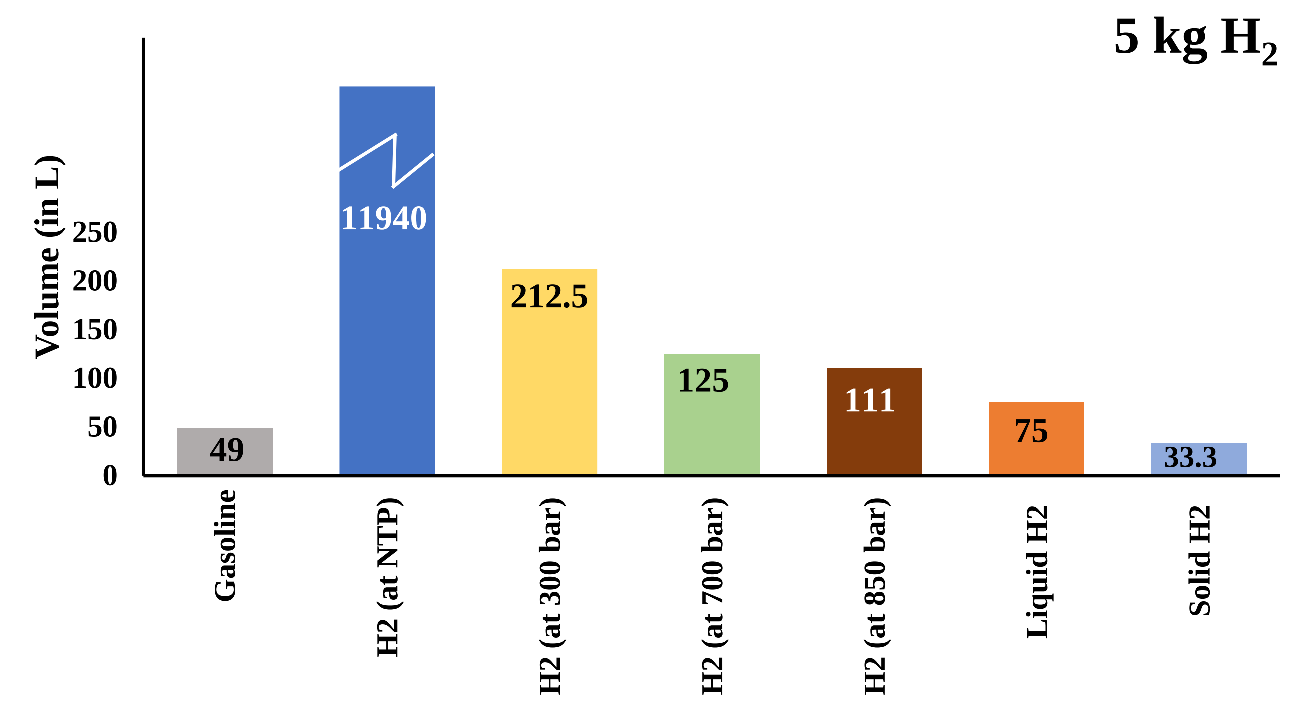


Fig 3. Volumetric comparison of Hydrogen with respect to Gasoline

For Hydrogen inversion temperature T is 202K at room temperature, μ_j of hydrogen is negative

➡ Cooling of gas is required during isenthalpic expansion

Because of low volumetric density, Large-scale Storage becomes economical to store hydrogen

ii. India’s Hydrogen Demand and National Green Hydrogen Mission

- ❑ Currently, India's hydrogen demand is approximately 6 million tonnes (MT) per year

- ❑ Hydrogen demand in India is projected to increase nearly fivefold, reaching approximately 28 million tons (MT) annually by 2050

❖ Key objective of National Green Hydrogen Mission for UHS

- ❑ To undertake research activities on underground storage to validate the performance in different geologies, to identify better and more cost-effective methods and to encourage improved designs.

- ❑ Demonstrate large-scale underground storage across various media at a capital cost lower than INR 3000 /kg by 2030.

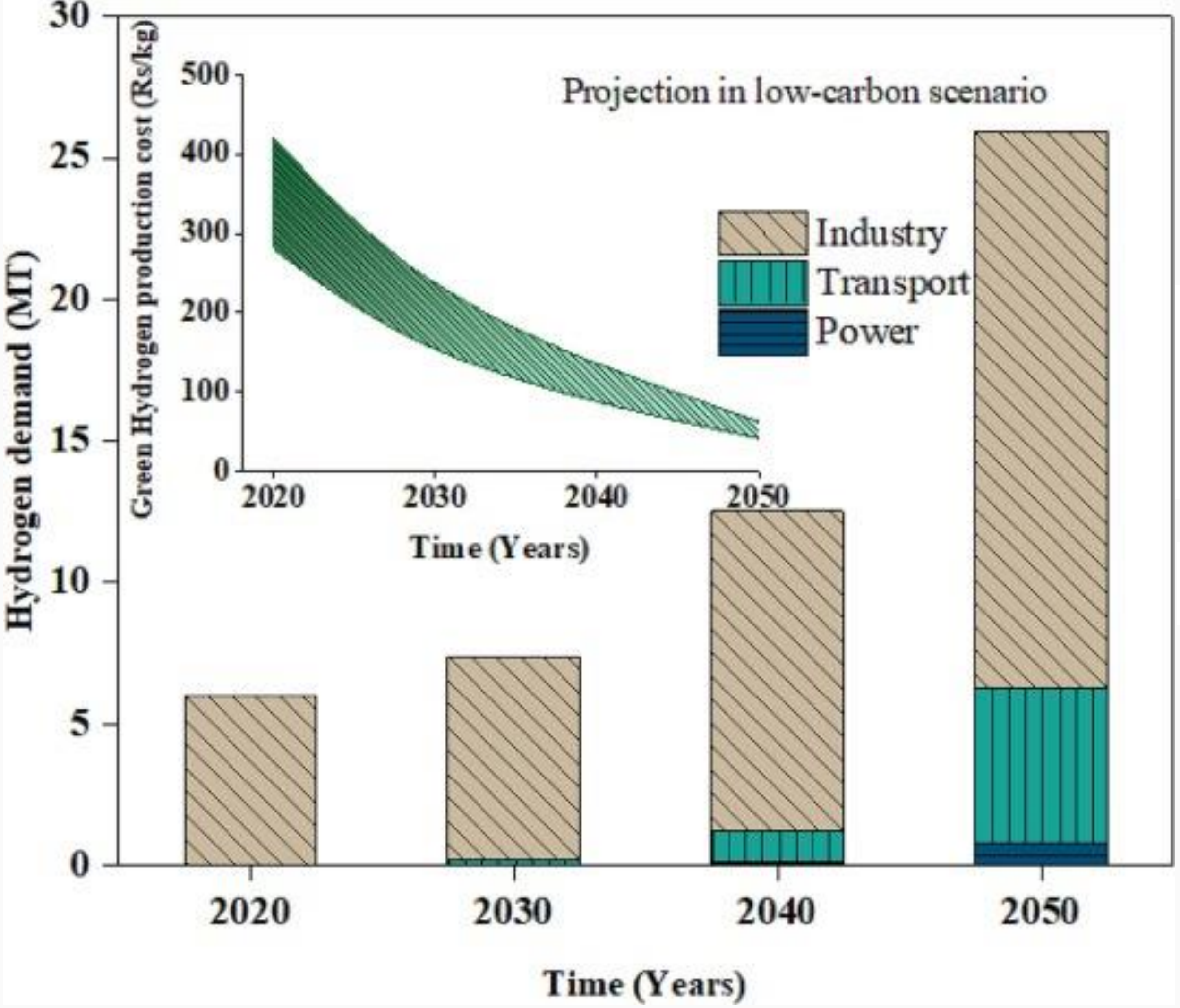


Fig 4 India’s hydrogen demand projection in low carbon scenario and production cost projection[2]

