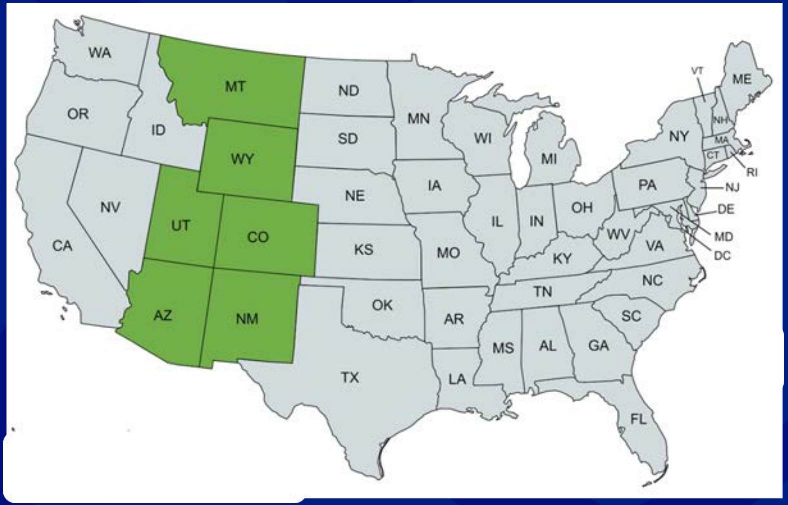
Hydrogen and the Low-Carbon Future: Opportunities for Energy Transition in the Intermountain West

Mohamed Mehana and Eric Guiltinan

Presented to I-WEST: August 16th, 2023



LA-UR 23- 29354

Acknowledgment

Fangxuan Chen, Joseph Heimerl, Mohamed Malki, Shaowen Mao, Martin Ma, Bailian Chen, Rajesh Pawar, Jolante van Wijk, Chelsea Neil, Michael Gross, Gaoxue Wang, Bijay K C, Luke Frash, Siddarth Komini Babu, Prakash Purswani, Ruyi Zheng, Tim German

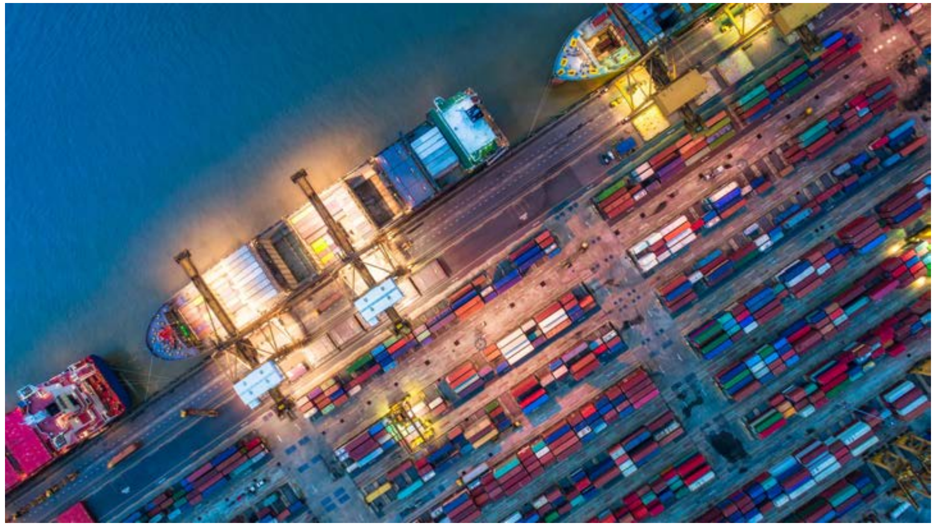
The US. DOE - Intermountain West Energy Sustainability & Transitions
LANL Technology, Evaluation, and Demonstration Program
LANL-LDRD Mission Foundation Research Program

LANL-LDRD Directed Research Program

Los Alamos
NATIONAL LABORATORY

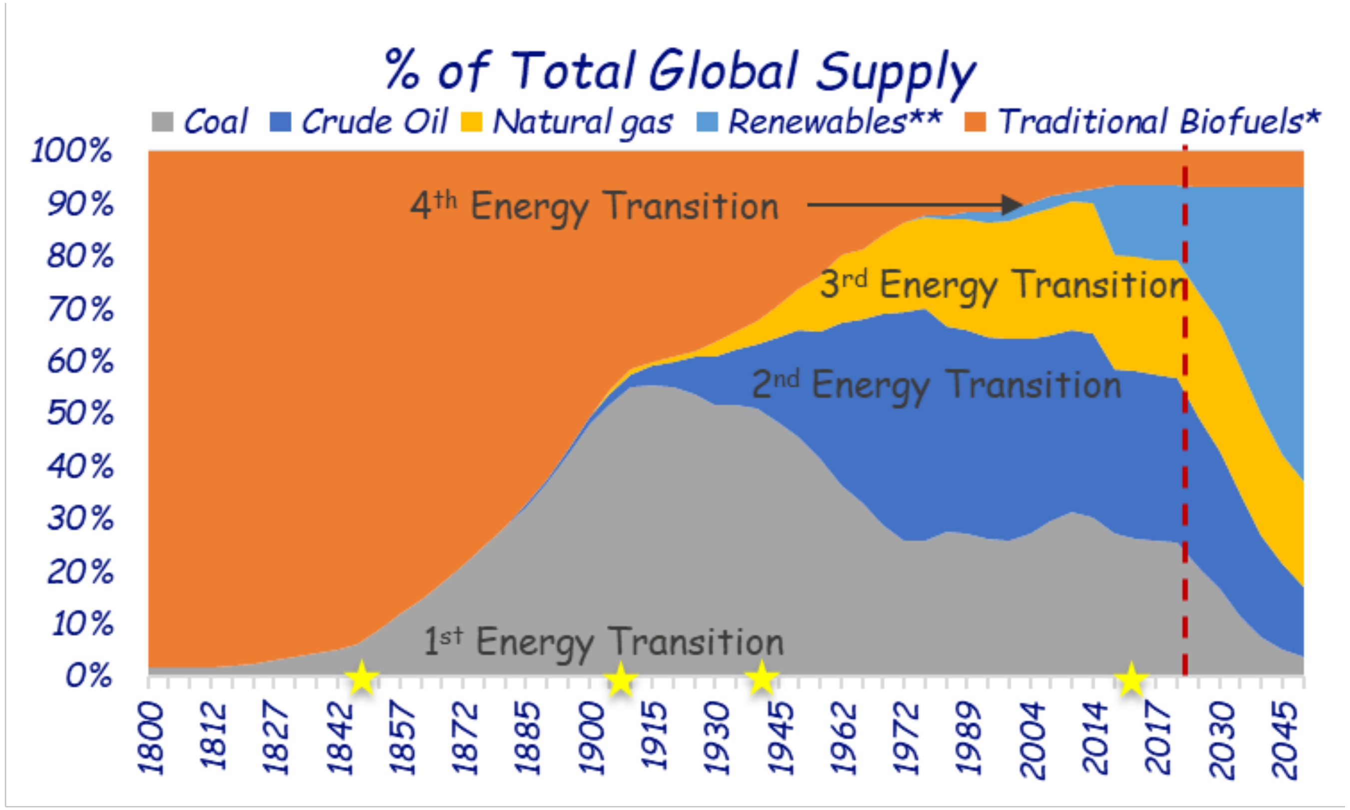
Why Hydrogen?

Emission-free energy source that can be used for energy storage and decarbonizing transportation.



Energy Transition

Throughout history there have been several energy transitions.



* Burning wood and other organic matter

** Wind, solar, geothermal and modern biofuels, includes nuclear

Data Source: Energy Outlook, BP, 2020

Where Does Hydrogen Come From?

Hydrogen is the one of the most abundant elements but H_2 is relatively scarce.

Grey – Fossil Fuel without CCS

Blue – Fossil Fuel with Carbon Capture and Storage (CCS)

Green – Excess Renewable Energy

Pink – Excess Nuclear Power

Palo Verde Generation Station

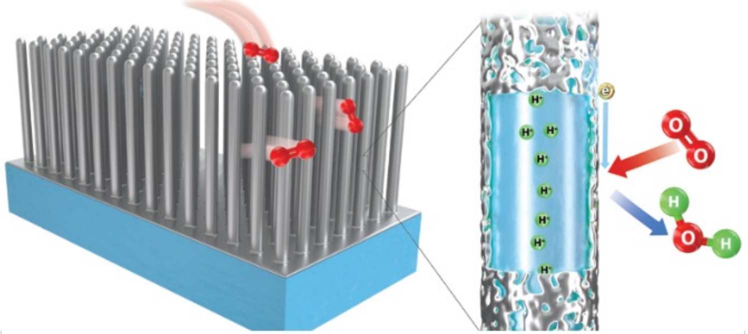
Image credit: https://www.paloverde.com

Hydrogen Economy

Production Cost:

Grey ~ $1.5/kg
Green ~ $5/kg

Utilization: ~60% efficient



Production

~75% efficient

Transport & Storage

~ 10% loss

1.25 Mgal Capacity
1.3 quadrillion insulating glass beads
credit: *www.nasa.gov*

Bipartisan Infrastructure Law and DOE Earthshots

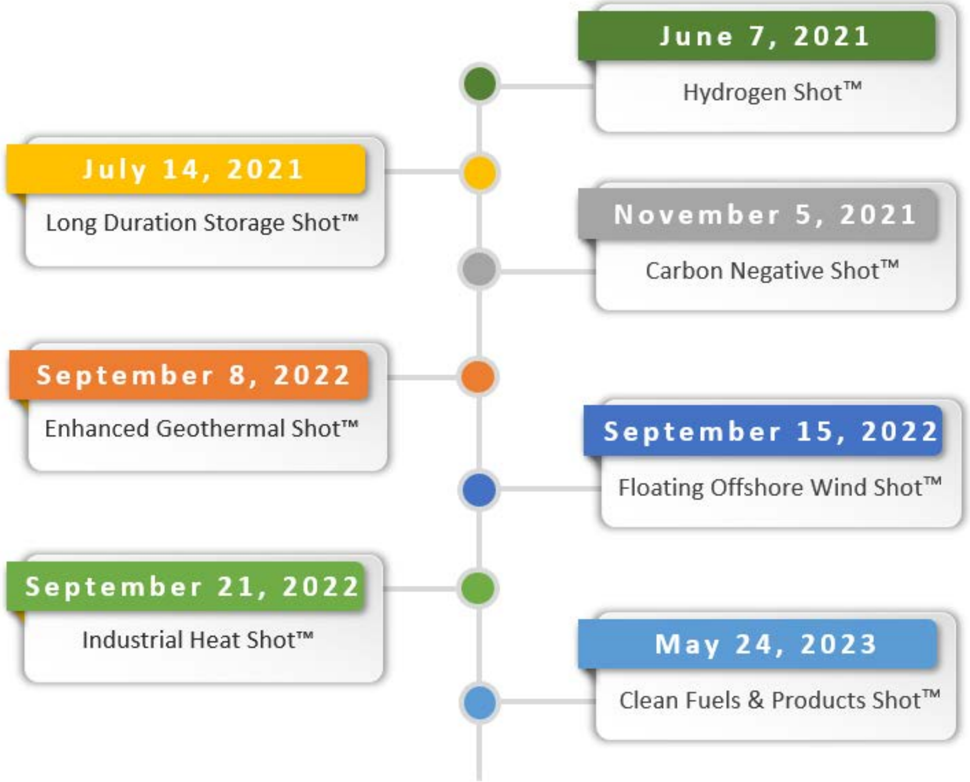
Bipartisan Infrastructure Law - Hydrogen Highlights

- **Covers $9.5B** for clean hydrogen:
  - $8B for at least four regional clean hydrogen hubs
  - $1B for electrolysis research, development, demonstration, commercialization, and deployment
  - $500M for clean hydrogen technology manufacturing and recycling R&D

President Biden Signs the Bipartisan Infrastructure Bill on November 15, 2021.
Photo Credit: Kenny Holston/Getty Images

- **Aligns with Hydrogen Shot priorities by directing work to reduce the cost of clean hydrogen to $2 per kilogram by 2026**
- **Requires developing a National Hydrogen Strategy and Roadmap**

U.S. DEPARTMENT OF ENERGY | OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY | HYDROGEN AND FUEL CELL TECHNOLOGIES OFFICE | 11

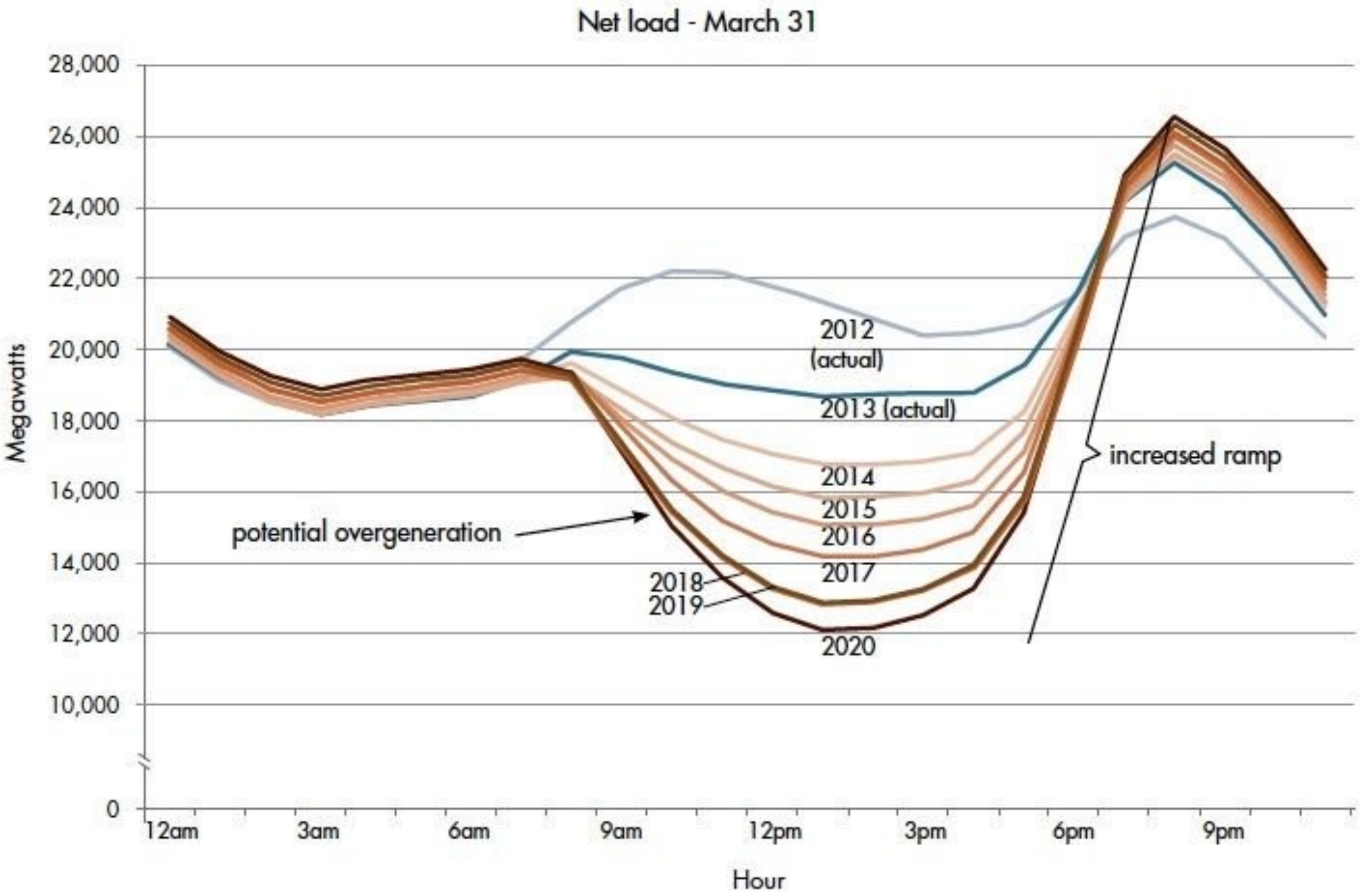


"Clean hydrogen is key to cleaning up American manufacturing… we're seeking feedback from the American public on how to make scaling-up this clean, affordable energy source a reality.“

– Secretary Granholm

Energy Curtailment

(Duck Curve)



