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Carbon Capture and Sequestration Strategy for Ohio

SARTA Hydrogen Fuel Cell Bus
Refueling Station
Canton, Ohio

MEC Conference on Clean and Renewable Energy

September 28, 2023

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Ohio Clean Hydrogen Hub Alliance

- **Concept**: develop regional clean hydrogen economy across industrial, energy and transportation sectors
  - 150 members from commercial, academic, government, economic development institutions
  - Goal: decarbonization of key sectors
- **Leadership:**
  - Stark Area Regional Transit Authority (SARTA)
  - Midwest Hydrogen Center of Excellence (MHCoE)
  - Cleveland State University
  - Dominion Energy Ohio
  - Battelle
  - World Economic Forum
    - *Transitioning Industrial Clusters*

Hydrogen Heights

Dominion Energy Test Facilities for Hydrogen Blending Operations
Boston Heights, Ohio
May 2023

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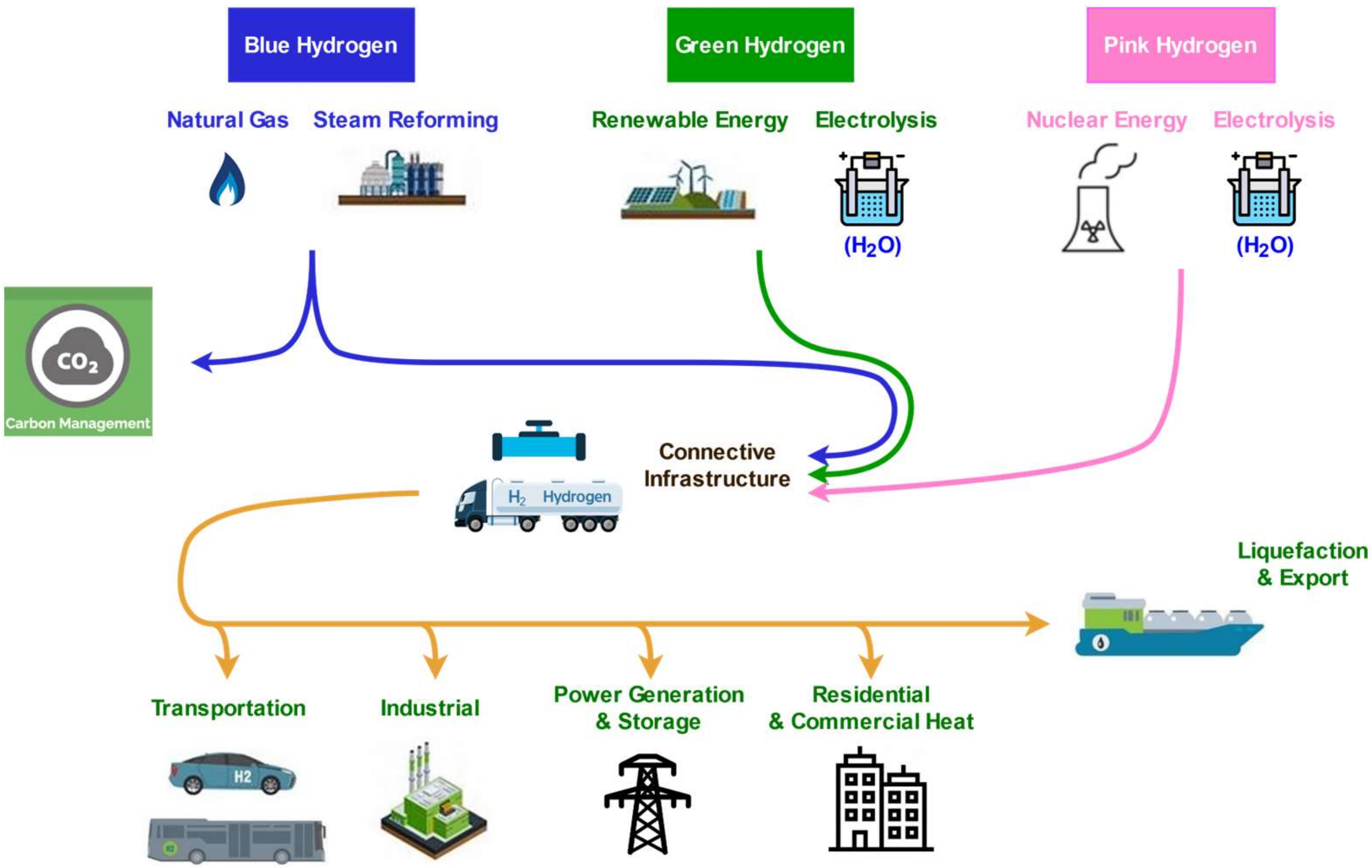
Mapping a Clean Hydrogen Economy



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Projecting Supply for Hydrogen in Ohio by Source

Source	2030	2040	2050
Electrolysis via Nuclear Power	9,300	50,700	59,600
Electrolysis via Renewable Sources	86,600	112,800	135,900
Natural Gas (SMR)	341,700	490,100	1,788,400
TOTAL	**437,600**	**653,600**	**1,983,900**

Units are in metric tons.