iii. Various methods of producing Hydrogen

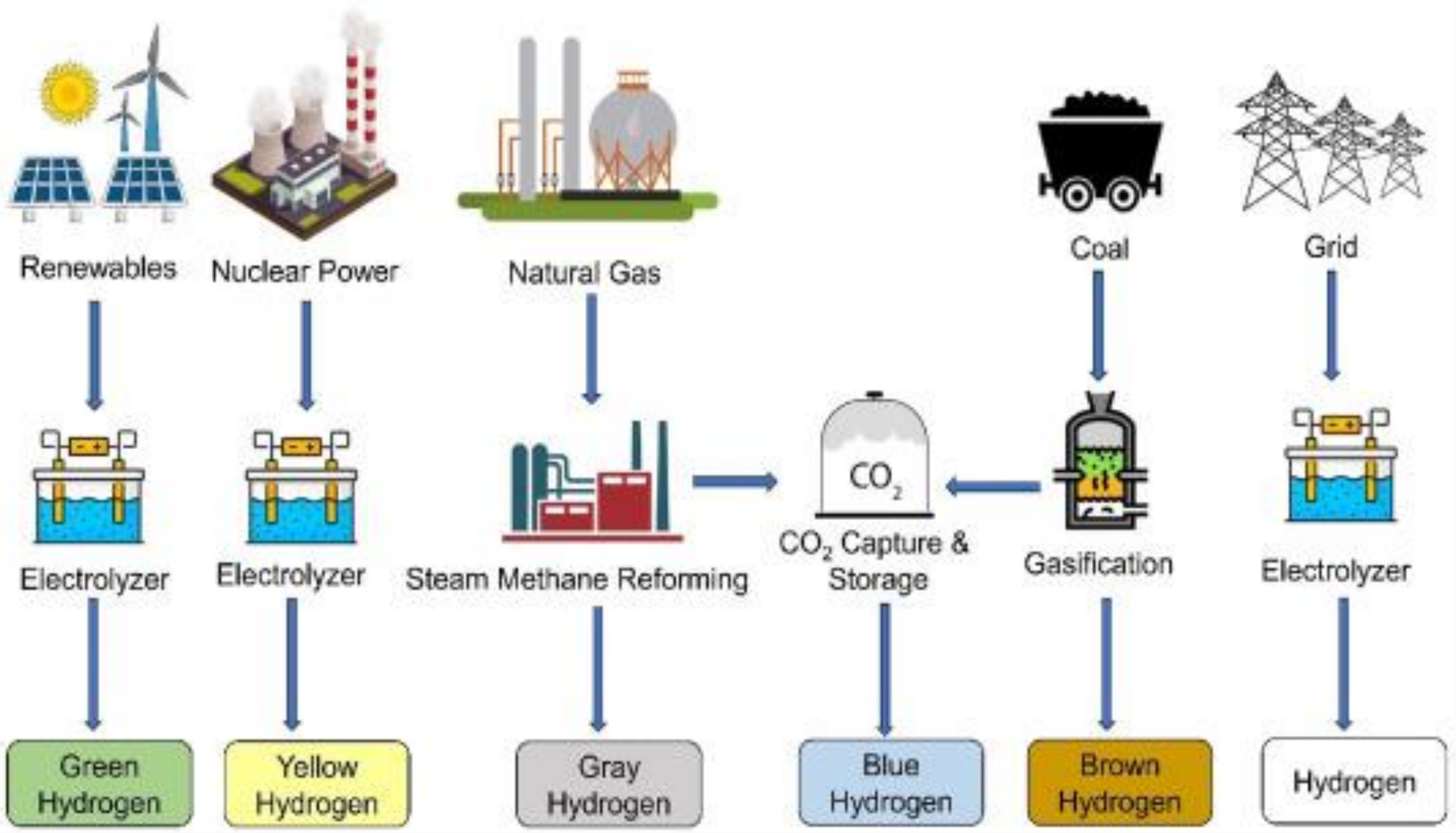
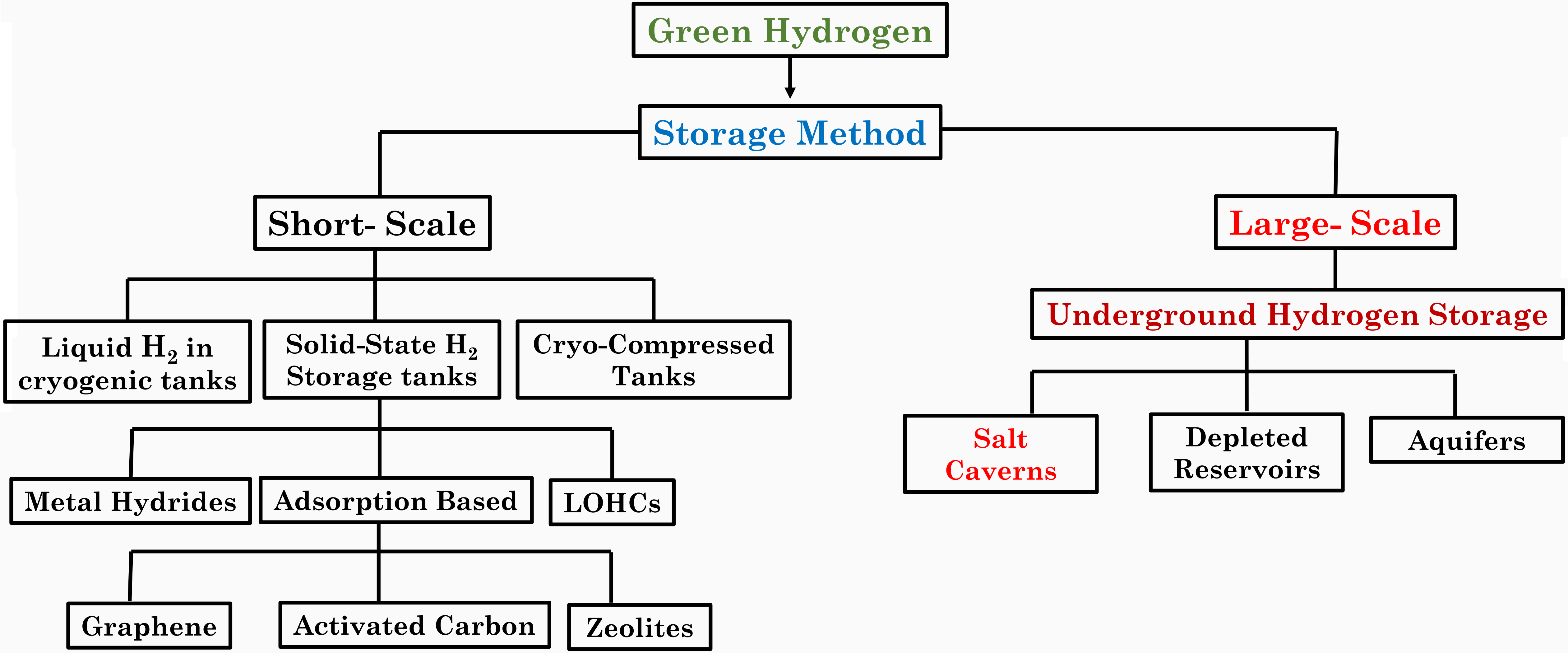