Source:
California Independent Service Operator

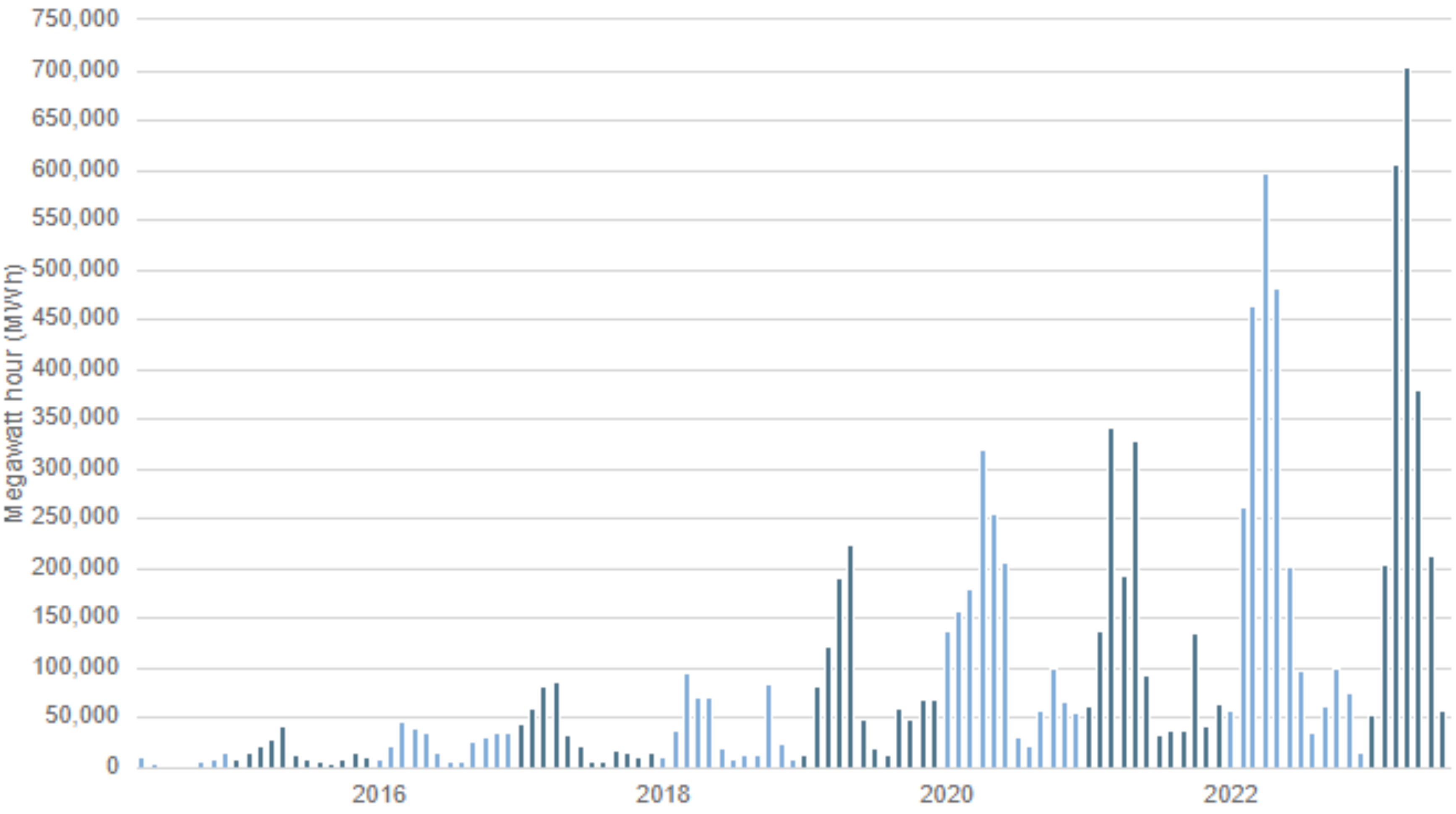
Energy Curtailment

2,449 GWh curtailed in 2022
2,218 GWh curtailed
January – July 1st 2023

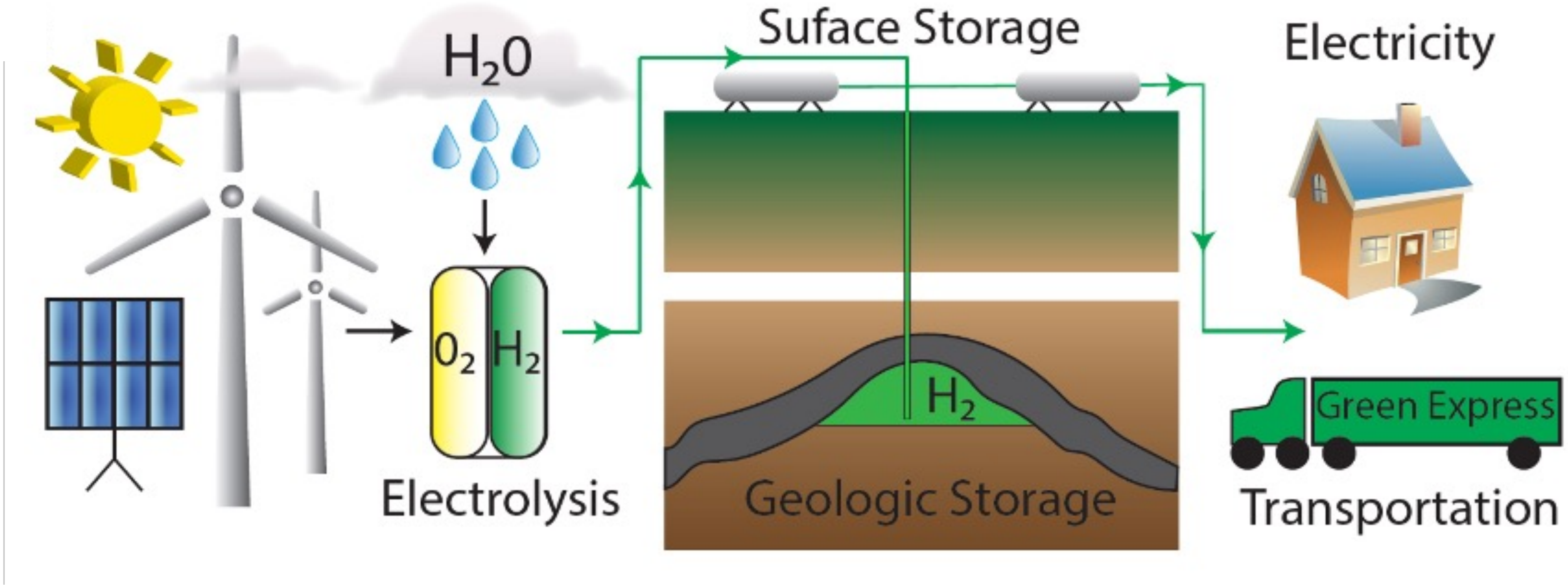
Source: California Public Utilities Commission

10,632 kWh US average (2021)

230,344 US homes curtailed

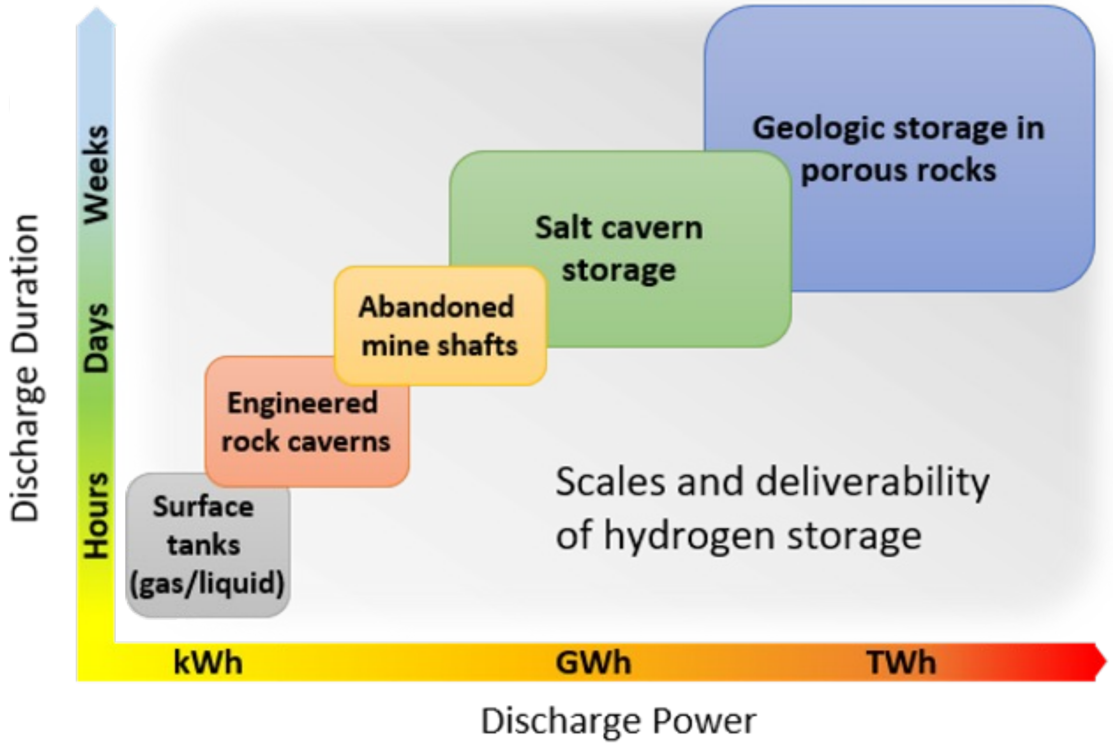


Green Hydrogen paired with Geologic Storage

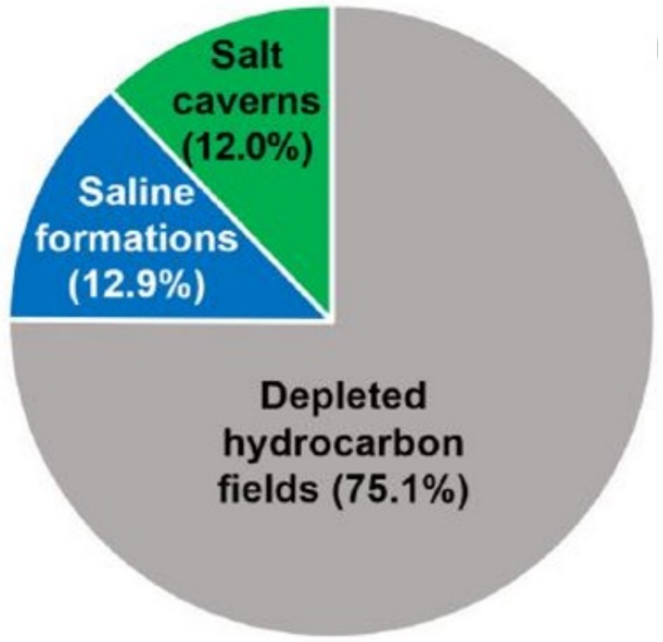


- Requirement for seasonal storage (energy mismatch)
- Batteries and surface tanks have storage limitations
- Geologic storage in the subsurface can achieve H_2 at scale

Types of Storage



Source: Edlmann (2021)

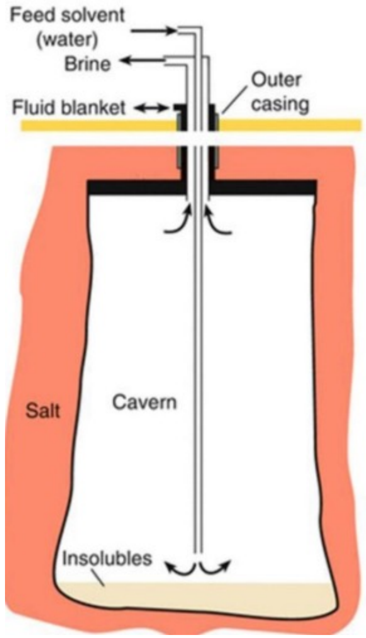


Source: Buscheck et al., 2023

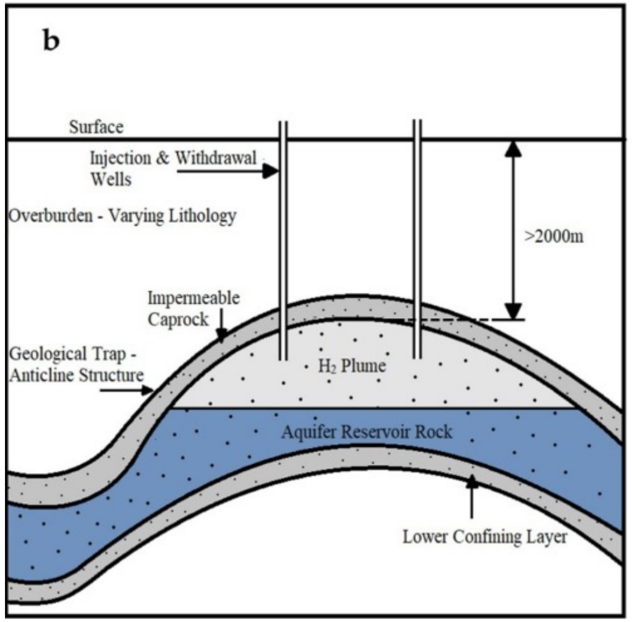
Geologic H_2 storage

Geological Type	Storage Capacity	Initial Cost	Cyclic Cost	Chemical conversion rate	Cushion gas requirement	Leakage risks	Usability purpose
Salt cavern	Low	High	Low	Low	Low	Low	Frequent
Saline aquifer	High	Average	Average	High	High	High	Seasonal
Depleted gas reservoirs	High	Average	Average	Average	Average	High	Seasonal

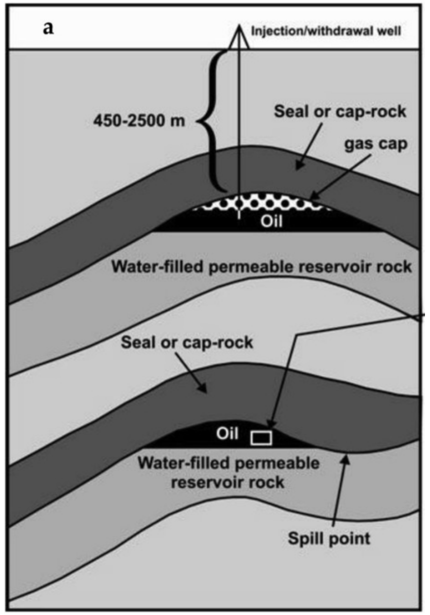
Salt cavern



Saline Aquifer



Depleted Reservoirs



Muhammed et al., 2021.

