USGS
science for a changing world

Northwestern University DEEPS lecture
May 21st, 2025 - Evanston, IL, USA

An overview of research on emerging subsurface energy technologies at the U.S. Geological Survey

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Carbfix second generation CO_2 injection site Iceland basalts 2024

U.S. Department of the Interior
U.S. Geological Survey

Introduction

U.S. Geological Survey (USGS)

- **Science agency within Department of Interior since 1879**
- **Objective and impartial science to policymakers & stakeholders (public, resource managers, etc.)**
- **Non-partisan, non-regulatory**
- **Positions: Geoscientists, hydrologists, biologists, analysts, technicians, data scientists, etc.**
- **Research in a Federal agency compared to academic setting**
- **Talk today: scientific observations not policy/advocacy**

Our Mission

The USGS monitors, analyzes, and predicts current and evolving Earth-system interactions and delivers actionable information at scales and timeframes relevant to decision makers.

What We Do

The USGS is a primary Federal source of science-based information on ecosystems, land use, energy and mineral resources, natural hazards, water use and availability, and updated maps and images of the Earth's features available to the public.

USGS

from https://www.usgs.gov/about/about-us/who-we-are

Introduction

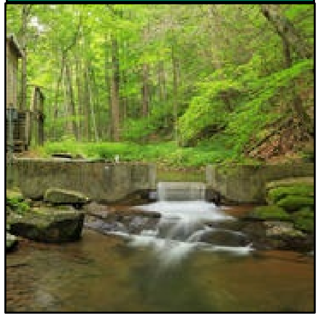
U.S. Geological Survey

Dept. of the Interior

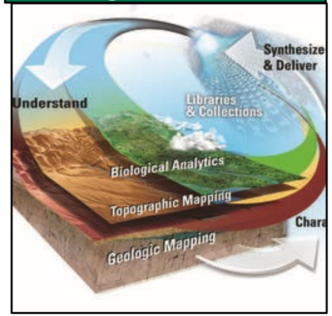
USGS

USGS mission areas

Water



Core Science Systems



Energy & Minerals

Ecosystems

Natural Hazards

"EMMA" programs

Minerals Resource Program

Energy Resource Program

An overview of research on emerging subsurface energy technologies at the U.S. Geological Survey

USGS-ERP Vision

"The Energy Resource Program (ERP) delivers the science necessary to inform decision making as the world's energy landscape evolves."

Lecture outline

1. Take stock of the current U.S. energy landscape

2. New roles for the subsurface in energy

a. Geologic energy storage

b. CO_2 mineralization and critical minerals

3. Other emerging USGS energy research and final thoughts

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Evolving energy landscape

Part 1: What is the current U.S. energy "portfolio"?

How do we produce & consume energy?

How are greenhouse gas (GHG) emissions trending?

Which new technologies are ascendent?

Pointers for students

-note the sourcing of energy data

-try to conceptualize "scale" and units of quantitative measure

-at intermission, brief peer discussion

-at end, time for detailed questions/discussion

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Evolving energy landscape

Electric power production – U.S.

units and scale

Power = rate that energy is transferred	**Watts (kW, MW, GW, TW)** home → town → metro → nation
Energy = capacity to do physical work	**Watt-hours (kWh, MWh, GWh, TWh)** home → town → metro → nation

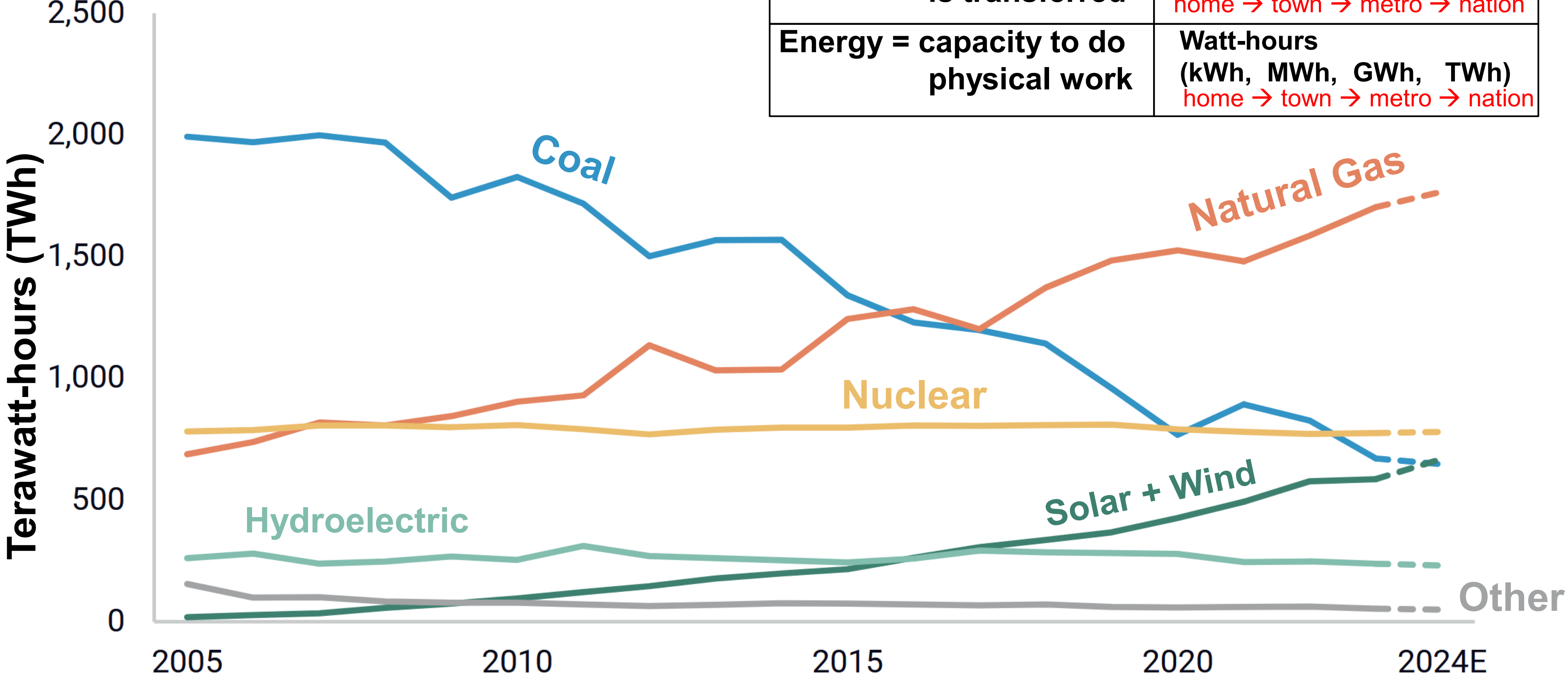


Figure: modified from Gaffney and others (2025)

Data source: U.S. Energy Information Agency "EIA" (Department of Energy)

Evolving energy landscape

Emissions by major sector – U.S.

- **recent U.S. GHG emissions reduction primarily from electrical power generation transition**
  - **coal → natural gas + wind + solar**

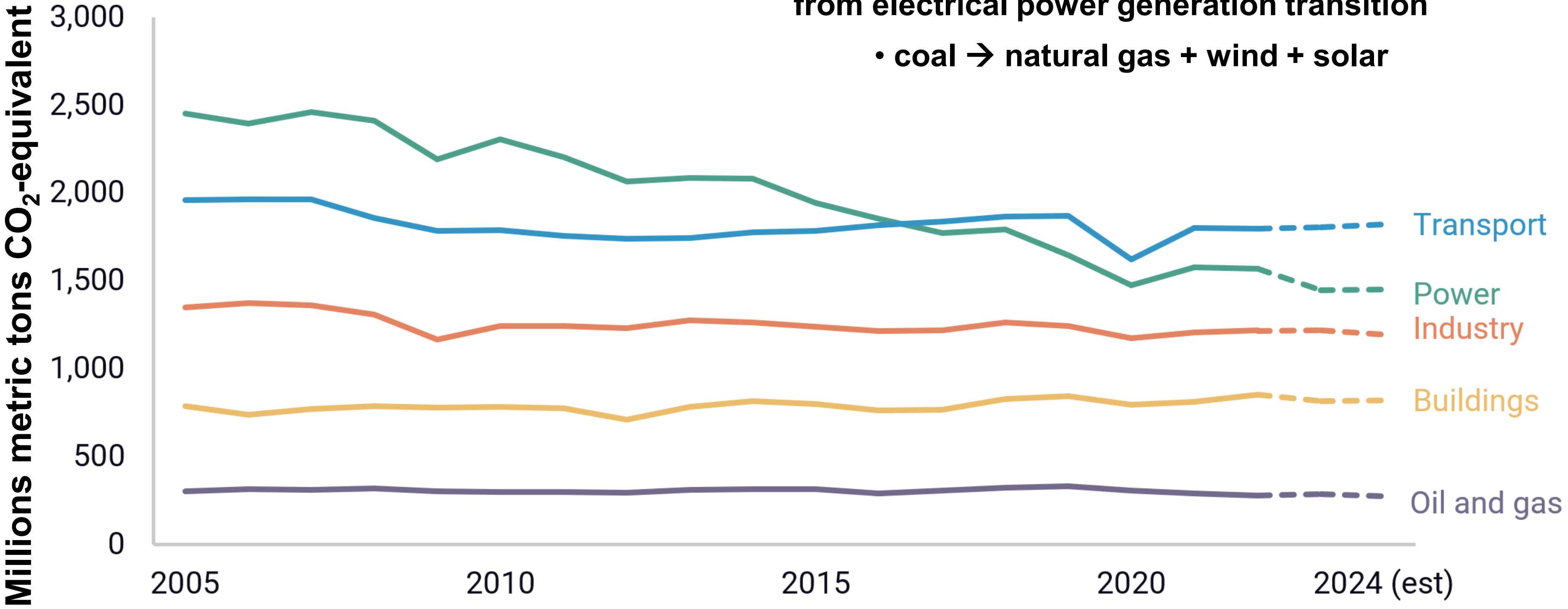
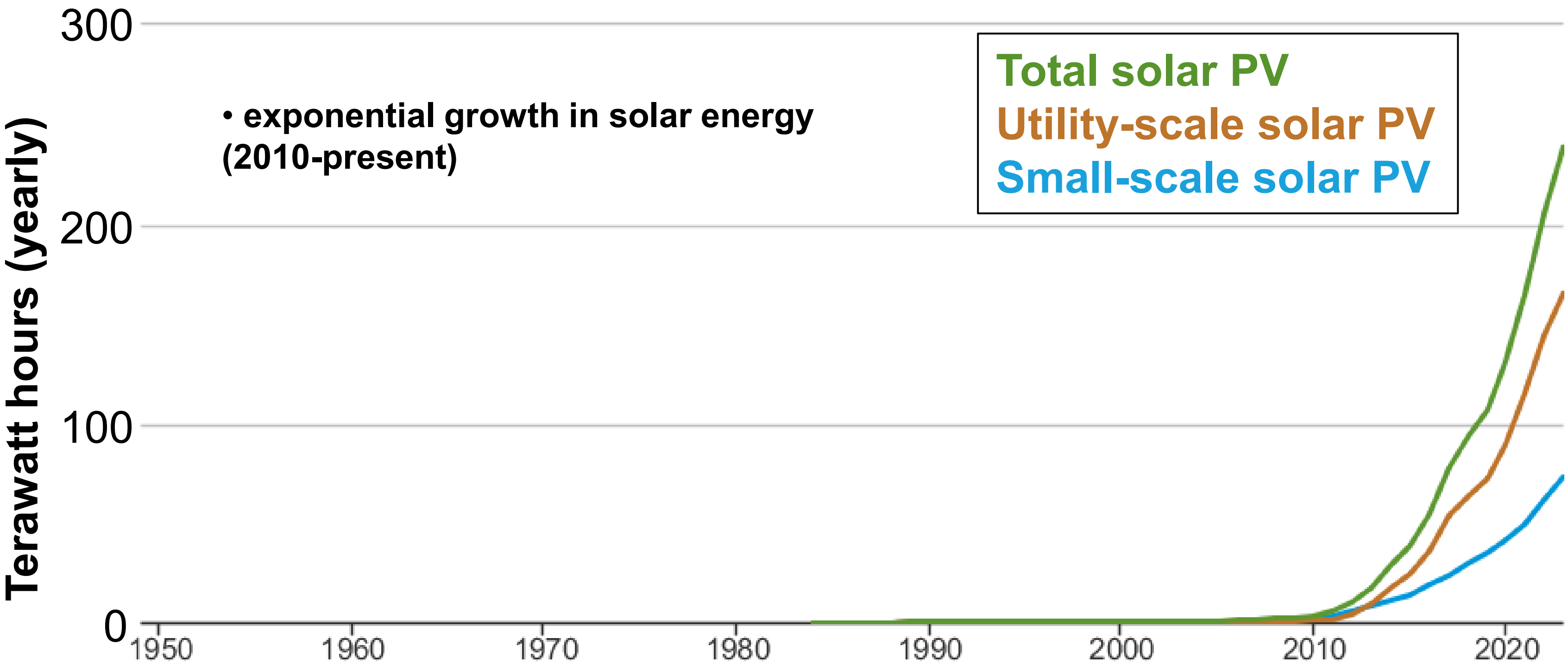


Figure: modified from Gaffney and others (2025)
Data source: U.S. Environmental Protection Agency "EPA"

Evolving energy landscape

Annual solar photovoltaic (PV) net electric generation - USA



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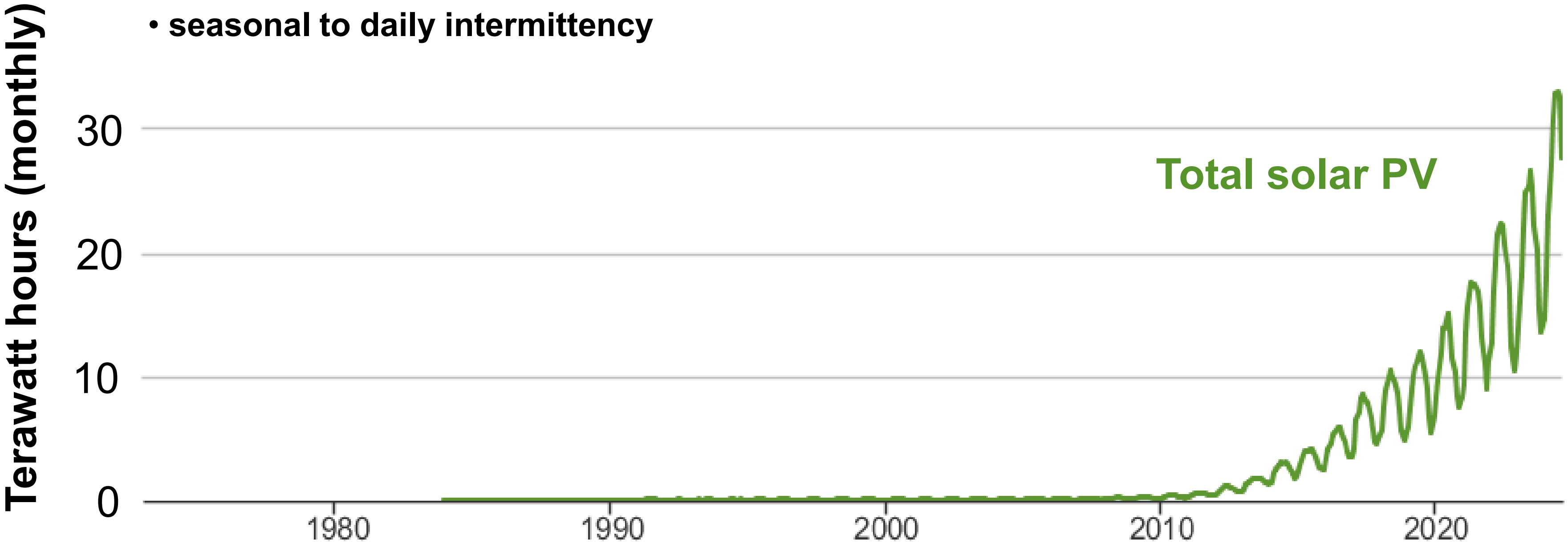
eia Data source: U.S. Energy Information Administration (2025)

Evolving energy landscape

Monthly solar photovoltaic (PV) net electrical generation - USA

- **“intermittency”: variable power output**
- **seasonal to daily intermittency**



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eia Data source: U.S. Energy Information Administration (2025)

Evolving energy landscape

Solar PV power intermittency

California net grid load = electric demand – (solar + wind production)

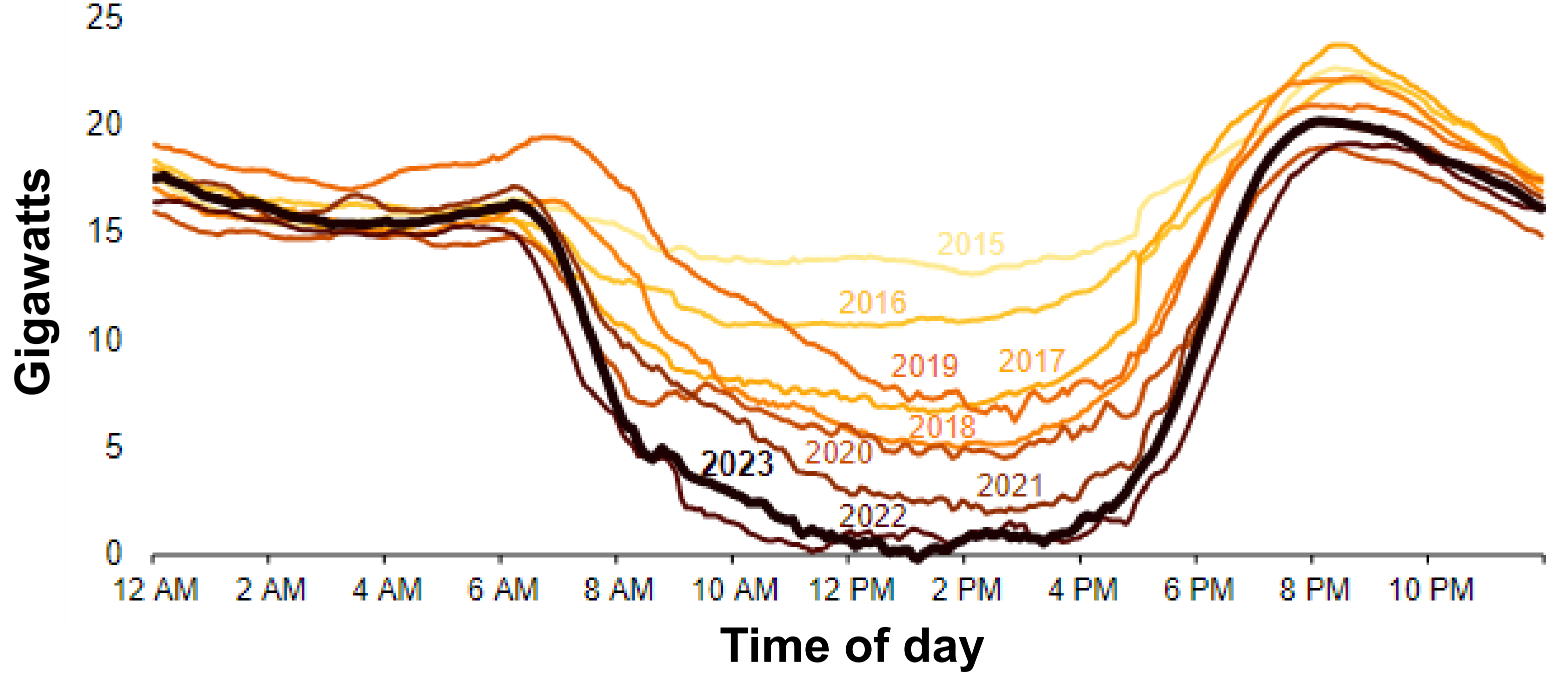

Figure: modified from U.S. Energy Information Agency (2023)

Evolving energy landscape

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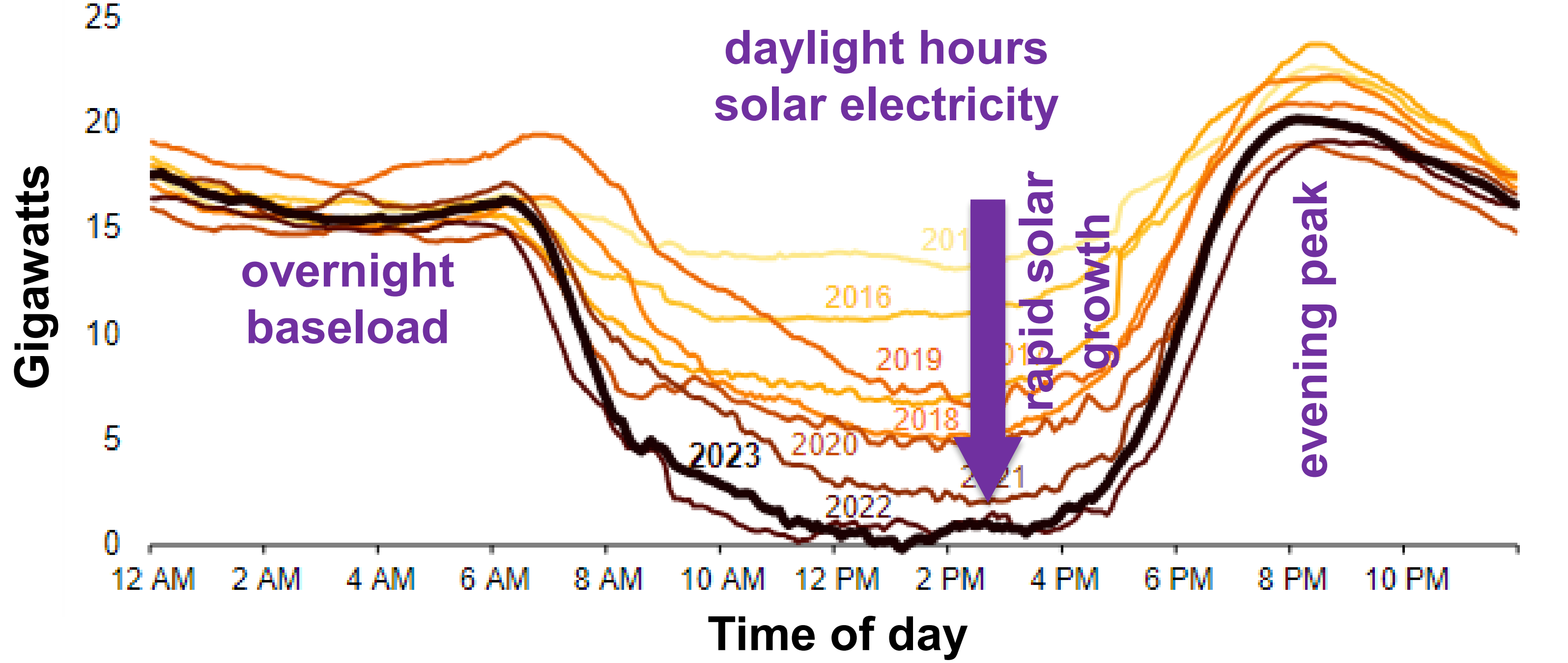