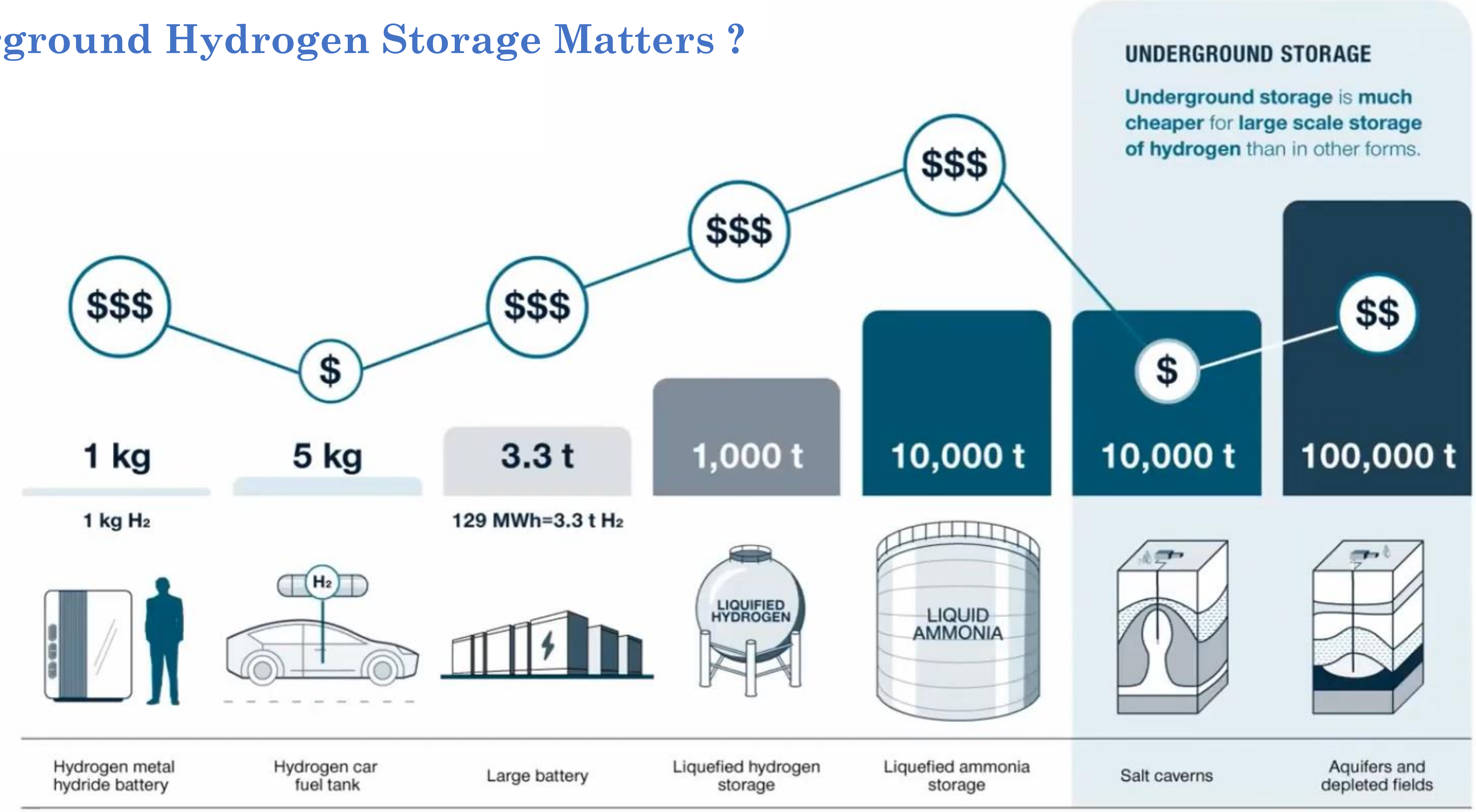
Fig 5. Various method of producing hydrogen [3].

iv. Various Storage Methods of Hydrogen



2. Motivation of Study

Why Underground Hydrogen Storage Matters ?



3. Literature Review

i. Why Salt Cavern?

Salt caverns are man-made artificial pits in thick underground salt deposits, mostly in cylindrical shape

- ➢ Salt caverns are created within salt deposits through a process known as solution mining.
- ➢ This method involves injecting fresh water into a well drilled into the salt rock.
- ➢ The water dissolves the salt, forming a brine solution, which is then extracted and pumped to the surface; this procedure is called leaching.
- ➢ As the brine is removed, it leaves behind a hollow space, forming a salt cavern.
- ✓ Once the leaching is completed and a desired shape is achieved, the brine is replaced with a cushion gas which may be nitrogen or natural gas.
- ✓ The cushion gas provides the minimum internal pressure required to maintain the integrity of the cavern.

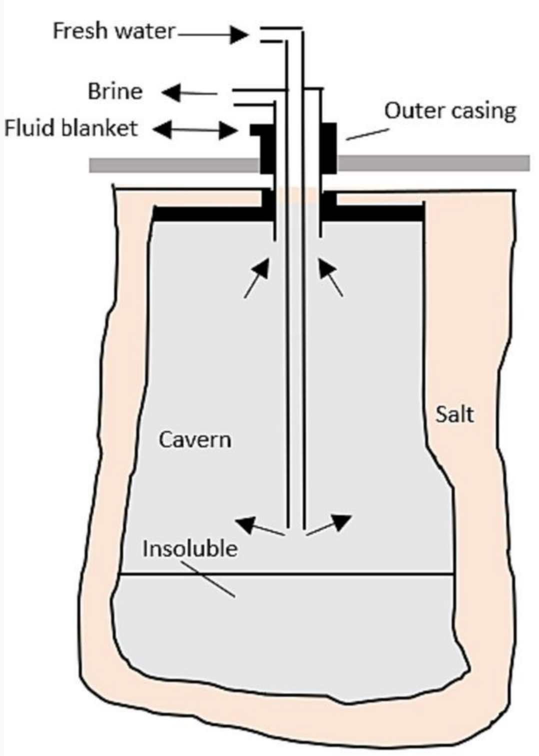


Fig 6. Solution mining process [4]