Hydrogen Projects at Los Alamos

Hydrogen Storage in Porous Rocks

Hydrogen Storage in Bedded Salt Caverns

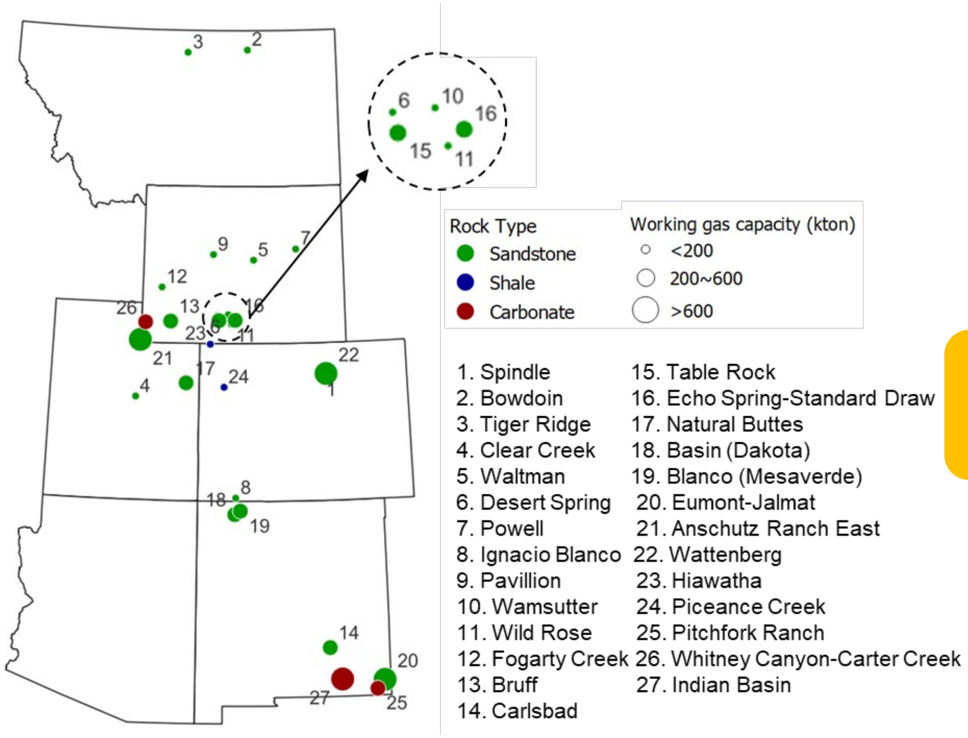
Hydrogen Economy in the I-WEST

Fuel Cell and Electrolyzer Research

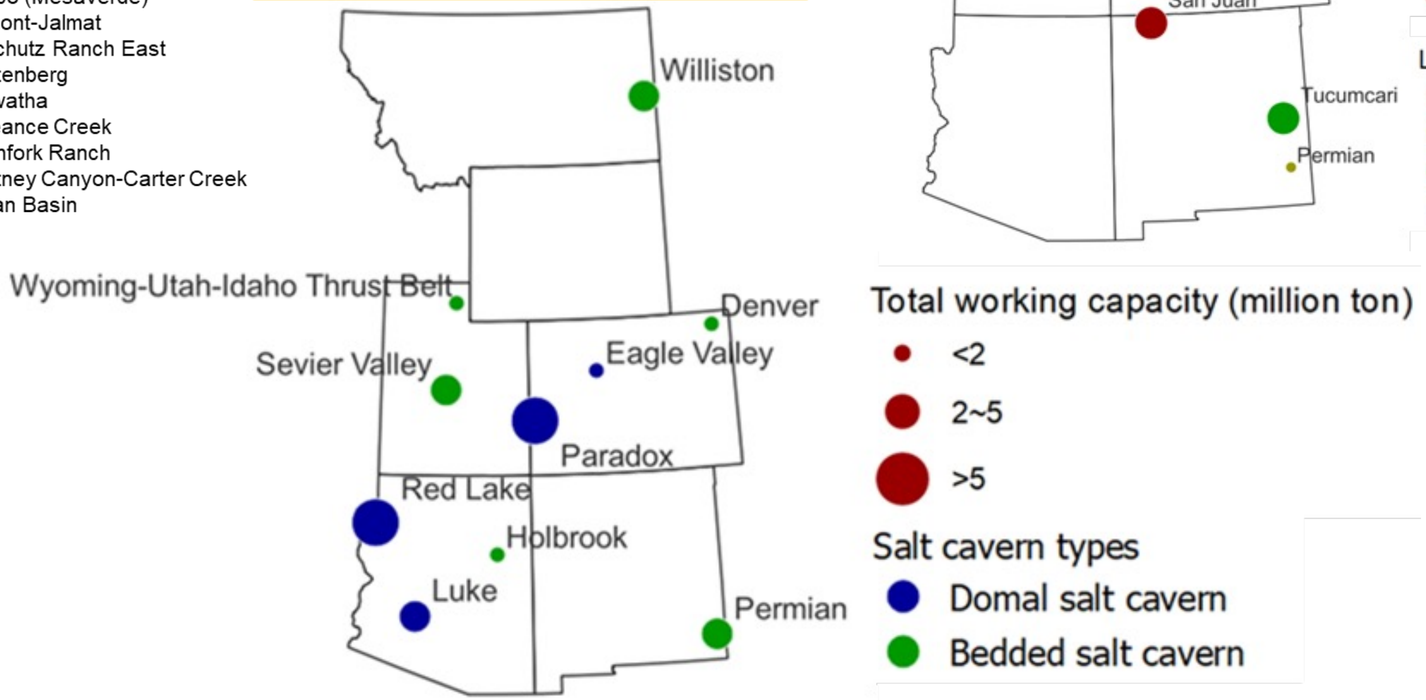
Million Mile Fuel Truck

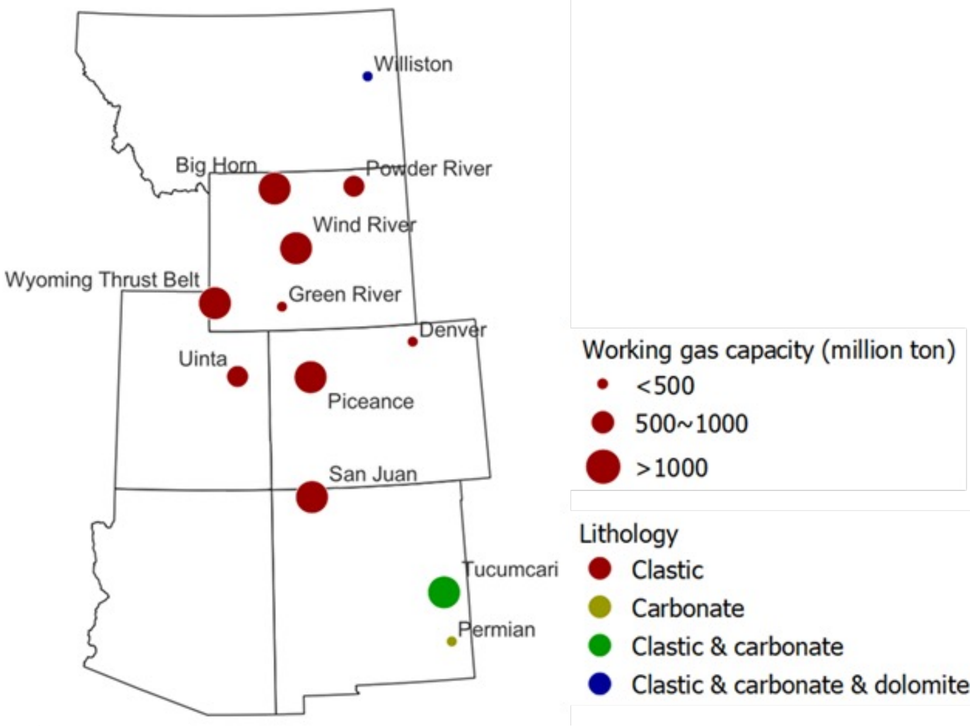
H_2 geologic storage capacity and cost

Saline Aquifers
Storage cost: 3.2 $/kg_H$_2$



Salt Caverns
Storage cost: 2.3 $/kg_H$_2$



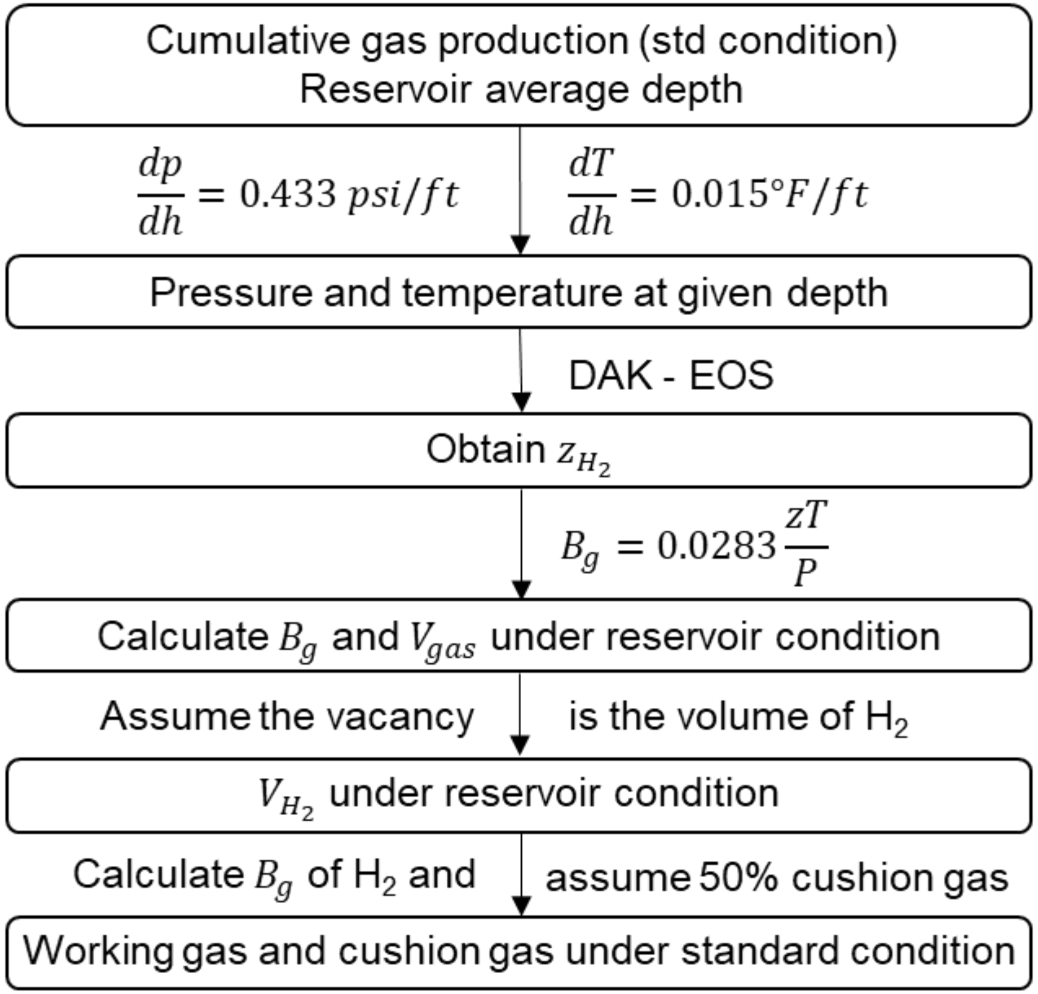


Depleted Gas reservoirs
Storage cost: 1.1 $/kg_H$_2$

H_2 storage in depleted gas reservoirs

Assumptions:

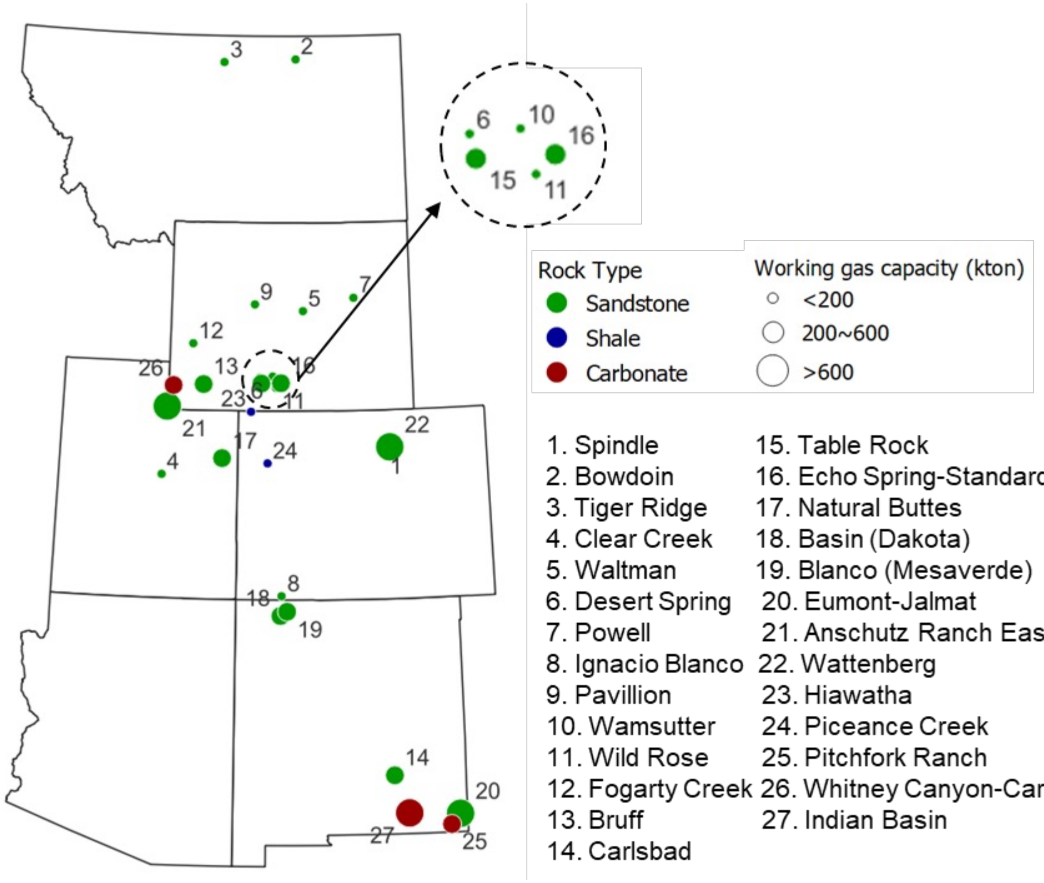
- Normal pressure and temperature gradients
- The cumulative production amount of natural gas under reservoir conditions is equal to the volume of stored H_2 in reservoir conditions;
- Cushion gas: H_2, 50% of total volume.



Lemieux et al., 2020; Lord Anna Snider, 2009 and Mouli-Castillo et al. 2021.

Working gas capacity in depleted gas reservoirs

The top 27 depleted gas reservoirs with high cumulative production:

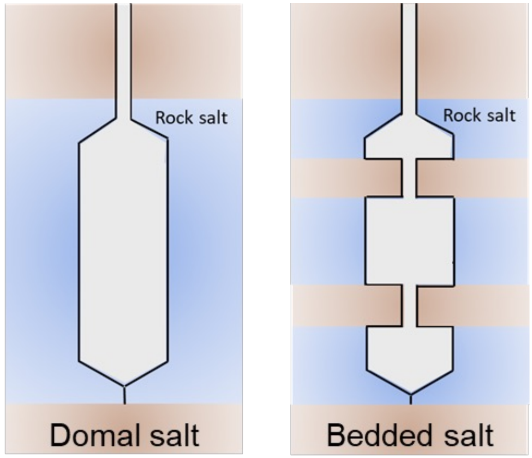


1. Spindle
2. Bowdoin
3. Tiger Ridge
4. Clear Creek
5. Waltman
6. Desert Spring
7. Powell
8. Ignacio Blanco
9. Pavillion
10. Wamsutter
11. Wild Rose
12. Fogarty Creek
13. Bruff
14. Carlsbad
15. Table Rock
16. Echo Spring-Standard Draw
17. Natural Buttes
18. Basin (Dakota)
19. Blanco (Mesaverde)
20. Eumont-Jalmat
21. Anschutz Ranch East
22. Wattenberg
23. Hiawatha
24. Piceance Creek
25. Pitchfork Ranch
26. Whitney Canyon-Carter Creek
27. Indian Basin

H_2 storage in salt caverns

Assumptions:

- Salt cavern shape
- Fracture pressure gradient (g_f): 0.016 MPa/m
- Minimum pressure gradient: 0.00835 MPa/m
- Cushion gas percentage: 20%



Average depth to the top of rock salt layer
Average thickness of rock salt layer (M)

↓

Calculate the volume of cavern

↓ $p_{max} = g_f h_n$; $p_{min} = g_{min}(h_c - h_0)$

Obtain the maximum and minimum pressure

↓ $m(p) = f \frac{pV}{RTZ}$

Calculate the amount of gas at pressure p

↓ $m(p_{max}) - m(p_{min})$

Working capacity of gas (in mass)

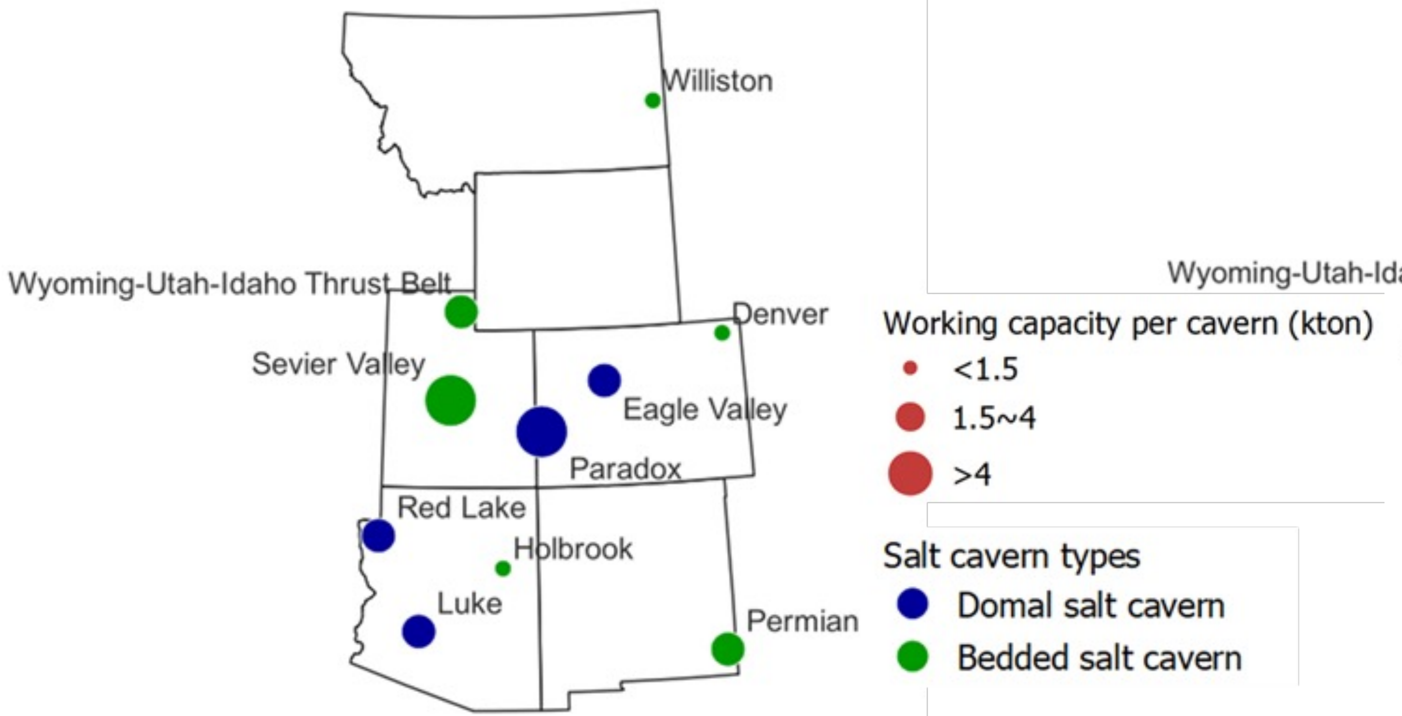
↓ $\Delta V_{Nm^3} = \frac{m(p_{max}) - m(p_{min})}{\rho_N}$

Working capacity of gas in normal condition (in volume)

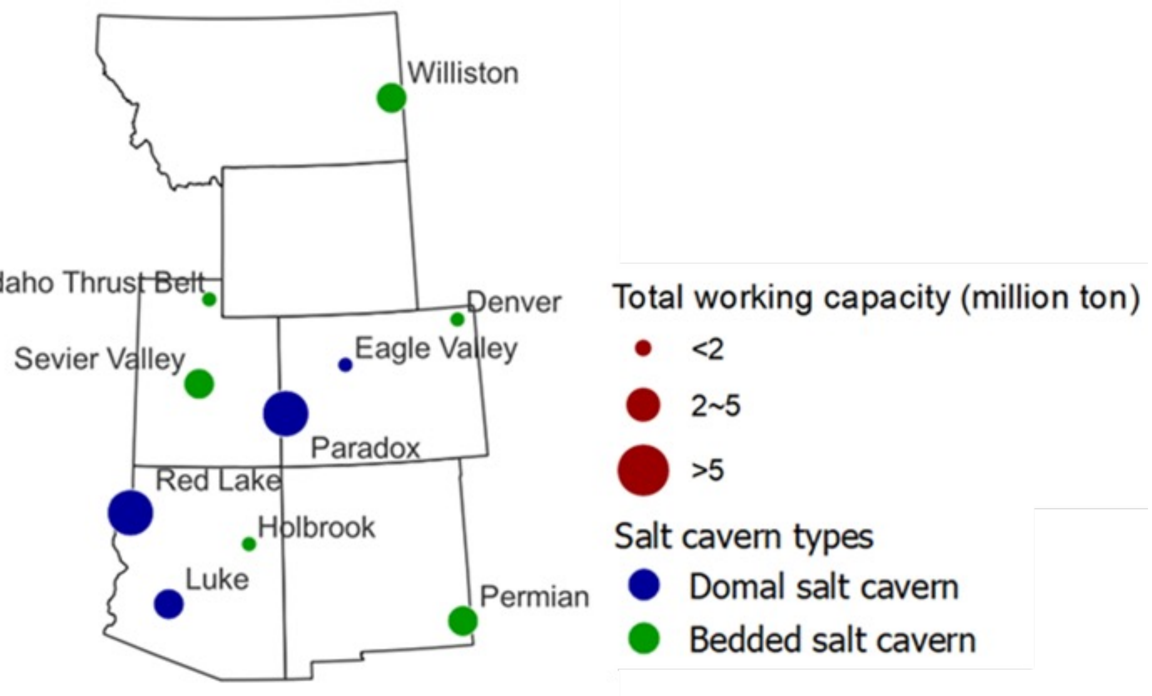
Lankof et al., 2020; Pierce et al., 1962.