Figure: modified from U.S. Energy Information Agency (2023)

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Evolving energy landscape

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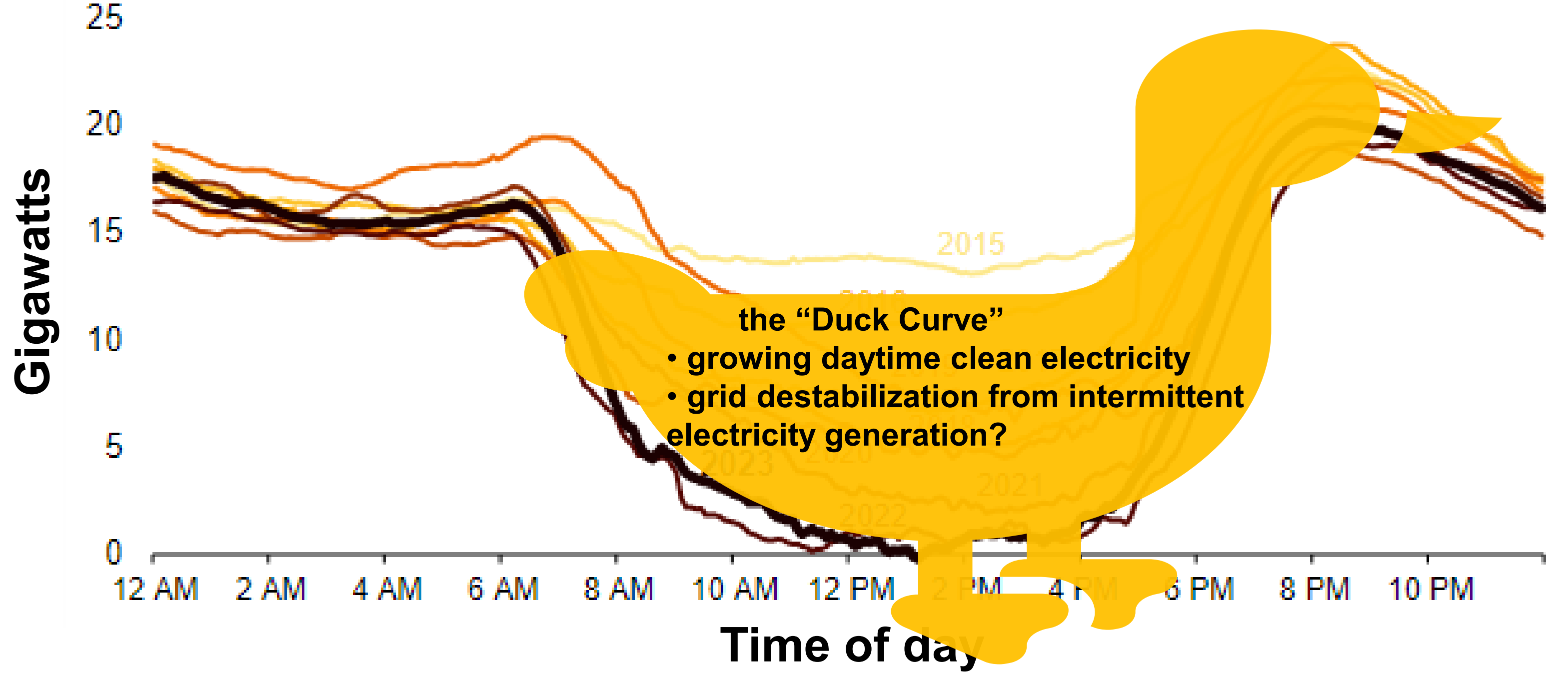

Figure: modified from U.S. Energy Information Agency (2023)

Evolving energy landscape

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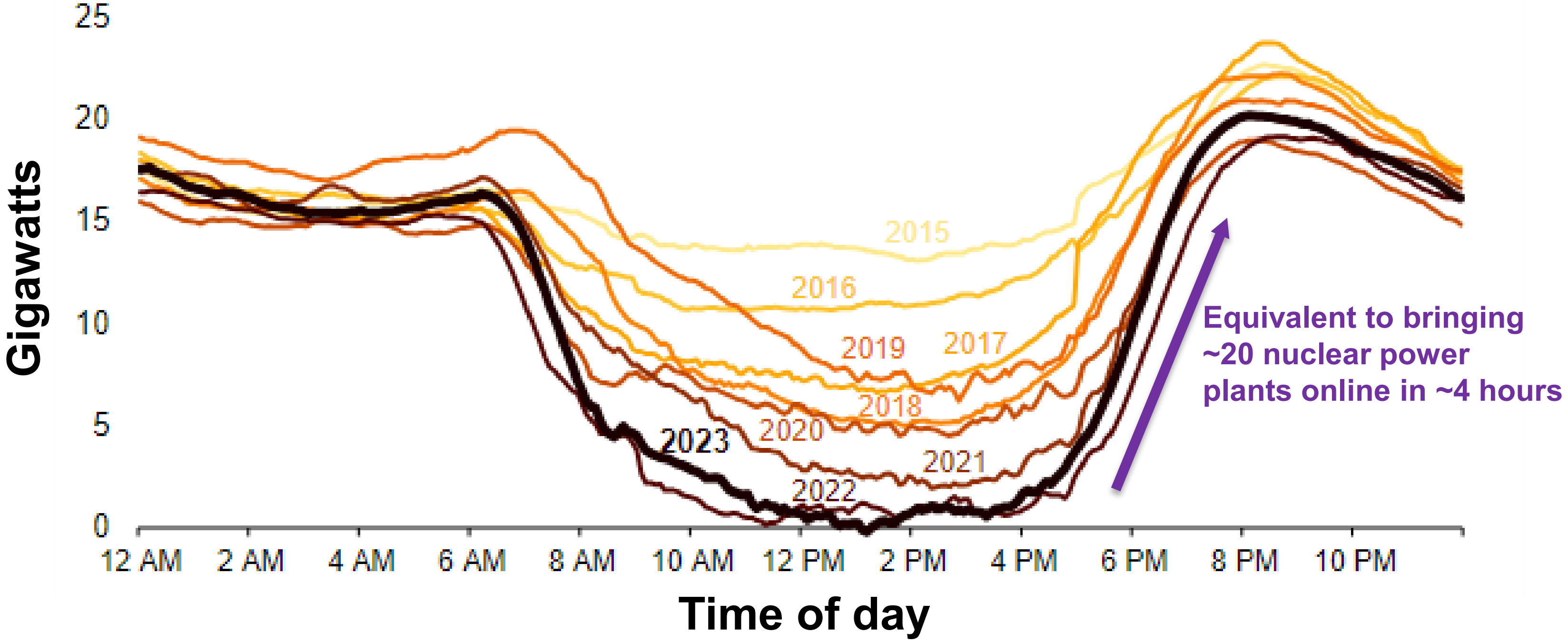

Figure: modified from U.S. Energy Information Agency (2023)

Evolving energy landscape

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California net grid load = electric demand – (solar + wind production)

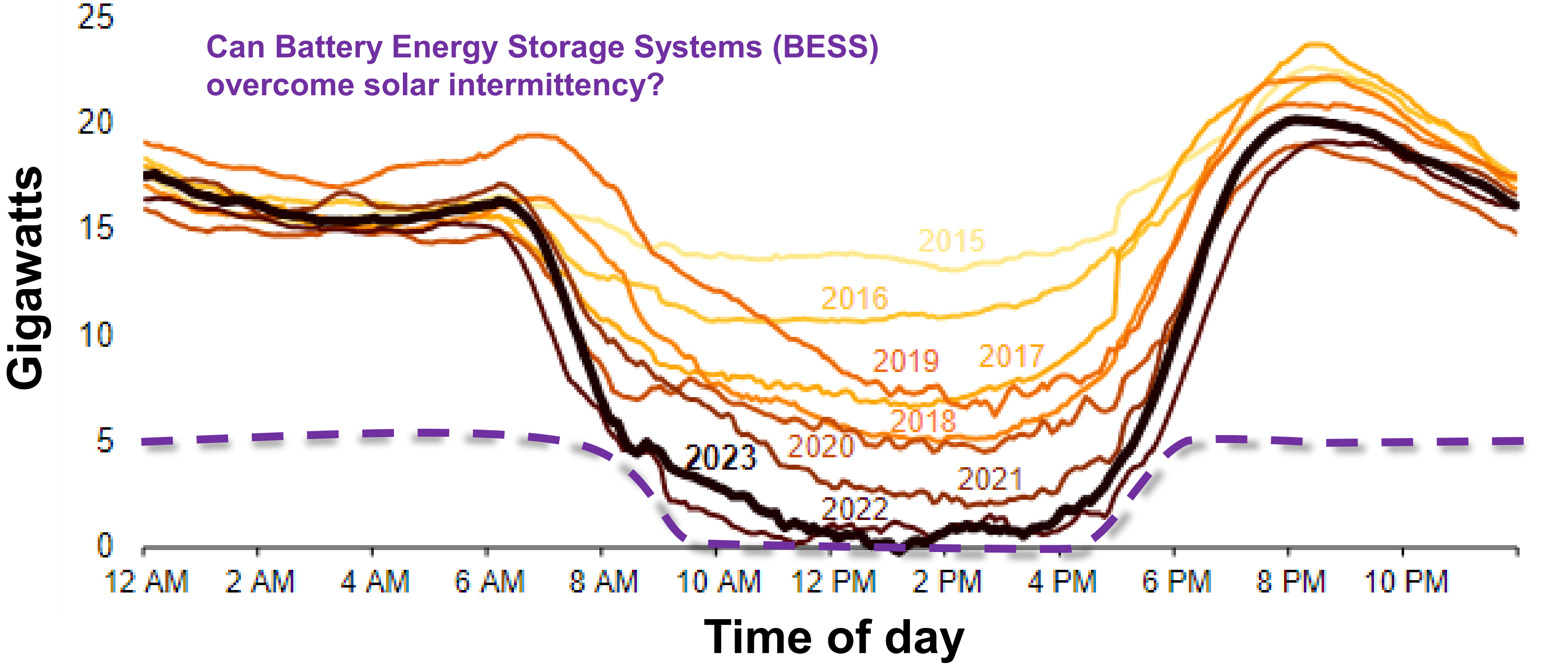

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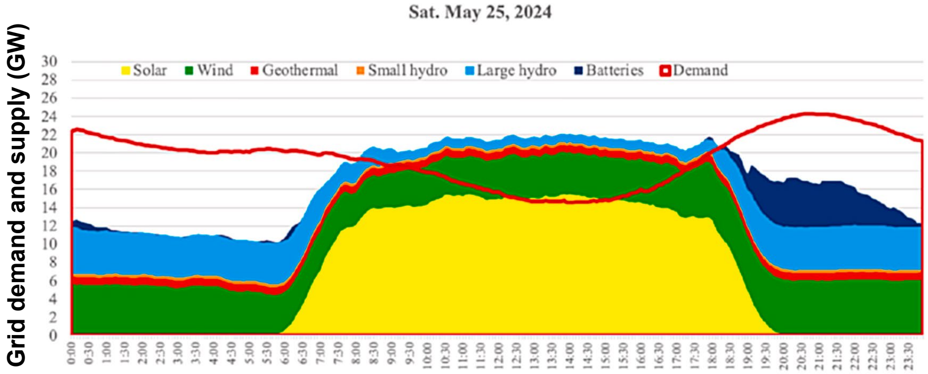
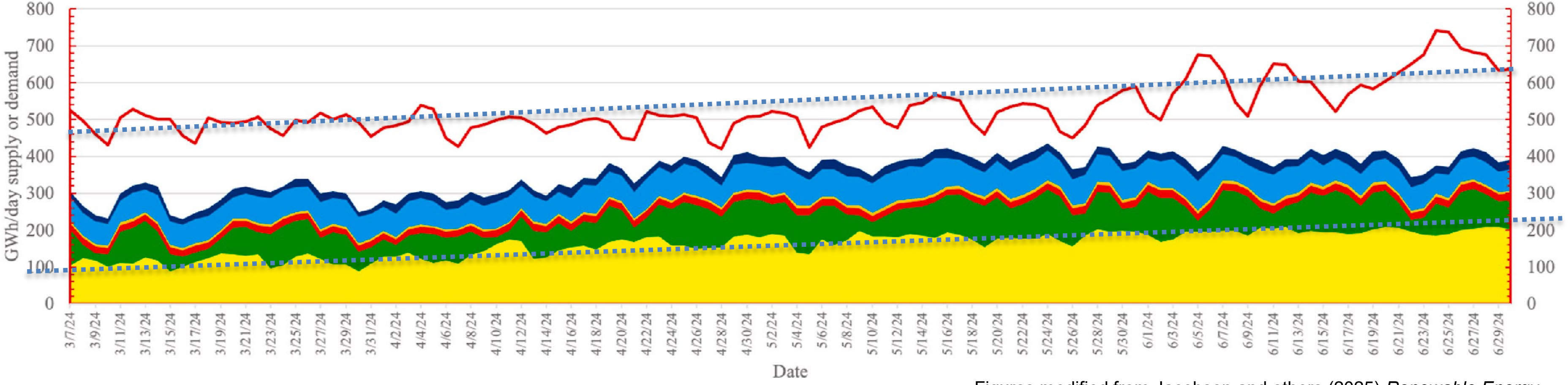
Figure: modified from U.S. Energy Information Agency (2023)

Evolving energy landscape
Renewable power intermittency

1. Diurnal (daily) intermittency
   - Batteries
   - Require critical minerals (Ni, Li, graphite, etc.)
2. Seasonal intermittency
   - More challenging?
3. Stochastic intermittency (aperiodic weather events)
   - More challenging?

Battery energy storage for California ISO (grid)





Figures modified from Jacobson and others (2025) *Renewable Energy*

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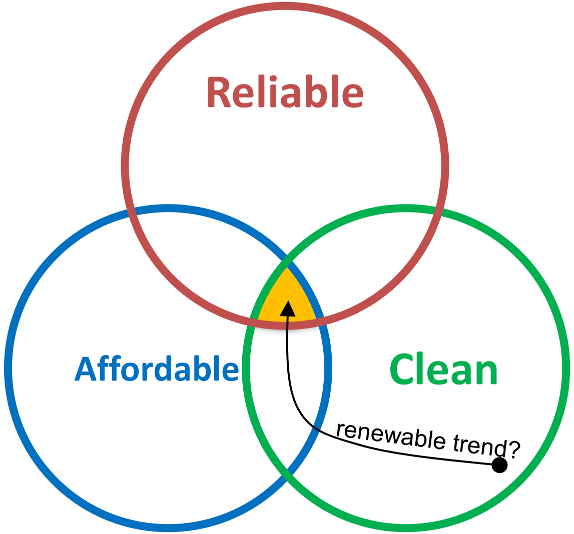
Evolving energy landscape
Electrical grid

Challenge: can **energy storage** address the daily to seasonal intermittency of renewable energy to:

1) maintain stable electric grids
2) further reduce GHG emissions from U.S. electricity production



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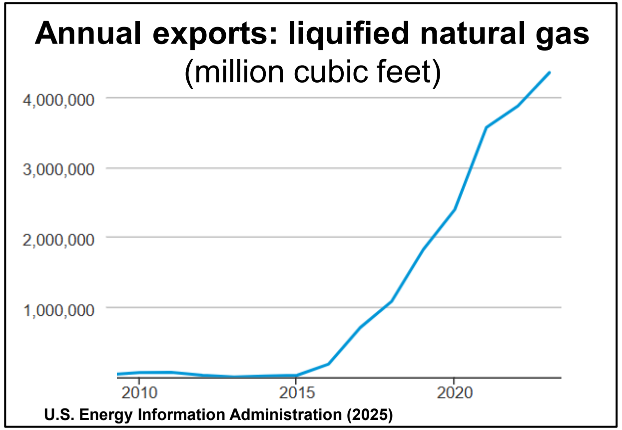
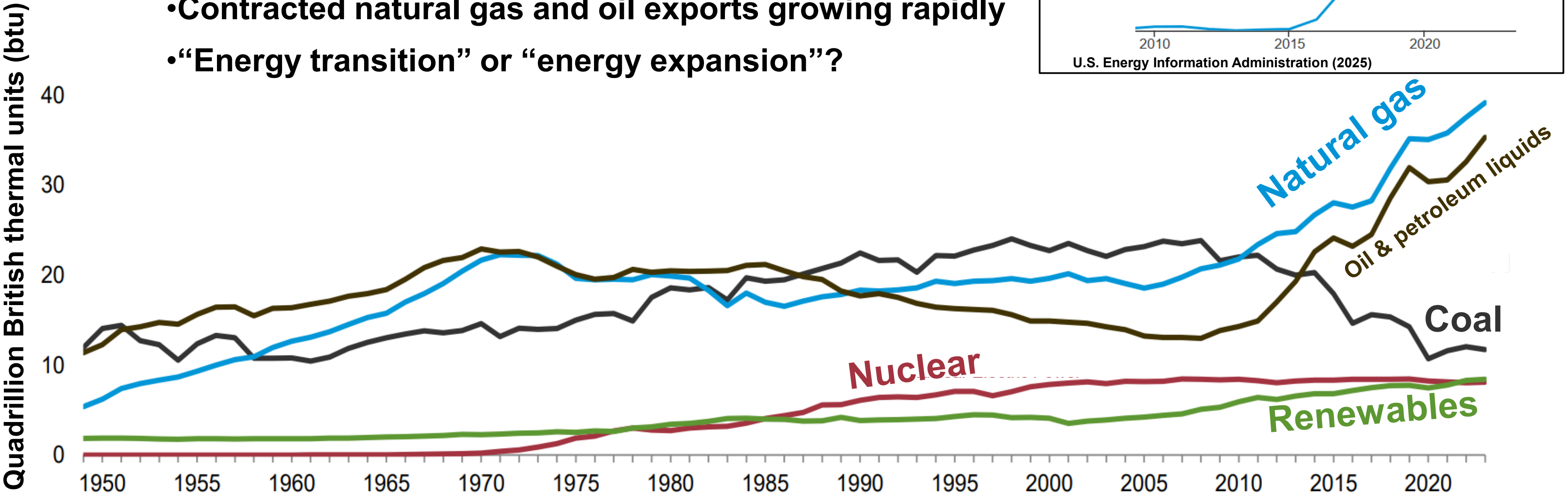
Evolving energy landscape

All Energy Consumption by Source – U.S.

Wider energy statistics

- U.S. natural gas and oil production at all-time highs
- Contracted natural gas and oil exports growing rapidly
- "Energy transition" or "energy expansion"?





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eia U.S. Energy Information Administration (2025)

Talk outline

1. Take stock of the current U.S. energy landscape

2. New roles for the subsurface in energy

3. Other emerging USGS energy research and final thoughts

U.S. energy landscape: main observations

- **Exponential growth in renewable electricity (solar + wind) is occurring**
- Growing volumes of oil and gas are being produced to meet energy demands of the U.S. and global trading partners
- **Energy storage** may be a key emerging technology to handle the scale-up of intermittent renewable energy AND natural gas distribution for export
- U.S.'s 2023 CO_2 emissions [4.9 Gigatons CO_2/yr] have decreased ~18% from mid-2000s peak [~6.1 Gigatons CO_2/yr] (U.S. EPA, 2025)
- **CO_2 capture, utilization, and sequestration (CCUS) and atmospheric CO_2 removal (CDR)** may be important mitigation technologies (IPCC AR6, 2023)

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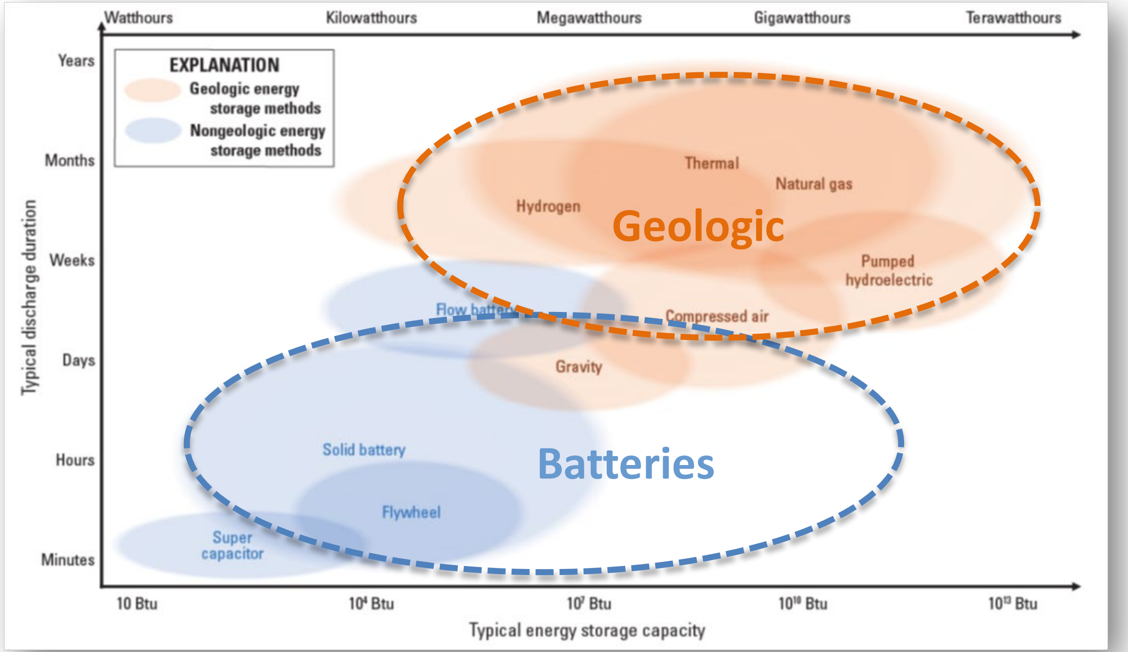
Geologic energy storage

Part 2: Can geologic energy storage promote energy security in the U.S. and enable decarbonization?