ii. Salt Cavern vs Aquifers vs Depleted Reservoirs

Parameters	Salt Caverns	Aquifers	Depleted Reservoirs
Geology rock type	Artificial pits in thick underground salt deposits, mostly cylindrical	Sandstones and conglomerates, Porous Media	Massive non-foliated metamorphic rocks, large sedimentary rocks
Availability	Particularly in Salt deposits	Found all over the world	Difficult
Depth range	Upto 2300 m	300-1800 m	300-2700 m
Storage capacity	Upto 10,00,000 m^3	upto 280 x 10^8 m^3	upto 280 x 10^8 m^3
Operating Pressure	35-270 bar	30–315 bar	15–285 bar
Cushion Gas Requirement	20-30%	50-60%	45-80%
Intial Cost	High	Average	Average
Operating Cost	Low	Average	Average
Gas Tightness	High	Low	High
Purity of Hydrogen	> 95%	Approx 50% reported in Czech Republic and France	Low
Usability purpose	Frequent	Seasonal	Seasonal

iii. Worldwide operated UHS sites

Country	Field	H_2 (%)	Working Condition	Depth (m)	Volume (m^3)	Status
Salt Caverns						
United Kingdom	Teesside	95	45 bar	365-430	210,000	Operating
USA	Clemens	95	70–137 bar	1000	580,000	Operating
USA	Moss Bluff	–	55–152 bar	1200	566,000	Operating
USA	Spindletop	95	68–202 bar	1340	906,000	Operating
Aquifers						
Czech Republic	Lobodice	50	90 bar/34 °C	430	Not reported	Operating
France	Beynes	50	Not reported	450	3.3×10^8	Operating with natural gas
Depleted Reservoirs						
Argentina	Diadema	10	10 bar/50 °C	600	Not reported	Operating
Austria	Underground Sun Storage	10	78 bar/40 °C	1000	Not reported	Operating

iv. Potential Sites for Underground Hydrogen Storage in India

Region	Type of Storage	Location	Depth (m)	Thickness (m)	Key Features	References
Bikaner-Nagaur-Ganganagar Basin	Salt Caverns	Northwestern Rajasthan, near Bikaner	500–750	Up to 200	High-purity halite (95–98%), favourable geomechanical properties near solar energy hubs.	C. Kumar et.al [5]
Rann of Kutch	Salt Caverns	Gujarat	300–600	Moderate	Salt flats with stable halite formations, located near industrial hubs and ports for hydrogen export.	S. Kumar et al. [2]
Cambay Basin	Salt Caverns, Depleted Reservoirs	Central Gujarat	Variable	Variable	Includes bedded salt formations and depleted hydrocarbon reservoirs, close to industrial zones.	S. Kumar et al. [2]

iv. Potential Sites for Underground Hydrogen Storage in India

Region	Type of Storage	Location	Depth (m)	Thickness (m)	Key Features	References
South Tapti Gas Field	Depleted Hydrocarbon Reservoirs	Mumbai Offshore Basin	Variable	Stacked sandstone layers	First study on UHS in offshore Indian depleted gas fields Total gas reservoir volume: 110 BCF, potential hydrogen storage capacity of ~37 million kg.	R. Kiran et al.[6]
Krishna-Godavari Basin	Depleted Hydrocarbon Reservoirs	Andhra Pradesh, eastern coast	1,500–3,000	High porosity	First study on hydrogen storage in both saline aquifers and oil/gas reservoirs in southeastern India. Cauvery Basin: 43.6 MT of H2, KG Basin: 47.2 MT of H2 in saline aquifers, and ~725 MT in gas reservoirs.	P. Nikhil et al. [7]

4. Research Gap & Problem Statement

- First and Foremost study related to UHS in Salt Caverns in Indian Context

- Our research primarily focuses on answering three questions

✓ Determine the volumetric storage capacity of the salt cavern in the Bikaner-Nagaur Ganganagar basin.

✓ Determine the cyclic injection and extraction (IE) process of hydrogen in salt caverns, investigating Injection and withdrawal rates.

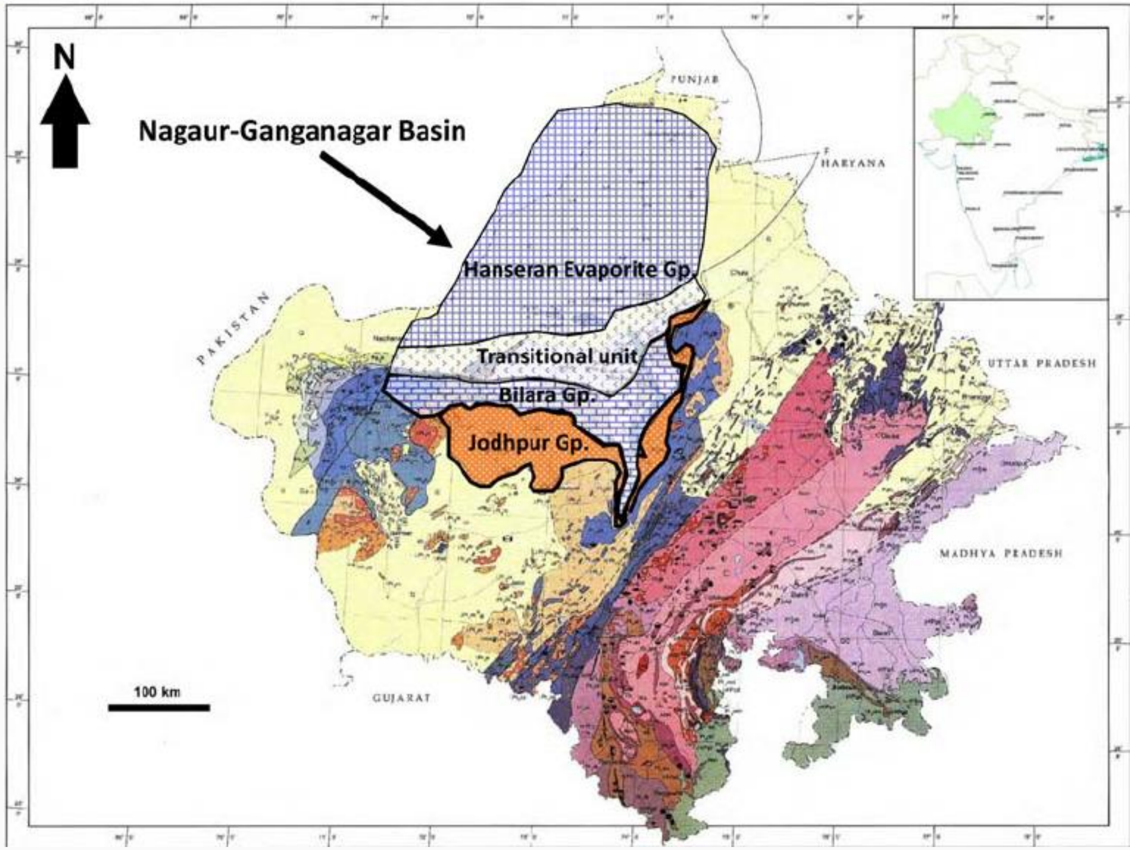


Fig 7. Geological map of Rajasthan with the outline of the Bikaner-Nagaur–Ganganagar basin in Western Rajasthan[6]

✓ Further research is required to explore integrating specific caverns into local or national energy grid systems.