Working gas capacity in salt caverns

- Ten potential locations to build salt caverns:
  - Top depth of rock salt layer: <1800 m; Thickness of salt layer: >122 m.
- Estimation of the maximum number of salt caverns in a region:
  - The distance between two caverns is four times the diameter of the cavern.



Single Cavern Capacity

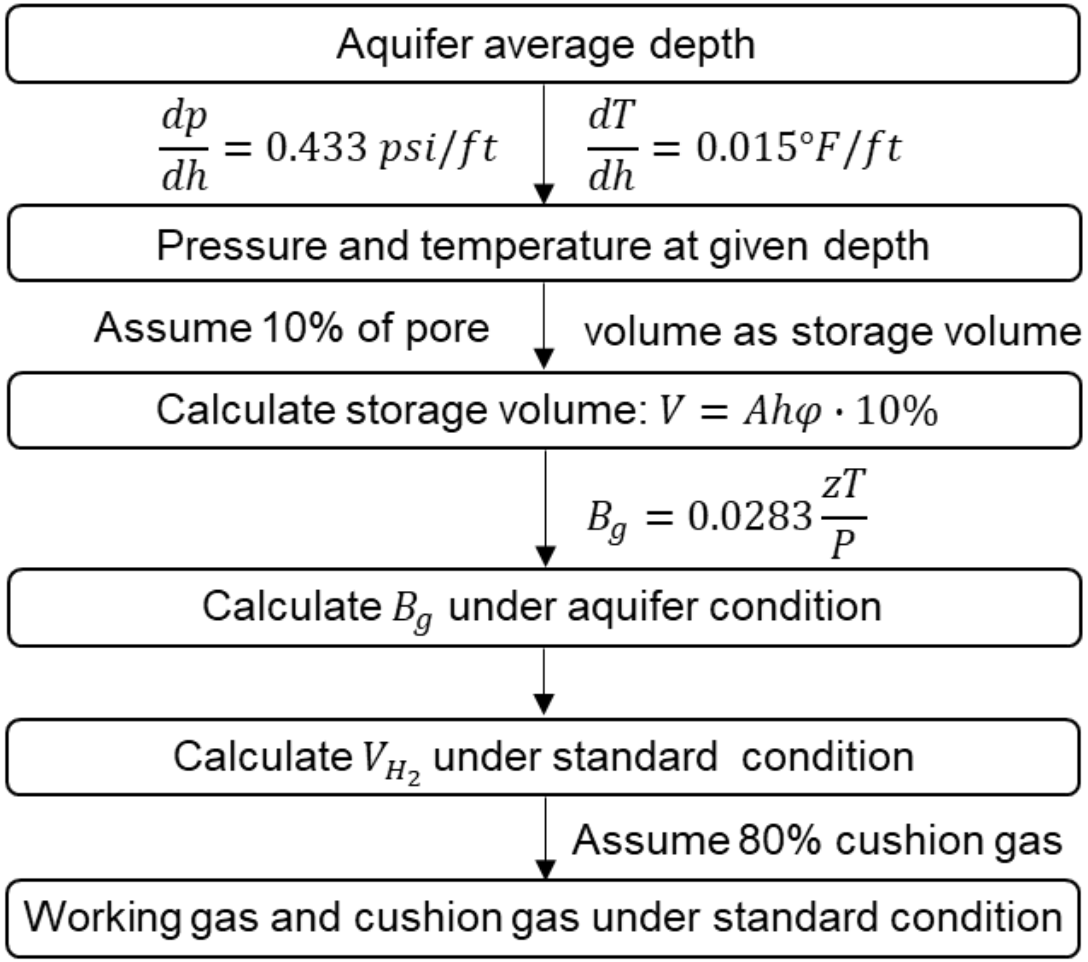


Total Capacity

H_2 storage in saline aquifers

Assumptions:

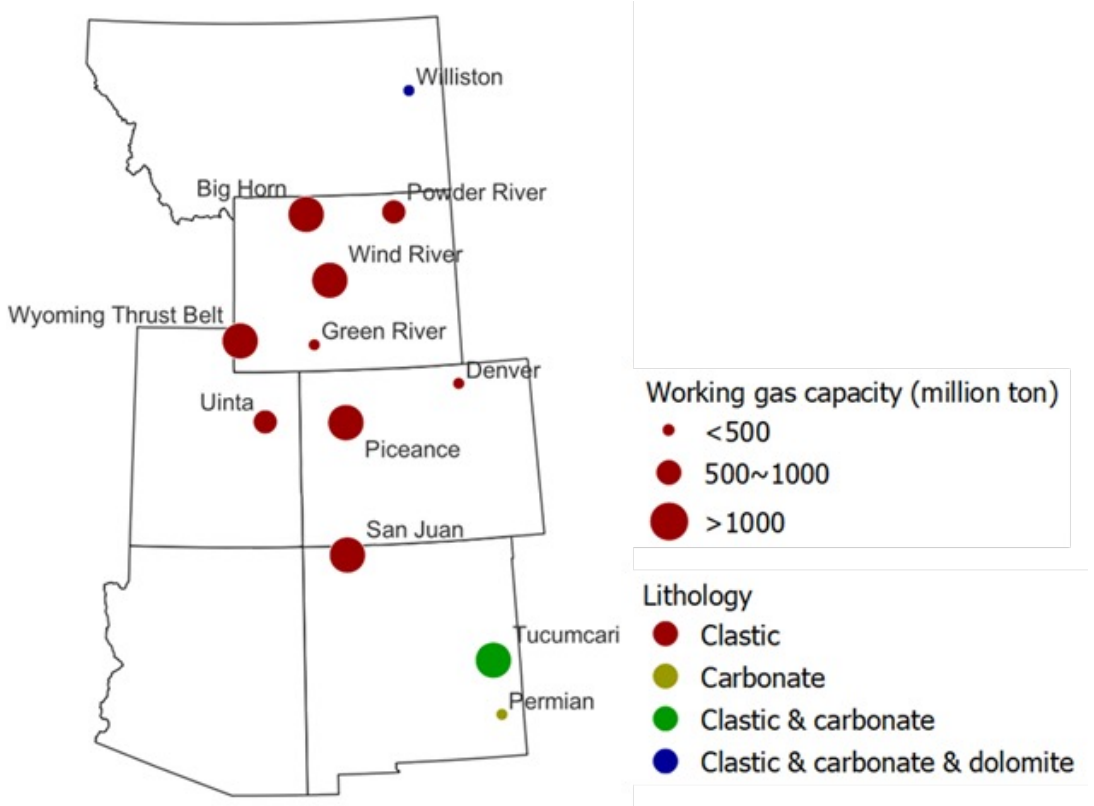
- Normal pressure and temperature gradients
- H_2 storage efficiency: 10%;
- Cushion gas: H_2, 80% of total volume.



Working gas capacity in saline aquifers

The top 12 saline aquifers with large drainage areas are selected:

- Further analysis is required to check sealing strength.



Cost Estimation of H_2 Storage

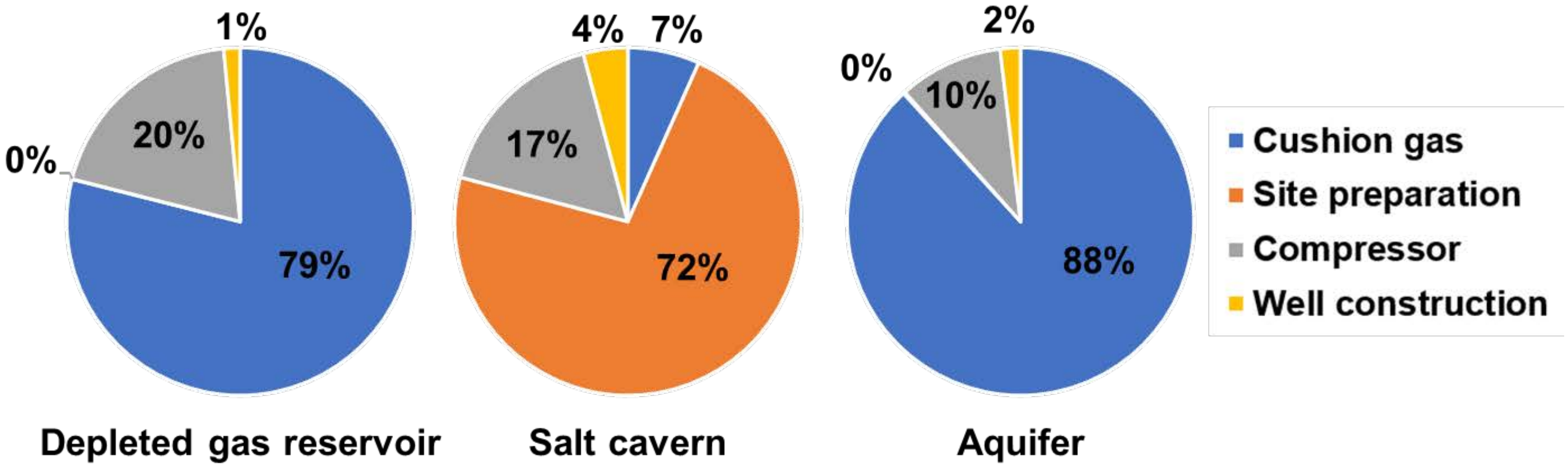
- Geological site: depleted gas reservoir, salt cavern, aquifer.
- Cost estimation: capital cost and levelized cost of hydrogen storage:
  - Capital cost: one-time expenditure:
    - Cushion gas cost
    - Geologic site preparation cost
    - Compressor capital cost
    - Well capital cost
  - Levelized cost of hydrogen storage ($/kg): average net present cost of hydrogen storage over its lifetime:
    - Levelized total capital cost
    - Compressor operation and maintenance (O&M) cost
    - Well operation and maintenance (O&M) cost

Lord et al., 2014.

H_2 Storage cost: cases summary

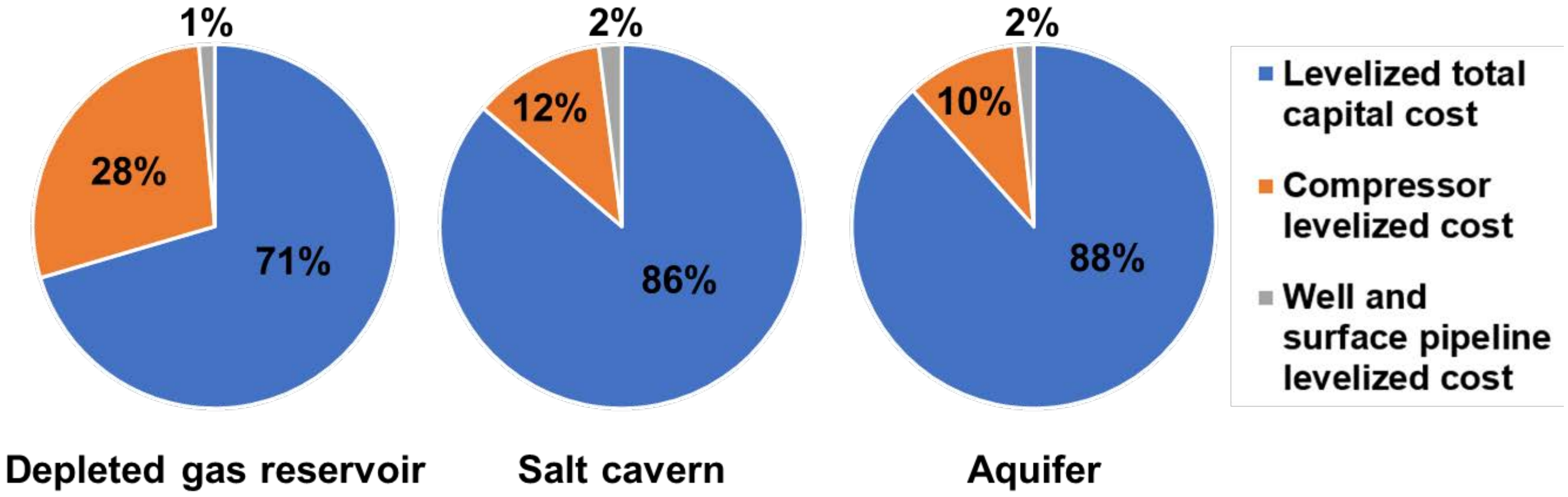
	Depleted gas reservoir	Salt cavern	Saline aquifer
Geological site	Watternberg field (CO)	Red Lake (AZ)	Baker dome (CO)
Storage volume underground (million ft^3)	8,200	15.5	5,602
Average depth (ft)	8,000	4,000	4,717
Average Pressure (psi)	3,479	1,732	2,057
Average temperature (F)	180	122	128
Total H_2 storage amount (kton)	3,546	4.2	1613
Working gas percentage (%)	50	80	20
Working gas capacity (kton)	1773	3.4	323
Cushion gas amount (kton)	1773	0.8	1290

H_2 Storage cost: capital costs of cases



	Depleted gas reservoir	Salt cavern	Aquifer
Geological site	Watternberg field (CO)	Red Lake (AZ)	Baker dome (CO)
Cushion gas cost (million $)	8,864	4.2	6,452
Geological site preparation cost (million $)	0	36.7	10
Compressor capital cost (million $)	1,977	9.4	642
Well capital cost (million $)	154	1.2	124
Total capital cost (million $)	**10,994**	**51**	**7,229**

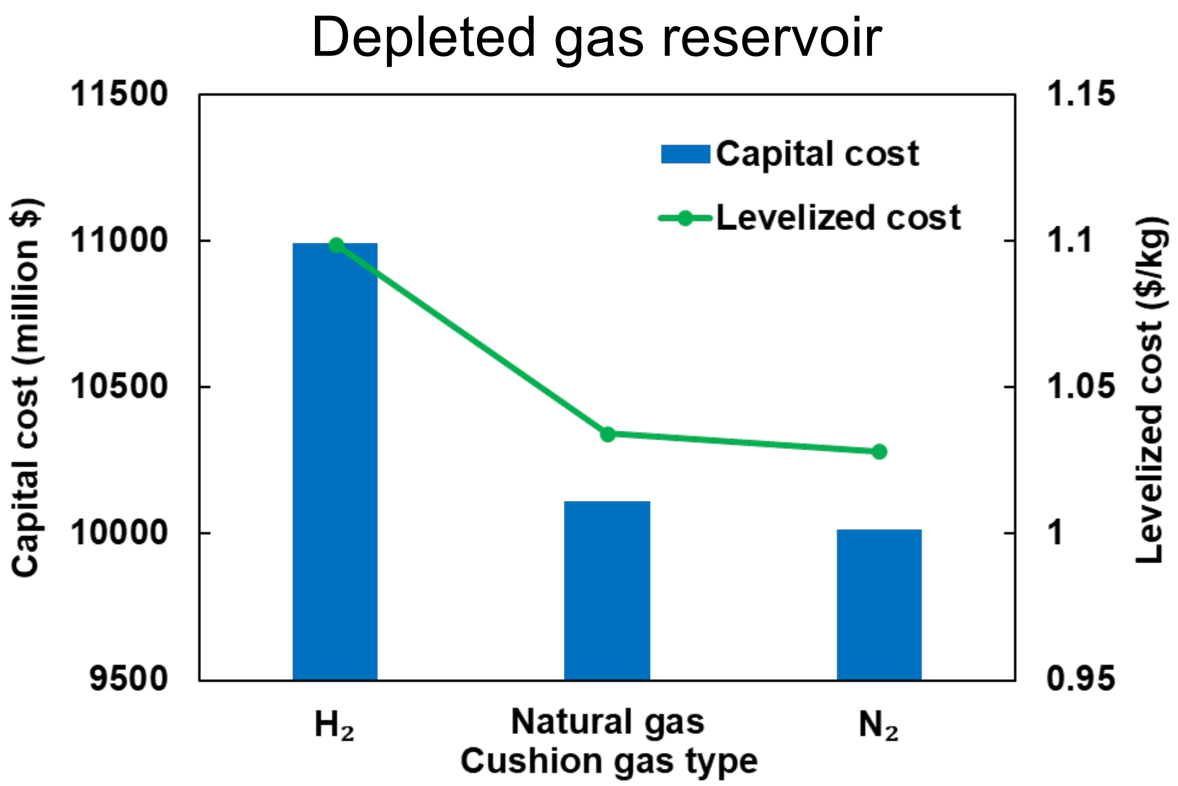
H_2 Storage cost: levelized costs of cases