USGS ERP Geologic Energy Storage task

- Leads: Marc Buursink & Matt Merrill
- Members: Sean Brennan, Colin Doolan, Joao Gallotti, Joe East, Phil Freeman, Brian Varela, Peter Warwick, Ashton Wiens, and myself



Buursink and others (2023) USGS Fact Sheet 2022-3082

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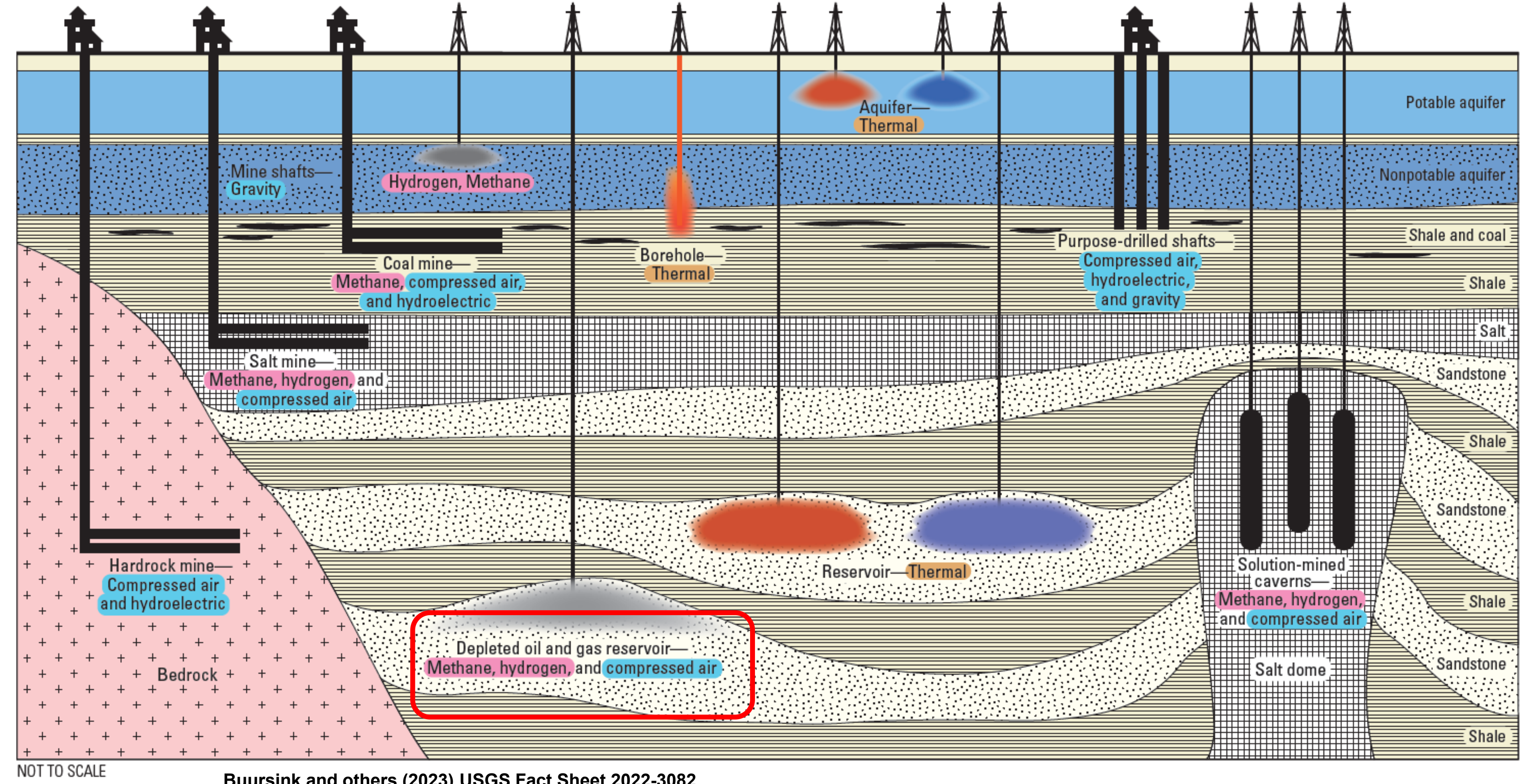
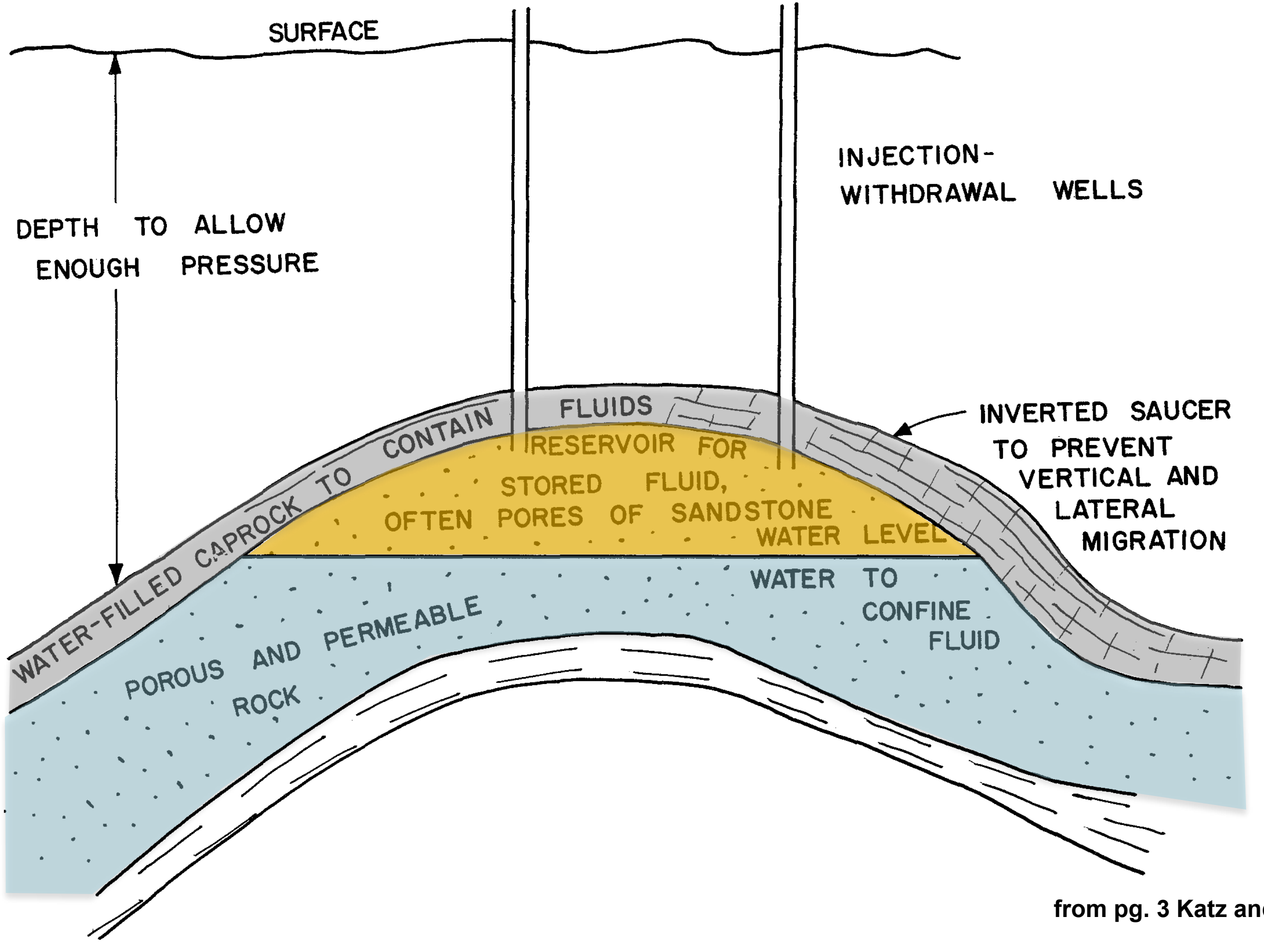


Buursink and others (2023) USGS Fact Sheet 2022-3082

Geologic energy storage: reservoirs



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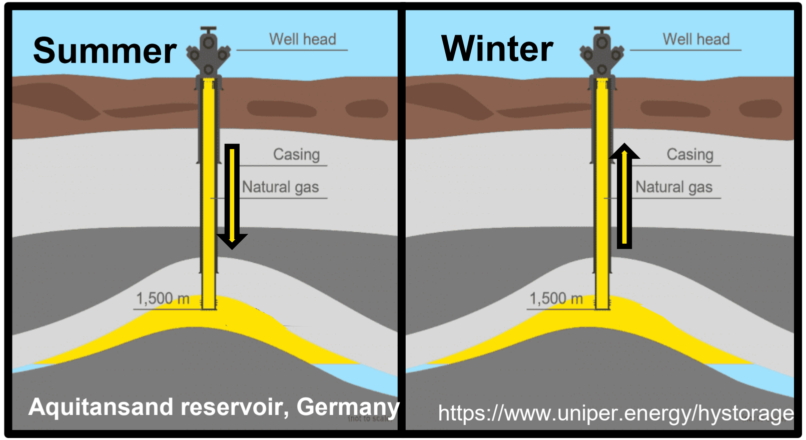
from pg. 3 Katz and Coats (1968)

The role of underground natural gas storage (UGS)

Reliable seasonal energy delivery

- **Energy cost stability: purchasing & injection during low demand months**
- **Reduces required interstate pipeline capacity for natural gas transmission**
- **Energy security: buffer from economic & geopolitical shocks**



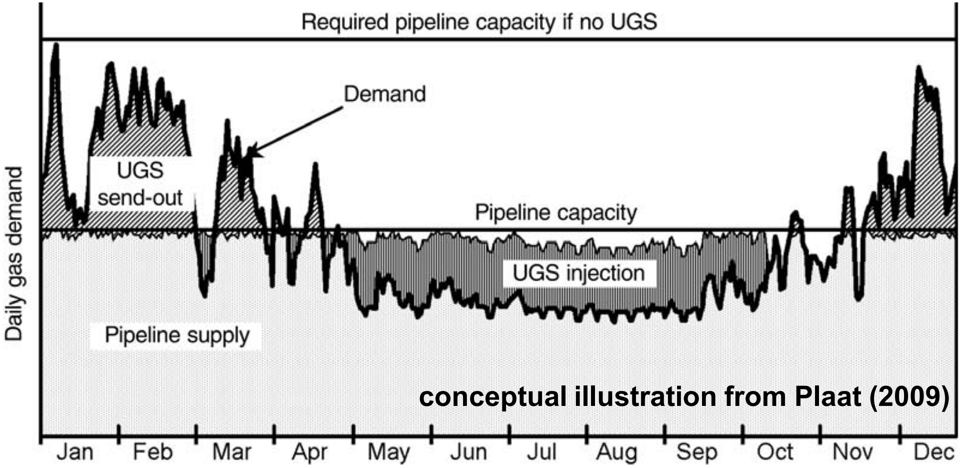
The New York Times

Europe Braces for a Winter Without Russian Gas

Underground storage sites around the continent have been fully stocked with emergency gas supplies. Nuclear power plants slated for closure in Germany will...

Nov 1, 2022

https://www.nytimes.com/2022/11/01/business/europe-energy-crisis.html



conceptual illustration from Plaat (2009)

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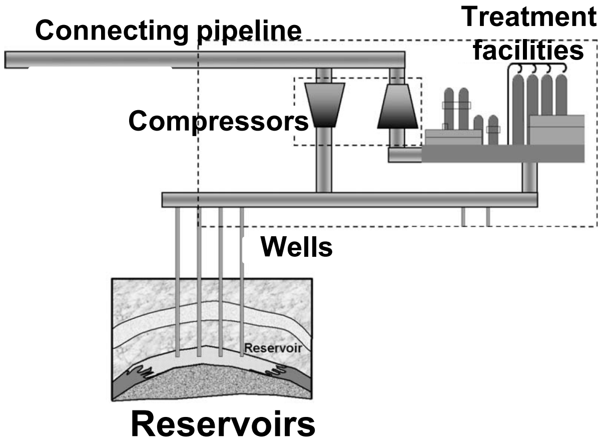
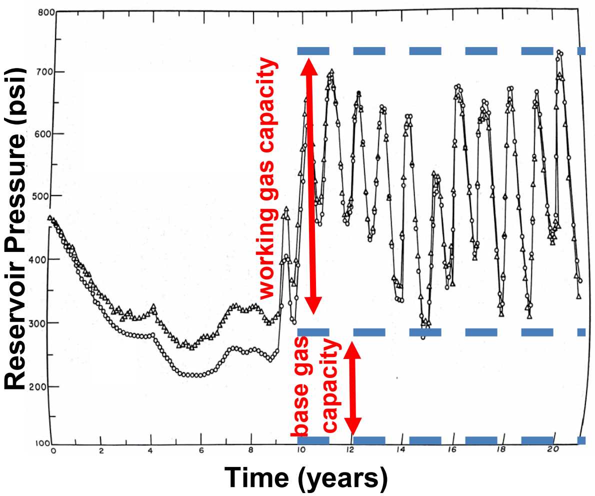
Some gas storage terminology

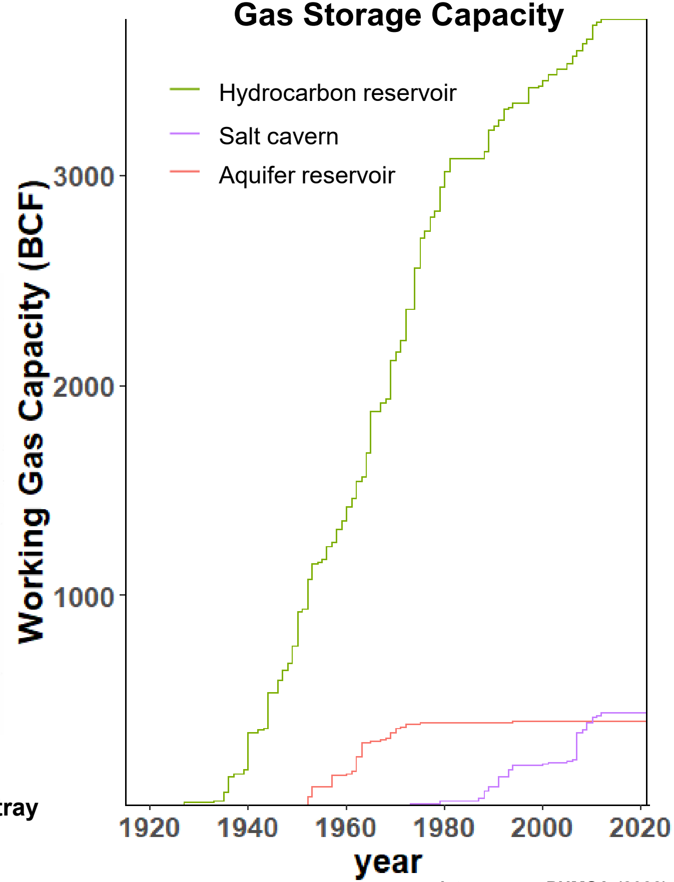
- Base gas + working gas = maximum total gas stored
- Natural gas units (billion cubic feet; BCF) in the United States
- Pressure-depleted oil and gas (hydrocarbon) reservoirs hold greatest storage capacity in the United States



modified from Plaat (2009)



Pressure predictions in UGS reservoir in Michigan Stray sandstone (modified from p. 228 Katz & Coats, 1968)



data source: PHMSA (2022)

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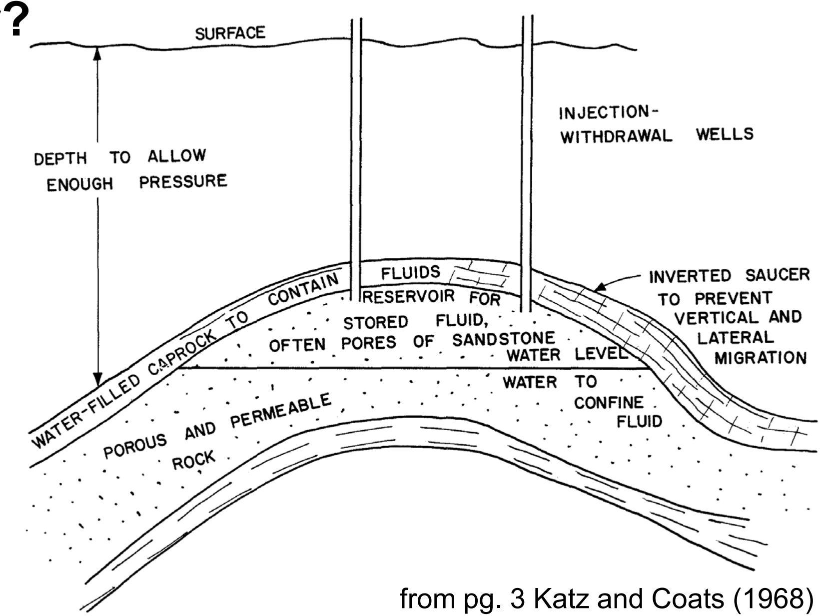
Motivation for USGS Energy Storage Assessments

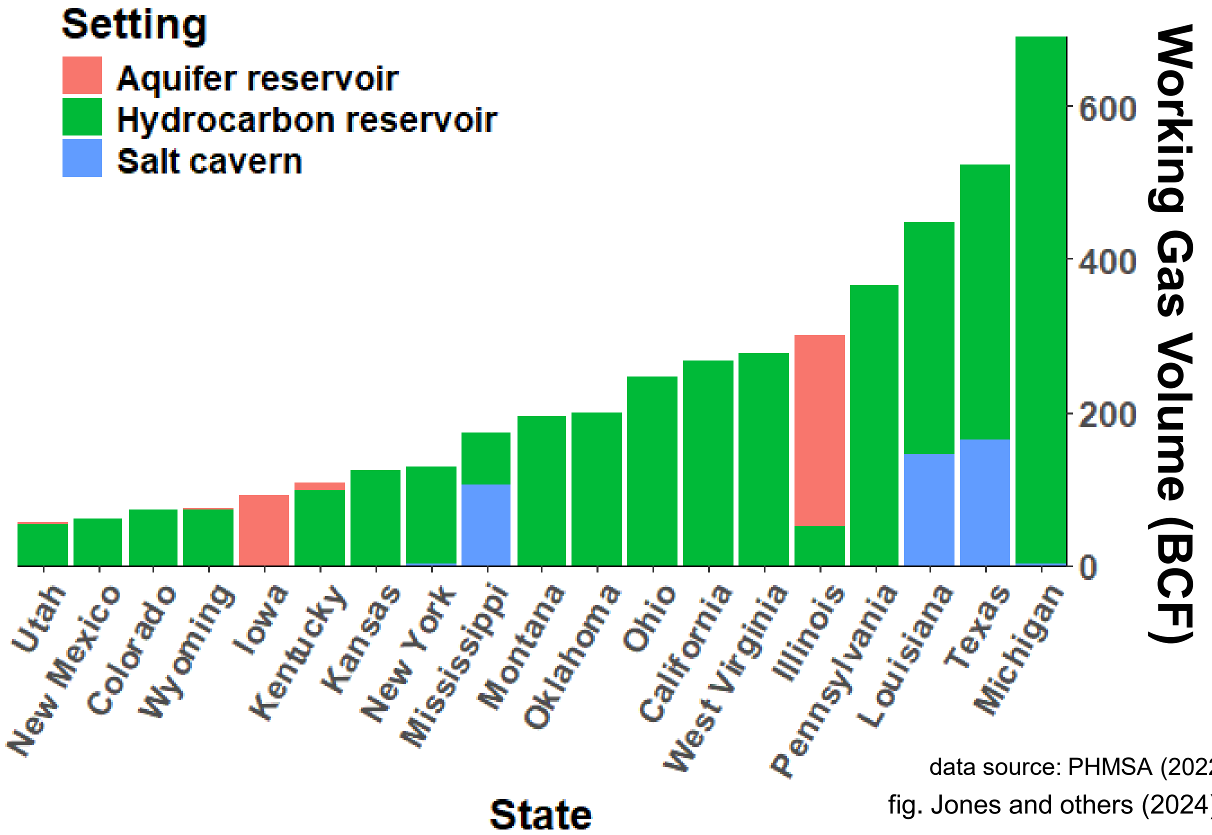
Given the growing need to increase underground gas storage capacity:

- **How can the USGS accurately predict natural gas storage "resources" in depleted gas reservoirs nationally?**



from pg. 3 Katz and Coats (1968)

Can existing UGS facility data predict storage resource capacity for possible future development?



data source: PHMSA (2022)

fig. Jones and others (2024)

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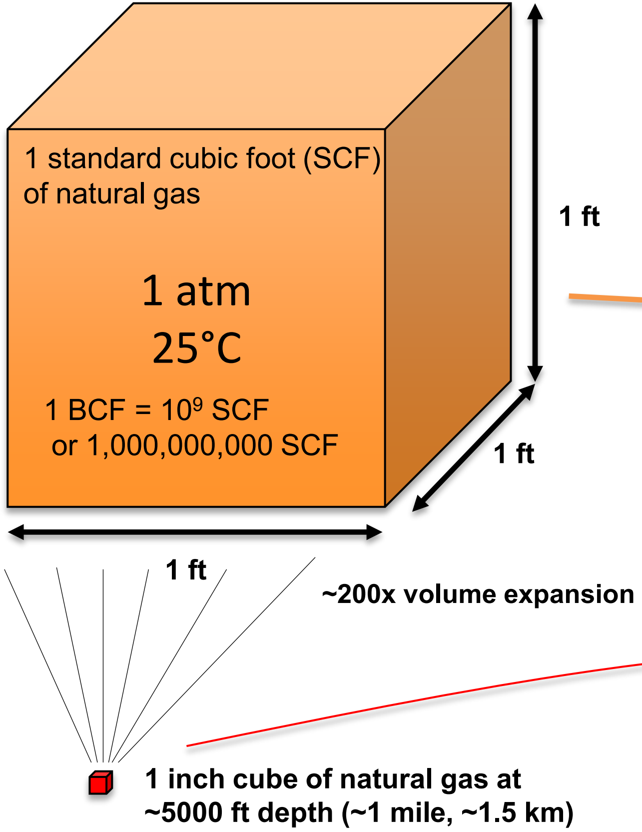
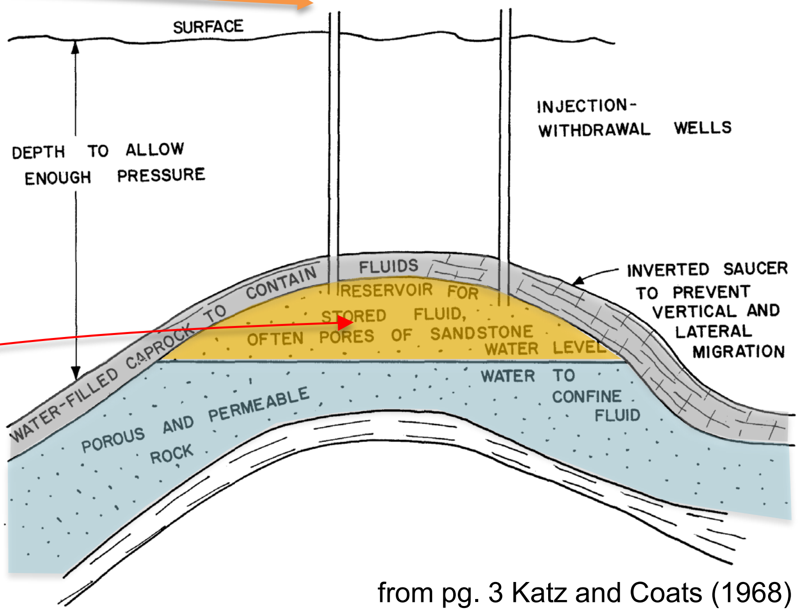
Sidebar – scale: natural gas units and fluid "compressibility"