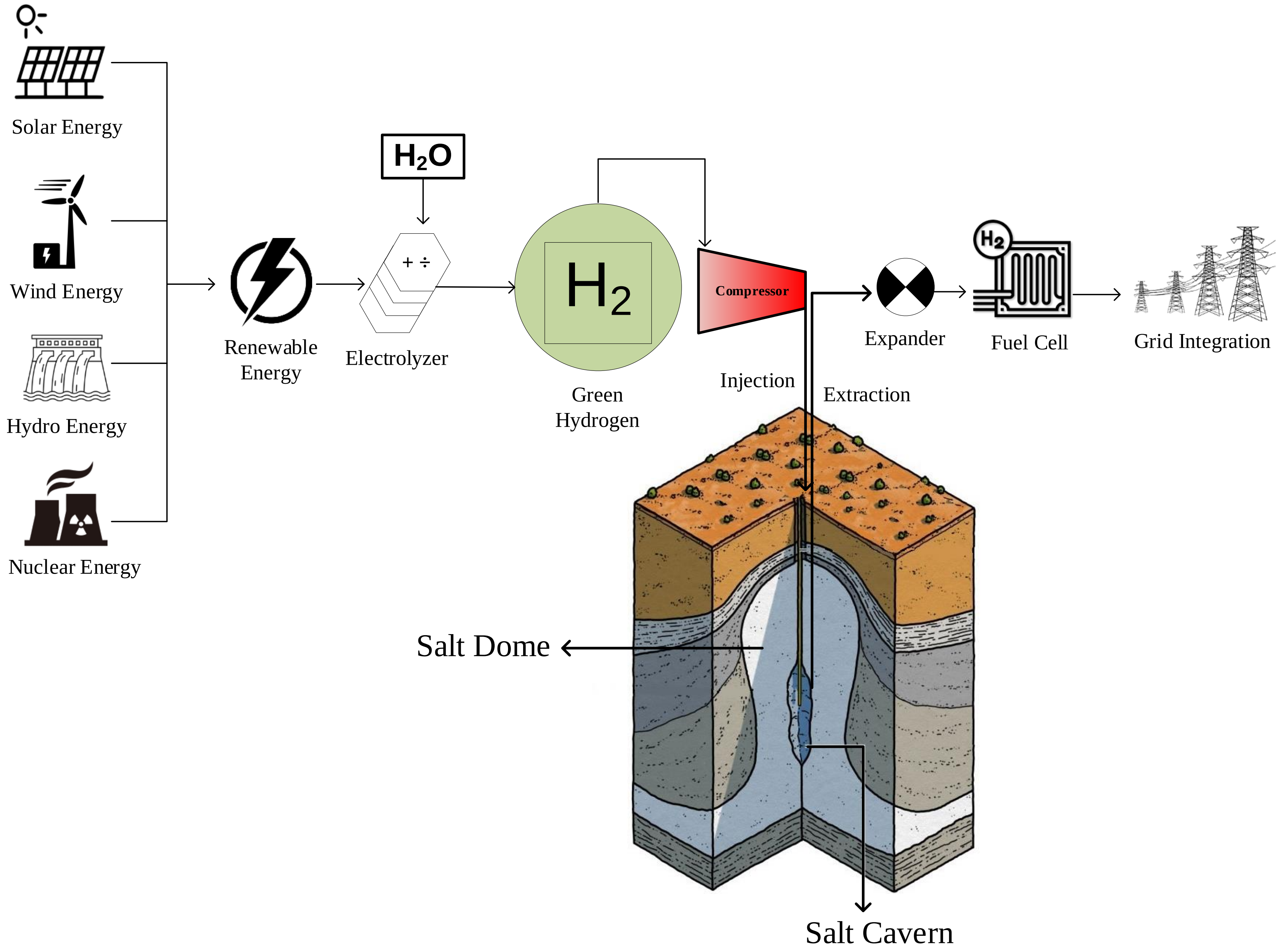


Fig 8 Energy cycle for UHS in salt cavern (created by Hardik Dave)

5. Bikaner-Nagaur- Ganganagar Basin

- The Bikaner-Nagaur-Ganganagar Basin, located in northwestern Rajasthan, is a key region within the Hanseran Evaporite Group.

- A plan has been proposed to develop underground salt caverns near Bikaner, India, with a total anticipated storage capacity of approximately 3.75 million metric tons (MMT) or 4.4 million cubic meters (MMm^3) of strategic crude oil reservoir.

- This initiative is part of Phase II of the storage program, as outlined in the Detailed Project Report (DPR) prepared by EIL in 2013.

- The site near Bikaner was chosen for its favorable geological conditions, including a bedded salt formation with suitable depth and thickness.

- Additionally, the presence of a shallow aquifer ensures an adequate yield of brackish groundwater, which is essential for the solution mining process.

- In 2023, this location is a prime focus for underground hydrogen storage under the National Green Hydrogen Mission.

5. Bikaner-Nagaur- Ganganagar Basin Salt Cavern Parameters

According to C. Kumar et al. findings [5].

- These storage caverns do not have lining and are only confined by the rock salt formation itself.
- The purity of its halite ranges from 95% to 98%.
- Rock salt is considered intrinsically tight when subject to the overburden pressure of an overlying rock column of some hundreds of meters of thickness, Average Young Modulus is 17.6 GPa
- **Salt dome depth range:** 500 m to 750 m
- **Operating Pressure range:** 30 bar to 150 bar
- **Cavern Height:** 150 m
- **Cavern Diameter:** 120 m
- **Edge Length L:** 300 m
- **No. of caverns can be formed:** 8

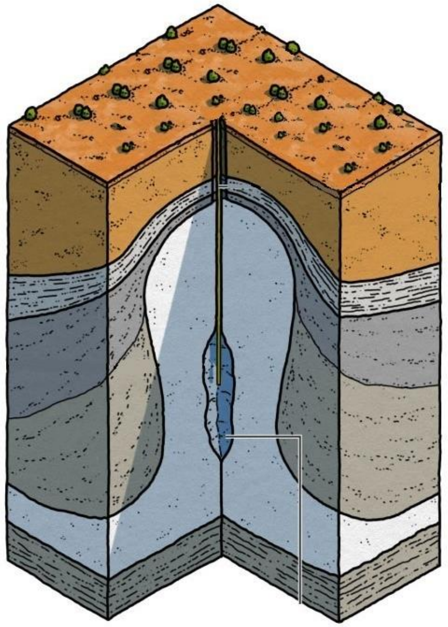


Fig 9 Schematic of Salt Dome (created by Hardik Dave)

6. Modelling studies in the field of UHS in Salt Cavern

Modeling Tool	Author(s)	Dimension	Acessibility	Key Objective	Key Findings
GeoH2 Tool	Maraggi et al.[9]	3D	Open Source	Volumetric and cyclic analysis of salt caverns	Provided accurate predictions for storage capacity and annual injection/withdrawal cycles in salt caverns.
Operate H2	M.L. Malki et al[10]	3D	Open Source	Optimize UHS performance using reduced-order models	Enabled rapid site screening and operational optimization with user-friendly GUI for hydrogen storage systems.
TOUGH+	Huang et al.[11]	2D and 3D	Open Source	Models hydrogen-brine interactions and capillary pressure, assessing H_2 losses in reservoirs	Cushion gases (N_2, CO_2) enhance H_2 recovery; N_2
CMG GEM	Ershadnia et al. [12]	3D	Commercial	Model gas injection and withdrawal cycles	Showed high withdrawal efficiency and minimized hydrogen purity degradation in salt caverns.
PetraSim TOUGH2	K. Luboń et al. [13]	3D	Commercial	Investigating the impact of capillary threshold pressure	Initial flow rates maintain high H_2 saturation, minimal gas infiltration into surrounding rock

7. Methodology

The GeoH2 Salt Storage and Cycling App is a single-phase real gas thermodynamic web-based simulator designed to estimate hydrogen (H_2) storage capacities and the processes of injection and withdrawal in salt caverns.