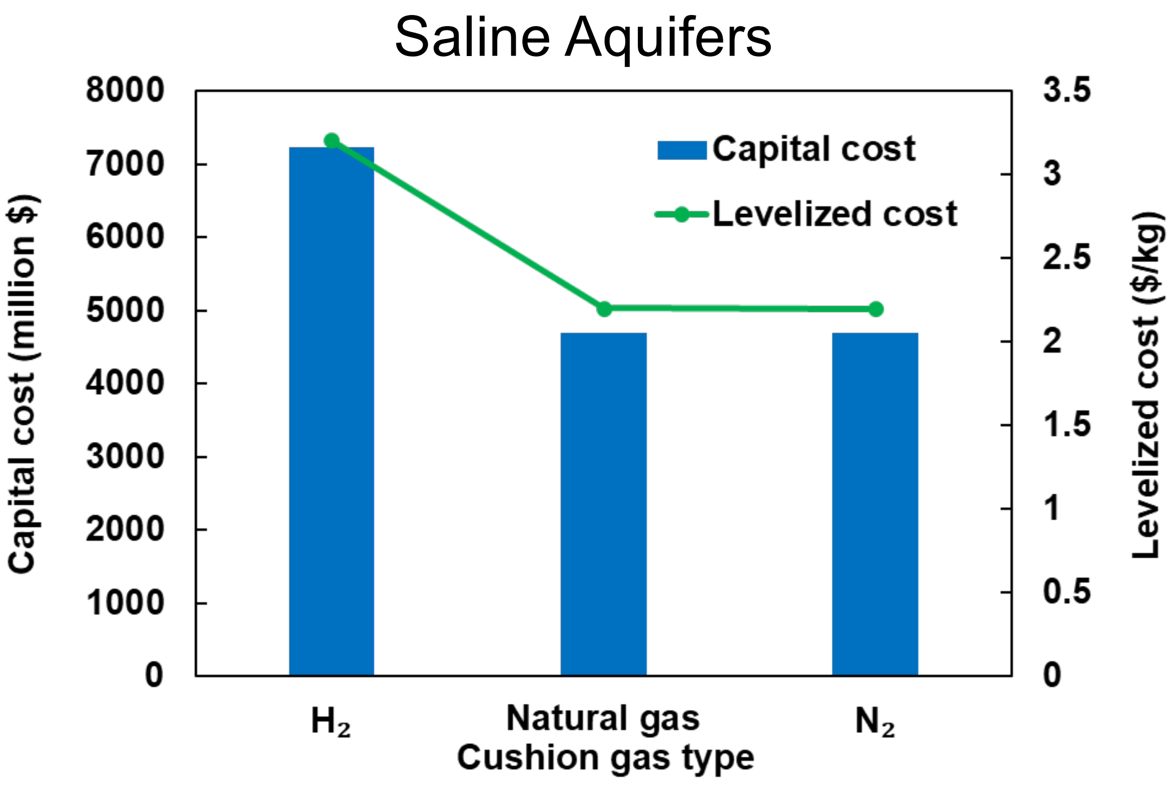


	Depleted gas reservoir	Salt cavern	Aquifer
Geological site	Watternberg field (CO)	Red Lake (AZ)	Baker dome (CO)
Levelized total capital cost ($/kg)	0.7927	1.9552	2.8644
Compressor levelized cost ($/kg)	0.2916	0.2916	0.2916
Well and surface pipeline levelized cost ($/kg)	0.0146	0.0503	0.0503
Levelized cost of H_2 storage ($/kg)	**1.0989**	**2.2971**	**3.2063**

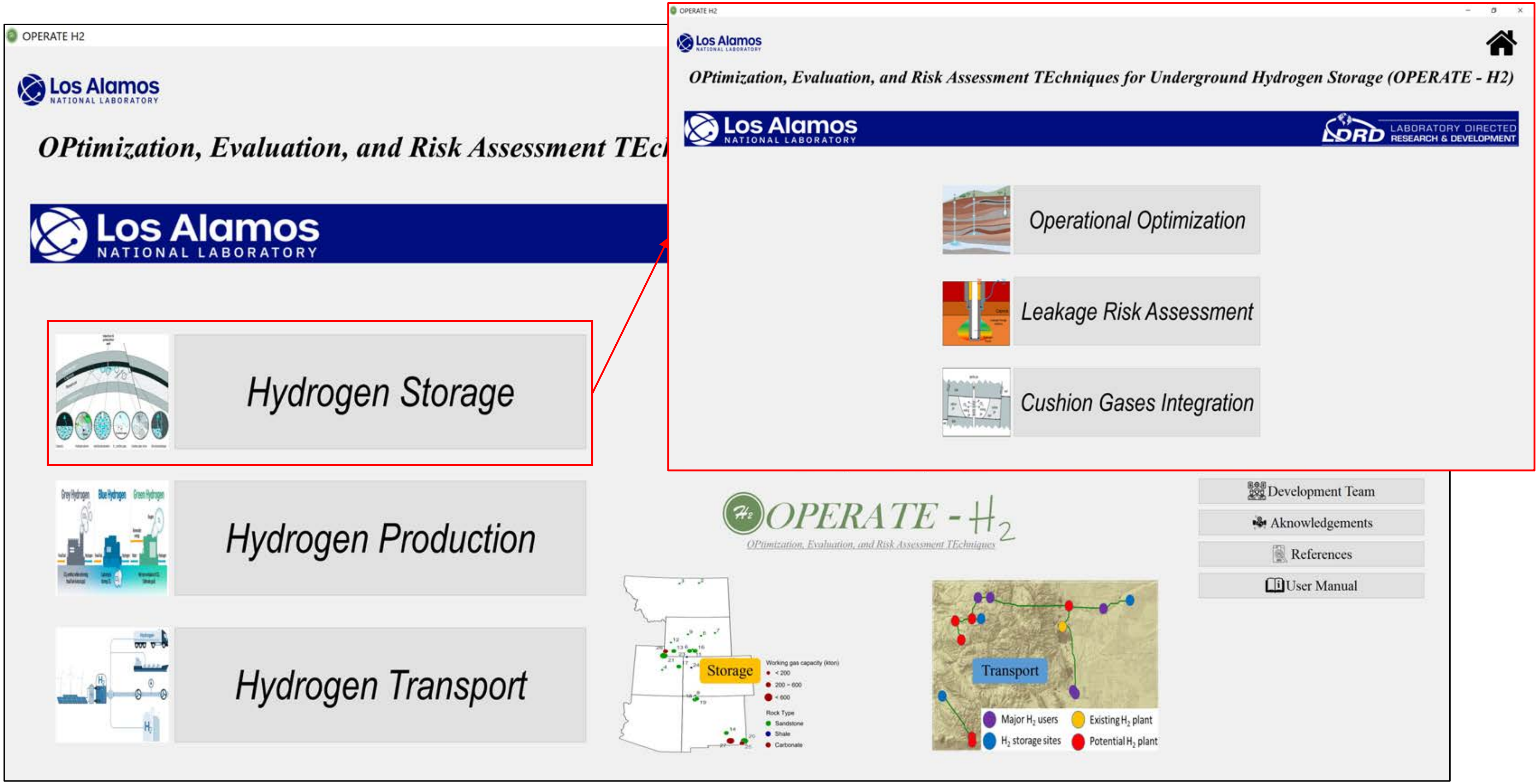
H_2 Storage cost: effect of cushion gas type

H_2: \$5/kg, natural gas: \$0.2553/kg, N_2: \$0.1826/kg, purification cost: \$2/kg H_2.





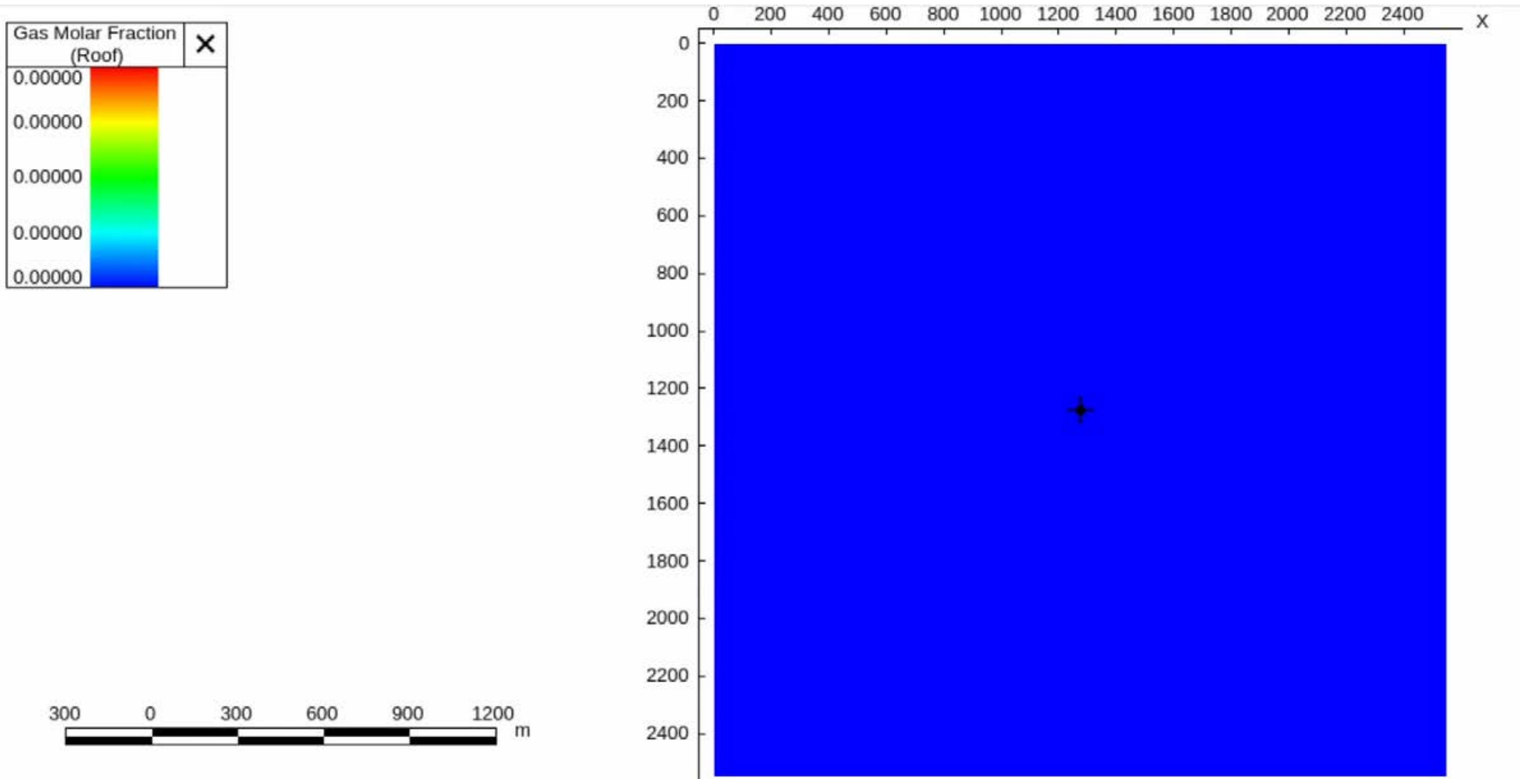
OPERATE-H_2


OPERATE H2
Los Alamos NATIONAL LABORATORY
OPtimization, Evaluation, and Risk Assessment TEchniques for Underground Hydrogen Storage (OPERATE - H2)
Los Alamos NATIONAL LABORATORY
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT
Operational Optimization
Leakage Risk Assessment
Cushion Gases Integration
Hydrogen Storage
Hydrogen Production
Hydrogen Transport
OPERATE - H2
OPtimization, Evaluation, and Risk Assessment TEchniques
Development Team
Aknowledgements
References
User Manual
Storage
Transport
Major H2 users
Existing H2 plant
H2 storage sites
Potential H2 plant
Working gas capacity (kton)
Rock Type
Sandstone
Shale
Carbonate

High-fidelity simulation of H_2 geologic storage

Comprehensive Datasets of high-fidelity Simulations to optimize

- Operations Optimization
- Leakage Risk
- Cushion Gas type and volume

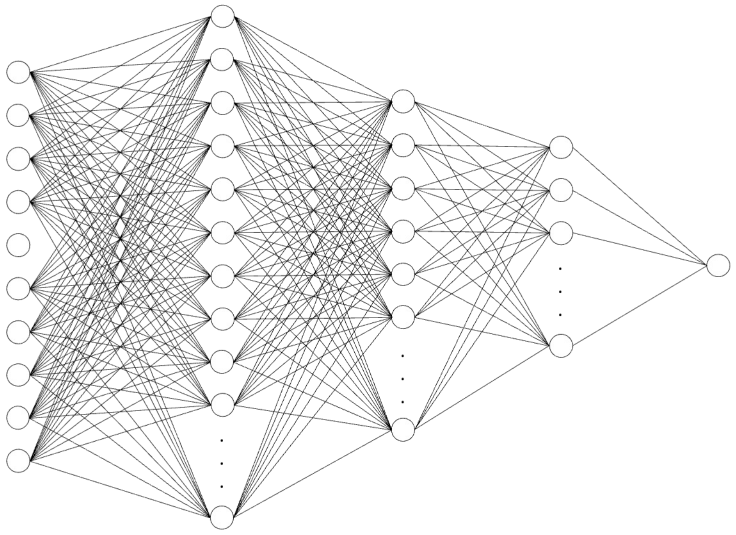


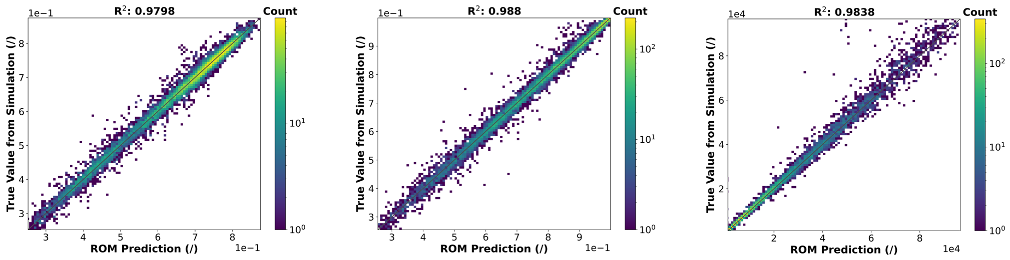
Reduced-Order Models (ROMs)

Uncertain Parameters

- Reservoir Depth
- Thickness
- Permeability
- Porosity
- Geothermal Gradient
- Net-to-Gross Ratio
- Injection Pressure Coefficient
- Production Pressure
- Initial Water Saturation

Artificial Neural Network (ANNs)





Objectives of Interest

Depleted Gas Reservoirs

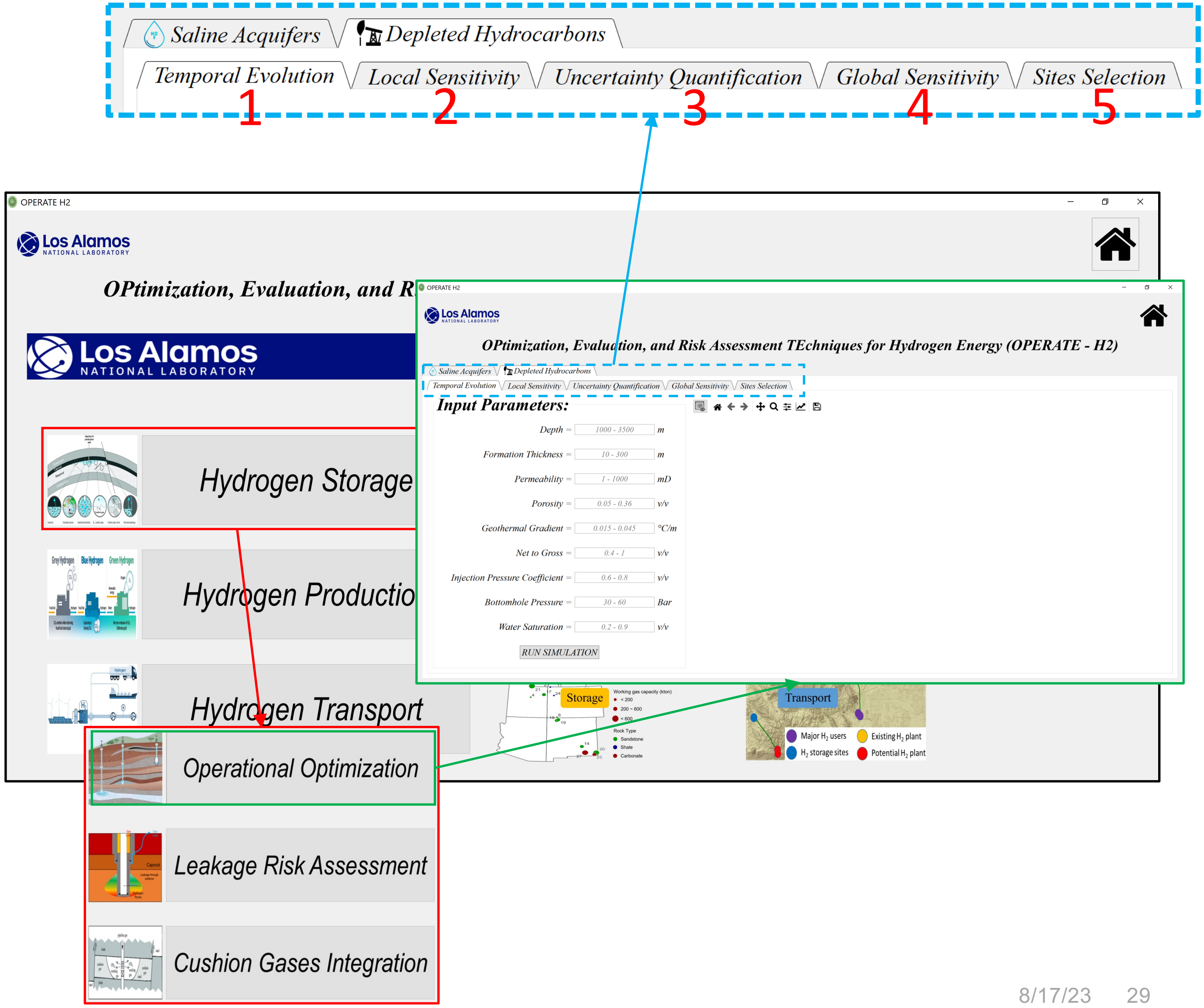
- H_2 Withdrawal Efficiency
- Produced H_2 Purity
- Produced Gas Water Ratio