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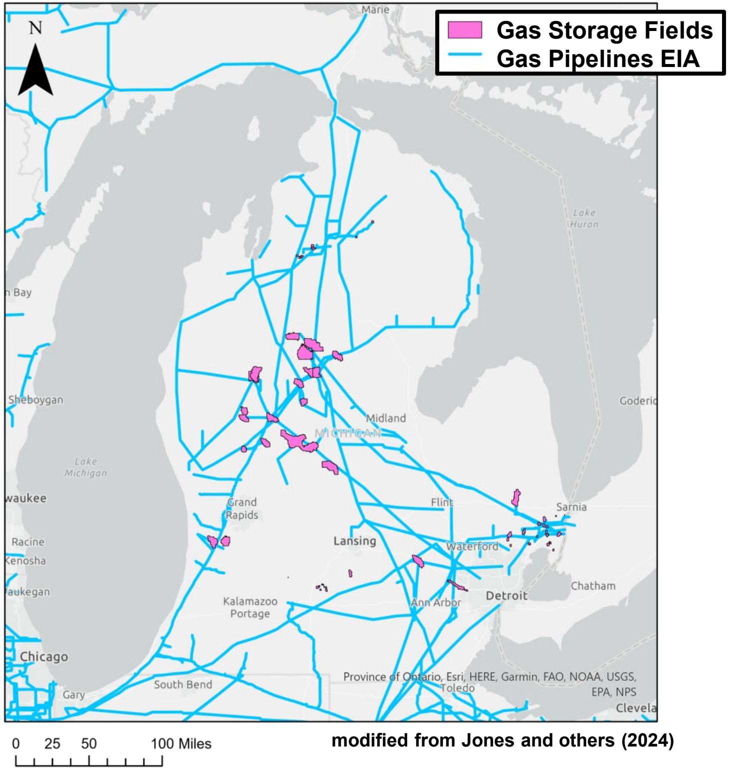
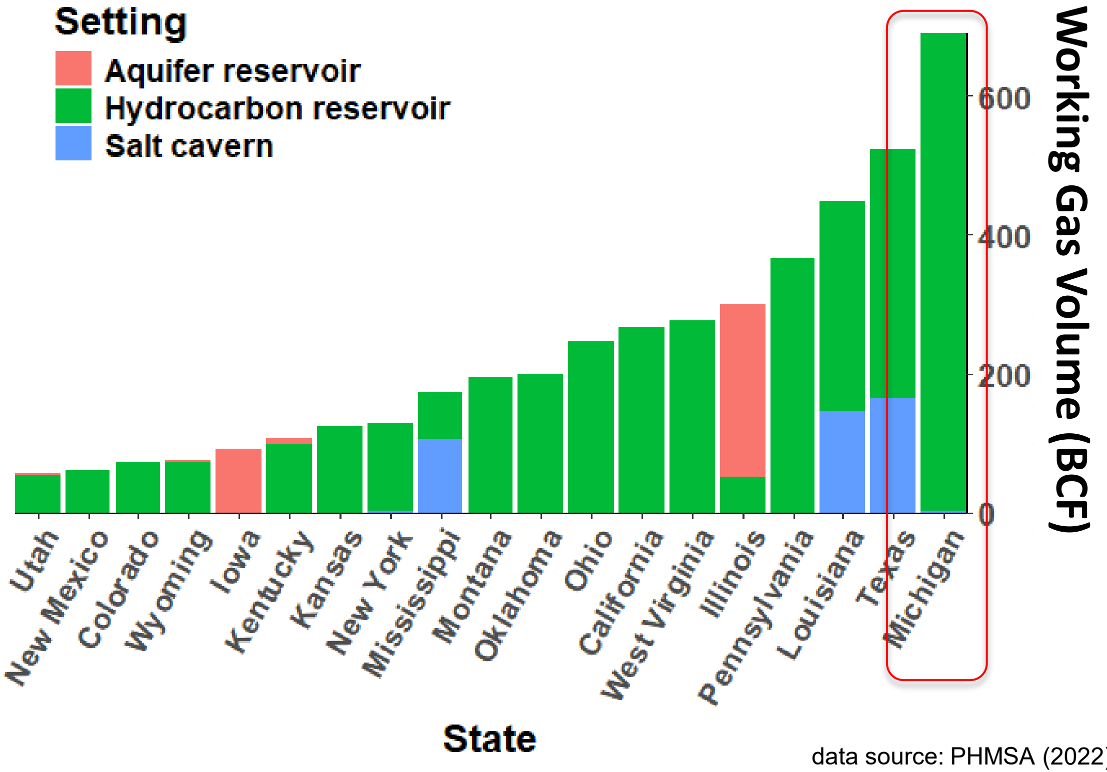


modified from Jones and others (2024)

Michigan: a hub for natural gas storge



data source: PHMSA (2022)

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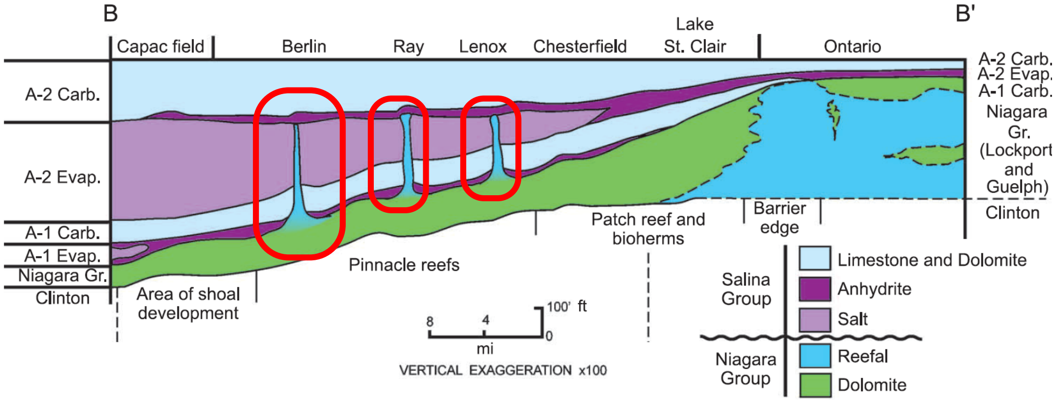
Michigan Basin UGS infrastructure

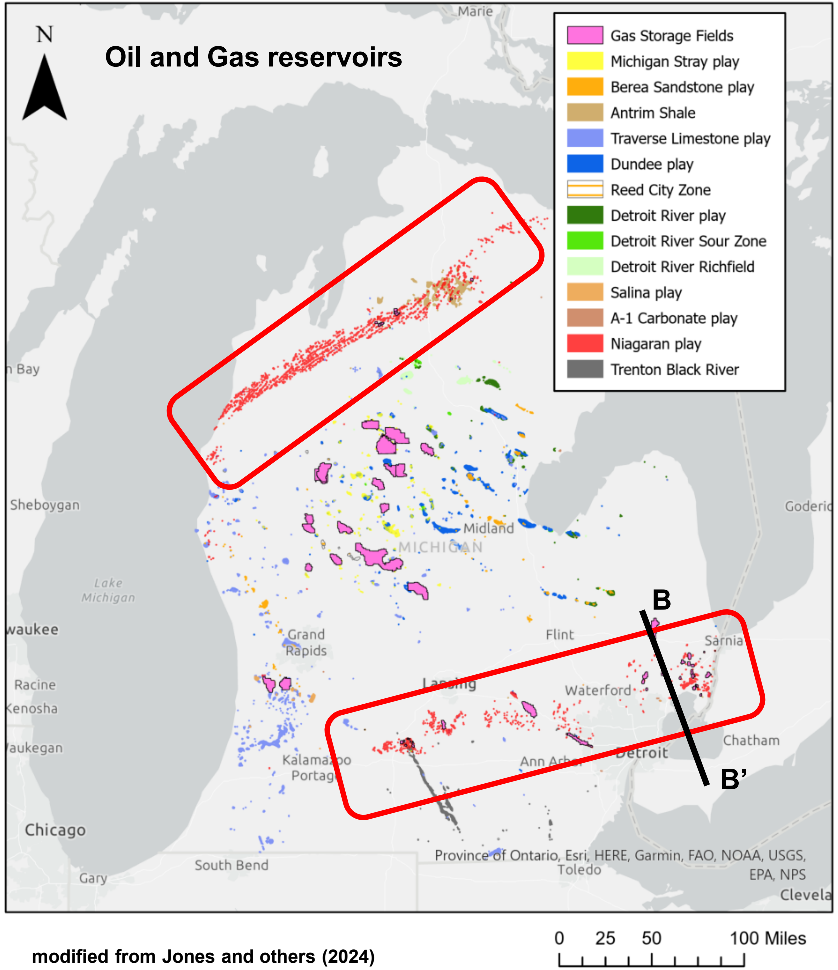
Silurian Niagara Group pinnacle reef rock reservoirs

- **~70% of current MI UGS capacity**
- **ideal finger-like UGS setting (permeability, seals)**
- **historically produced 2 trillion SCF of natural gas**



modified from Grammar and others (2009) (modified from Burgess & Benson, 1969)

Gr. – Group; Carb. – carbonate; Evap. – evaporite



modified from Jones and others (2024)

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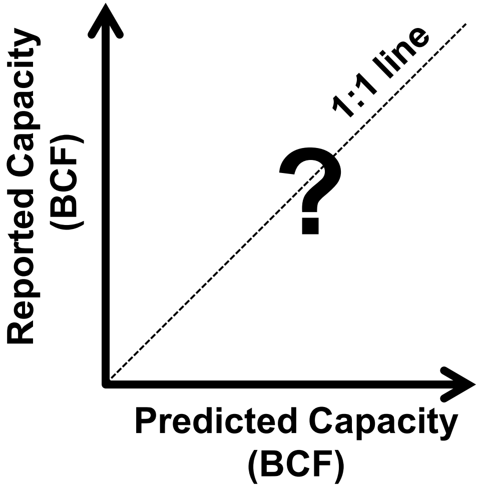
Gas Storage Methodology

Predicting new UGS capacity from existing gas storage facilities in the Michigan Basin

Working gas volume → *f*(geology & other reservoir parameters)?



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Data Sources

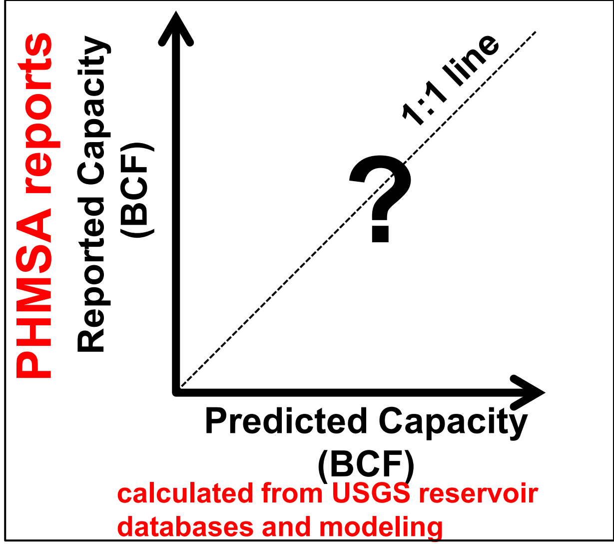
Methodology

Find: existing UGS facility data

Match: UGS facility data with historical oil & gas reservoir dataset

Primary data sources

- PHMSA - U.S. Pipeline & Hazardous Materials Safety Administration (U.S. DOT)
- Nehring Associates Database and USGS Comprehensive Resource Database (Carolus and others, 2018)



PHMSA data (2022)

– Underground Gas Storage facility

- Working gas capacity
- Maximum storage pressure (psi)
- Name of Reservoir & Field
- Latitude / Longitude
- Depth of Reservoir

Hydrocarbon reservoir datasets (historic)

- Name of Reservoir & Field
- Latitude / Longitude
- Depth of Reservoir
- Gas production stats
- Oil production stats
- Area
- Thickness
- Porosity
- Discovery pressure
- Lithology & more…

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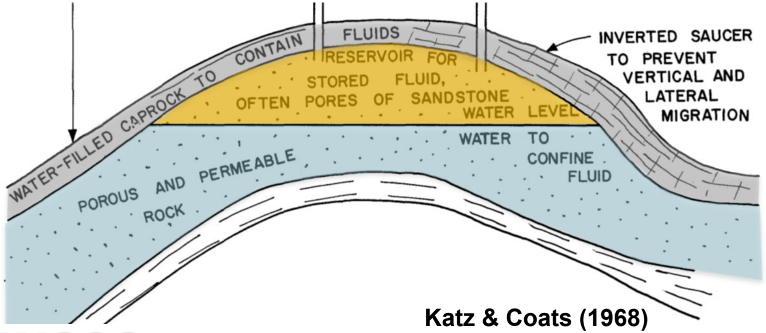
Theoretical natural gas storage capacity vs. reported data

Methodology

Find: existing UGS facility data

Match: UGS facility data with historical oil & gas reservoir dataset

Apply: storage calculations and compare to existing UGS facility capacity data



Katz & Coats (1968)

Gas Production
Method 1

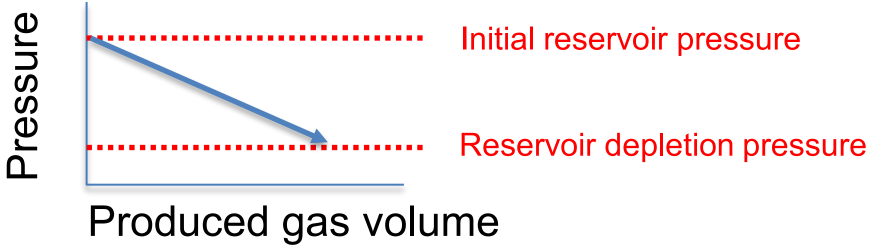
~gas out = gas in

Volumetrics
Method 2

$$TGV_{natgas,sc} = OGIP_{vol} = \frac{S_{gi} * \phi * Area_{RES} * \text{Net Pay}}{FVF_{natgas}}$$

Material Balance
Method 3

~gas production per change in reservoir pressure



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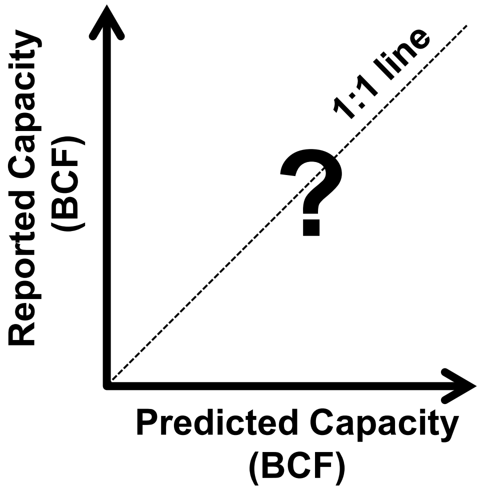
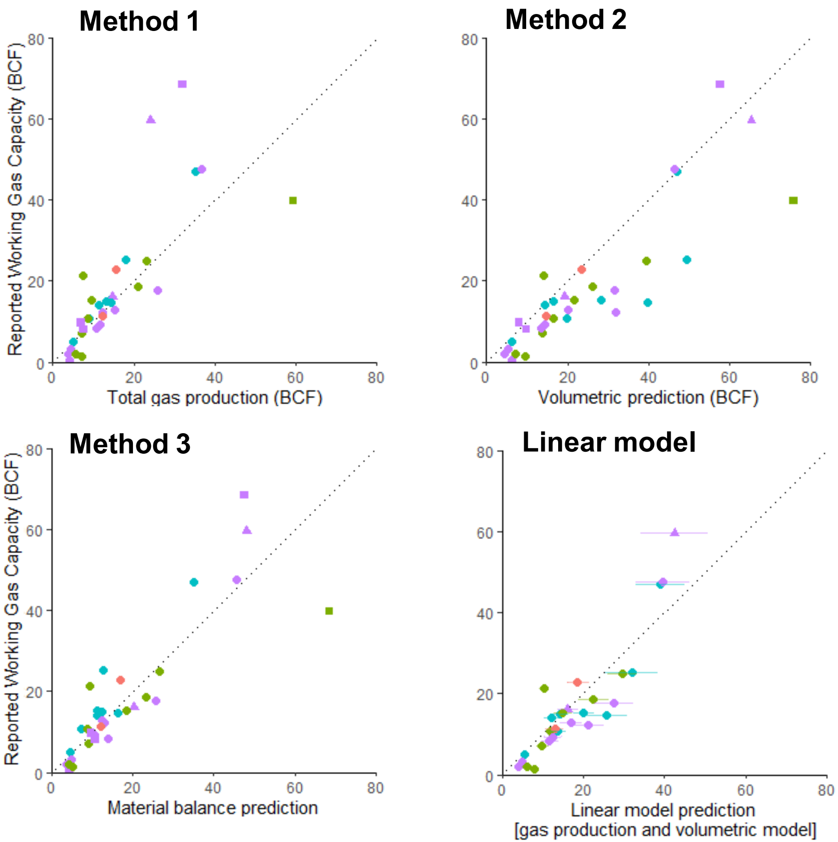
USGS natural gas storage assessment

Performance of governing equations

- **Statistically significant correlations, generally high r^2**
- **Limitations of input data (grouping, production records, etc.)**
- **Linear modeling (combinations of reservoir variables) provides high r^2**

Working gas volume → *f*(geology & other reservoir parameters)?





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Jones and others (2024)

USGS natural gas storage assessment

Methodology

Find: existing UGS facility data

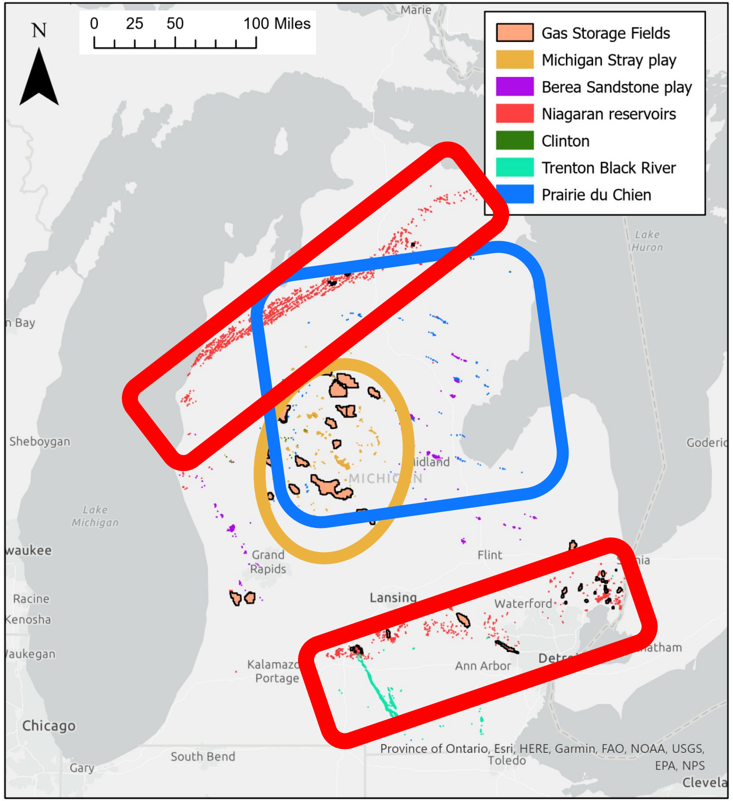
Match: UGS facility data with historical oil & gas reservoir dataset

Apply: storage calculations for reservoirs and compare to existing UGS facility capacity data

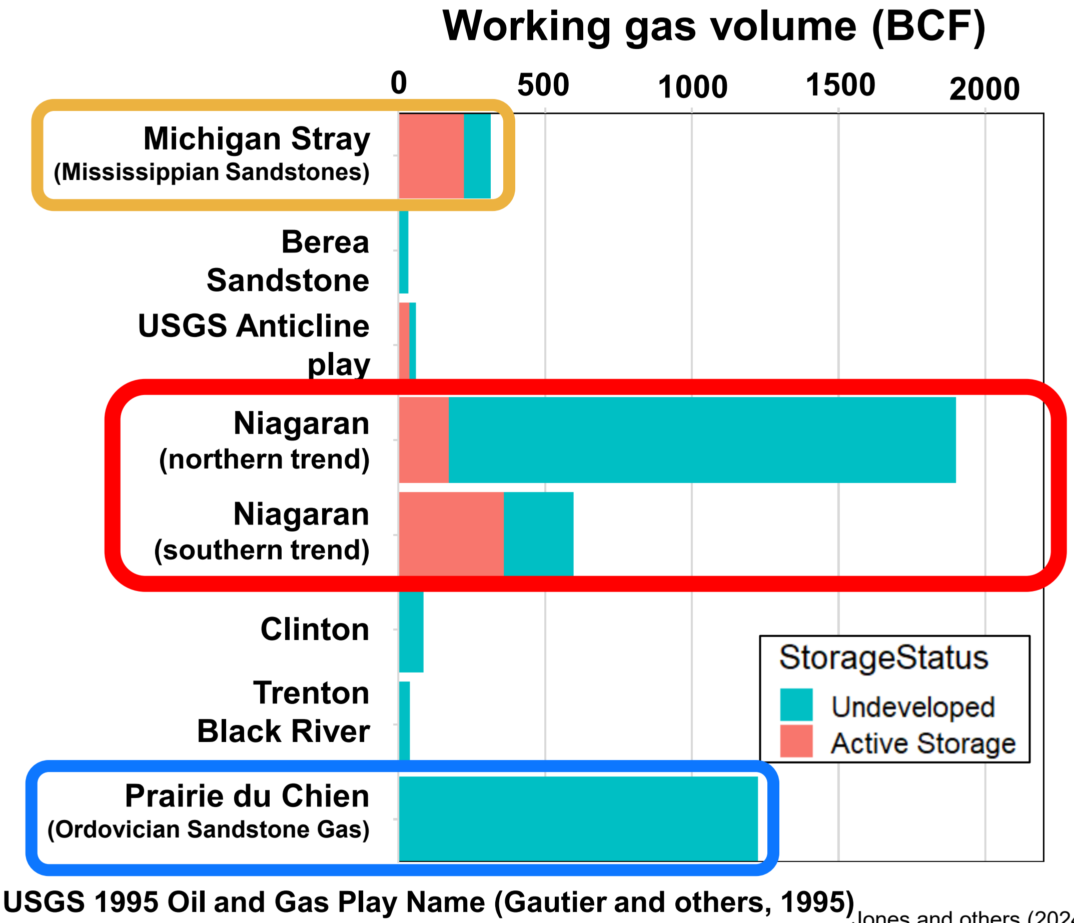
Calibrate: storage capacity in unconverted reservoirs based on comparison