Volumetric Module

Assumptions:

1. Single-phase single component gaseous H_2.

2. Perfect mixing: pressure and temperature are uniform within the cavern.

3. H_2 acts as cushion gas.

4. No presence of insolubles in the salt cavern

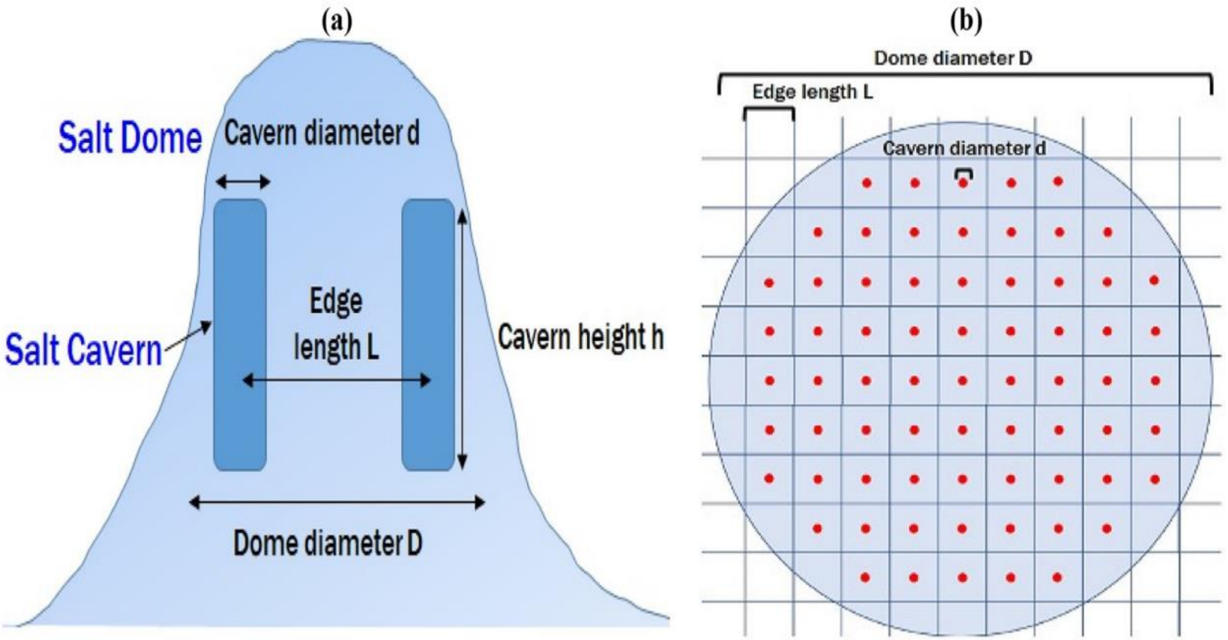


Fig 10. Schematic illustrating salt caverns in a salt dome: (a) lateral view and (b) top view. [9]

5. All caverns have the same shape and volume.

6. Safety factor (f_{safety}) safety factor for calculating maximum allowable working pressure (MAWP): 0.75-0.85.

i. Governing Equations

Total number of caverns, n

$$n(D,L) = \frac{\pi\left(\frac{D}{2}-\sqrt{1/2L}\right)^2}{L^2} \quad (1)$$

Effective number of caverns

$$n_{eff} = f_{bult}\, n \quad (2)$$

Geometric volume of cylindrical caverns

$$V_{cavern} = \pi\left(\frac{d}{2}\right)^2 h \quad (3)$$

Total geometric volume of caverns

$$V_{total} = n_{eff} V_{cavern} \quad (4)$$

Working gas volume per cavern

$$V_{gas\ cavern} = \left[\frac{\rho(T, f_{safety}\ P_{overburden})}{\rho(T_{std}\ P_{std})}\right](1 - f_{cushion})V_{cavern} \quad (5)$$

i. Governing Equations

Total working gas volume

$$V_{gas\,total} = n_{eff}\, V_{gas\,cavern} \qquad (6)$$

Energy per cavern

The energy per cavern is the combustion energy of the working gas volume based on the lower heating value LHV per unit volume of H_2 (290 Btu/scf).
Reference conditions for the evaluation of the LHV are 77°F and 14.69 psi

$$E_{cavern} = V_{gas\,cavern} LHV \left[\frac{\rho(77°F\,,P_{std})}{\rho(\,T_{std}\;\;P_{std})}\right] \qquad (7)$$

Total energy

$$E_{\,total} = n_{eff}\, E_{cavern} \qquad (8)$$

Mass per cavern

$$M_{cavern} = \rho(\,T_{std}\;\;P_{std})\, V_{gas\,cavern} \qquad (9)$$

Total mass

$$M_{total} = n_{eff}\, M_{cavern} \qquad (10)$$

ii. Input and Output Parameter of Volumetric Module

Inputs

Please, complete the following input variables and then click the RUN button:

Case Name	1
Salt Dome Diameter, D [ft]	6262.00
Cavern height, h [ft]	1000.00
Cavern diameter, d [ft]	100.00
Edge length, L [ft]	600.00
Overburden pressure, Poverburden [psi]	1647.00
Salt Dome Temperature, T [F]	89.00
Number or Fraction of caverns, f_built [fraction or number]	0.50
Fraction of cushion gas, f_cushion [fraction]	0.30
Safety factor for calculating maximum allowable working pressure, f_safety [fraction]	0.85

RUN

Outputs

Here are the results of the volumetric calculations:

Download data as a CSV file

1	Value
Total Number of Caverns	63
Effective Number of Caverns	31
Geometric Volume of Cavern [BScf]	0.0079
Total Geometric Volume [BScf]	0.2435
Working Gas Volume of Cavern [BScf]	0.4696
Total Working Gas [BScf]	14.5581
Energy per Cavern [GWh]	3.0053
Total Energy Stored [GWh]	93.1657
Hydrogen Mass Cavern [Ton]	1.1308
Total Hydrogen Mass [Ton]	35.0545

Input Data taken from Simone et al. , 2021 to validate GeoH2 Salt Storage and Cycling App

Production Module of GeoH2 app

Governing Equations

Mass Flow Rate $P_C = P\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$

where:

Pc is the critical pressure (Ma = 1).)

Pwf is the downstream, bottomhole flowing pressure.

P is the upstream (salt cavern pressure).