Saline Aquifers

- H_2 Withdrawal Efficiency
- Produced Gas Water Ratio

OPERATE-H_2: Features and Functionalities

- Performance Evolution: visualize UHS performances across cycles.
- Local Sensitivity Analysis: study individual parameter impact on UHS.
- Uncertainty Quantification: identification of key UHS influencing factors with tornado plots
- Global Sensitivity Analysis: a comprehensive view of geologic and operational parameter interactions.
- Site Selection: identify the most promising sites for UHS operations



Evolution of UHS Performances Over Cycles

Efficiency:

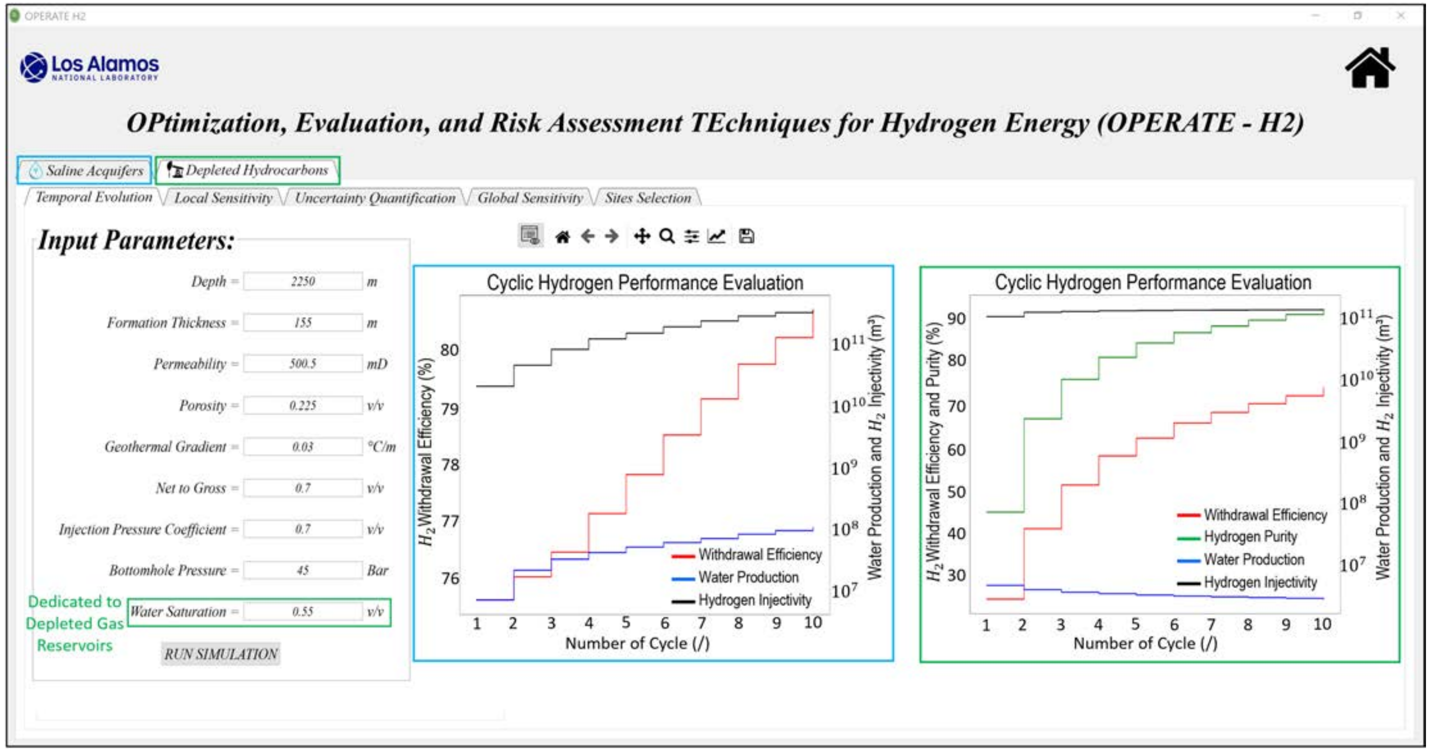
- Improves across cycles.

Hydrogen Purity:

- Aquifers: High purity standards.
- Depleted Gas Reservoirs: Risk of contamination

Water Production:

- Aquifers: High water production
- Depleted Gas Reservoirs: Lower water production



Uncertainty Quantification on UHS parameters

Withdrawal Efficiency

- Depth, permeability, and PINJ.

Hydrogen Purity

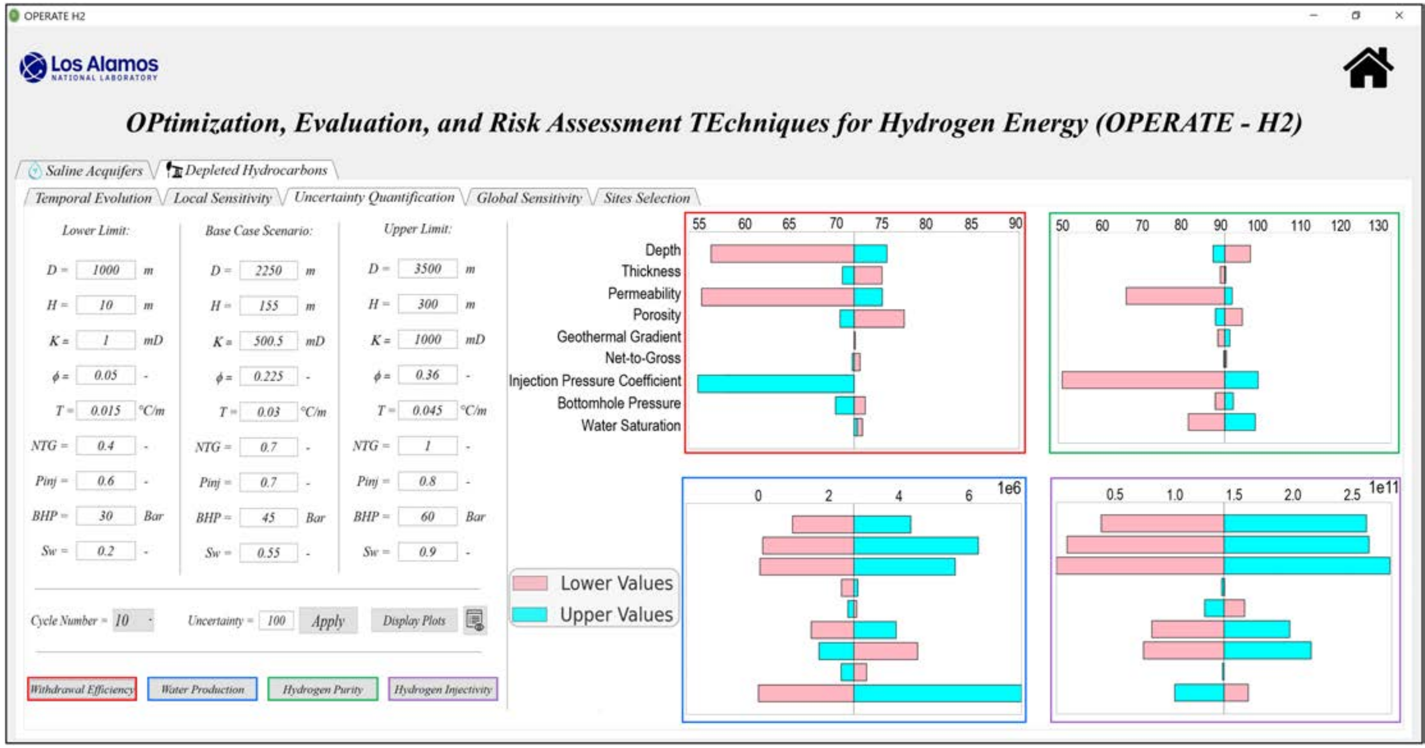
- PINJ, permeability, water saturation, reservoir depth.

Injection Capacity

- Depth, formation thickness, permeability.

Water Production

- Depth, thickness, permeability, net-to-gross ratio, and PINJ.



Site Screening - Depleted Gas

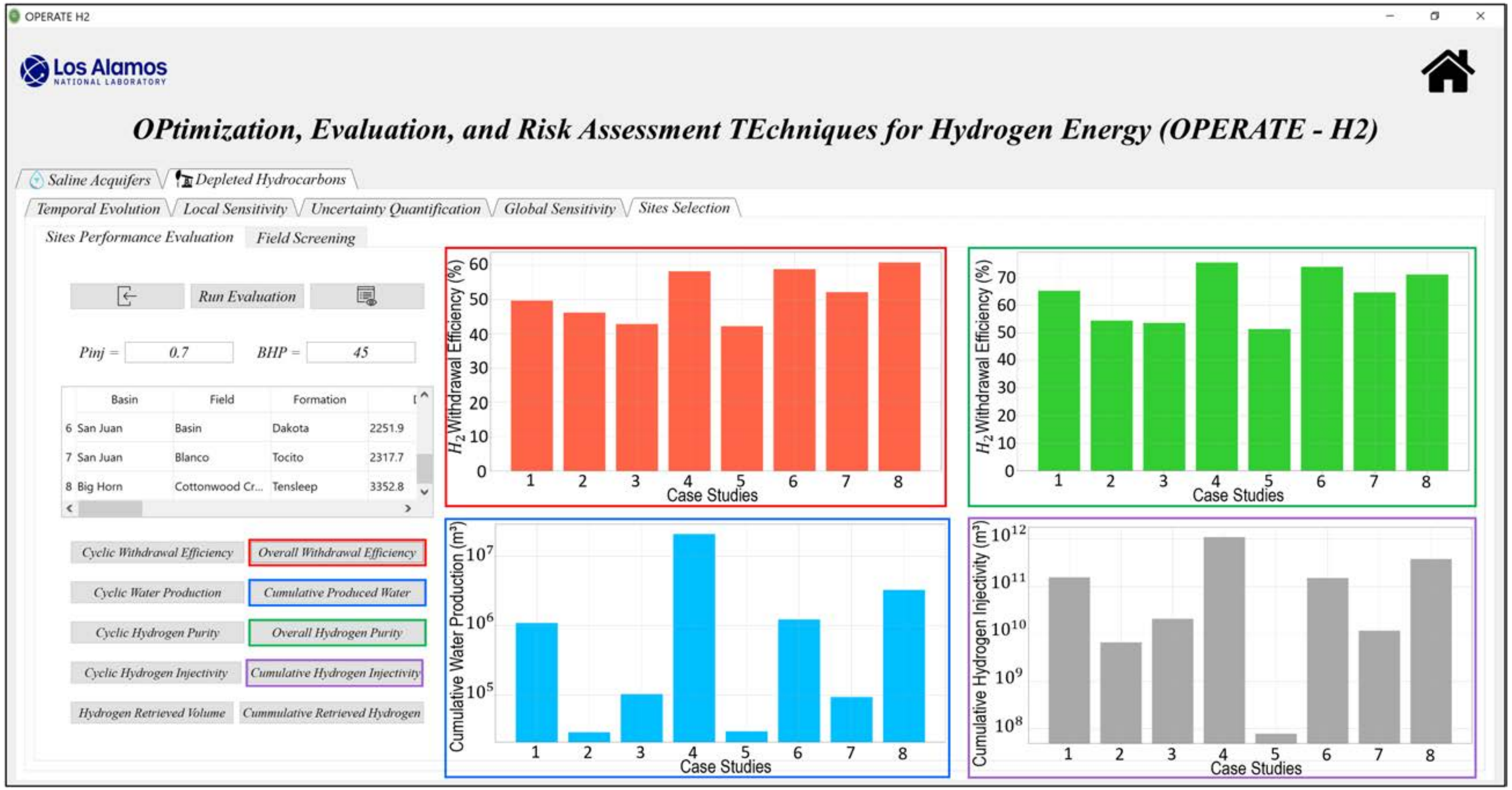
Withdrawal Efficiency

Hydrogen Purity

Injectivity

Water Production

	State	Basin	Field	Formation	Depth	Thickness	Porosity	Permeability	Geothermal Gradient	Water Saturation
1	Colorado	Anadarko	Arapahoe	Morrow	1641.3	222.5	0.133	50.60	-	-
2		Denver-Julesburg	Wattenberg	Greenhorn	2859.8	71.5	0.09	2	-	0.30
3				Lyons	2639.0	122	0.172	7.84	0.043	-
4		San Juan	Ignacio Blanco	Dakota	2484.7	122	0.23	370	-	0.51
5	Montana	Williston	North Buffalo	Red River	2742.5	29.56	0.2	8	0.036	0.38
6	New Mexico	San Juan	Basin	Dakota	2251.9	16.5	0.2	400	0.03	0.4
7			Blanco	Tocito	2317.7	15.24	0.15	52.5	-	0.36
8	Wyoming	Big Horn	Cottonwood Creek	Tensleep	3352.8	22.86	0.16	425	-	-



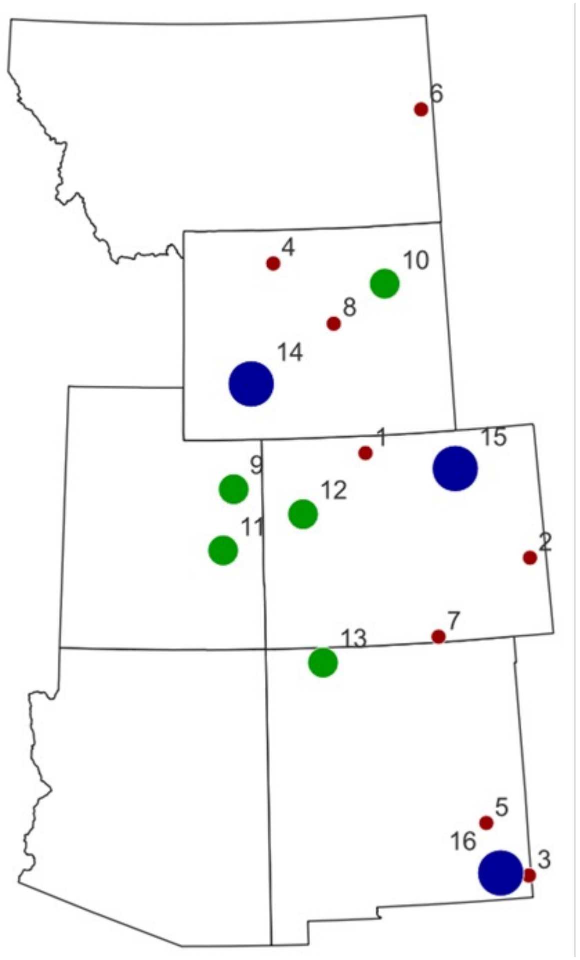
H_2 production methods using natural gas and coal

Fossil fuel	Production method	H_2 Production (kg H_2/kg fuel)	CO_2 footprint (kg CO_2/kg H_2)
Natural gas	Steam methane reforming (SMR)	0.26-0.29	9.4-11.4
	Auto thermal reforming	0.31-0.35	8.4-11.0
	Pyrolysis	0.22-0.25	1.8-4.9
Coal	Surface Coal Gasification (SCG)	0.06-0.15	16.4-23.4
	Underground Coal Gasification (UCG)	0.04-0.12	17.1-35.6

Cost Estimation – Assumptions

- The lifetime of a H_2 production plant is 25 years. The discount rate and inflation factor are 7% and 2.5%, respectively.
- The H_2 production capacities of SMR, SCG, and UCG plants are 63, 0.1, and 0.2 million tons/year.
- The financial year is 2022 and the currency is the US dollar.
- The capacity of CO_2 injection well is 1 million tCO_2/year and the pressure of CO_2 in pipelines is 9 MPa.
- CO_2 is assumed to be stored in underground storage formations at an average depth of 1,500 m below the surface.
- The captured CO_2 is either stored underground for CO_2 sequestration or converted to formic acid for CO_2 utilization. Pipelines are required for sequestration. Formic acid plants are built near CO_2 capture sites.