Assess: storage capacity in conventional gas reservoirs using calibration equations

Example calculations Michigan Basin natural gas storage resources



USGS geospatial data: State of Michigan Department of Environment, Great Lakes, and Energy (EGLE) (2024)



Jones and others (2024)

Example calculations Michigan Basin natural gas storage resources

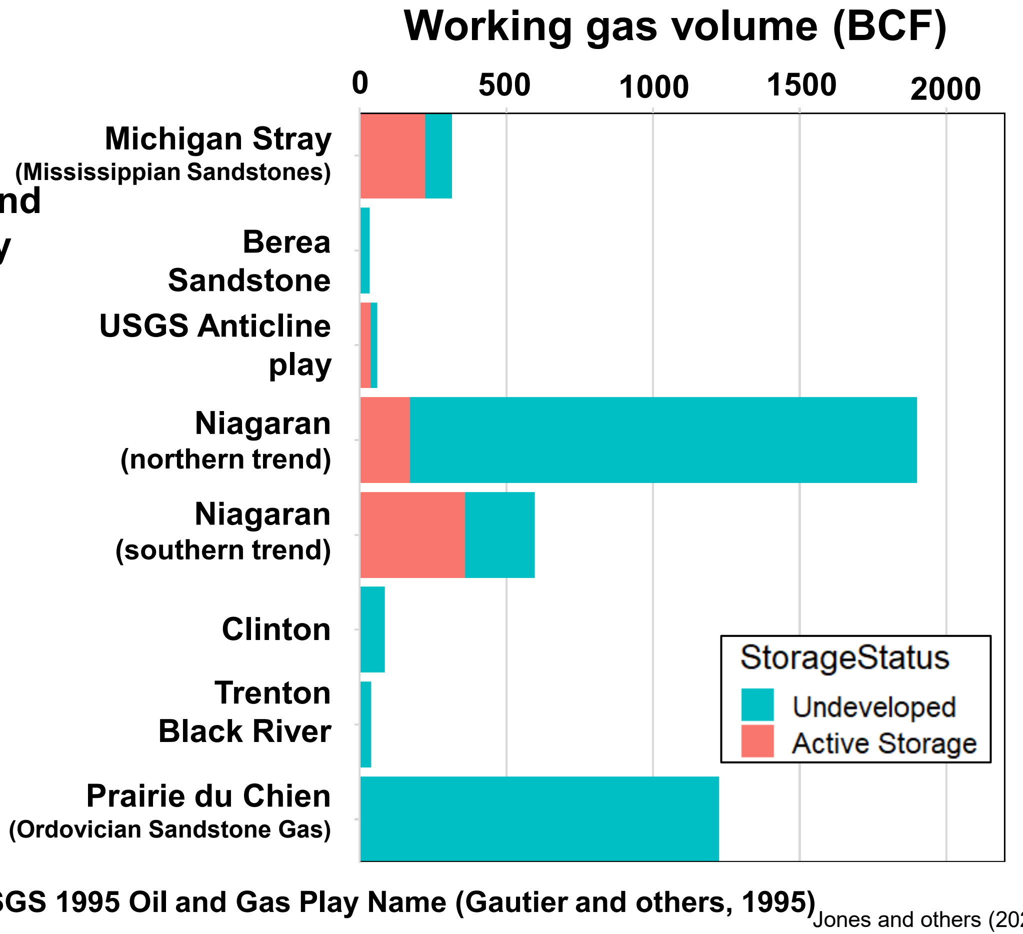
Highlights

• equations based on different parameters and statistics from gas reservoirs can accurately predict natural gas storage volumes

• the USGS is conducting a national assessment for underground natural gas storage resources

• large undeveloped gas storage resources remain in Michigan, U.S.

• subsurface stores of natural gas can help ensure grid stability and bolster against "shocks" in global energy markets



Jones and others (2024)

USGS

Can traditional geologic energy storage be decarbonized?

* ~30 Megatons of CO_2/yr = emissions from annual natural gas storage/combustion cycle in Michigan

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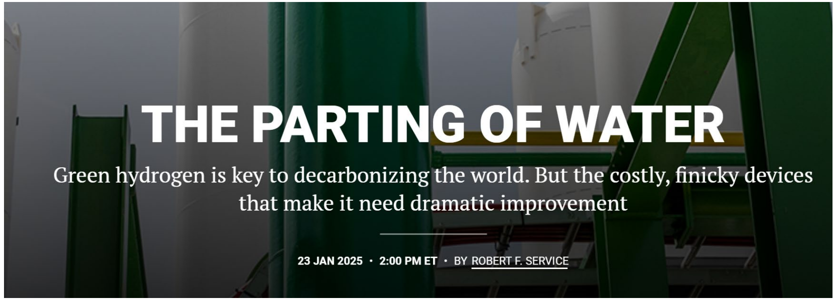
Decarbonization of geologic energy storage

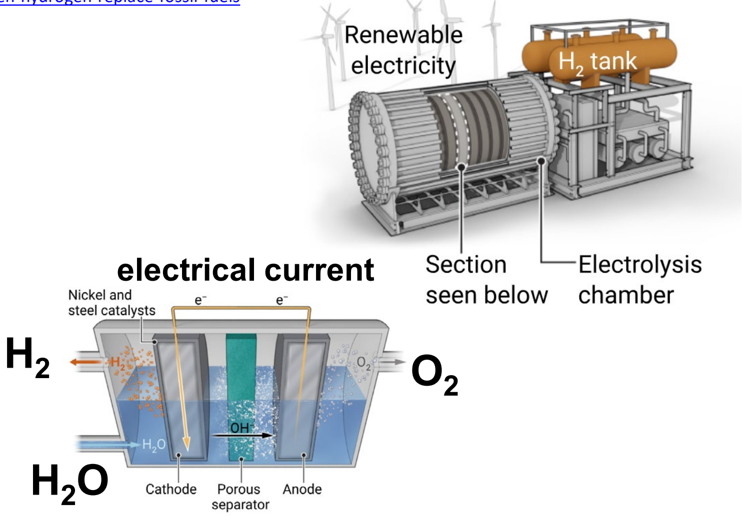
H_2 storage opportunities?



https://www.science.org/content/article/will-new-generation-water-splitting-devices-help-green-hydrogen-replace-fossil-fuels

"Coupling of power-to-gas processes with underground gas storage could effectively allow surplus electricity to be stored for later use."

- Hellerschmied and others (2024) *Nature energy*



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Decarbonization of geologic energy storage

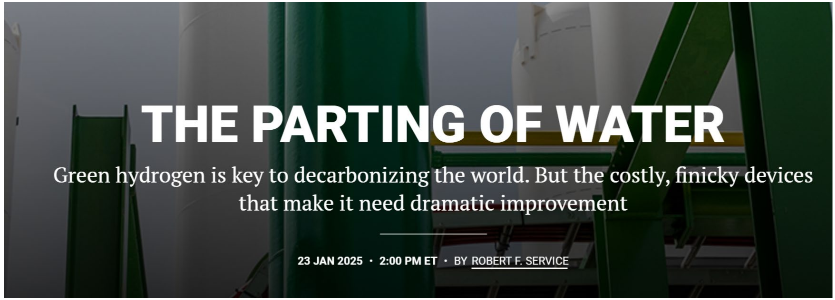
H_2 storage opportunities?

- Gases produced from low-emission electricity can be stored and might help decarbonize
- H_2 (and NH_3) molecular energy storage can far exceed energy storage duration of existing batteries
- "Green" H_2 can be produced from electrolysis from renewable energy
    - USGS also research occurrence of geologic hydrogen (Gelman and others, 2025)

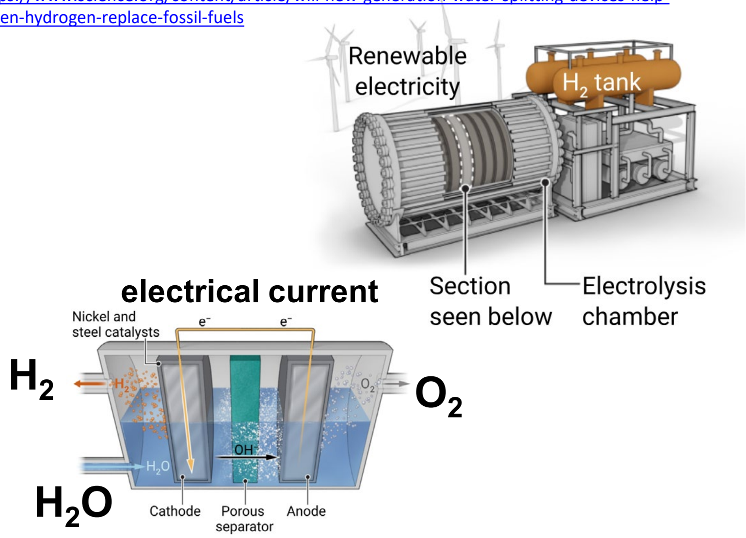
Challenges

- leakage risks, transport, early technology is expensive, potential geomicrobiological interactions, and many more!

- Limit warming to 1.5°C by 2050 requires production of 327 million tons of green H_2 per year (IEA, 2023)
- H_2 blending into energy supply requires additional underground storage capacity (Lackey and others, 2023)



https://www.science.org/content/article/will-new-generation-water-splitting-devices-help-green-hydrogen-replace-fossil-fuels



USGS

Decarbonization of geologic energy storage

H_2 storage opportunities?

1. Diurnal (daily) intermittency
   - Batteries
   - Require critical minerals (Ni, Li, graphite)
2. Seasonal intermittency
3. Stochastic intermittency (aperiodic weather events)

batteries

hydrogen?

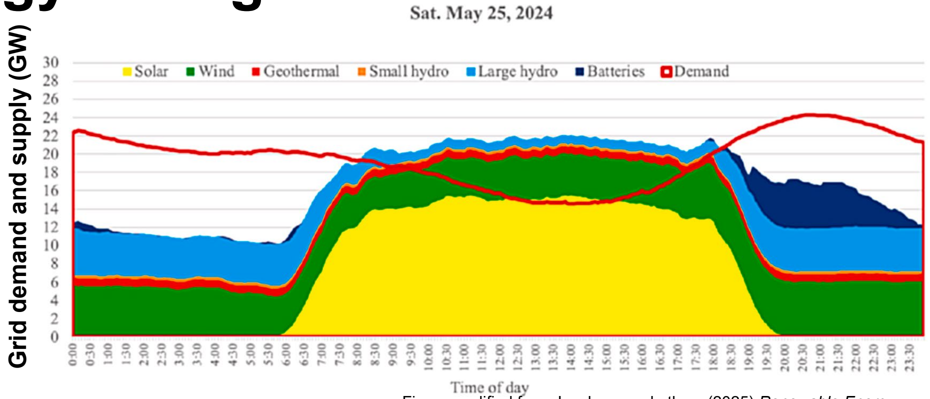
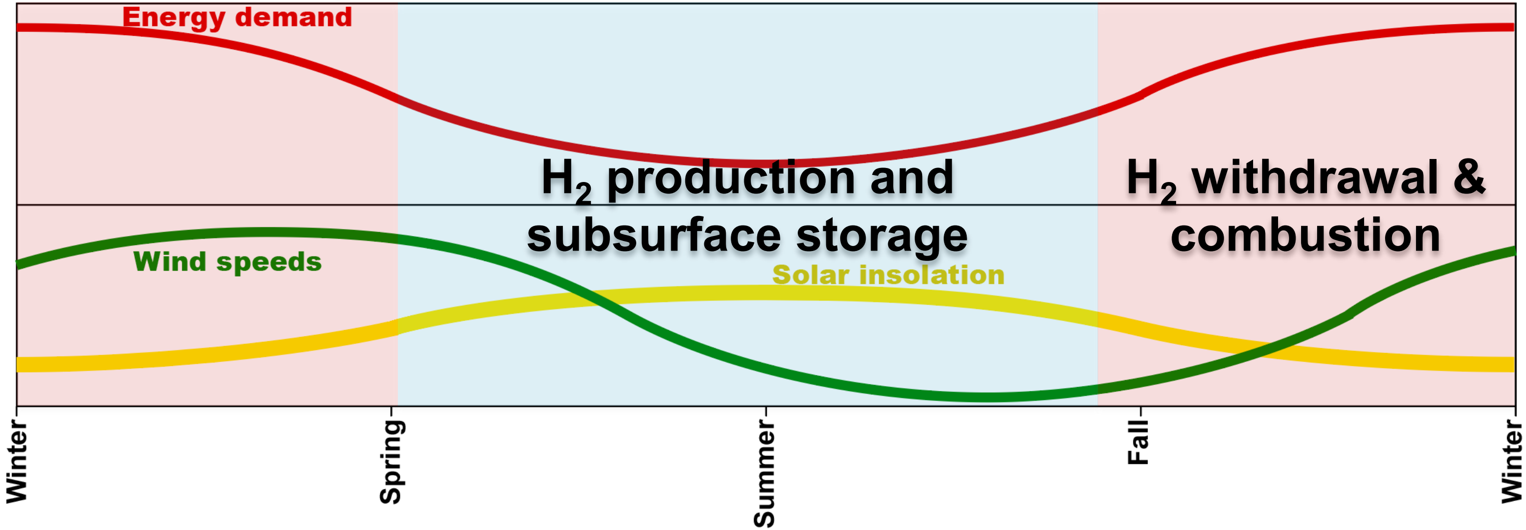


Figure modified from Jacobson and others (2025) *Renewable Energy*



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How can we predict the H_2 storage resources of depleted gas reservoirs in the United States?

Scenarios

- pure H_2 injections
- blends of H_2 and methane (CH_4)

USGS

H_2 underground storage

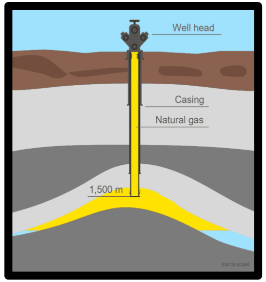
- **Established technique to quantify pore volume in depleted gas reservoirs for new storage**
  - Gas production, volumetrics, pressure history
  - What about substituted fluids (H_2, CO_2, He) that differ from extracted fluid (natural gas)?
- **Non-ideal gas behavior in subsurface: equations of state required**
  - Fluid properties are a function of pressure and temperature
  - NIST publishes equations of state for different fluids
    - U.S. National Institute for Standards and Technology
    - See RefProp software: https://www.nist.gov/srd/refprop
  - Different Z-factors for different molecules at different pressures and temperatures!

$$M_{H2} = \rho_{H2,res} * WGV_{natgas,res}$$

mass of H_2 that might be stored in reservoir

density of H_2 at reservoir pressures and temperatures

volume of working natural gas at reservoir pressures and temperatures



https://www.uniper.energy/hystorage

$$PV = nRT$$

pressure, volume, number of moles, Gas constant, temperature

Ideal gas behavior

$$1 = \frac{nRT}{PV}$$

Non-ideal gas behavior

$$Z(P,T) = \frac{nRT}{PV} \neq 1$$

USGS

see Jones and others (2024)

Potential new roles for depleted hydrocarbon reservoirs?

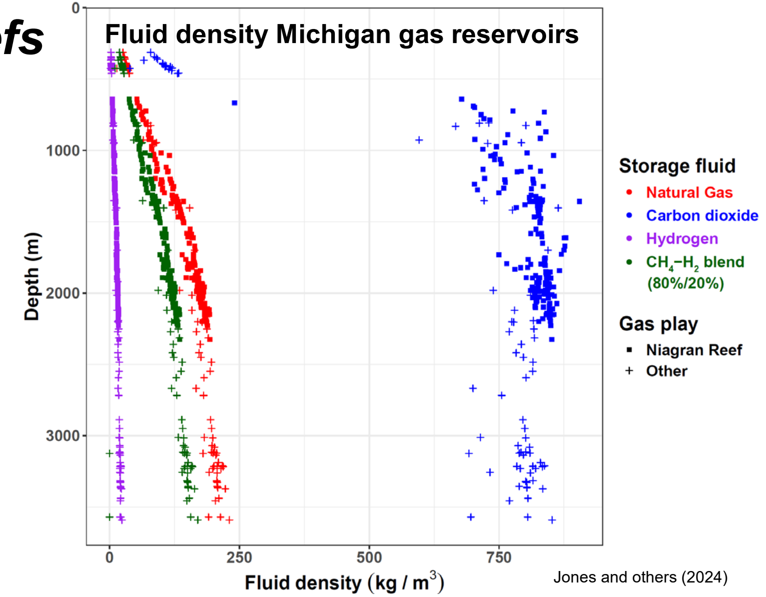
H_2 storage calculation Michigan Pinnacle Reefs

- **Pinnacle reefs low risk of H_2 leakage – sealed by evaporites**
- **~4.5 metric megaton storage for 100% H_2, 148 TWh of chemical energy**
- **Michigan used 121 TWh for electricity in 2023 (U.S. EIA, 2023)**
  - **Finite pore volumes for storage may create use competition in future (natural gas, H_2, CO_2, wastewater)**

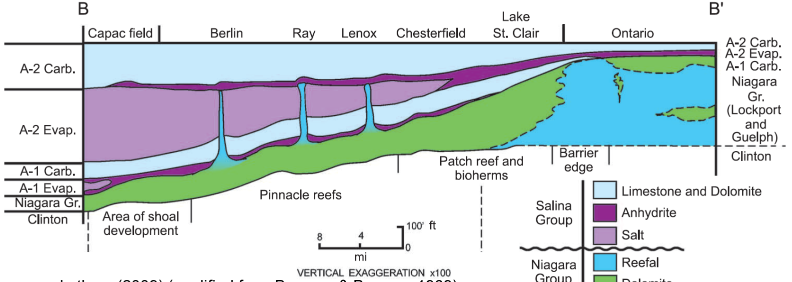
	WGV_{sc}	Mass	WGE
Fluid	*BCF*	*Mt*	*TWh*
Natural Gas (100% vol.)	2,490	49	644
H_2/CH_4 (10%/90% vol.)	2,310	39	555
H_2/CH_4 (20%/80% vol.)	2,220	34	493
H_2 (100% vol.)	1,910	4.5	148
CO_2 (100% vol.)	4,510	230	0

Jones and others (2024)

Abbreviations:
WGV_{sc} – working gas volume at surface conditions
WGE – working gas energy
Mt – metric megatons
TWh – terawatt hours



Jones and others (2024)



Grammar and others (2009) (modified from Burgess & Benson, 1969)

USGS

Potential new roles for depleted hydrocarbon reservoirs?

H_2 storage calculation Michigan Pinnacle Reefs

Long-term storage potential (Michigan)

- **148 TWh of H_2 energy storage resource**
  - **~40% turbine efficiency = ~60 TWh of electrical power (half of annual electrical demand in Michigan)**

	WGV_{sc}	Mass	WGE
Fluid	*BCF*	*Mt*	*TWh*
Natural Gas (100% vol.)	2,490	49	644
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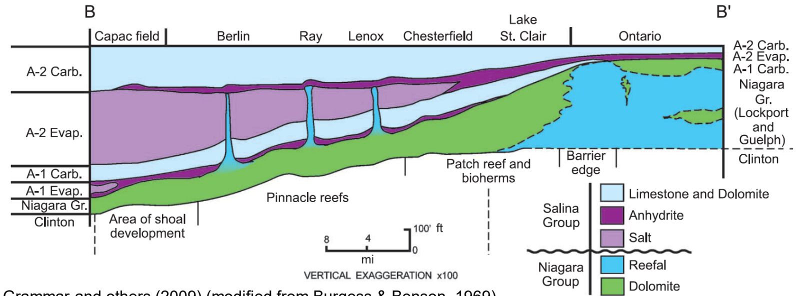
Jones and others (2024)



Grammar and others (2009) (modified from Burgess & Benson, 1969)

Existing short-term battery storage (California)

- **11.5 GW battery power capacity as of January 2025 ([California Independent System Operator (CAISO)])**
- **16 TWh Annual energy storage capacity**
  - **Assuming max. capacity output discharge 365 days/yr for 4 hours/day**

Potential new roles for depleted hydrocarbon reservoirs?

H_2 storage test

- Successful storage of 10% H_2:90% CH_4 (methane) in depleted gas reservoir in Austria (Hellerschmied and others, 2024)
- 84% H_2 recovery after 285 days
- Risks remain to be fully studied
- Only a matter of time until a pilot H_2 storage project in U.S.?
  - Recent research initiative from U.S. Department of Energy SHASTA initiative https://edx.netl.doe.gov/sites/shasta/

nature energy

Article https://doi.org/10.1038/s41560-024-01458-1

Hydrogen storage and geo-methanation in a depleted underground hydrocarbon reservoir

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Intermission breather

Think-pair-summarize exercise (~2-3 minutes)

-what caught your attention from the U.S. energy portfolio and energy storage sections?

-write down any fundamental questions or differing perspectives

-up next: geologic and mineral-based CO_2 management and associated critical mineral resources

USGS

Geologic carbon management

Part 2b: USGS research of geologic strategies for sequestering or removing anthropogenic CO_2 emissions

- Global CO_2 emissions growth is slowing but no emissions peak yet
- To reach net-zero CO_2 and avoid the worst outcomes from climate change and ocean acidification requires CO_2 sequestration and removal (IPCC AR6, 2023)
- Difficult-to-abate emissions (steel making, cement production, air travel, etc.)