γ is the isentropic coefficient, approximated by the heat capacity ratio cp/cv.

$$\dot{m} = \left\{ C_d A \sqrt{\left(\frac{2\gamma}{\gamma+1}\right) P\rho \left(\frac{P_C}{P}\right)^{\frac{2}{\gamma}} \left[1 - \left(\frac{P_C}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]} \right\} \qquad P_{wf} \leq P_c$$

$$\dot{m} = \left\{ C_d A \sqrt{\left(\frac{2\gamma}{\gamma+1}\right) P\rho \left(\frac{P_{wf}}{P}\right)^{\frac{2}{\gamma}} \left[1 - \left(\frac{P_{wf}}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]} \right\} \qquad P_{wf} > P_c$$

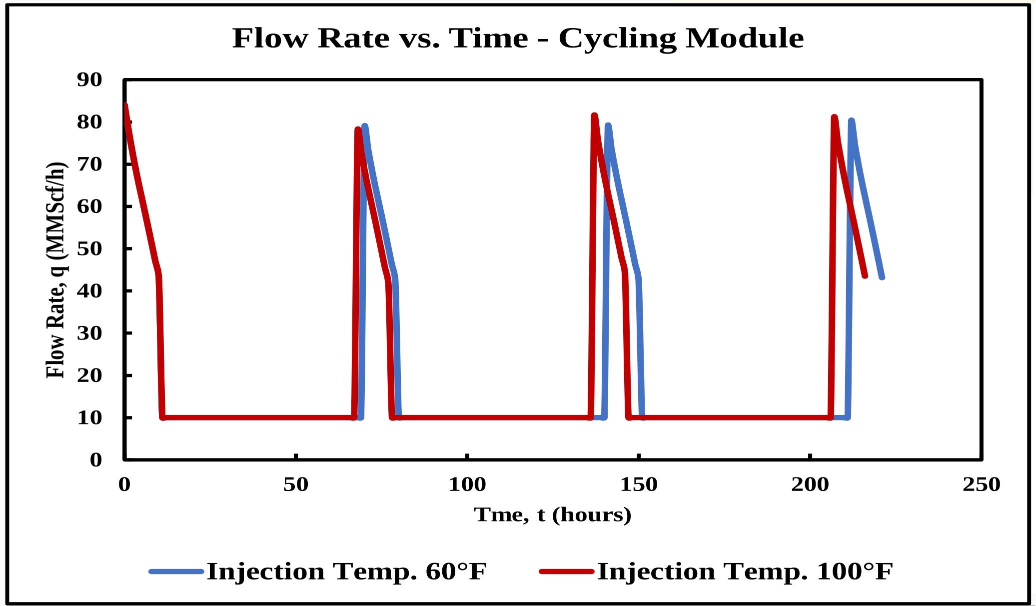
where

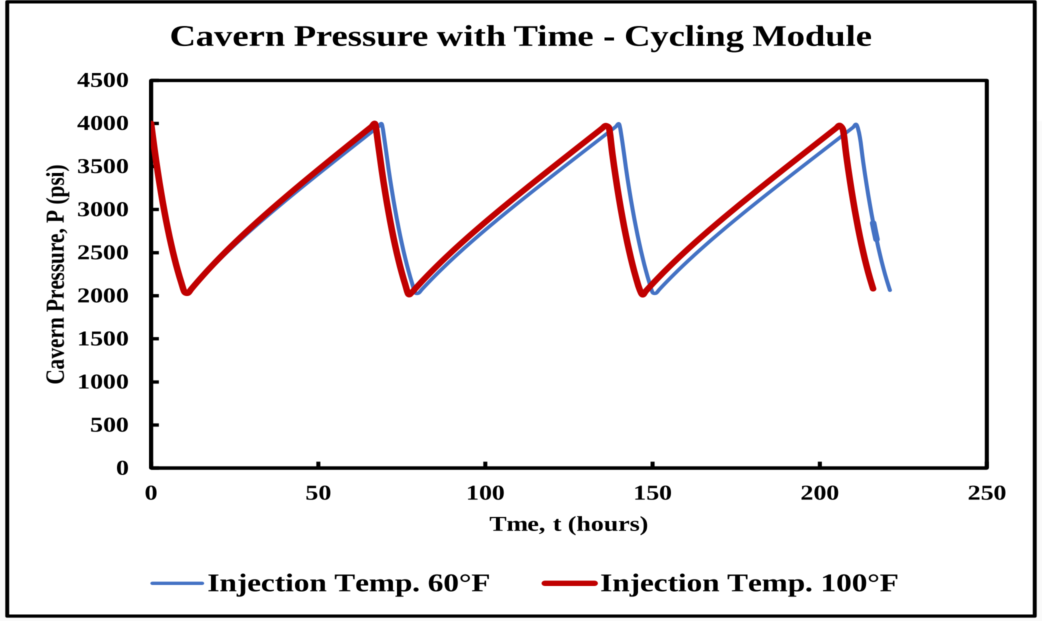
- ρ is the density of the gas at the upstream (salt cavern) conditions.
- Cd is the discharge coefficient of the pipe, reference value: 0.60.
- A is the cross-sectional area of the pipe.

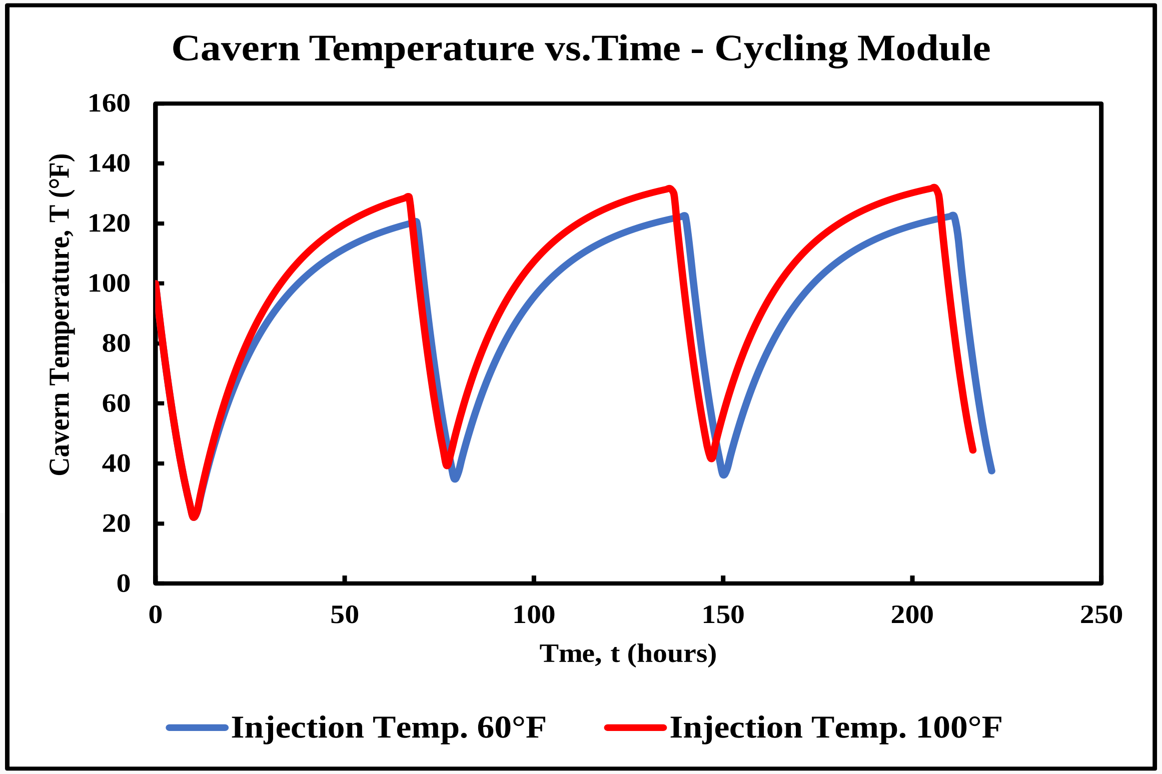
Cyclic Module.