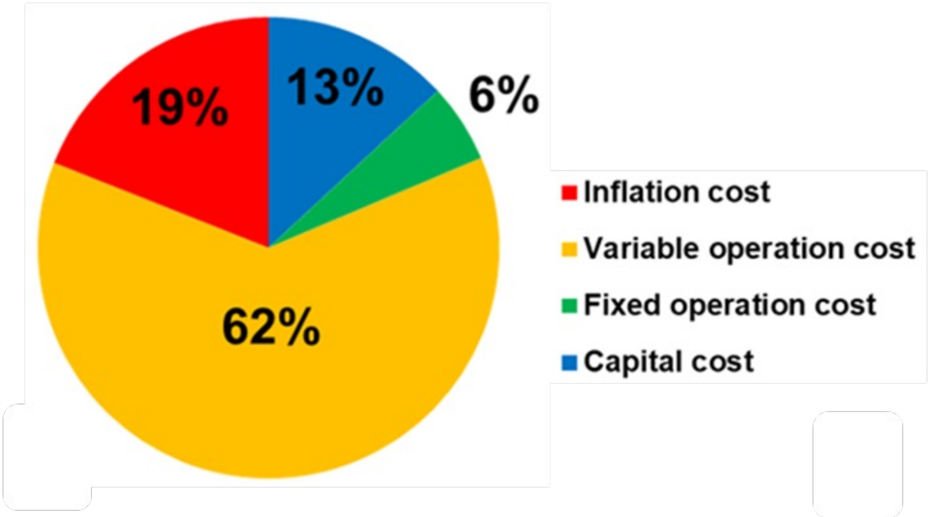
Potential H_2 production from natural gas (SMR) and cost

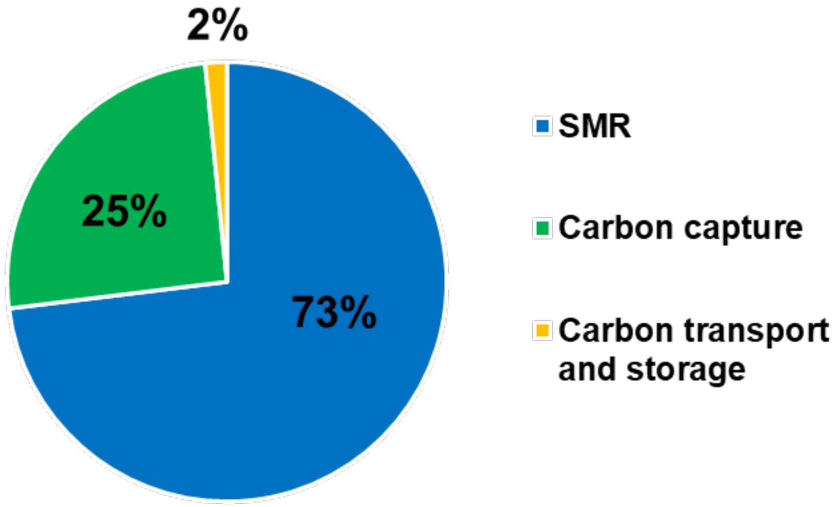


H2 production (million ton)
- <1
- 1~5
- >5

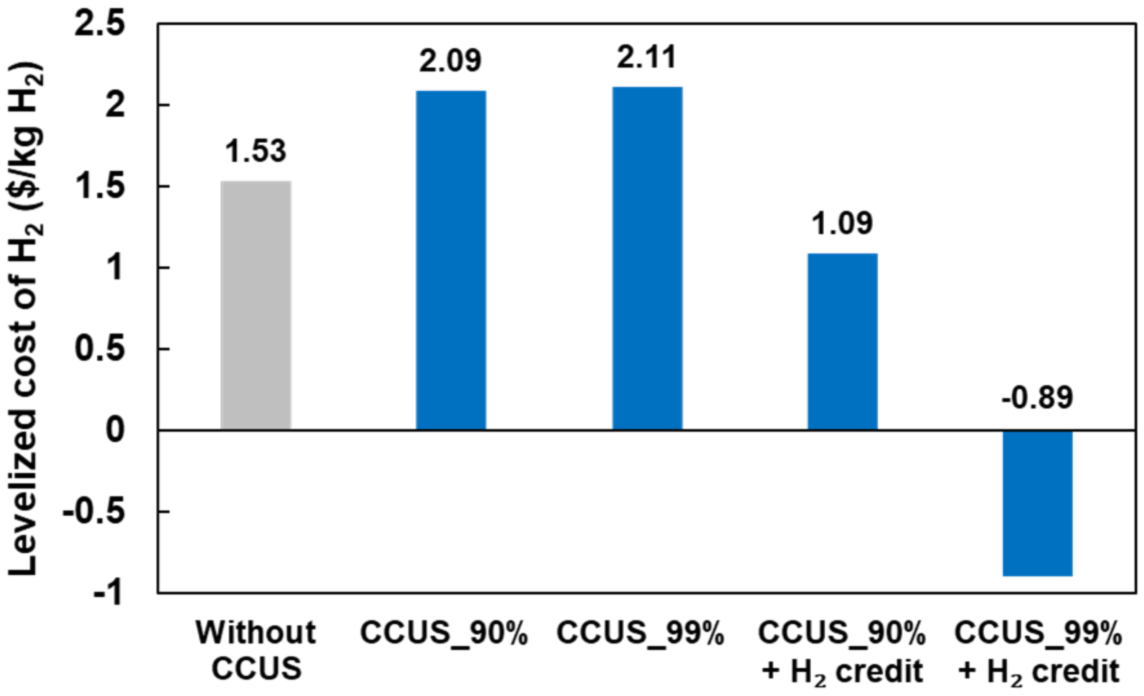
1. North Park
2. Anadarko
3. Central Basin Platform
4. Big Horn
5. Northwest Shelf
6. Williston
7. Raton
8. Wind River
9. Uinta
10. Powder River
11. Paradox
12. Piceance
13. San Juan
14. Green River
15. Denver
16. Delaware

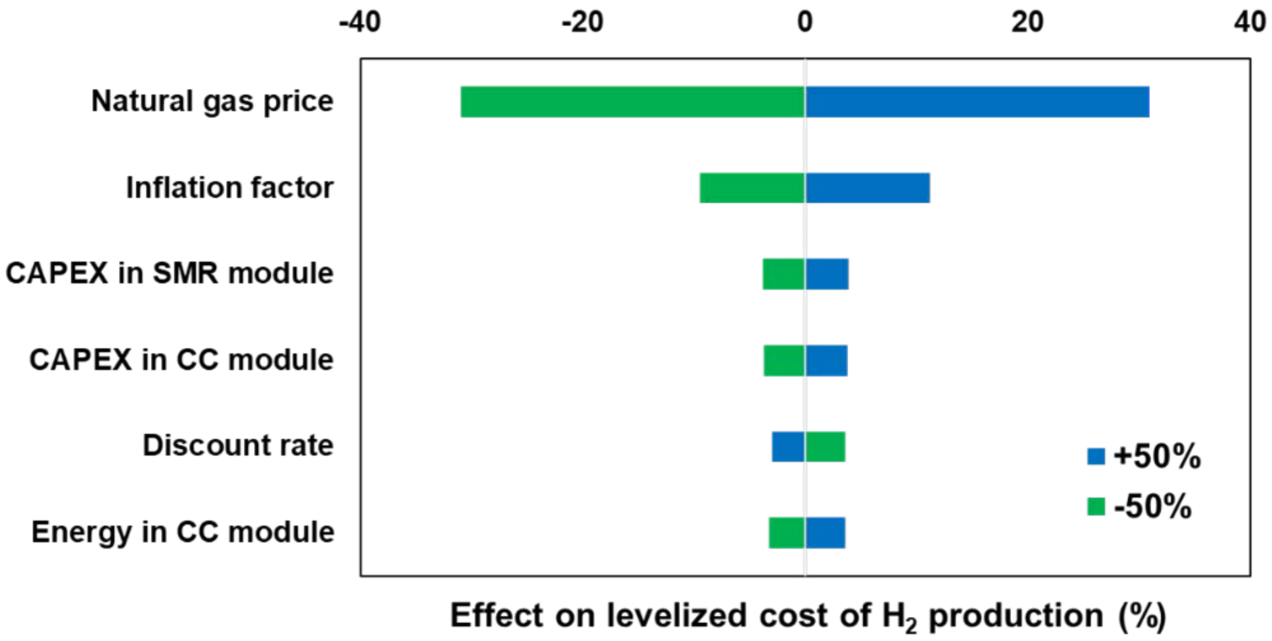
San Juan Basin



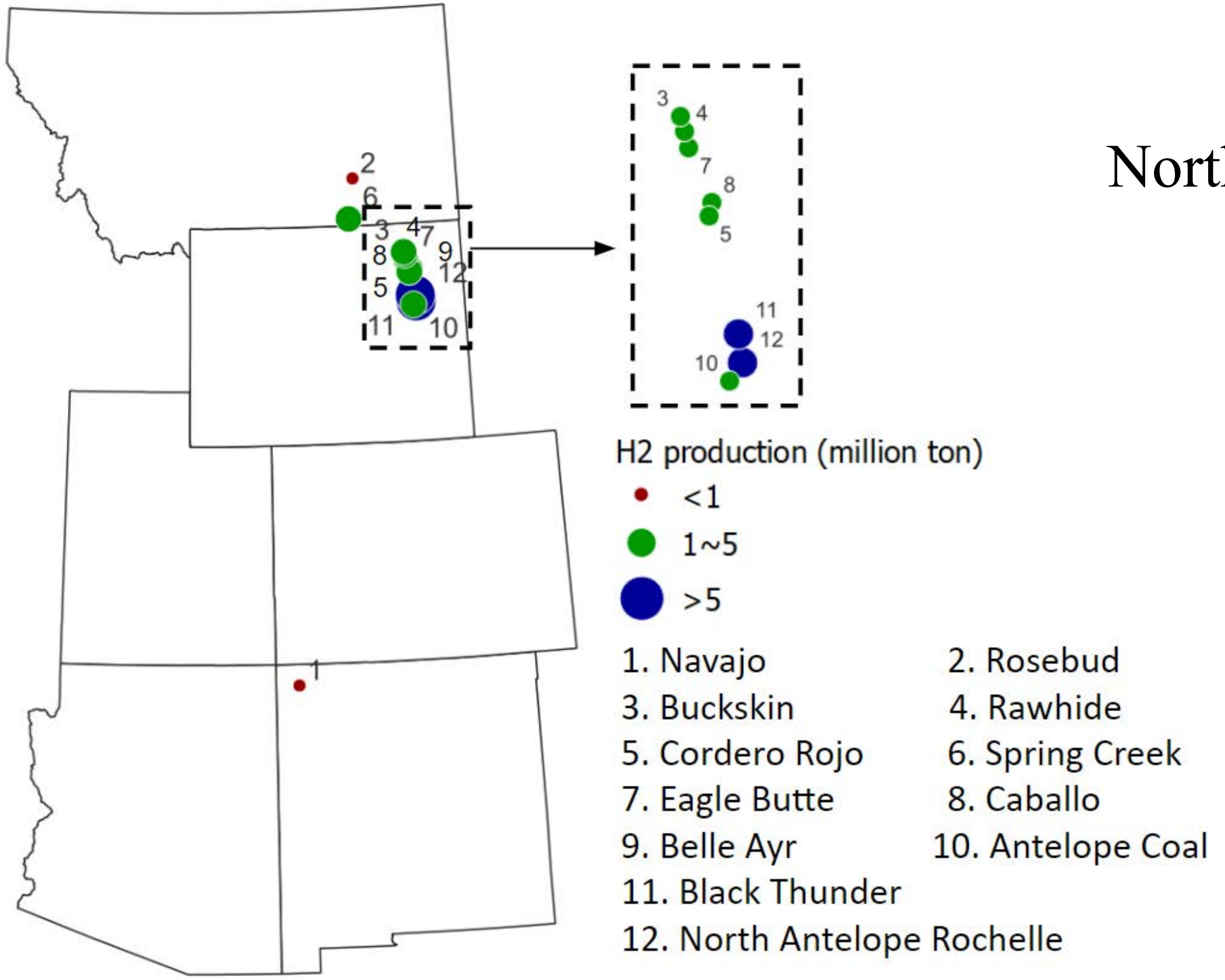


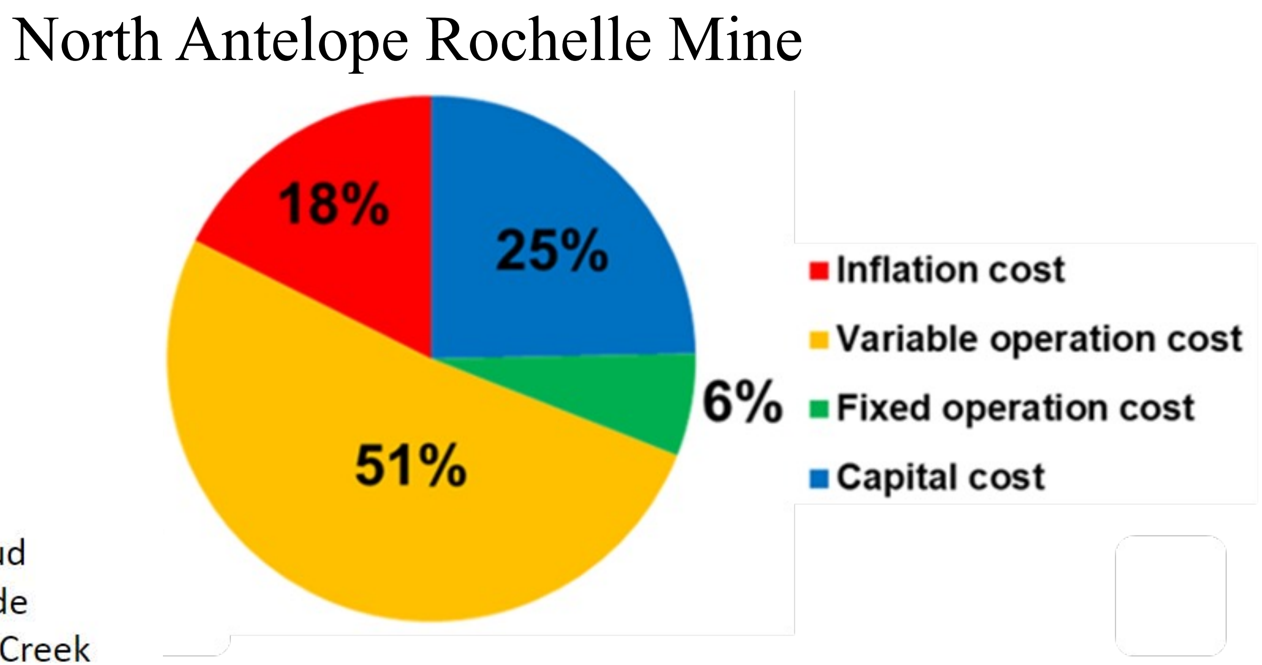
Cost estimation of H_2 production using SMR



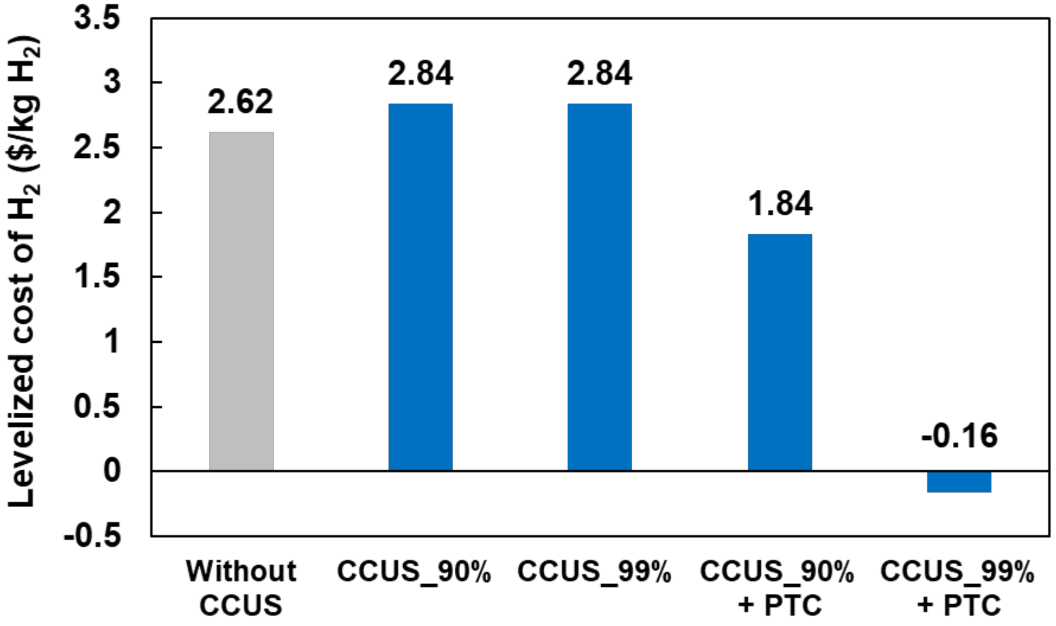


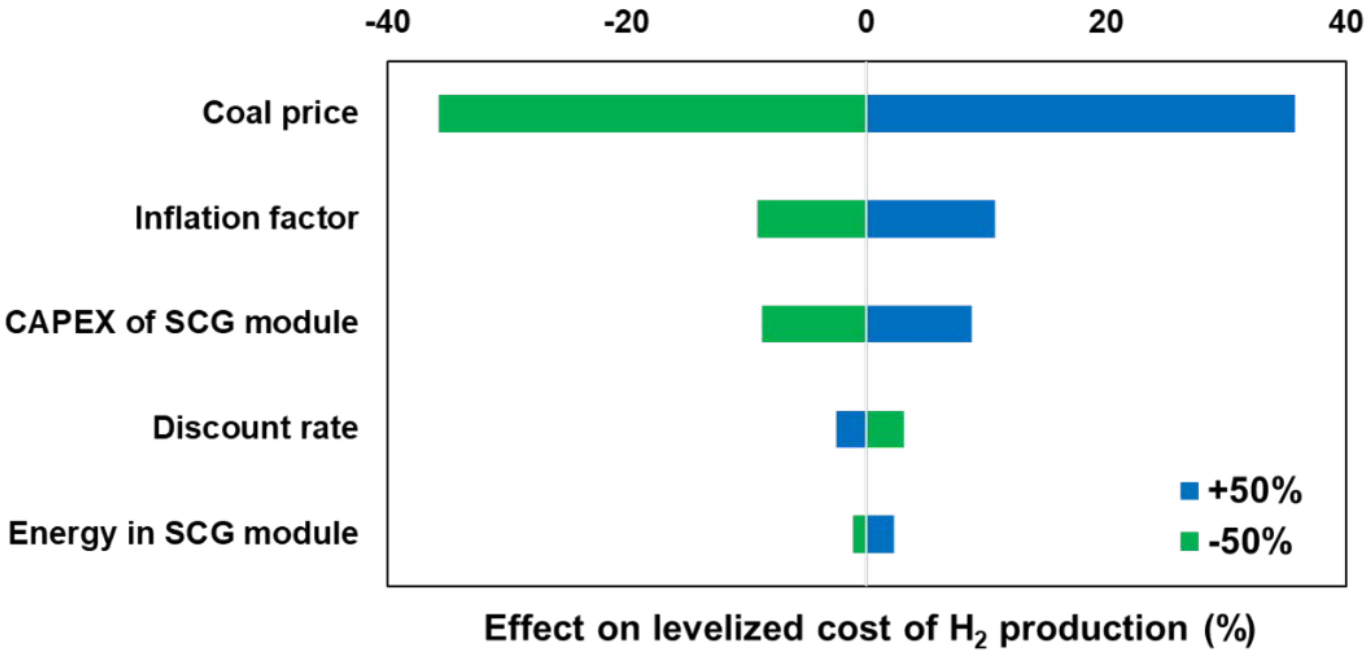
Potential H_2 production from coal (SCG) and cost