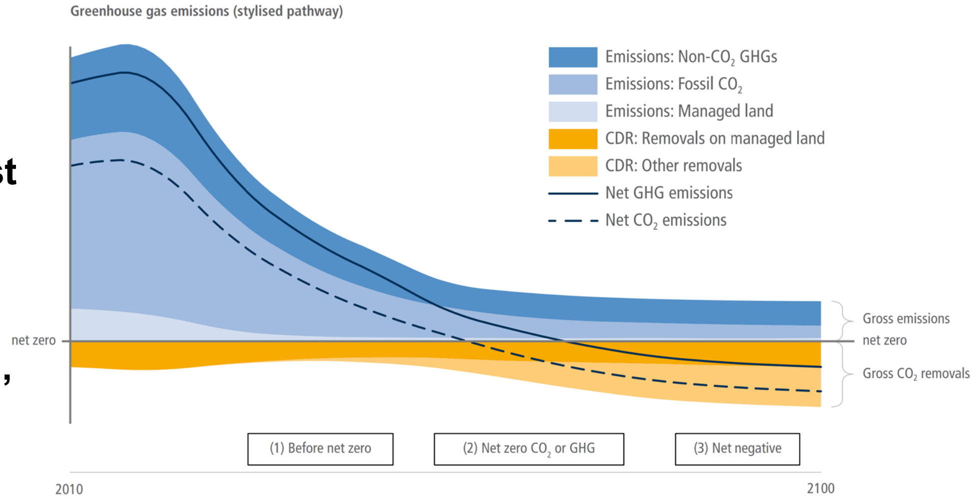

Figure from IPCC AR6 Working Group III Full Report (2023, p. 1263)

CDR – carbon dioxide removal

USGS

Geologic carbon management

International Energy Agency (IEA, 2023):

IEA Net Zero Roadmap invokes 6 Gigatons (Gt) of CO_2 removal per year by 2050

Long-term, how can CO_2 be removed or sequestered durably?

1. **Subsurface storage of CO_2 in geologic formations as a gas (in supercritical state)**
   - **"CO_2 sequestration"**
2. **Reaction of CO_2 with minerals**
   - **"CO_2 mineralization"**

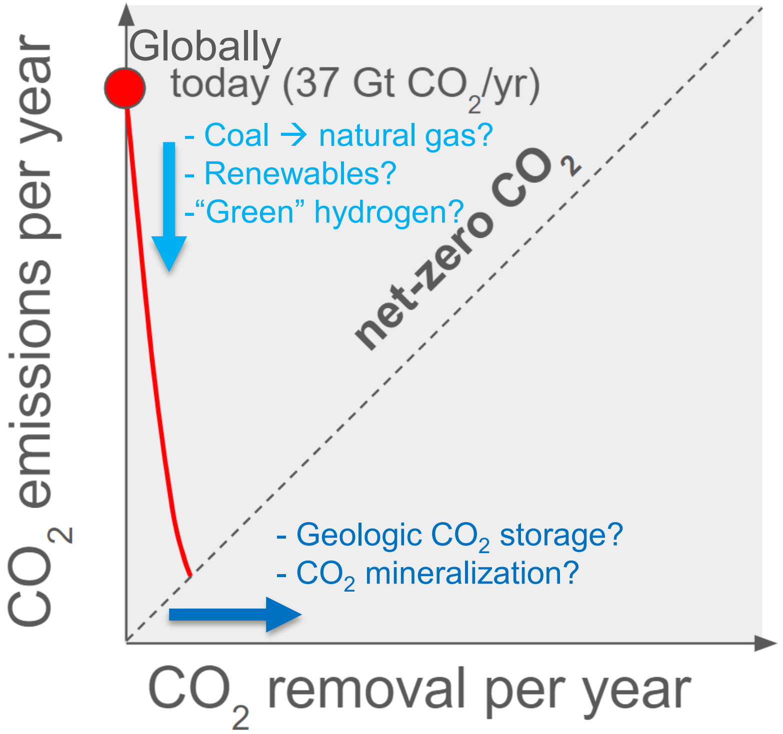

figure adapted from Dr. M. Mazzatti (ETH Zurich)

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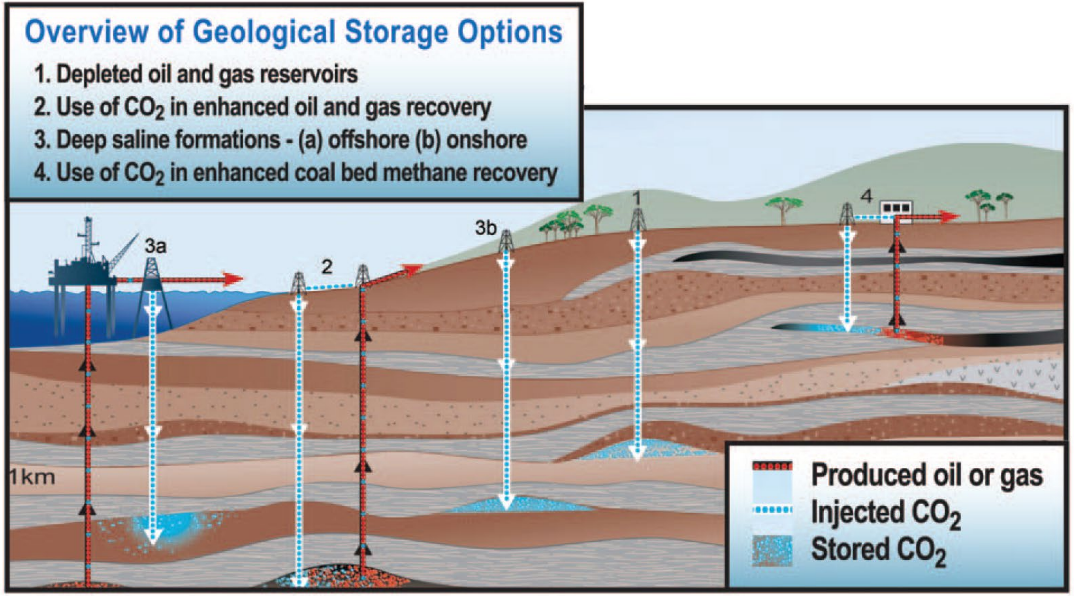
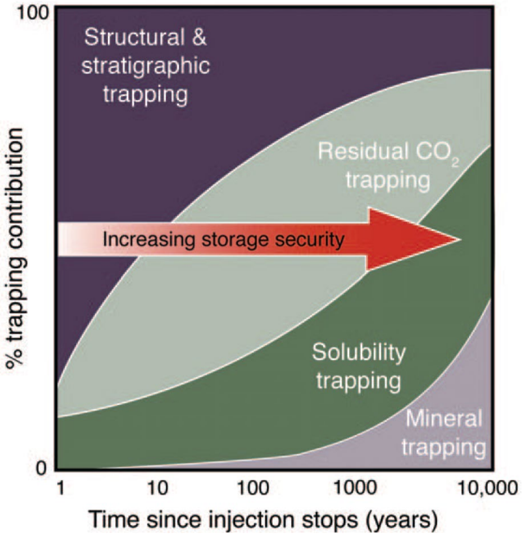
Geologic carbon management

1) USGS research: geologic CO_2 storage





Figures from Benson and Cole (2008)

- **Geologic storage resource questions: where, how much, and risks?**

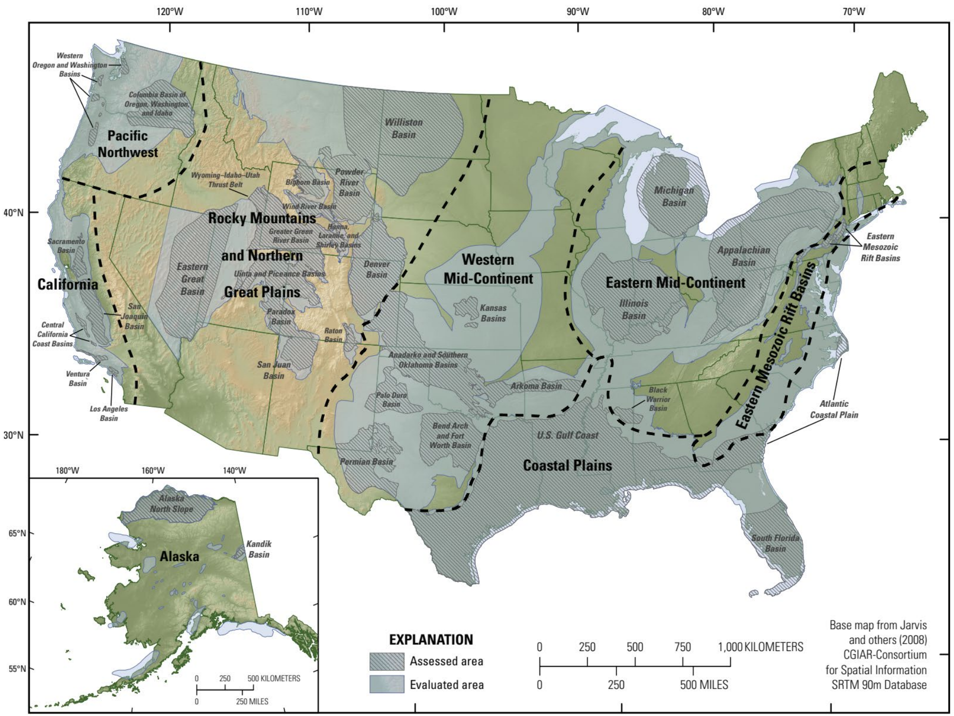
USGS

Geologic carbon management

1) USGS research: CO_2 storage

- **Energy Independence and Security Act 2007 directed USGS to assess CO_2 storage potential in the saline aquifers of the U.S.**
- **National assessment results published in 2013**
- **~3,000 Gt CO_2 technically accessible storage resource in U.S.**
  - **2023 U.S. emissions = 5 Gt CO_2**
  - **Theoretically 100s yrs storage capacity**

CO_2 storage resource type and class		P_5	P_{50}	P_{95}	Mean
Symbol	Name				
Storage resource estimated from geologic models					
B_{SR}	Buoyant trapping storage resource	19	31	110	44
$R1_{SR}$	Residual trapping class 1 storage resource	97	140	200	140
$R2_{SR}$	Residual trapping class 2 storage resource	2,100	2,600	3,300	2,700
$R3_{SR}$	Residual trapping class 3 storage resource	58	120	230	130
TA_{SR} (total)	Technically accessible storage resource	2,300	3,000	3,700	3,000
Storage resource estimated from petroleum production volumes					
KRR_{SR}	Known recovery replacement storage resource	11	13	15	13



U.S. Geological Survey Geologic Carbon Dioxide Storage Resources Assessment Team (2013)

USGS

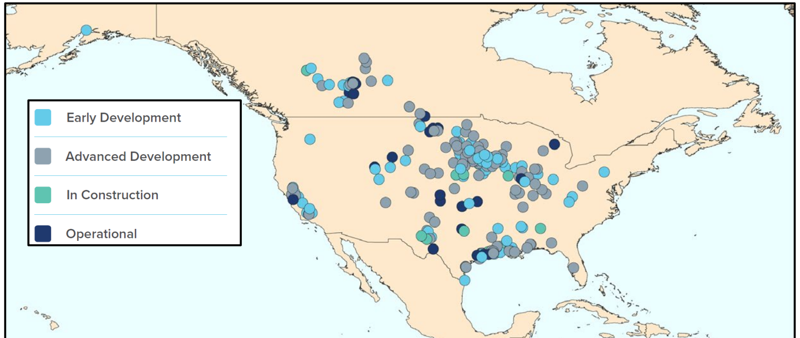
Geologic carbon management

1) USGS research: CO_2 storage

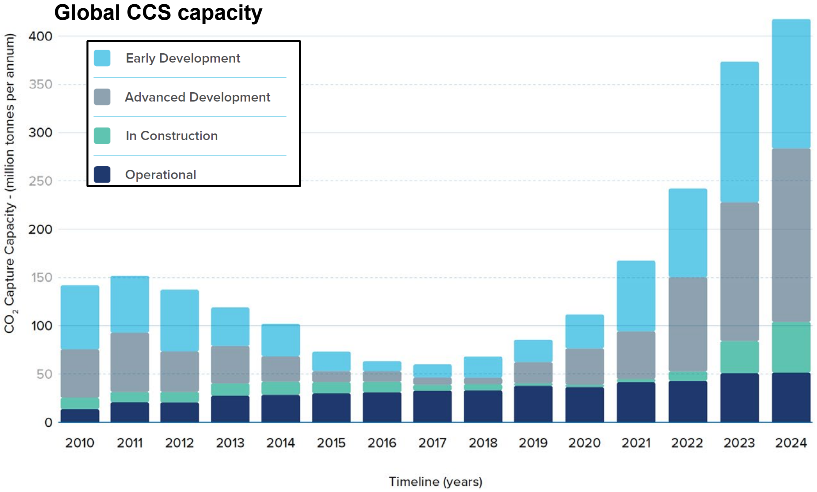
- **Carbon capture and storage (CCS) capacity growth accelerating**
- **near ~0.1 Gt CO_2/yr CCS capacity in 2024 globally**
- **0.3 Gt/yr capacity in development (Global CCS Institute, 2024)**
- **IEA (2023) net-zero targets are ~1 Gt/yr by 2030 and ~6 Gt/yr by 2050**

<u>Risks and concerns</u>

- **Corrosion, leakage, variable costs, nascent technology, etc.**
- **Not all areas of U.S. have subsurface geology for CO_2 storage resources**



Global CCS Institute (2024)



Global CCS Institute (2024)

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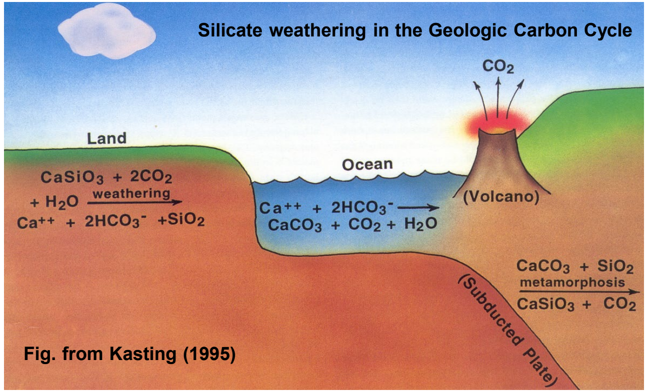
Geologic carbon management

2) USGS research: CO_2 mineralization



<u>The primary geologic carbon sink</u>

- **Silicate mineral weathering (Urey, 1952; Berner & others, 1983)**

Step 1: $CaSiO_{3\,(s)} + 2\,CO_2 + H_2O \rightarrow 2\,HCO_3^- + Ca^{2+} + SiO_2$

Initially, 2 moles of CO_2 consumed per 1 mole of silicate mineral weathered, produces alkalinity (bicarbonate)

Step 2: $2\,HCO_3^- + Ca^{2+} \leftrightarrow CaCO_{3\,(s)} + CO_2 + H_2O$

1 mole of CO_2 *released* per 1 mole of carbonate mineral precipitated

Full reaction: $CaSiO_{3\,(s)} + CO_2 \rightarrow CaCO_{3\,(s)} + SiO_2$

1 mole CO_2 consumed per 1 mole of silicate mineral weathered, once 1 mole of carbonate mineral is precipitated

USGS **Technological rationale: can silicate weathering be accelerated to remove CO_2?**

Geologic carbon management

2) USGS research: CO_2 mineralization

Mafic!

Mg, Fe, Ca-rich silicate minerals

Which common minerals react on relevant timescales?

wollastonite	$CaSiO_3 + CO_2 \rightarrow CaCO_3$
olivine	$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$
pyroxenes	$CaMgSi_2O_6 + 2CO_2 \rightarrow CaMg(CO_3)_2 + 2SiO_2$
serpentine polytypes	$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$
brucite	$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$

and basaltic glass

from National Academies (2019)

USGS

Geologic carbon management

2) USGS research: CO_2 mineralization

In subsurface, CO_2 injection into basalts

Orange Mountain Basalt, New Jersey

Vesicular (bubbles) lava flow boundary

Vesicular (bubbles) lava flow boundary

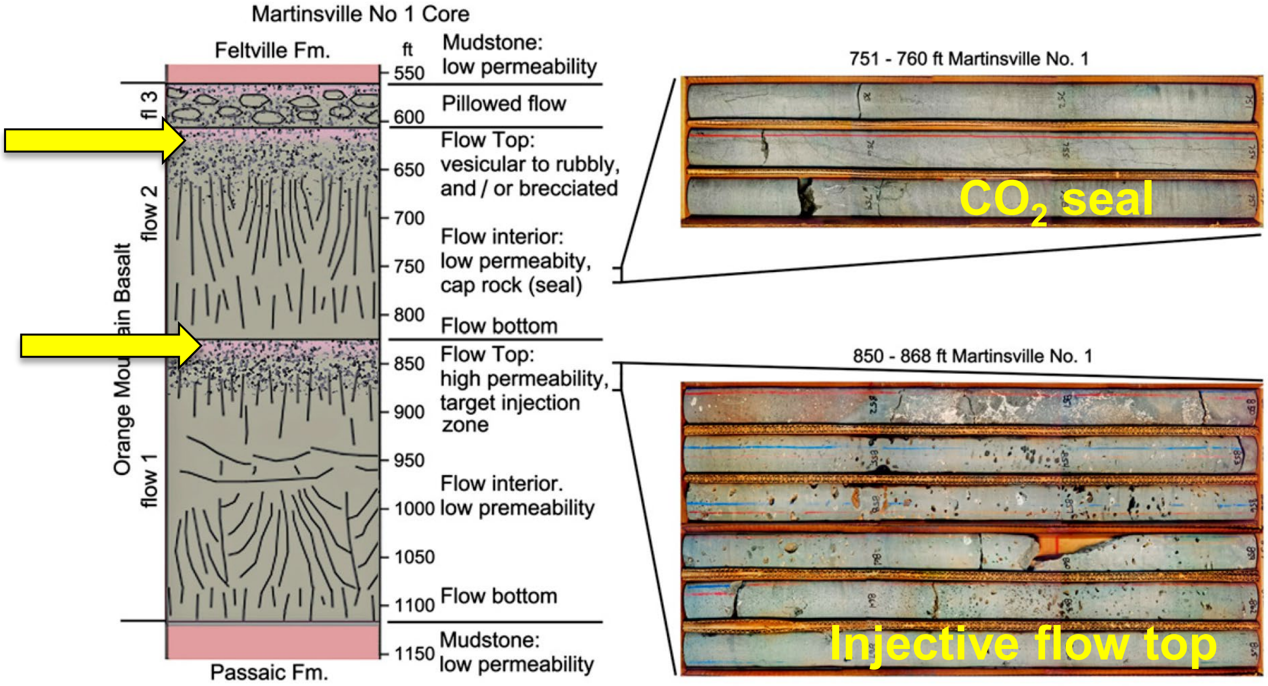


Fig. from Goldberg and others (2010)

Fm. - geologic formation

Geologic carbon management

2) USGS research: CO_2 mineralization

More rapid and secure trapping of CO_2 (weeks to years) than in traditional saline aquifers

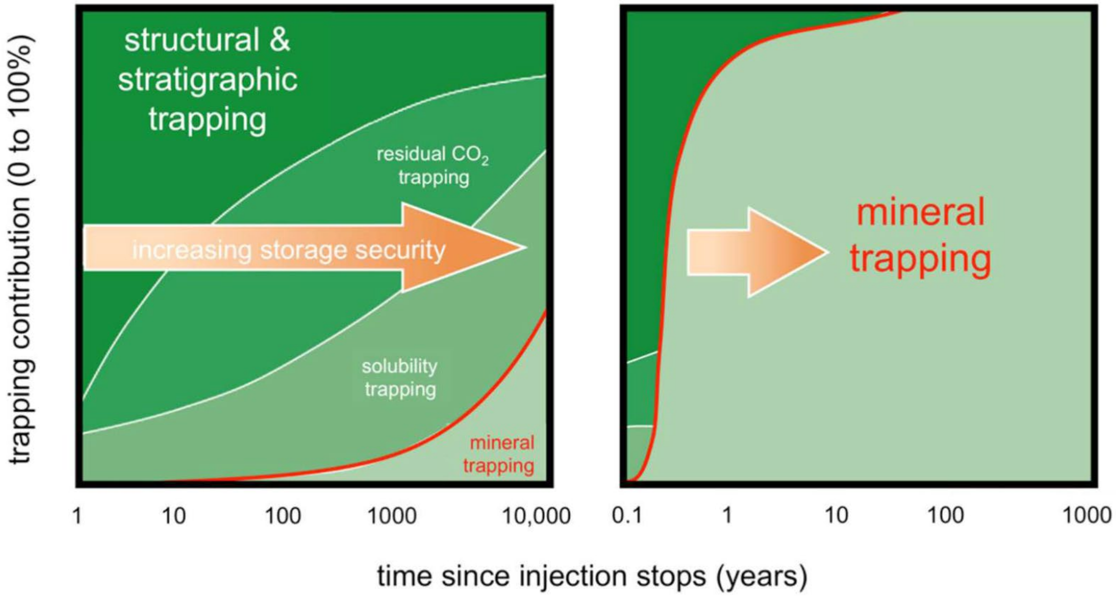


Fig. from Kelemen and others (2019) based on IPCC (2005)

USGS

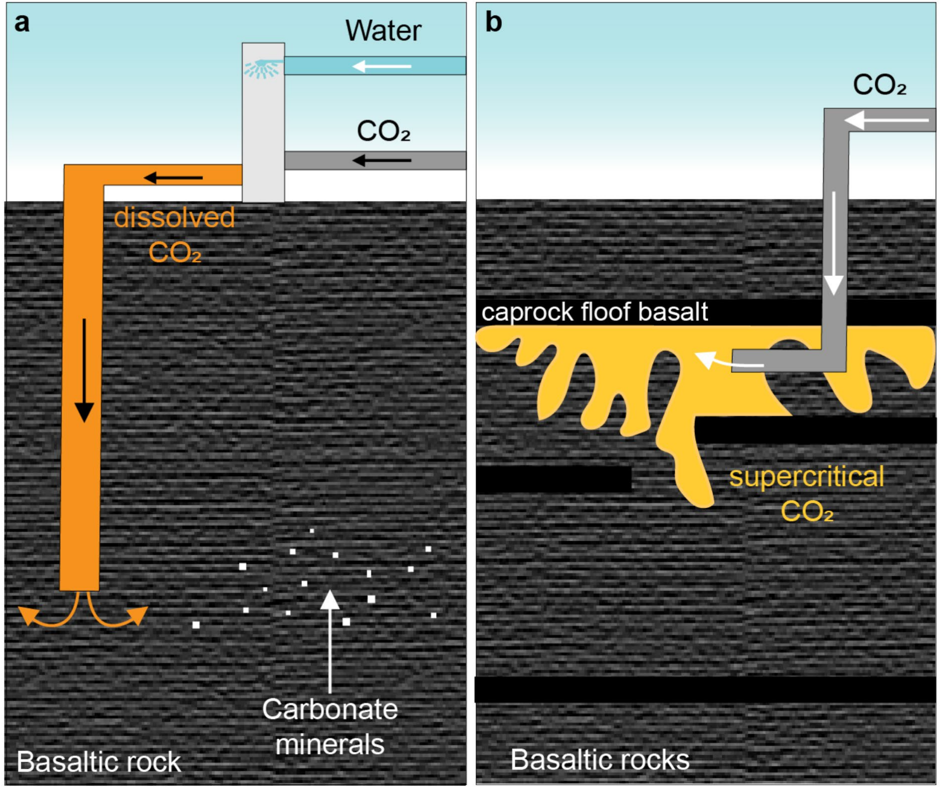
Geologic carbon management

2) USGS research: CO_2 mineralization

Does it work?