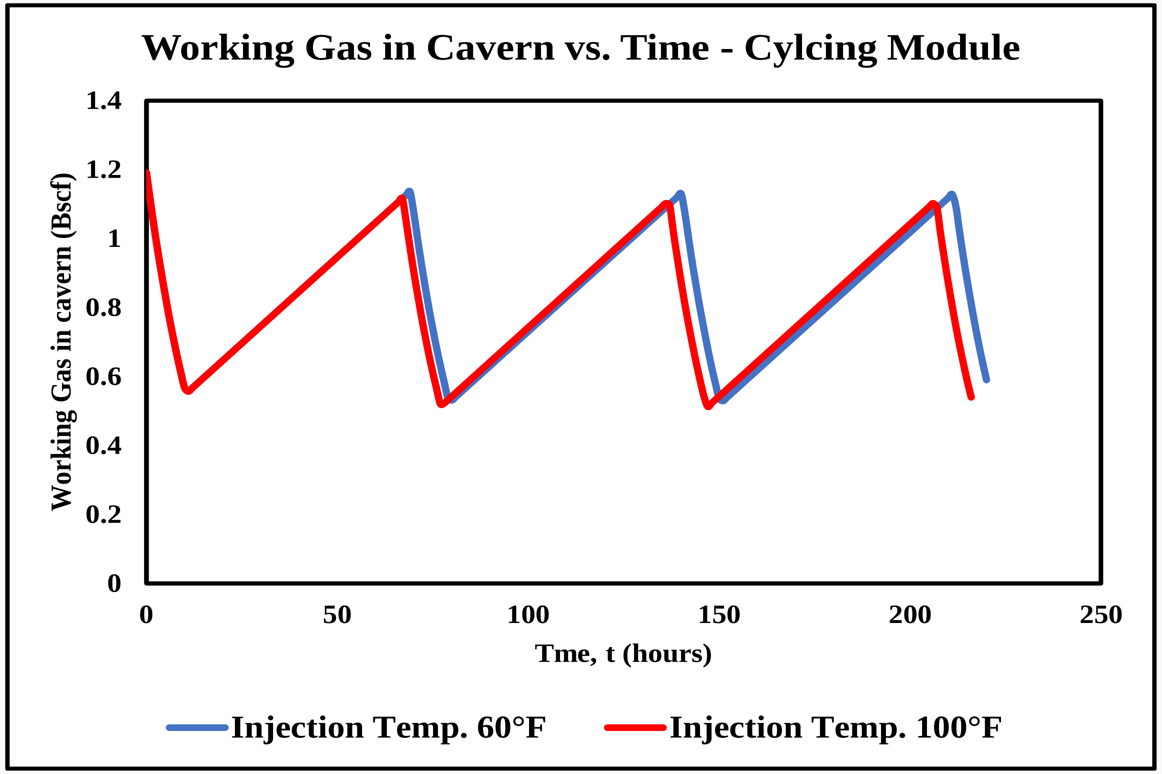
Input	Case 1	Case 2
Injection Temperature $T_{inj,}$ [°F]	60	100
Initial Pressure P_i $[psi]$	4000	4000
Initial Temperature $T_{i,}$ [°F]	100	100
Maximum operating Pressure P_{final} $[psi]$	4000	4000
Diameter, d $[ft]$	100	100
Height, h $[ft]$	1000	1000
Fraction of cushion gas $f_{cushion}$	0.3	0.3
Tubing internal diameter, d_{tubing} $[in]$	3.46	3.46
Discharge coefficient, C_d	1	1

Process	Production	Injection	Production	Injection	Production	Injection	Production
Final Pressure $[psi]$		4000		4000		4000	
Injection rate $[MMScf/h]$		10		10		10	
Final Pressure $[psi]$	2000		2000		2000		2000
Bottom hole flowing pressure $[psi]$	1500		1500		1500		1500






Cavern Temperature vs.Time - Cycling Module
Cavern Temperature, T (°F)
0
20
40
60
80
100
120
140
160
0
50
100
150
200
250
Tme, t (hours)
Injection Temp. 60°F
Injection Temp. 100°F


Working Gas in Cavern vs. Time - Cylcing Module
Working Gas in cavern (Bscf)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
50
100
150
200
250
Tme, t (hours)
Injection Temp. 60°F
Injection Temp. 100°F

8. Results

Input parameters of Salt cavern		
Parameters	In meters [m]	In feet [ft]
Depth Range	500 -750	1640-2460
Overburden Pressure	141 bar	2050 psi
Diameter of salt dome	1908	6262
Diameter of salt cavern	120	394
Height of salt cavern	150	492
Edge length, L	300	984
Salt dome temperature	36.6°C	98°F
Fraction of Caverns	0.5	
Fraction of cushion gas	0.3	
Safety factor for calculating MAWP	0.85	

Output for Bikaner-Nagaur-Ganganagar basin salt caverns	
Total number of caverns	19
Effective number of caverns	9
Geometric Volume of Cavern [BScf]	0.06
Total Geometric Volume [BScf]	0.5399
Working Gas Volume of Cavern [BScf]	4.5628
Total Working Gas [BScf]	41.0649
Energy per Cavern [GWh]	366.18
Total Energy Stored [GWh]	3259.68
Hydrogen Mass in Cavern [Ton]	10986.7
Total Hydrogen Mass [Ton]	98880.3

8. Results

Comparison of Bikaner-Nagaur-Ganganagar single Salt Cavern with others

Location	Depth [in m]	Height [in m]	Diameter [in m]	Storage Volume [in m^3]	Storage [in GWh]	Reference
Teesside (UK)	430	304.8	30.5	2,10,000	14.66	[2]
Cheshire Basin (UK)	700	200	58	5,28,148	210	[14]
Bikaner-Nagaur-Ganganagar Basin (India)	750	150	120	16,95,600	366.18	-

9. Conclusion

- Based on the results, it can be concluded that the Bikaner-Nagaur-Ganganagar basin salt dome has immense potential for hydrogen storage.
- Each cavern can store approximately 336 GWh of energy, and since up to nine caverns can be created,
- The total energy storage capacity could reach up to 3 TWh.

10. Future Scope

- **Evaluation of the injection and withdrawal rates of hydrogen.**
- **Grid Integration:** Further research should focus on integrating hydrogen storage systems with the national grid system.
- **Evaluation of the effects of cyclic loading and unloading on cavern integrity.**
- **Cost analysis of Cavern Construction and operating cost**

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THANK YOU

Questions?