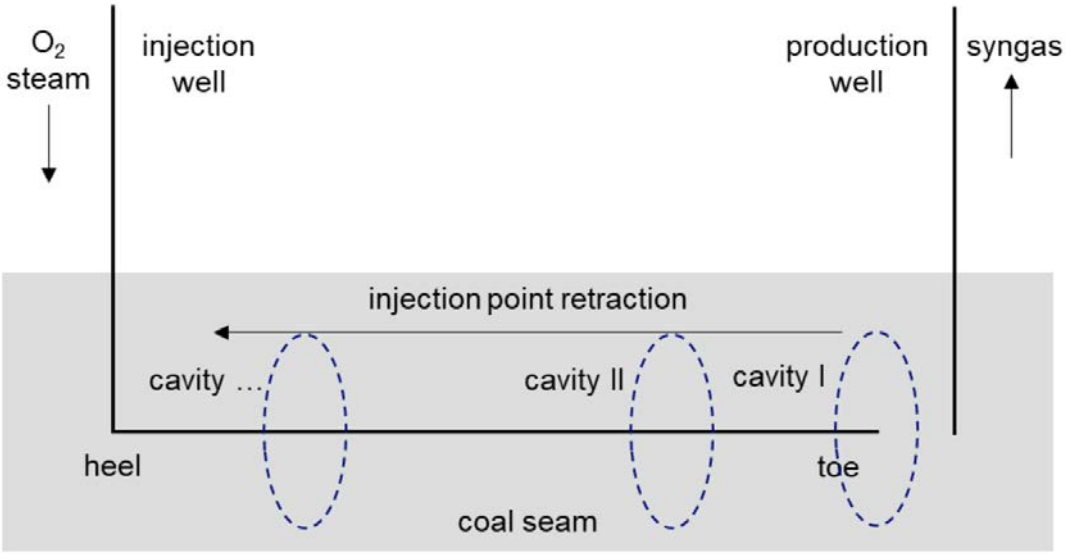


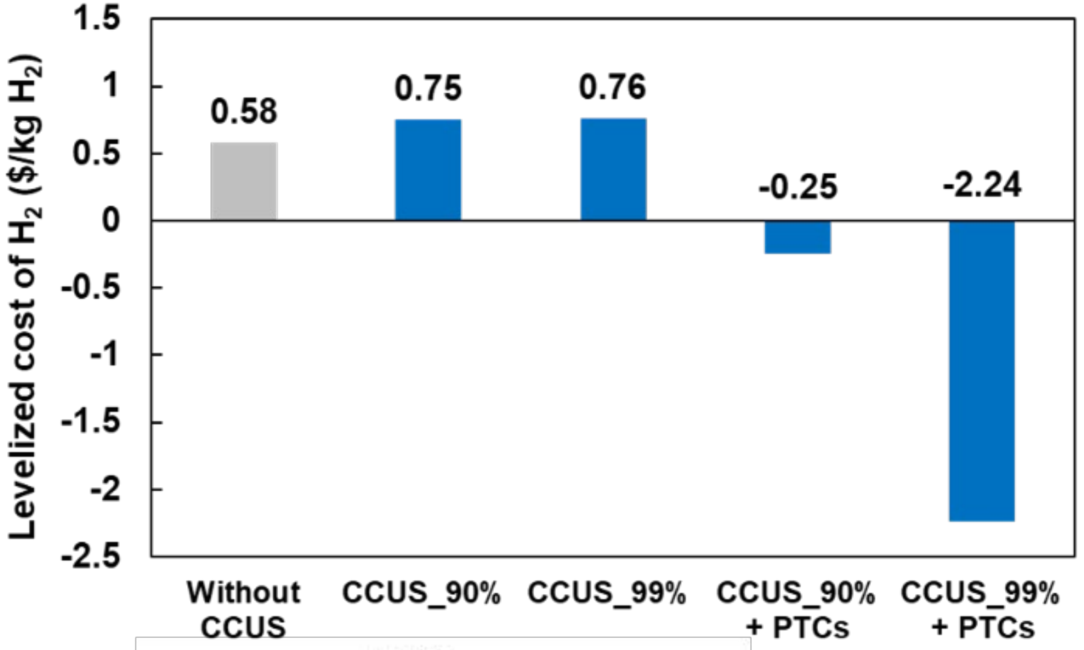
Cost estimation of H_2 production using SCG

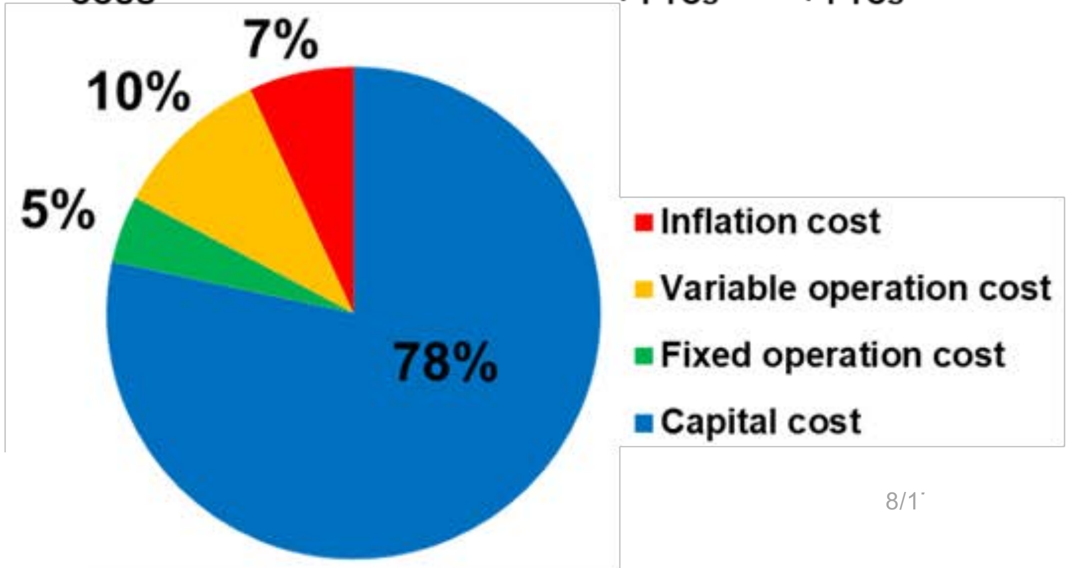




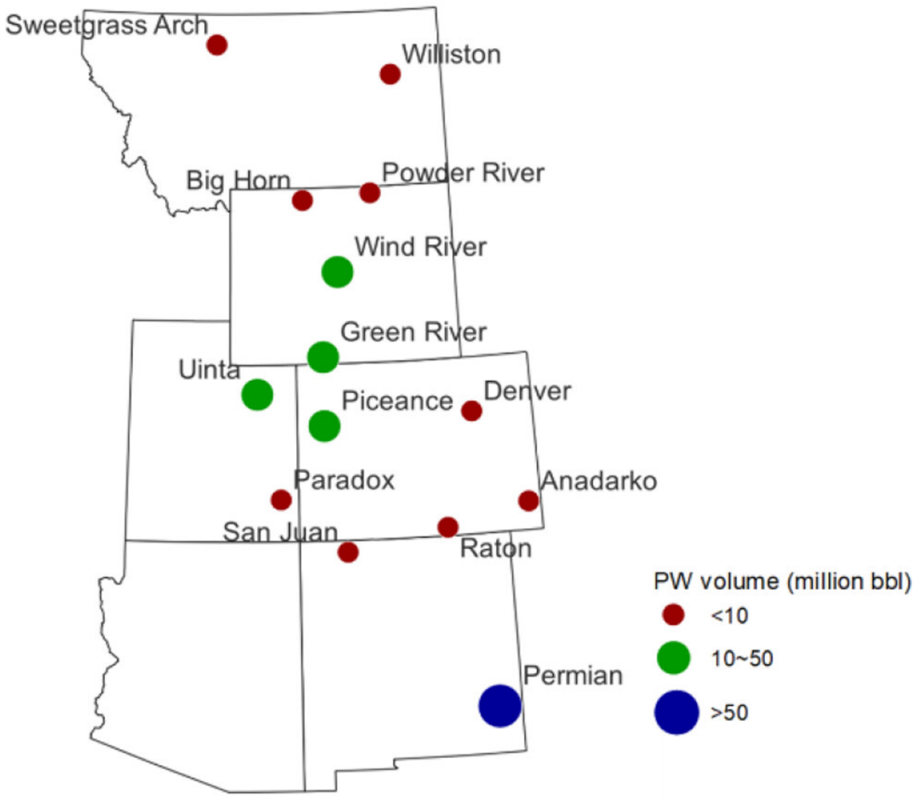
Cost estimation of H_2 production using UCG

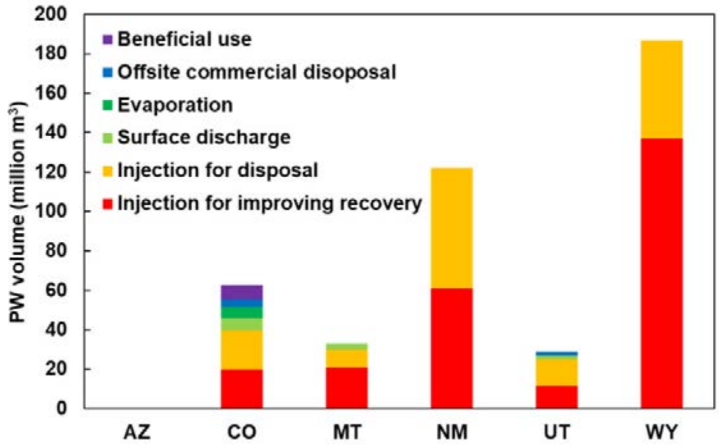


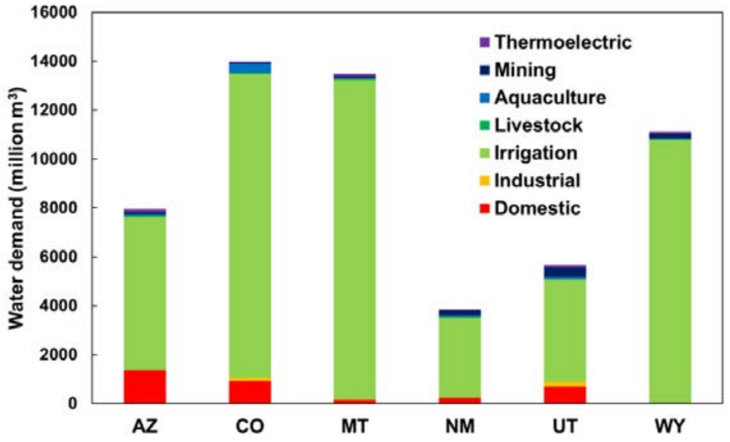


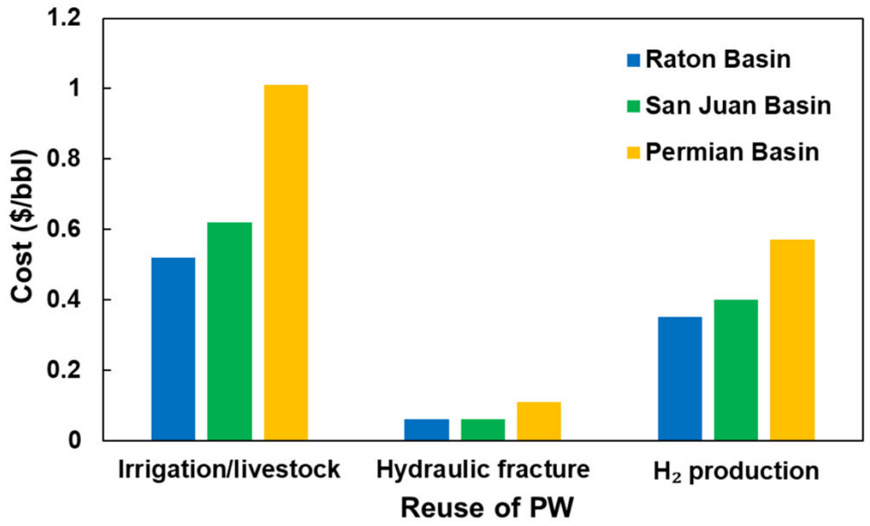


Reuse of Produced Water in the I-West Region

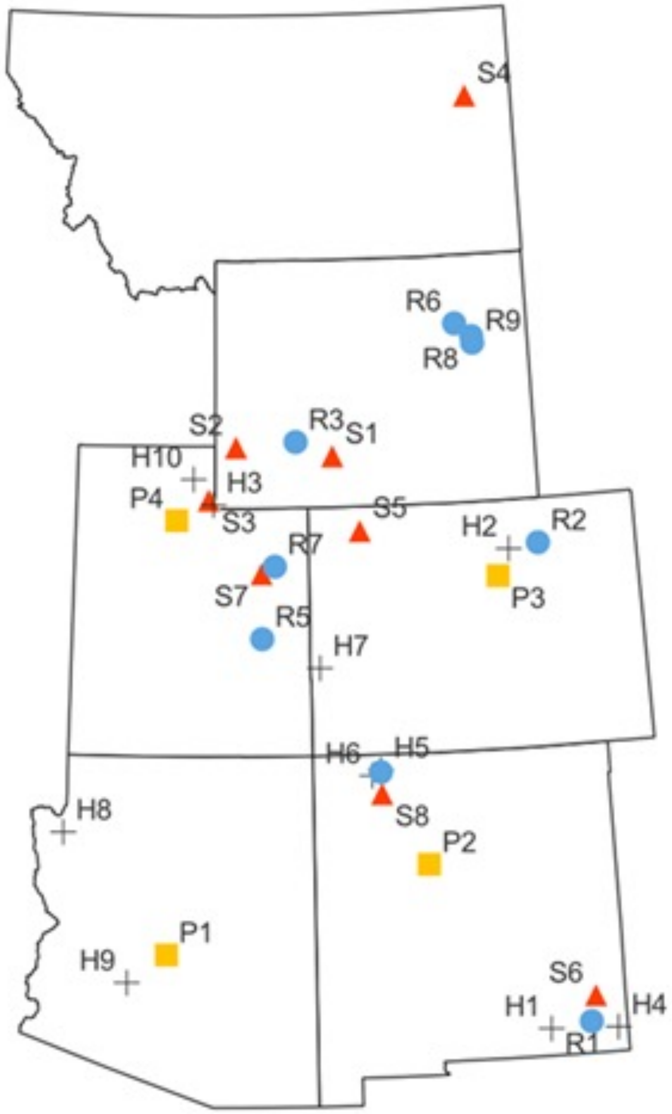








Potential H_2 Hub Sites



● H2 Production Sites
+ H2 Storage Sites
■ Densely Populated Regions
▲ CO2 Sequestration Sites

H_2 Production Sites:
R1: Delaware
R2: Denver-Julesburg
R3: Green River-Overthrust
R4: San Juan
R5: Paradox
R6: Powder River
R7: Uinta
R8: Black Thunder
R9: North Antelope Rochelle

H_2 Storage Sites:
H1: Indian
H2: Wattenberg
H3: Anschutz Ranch East
H4: Eumont-Jalmat
H5: Blanco (Mesaverde)
H6: Basin (Dakota)
H7: Paradox H8: Red Lake
H9: Luke
H10: Wyoming Thrust Belt

Densely Populated Regions:
P1: Phoenix (Maricopa)
P2: Albuquerque (Bernalillo)
P3: Denver (Denver)
P4: Salt Lake City (Salt Lake)

CO_2 Sequestration Sites:
S1: Green River-Nugget2
S2: Wyoming Thrust Belt-Tensleep4
S3: Wyoming Thrust Belt-Tensleep5
S4: Williston-Red River2
S5: Green River-Nugget1
S6: Permian-Canyon4
S7: Uinta-Morrison7
S8: San Juan-Morrison2

Thank You!!

Mzm@lanl.gov and Eric.Guiltinan@lanl.gov

Los Alamos NATIONAL LABORATORY