- **Few injection sites with this technology**
- **Wallula, Washington, U.S.**
    - **Pacific Northwest National Laboratory**
    - **1000 tons of CO_2 injected into Columbia River Basalt (McGrail and others, 2017)**
    - **Successful mineralization and plans to redrill these basalts for potential larger scale injections in 2025 (megatons CO_2)**
- **Carbfix projects in Iceland**
    - **Dissolve CO_2 in water for highest reactivity (95% in < 2yrs)**
    - **Massive expansion of operations planned with new Coda terminal (2026-31)**

Carbfix, Iceland Wallula, WA, USA



Snaebjörnsdóttir and others (2020)

Geologic carbon management

Carbfix Coda terminal plans, Iceland

Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Maritime transport

The CO_2 will be exported from industries with carbon capture capabilities across North Europe. There, the CO_2 will be compressed and transported by specifically designed gas carriers in a cold liquid form. Overall, the CO_2 emissions related to the transport and storage operations account for less than 4% of the total CO_2 to be permanently mineralised by the Coda Terminal.

Phase 4: 3 million tons of CO_2/year

Iceland emissions 1.5 million tons of CO_2/year

Nation of Iceland CO_2 net-zero by 2029?

Phase 1

700 thousand tonnes of CO_2 per year. One ship in operation. 2027

Phase 2

1,4 million tonnes of CO_2 per year. Two ships in operation. 2029

Phase 3

2,1 million tonnes of CO_2 per year. Five ships in operation. 2030

modified from Carbfix.com (accessed January 2025)

USGS

Geologic carbon management

2) USGS research: CO_2 mineralization

**Led previously by Madalyn Blondes now at Carbfix*

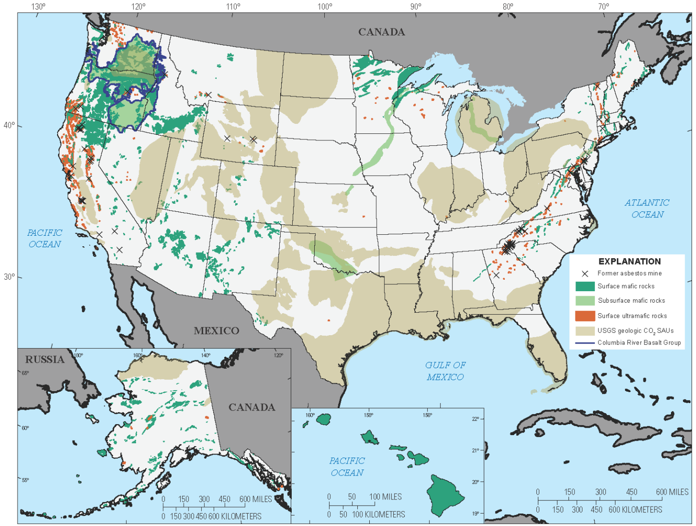
2019 USGS CO_2 mineralization feasibility study

<u>2023 Congressional request to USGS</u>

- **Assess CO_2 mineralization resources of the U.S. and “sources of alkalinity”**
- **Assessment objectives questions are similar to original CO_2 saline aquifer storage assessment**
    - **Where, how much, and how quickly can CO_2 be reacted with minerals for removal?**
- **Settings:**
    - **Subsurface injection (basalts, peridotites)**
    - **Mafic mine tailings (mine wastes)**

USGS science for a changing world

Carbon Dioxide Mineralization Feasibility in the United States



Scientific Investigations Report 2018–5079

Blondes and others (2019)

USGS

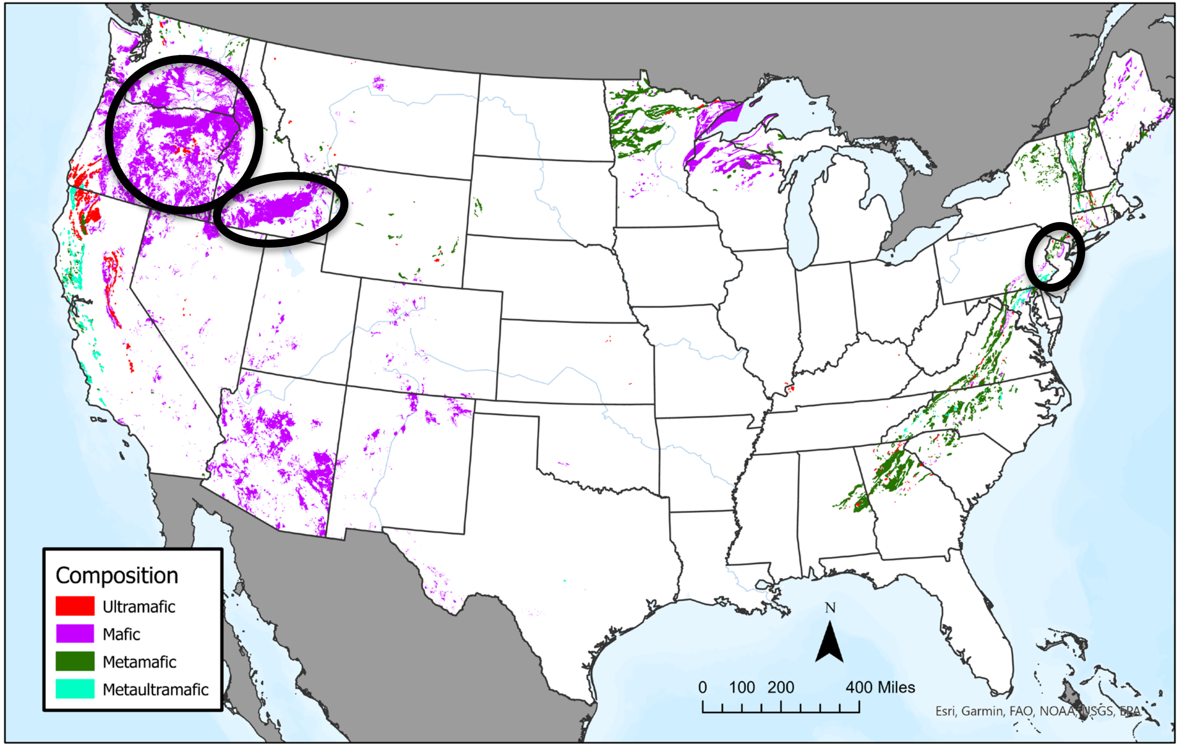
Geologic carbon management

2) USGS research: CO_2 mineralization national assessment

<u>Priority subsurface assessment targets</u>

- **Columbia River Basalt**
- **Snake River Basalt**
- **Hawaiian basalts**
- **CAMP Basalts (Central Atlantic Magmatic Province)**

- **Subsurface results publication estimate: 2026**

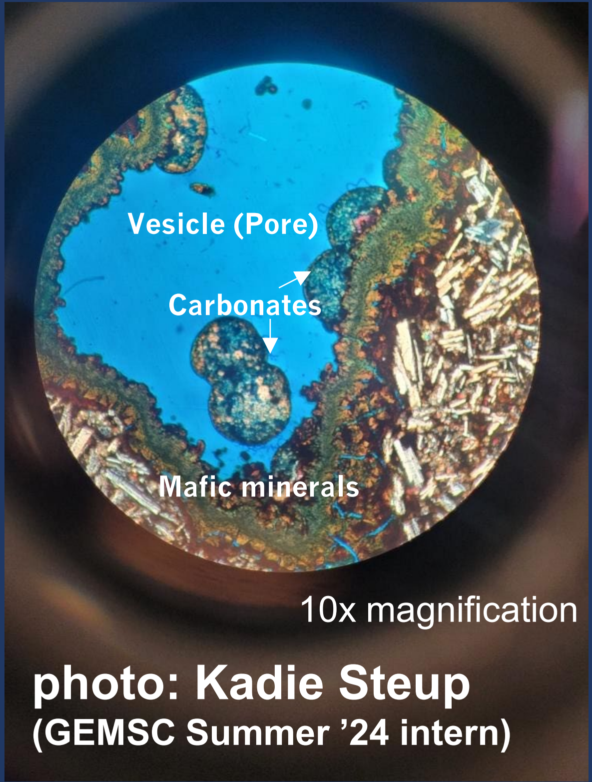


Jones and others (in prep.)

Interdisciplinary science of CO_2 mineralization

Energy gases + water + minerals

Thin section of carbonated basalts (Wallula, WA)

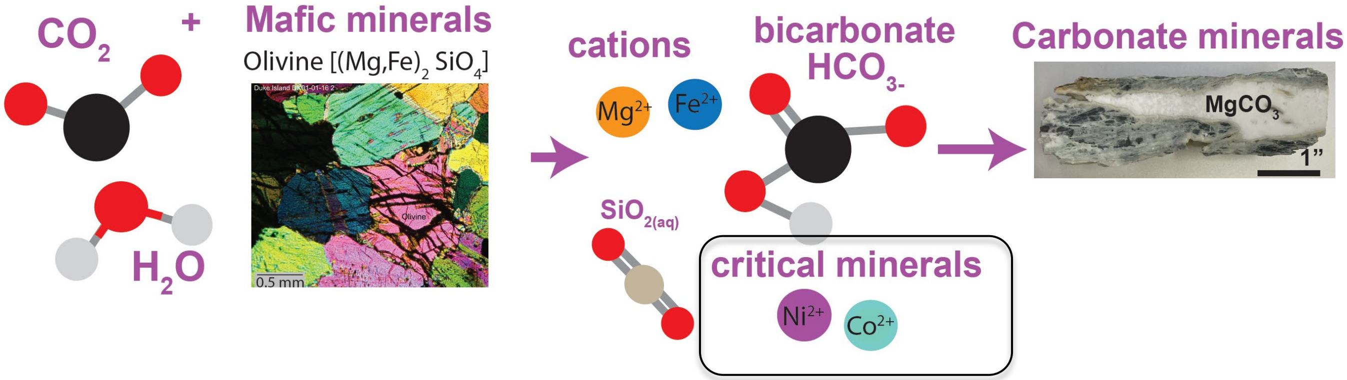


Ni-rich peridotite samples in cores from Minnesota

Critical minerals: a byproduct from CO_2 mineralization?

Carbon negative injective mining

- **Olivine mineral group**
  - **Highly reactive in low pH, CO_2 rich fluids**
  - **Rich in Ni and Co (critical minerals key for electrification)**



MINER Project: USGS-Pacific Northwest National Lab collaboration (ARPA-E program)

- PNNL collaborators: Quin Miller, Nabajit Lahiri, Todd Schaef, Heath Stanfield
- https://arpa-e.energy.gov/programs-and-initiatives/search-all-projects/supercritical-co2-based-mining-carbon-negative-critical-mineral-recovery

USGS

Pacific Northwest NATIONAL LABORATORY

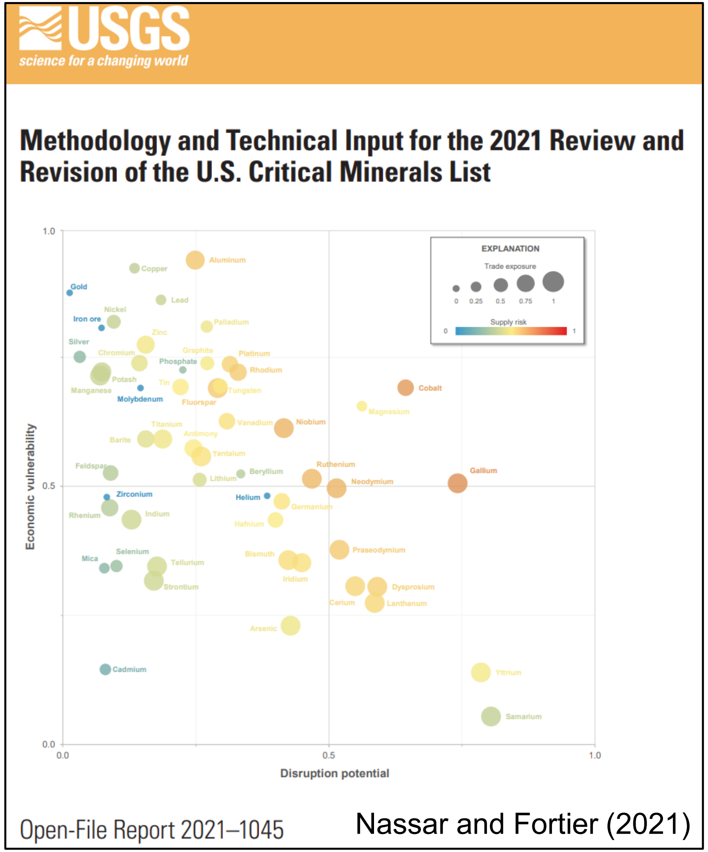
What are critical minerals – how do they govern electrification?

Critical minerals: a byproduct from CO_2 mineralization?

What are critical minerals?

The Energy Act of 2020 defines “critical minerals” as minerals, elements, or materials, that:

1) are essential to U.S. economy or national security
2) have a supply chain vulnerable to disruptions
3) serve an essential function in manufacturing of significant products in the U.S.



Nassar and Fortier (2021)

USGS

Critical minerals: a byproduct from CO_2 mineralization?

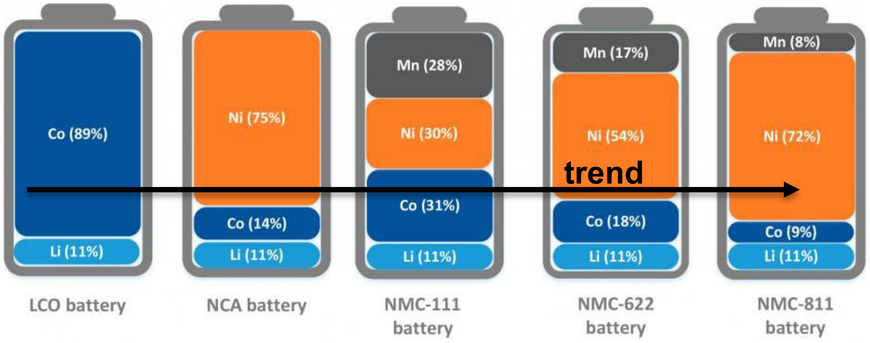
Critical minerals and electrification: batteries

Nickel (Ni)
- added in USGS update (Nassar and Fortier, 2021)

https://www.usgs.gov/media/images/critical-mineral-commodities-renewable-energy

Li-ion “NMC” battery
(Nickel-Manganese-Cobalt)

LCO – lithium cobalt oxide
NCA - Lithium Nickel Cobalt Aluminum Oxide



modified from British Geological Survey (2021)

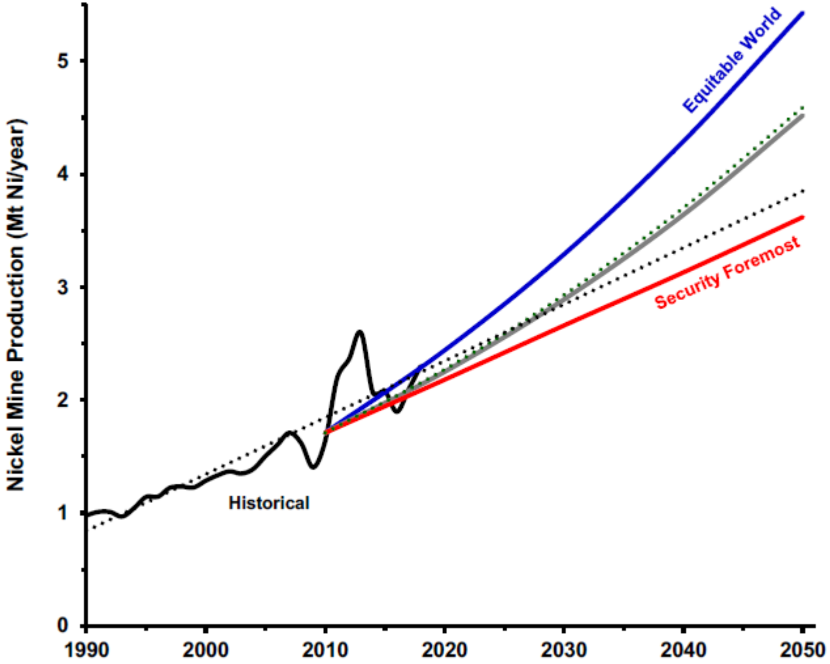
USGS

Critical minerals: a byproduct from CO_2 mineralization?

Critical minerals in batteries

"The final challenge facing the Ni industry is a positive one: potential rapid increases in demand as a result of the transition to a carbon-neutral economy **using EVs, renewable energy, and energy storage batteries**… One key component of this is the lithium-ion battery, which, despite its name, actually **contains more Ni than it does Li…**"

-Mudd and Jowitt (2022) *Economic Geology*



adapted from Elshkaki and others (2017) by Mudd and Jowitt (2022)

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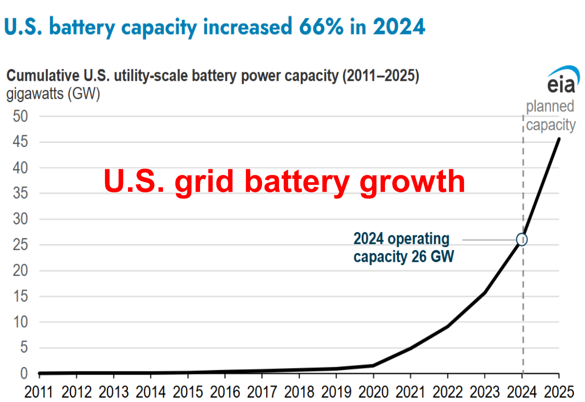
Critical minerals: a byproduct from CO_2 mineralization?

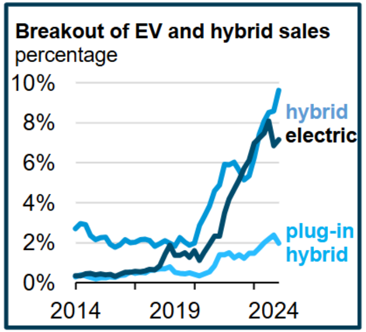
Critical minerals in batteries

Projections of rising demand for Nickel mining

- **exact demand is a function of metal recycling, rate of EV adoption, battery energy storage utilization, etc.**
- **minimizing adverse surface environmental effects from new and historic Ni mining operations is important**
- **only one active Ni mine in the U.S.! (Eagle Mine, MI)**

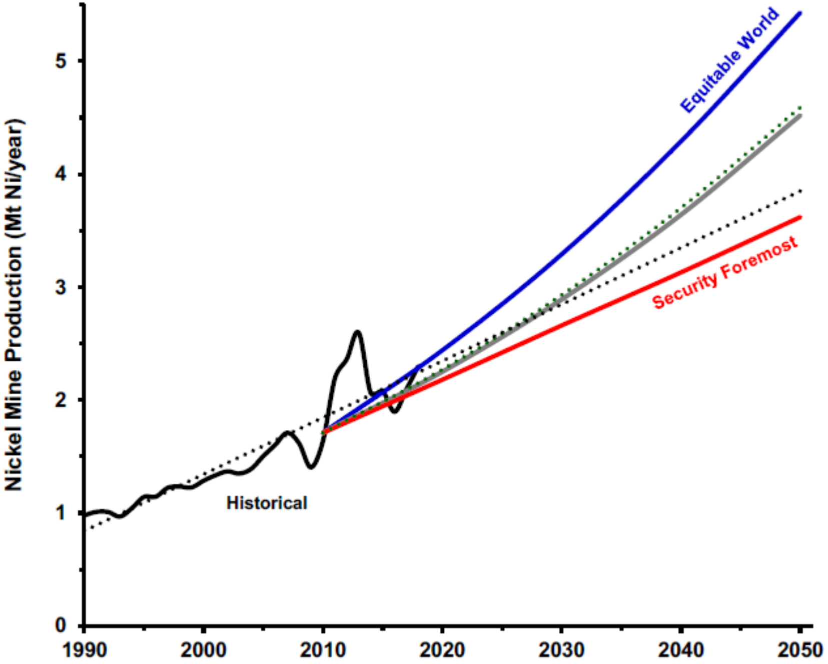


U.S. EIA (2025b)



U.S. car sales

U.S. EIA (2024)



adapted from Elshkaki and others (2017) by Mudd and Jowitt (2022)

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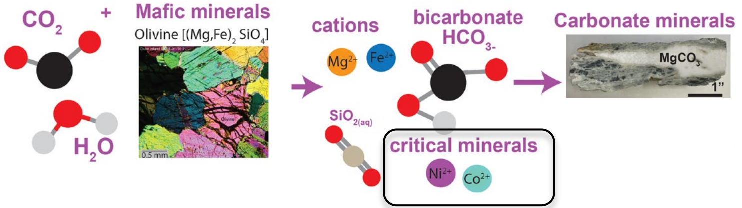
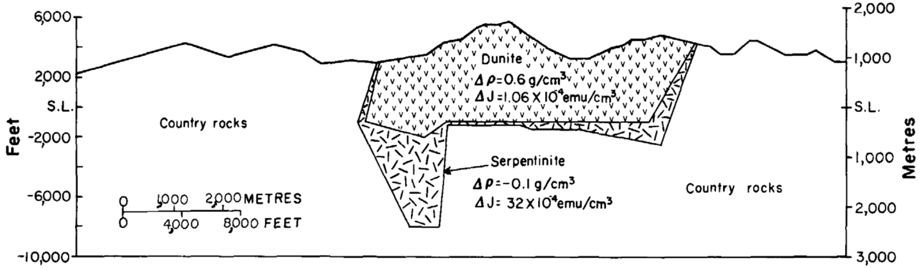
Critical minerals: byproduct resources from CO_2 mineralization?

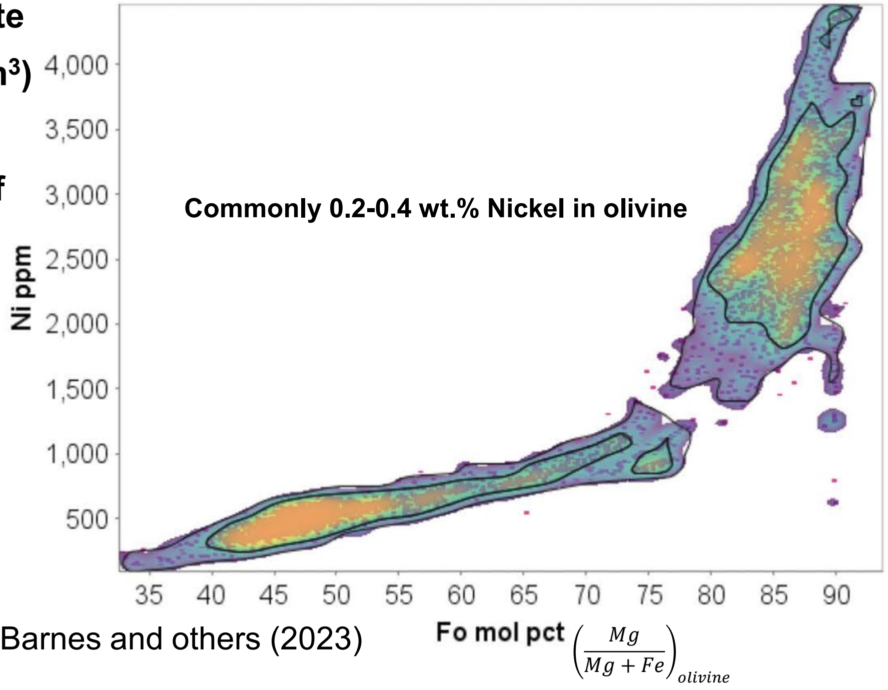
Olivine-hosted nickel



- olivine is highly reactive with CO_2
- olivine is also enriched in Ni & other metals (Co, Cr, etc.)
- olivine can be concentrated in mafic-ultramafic mine waste
- ophiolitic peridotite massifs (>50% olivine, 100s-1000s km^3)
- Twin Sisters Dunite, Washington (>90% olivine, 190 km^3)
- theoretically, 0.001% recovery would equate to millions of tons of nickel for batteries



Thompson and Robinson, *GSA Bulletin* (1975)



Barnes and others (2023)

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Preliminary Information-Subject to Revision.

Carbon negative nickel mining?

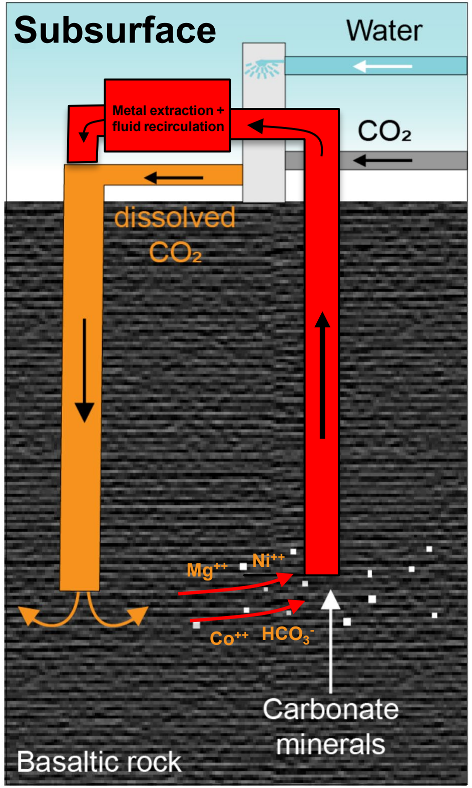
ARPA-E MINER Program research (funding from U.S. Department of Energy)

- Can CO_2 be utilized (CCUS) to:
  - extract Ni & other metals from new mafic mineral targets?
  - offset or negate emissions from Ni production?
  - recover remaining mineral value from tailings?

Surface mine waste tailings

1 2 3 5 6

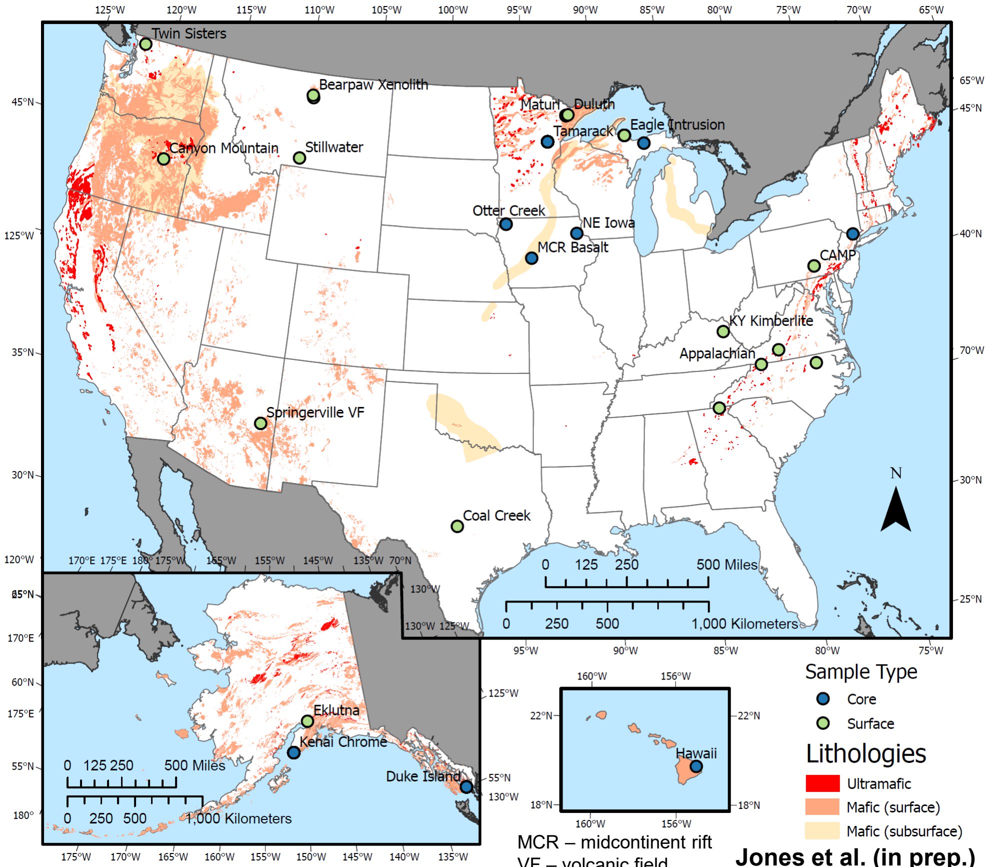
Belvidere Asbestos Mine, Vermont Department of Environmental Conservation
https://dec.vermont.gov/geological-survey/vermont-geology/Belvidere



modified from Snaebjörnsdóttir and others (2020)

Critical minerals: byproducts from CO_2 mineralization?

Ranking targets



MCR – midcontinent rift
VF – volcanic field
CAMP – Central Atlantic Magmatic Province

Jones et al. (in prep.)

Preliminary Information-Subject to Revision.

Carbon negative injective mining

- **Samples analyzed from ~20 sites in U.S.**
- **Measured for olivine mineral abundance using X-ray diffraction (XRD)**
- **Measured for major (Mg, Ca) and trace elements (Ni, Co, etc.)**

Ashton Wiens (Research Statistician) **Kadie Steup** (Undergraduate Intern)

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Critical minerals: byproducts from CO_2 mineralization?

Ranking targets

Exploration vector design

- Statistical relative scoring of geologic units for amenability

Divalent cation score $\mu_1(x) = f(MgO + CaO + FeO)$

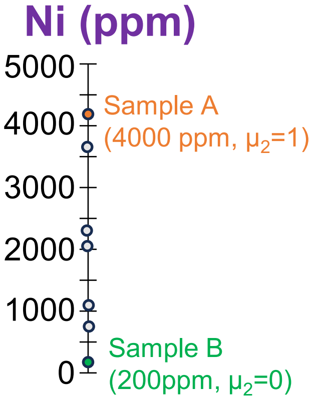
Nickel score $\mu_2(x) = f([Ni])$

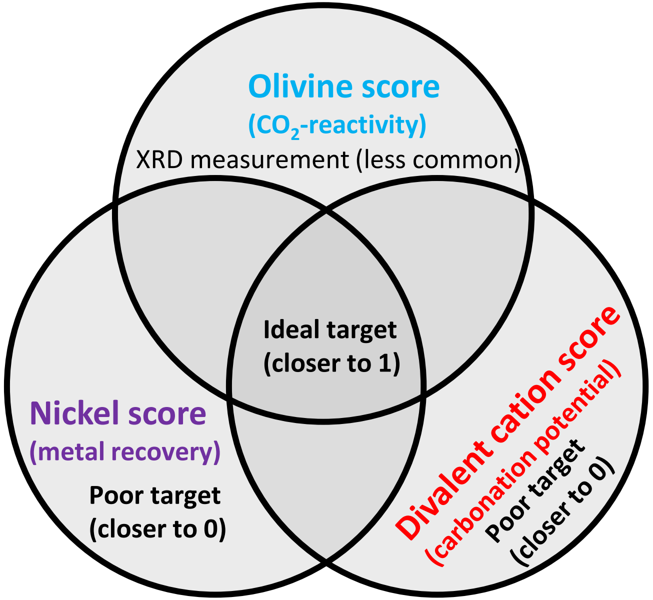
Olivine score $\mu_3(x) = f([Olivine])$

Fuzzy logic sets:

$$f(z) = \frac{z - \min(z)}{\max(z) - \min(z)}$$

$$\mu(z) = \mu_1 \times \mu_2 \times \mu_3$$





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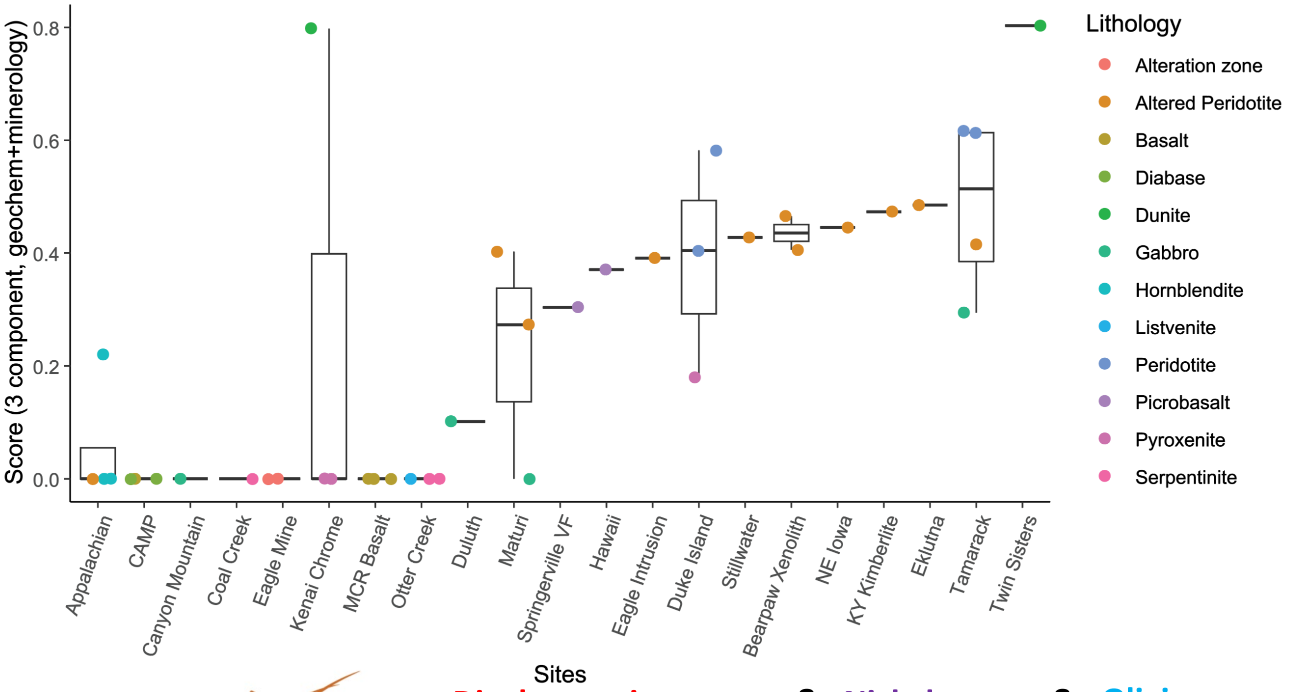
Critical minerals: a byproduct from CO_2 mineralization?

Ranking Targets



Key takeaways

- Dunite and peridotite lithologies score with the highest potential for coupled CO_2 mineralization and nickel resources
- Picrobasalts, like in Hawaii, score reasonably well and have vesicular texture ideal for subsurface injection of CO_2
- This exploration vector is being "upgraded" to apply to large geochemical sample sets

Divalent cation score & **Nickel score** & **Olivine score**

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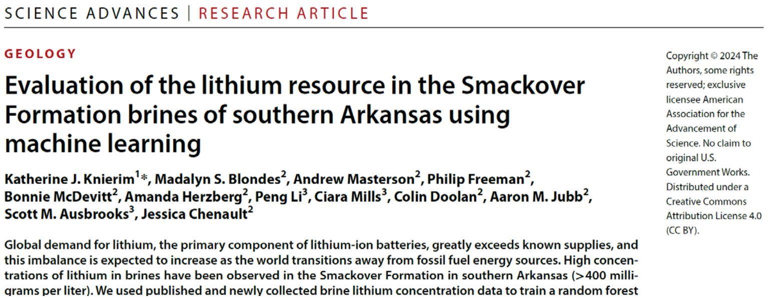
Additional emerging energy research topics at USGS (ERP)

- Geothermal (3D temperature maps)
- Lithium for batteries from brines (Andrew Masterson)
- Frontier U.S. oil and gas resources
- Geologic hydrogen
- Coal waste reuse and more



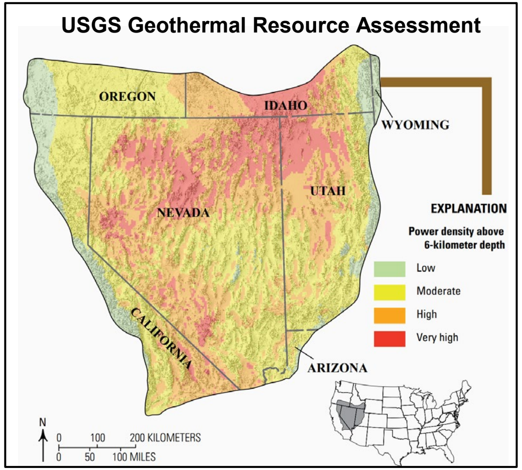
SCIENCE ADVANCES | RESEARCH ARTICLE

GEOLOGY

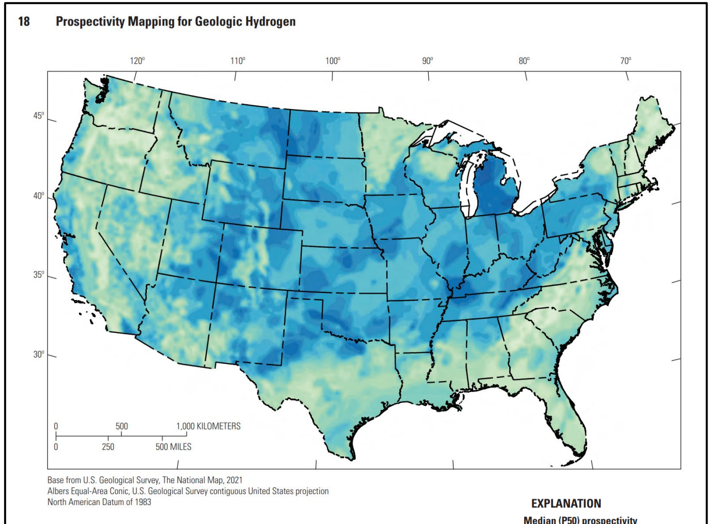
Evaluation of the lithium resource in the Smackover Formation brines of southern Arkansas using machine learning

Katherine J. Knierim[1]*, Madalyn S. Blondes[2], Andrew Masterson[2], Philip Freeman[2], Bonnie McDevitt[2], Amanda Herzberg[2], Peng Li[3], Ciara Mills[3], Colin Doolan[2], Aaron M. Jubb[2], Scott M. Ausbrooks[3], Jessica Chenault[2]

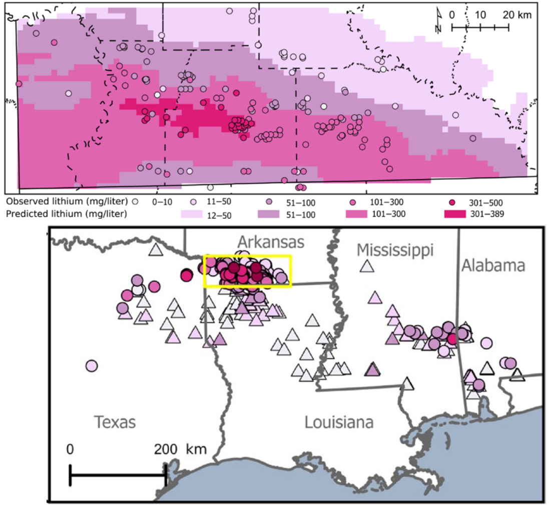
Global demand for lithium, the primary component of lithium-ion batteries, greatly exceeds known supplies, and this imbalance is expected to increase as the world transitions away from fossil fuel energy sources. High concentrations of lithium in brines have been observed in the Smackover Formation in southern Arkansas (>400 milligrams per liter). We used published and newly collected brine lithium concentration data to train a random forest



Burns and others (2025)



Gelman and others (2025)



Knierim and others (2024)

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Conclusions

Subsurface geology and U.S. energy portfolio

- **Increasing natural gas and renewable energy production is displacing coal consumption and decreasing national CO_2 emissions**
- **Energy storage and critical minerals key to sustaining growth rates for emerging renewable energy sources**
- **Subsurface energy stores of natural gas can ensure grid stability and bolster against "shocks" in global energy markets**
- **Many subsurface CO_2 management technologies beginning to "scale-up," others in pilot project/test phases**
- **CO_2 mineralization may provide an untapped resource of critical minerals like nickel from the subsurface and mine wastes ("CO_2 utilization" in CCUS)**

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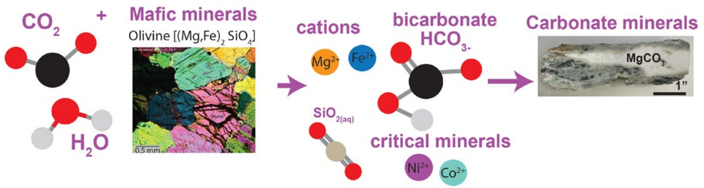

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Conclusions

Federal science

- USGS Energy Resource Program meets congressional and administration requests for info on emerging resources in energy geology
- Key role of federal research "ecosystem"
  - Interior - USGS, Bureau of Land Management (BLM), Bureau of Ocean Energy Management (BOEM);
  - Energy - EIA, National Labs, ARPA-E;
  - EPA;
  - Commerce – NIST, National Oceanic and Atmospheric Administration (NOAA);
  - National Science Foundation (NSF)
- Future of energy, as always, is unpredictable
  - Not discussed today: policy, economics and geopolitical considerations – major driver of energy market and innovation

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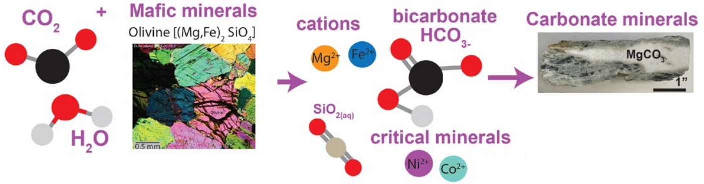

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Conclusions
careers in energy geology

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Opportunities for Earth Scientists

- Subsurface geology will be key to meeting energy demands of the U.S. for decades to come and beyond
- Classic geoscience skills are finding new applications (minerals matter!) – carbon management and beyond
- Advice and cautions for emerging technologies:
    - at some level, remain a generalist
    - learn to self-train and enjoy research
    - seek out opportunities in applied energy & mineral geology & geospatial data
    - seek out positions in organizations/institutions that nurture your long-term development as a scientist
    - scrutinize business/science/funding models
    - don't be afraid to reach out to those in the field!

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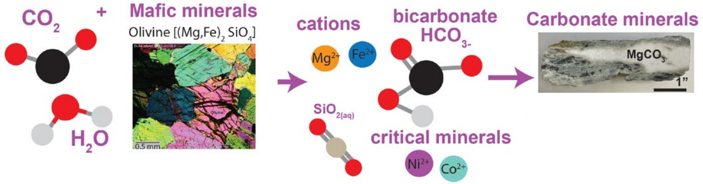

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Conclusions

Acknowledgments (USGS is collaborative science!)

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- USGS - GEMSC summer intern Kadie Steup
- Greg Lackey and SHASTA Group (U.S. Department of Energy - National Energy Technologies Laboratory)
- Autumn Haagsma, Bill Harrison & colleagues (Michigan Geologic Survey - MGRRE)
- H. Todd Schaef, Quin Miller, Nabajit Lahiri, C. Heath Stanfield, Matt Villante (PNNL)

Websites

Energy & Minerals-centric USGS links

- Energy and Minerals Mission Area | USGS
- Energy Resources Program | USGS
- Mineral Resources Program | U.S. Geological Survey
- Carbon Mineralization | USGS
- Geologic Energy Storage | USGS
- Carbon and Energy Storage, Emissions and Economics (CESEE) | U.S. Geological Survey
- Geology, Energy & Minerals Science Center | USGS

Other federal agencies

- U.S. Energy Information Administration – EIA
- ARPA-E | U.S. Department of Energy

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