- Electrolytic production limited to 15% of power generation capacity.
- Hydrogen from natural gas is what must be supplied to meet demand after accounting for pink and green hydrogen.
- 1.8 million metric tons of hydrogen supplied via SMR would require around 280 bcf of natural gas.
  - 280 bcf ≈12.5% of what Ohio shale wells produced annually.

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Why Do We Need Geologic Storage?

Total Great Lakes Region Carbon Sink Potential 2022-2050

Potential Carbon Dioxide Sinks	Cumulative CO2 Removal Capacity (gigatons)
Reforestation	2.2
Aggregates for Construction and Concrete	0.79
Geologic Storage Deep saline aquifers Depleted oil and gas reservoirs	 14-51 1.8-5.3

Great Lakes Region CO2 Emissions: 1.5 Gigatons/yr

(1 gigaton = 1 billion metric tons)

Source: "Capturing the Economic Opportunity of Carbon"
Global CO2 Initiative, University of Michigan 2022

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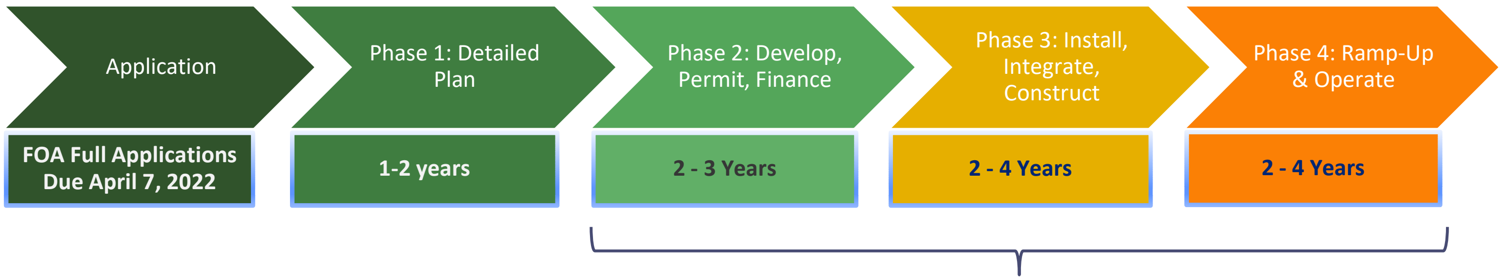
Dept of Energy Clean Hydrogen Hub Timeline



Funding of between $400M and $1.25B for phases 2-4 combined.

- **Concept papers Submitted November 2022**
  - 33 (of 79) concepts have been “encouraged” by the DoE
  - 6-10 hubs expected to be funded
  - $7 billion available (of total $8 B program)
  - Target of 4 kg CO2e per kgH2 for lifecycle greenhouse gas emissions

- **Objectives, Requirements, and Guiding Principles**
  - Feedstock, End-use, and Geographic Diversity
    - At least 2 hubs in regions with abundant natural gas resources
  - Production capacity of at least 50 to 100 metric tons/day
  - 50% non-federal cost share
  - Justice40 and Employment goals (priority for hubs creating long term jobs)

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Regional Hub Concepts Encouraged

- **Appalachian Regional Clean Hydrogen Hub (ARCH2):**
  - Focused on natural gas from Appalachia (Blue H2)
    - At least 9 other Blue H2 encouraged concepts
  - Led by Battelle, GTI
  - Public Collaborators:
    - MOUs from WV, Ohio, KY
    - OH2 Hub, SARTA
    - OH: Chamber of Commerce, Business Roundtable, JobsOhio
    - Universities, MHCoE
  - Private Collaborators:
    - Over 150 companies
    - Includes: EQT, Dominion, B&W, Long Ridge, AEP
- **Great Lakes Clean H2 Coalition**
  - Pink H2 Strategy (Energy Harbor)
  - Focused on Toledo markets
- **Midwest Alliance for Clean Hydrogen (MachH2)**
  - Multi-state, from MN to Ohio (NW Indiana focus?)
  - Ohio signed MOU
  - Pink, Green H2
- **Decarbonization Network of Appalachia (DNA)**
  - Blue H2 (natural gas)
  - Shell, Equinor
  - Team Pennsylvania

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Federal Investment Into Clean Energy

- **Bipartisan Infrastructure Bill**
  - $73 billion over 5 years on grid infrastructure
  - $50 billion over 5 years for weatherization
  - $9.5 billion for hydrogen infrastructure, research
  - $12 billion for carbon capture and sequestration
- **Inflation Reduction Act**
  - No Cap – federal tax credits that can be converted to cash – 30-50% of project cost
  - Covers renewable power, geothermal, microgrids, H2
  - McKinsey estimates it at over $400 B over ten years
    - Does not include H2
  - *With H2, estimated at $1 trillion*

Inflation Reduction Act H2 Opportunities

- H_2 production tax credit up to $3/kg depending on lifecycle CO_2 intensity

kg of CO_2 per kg of H_2	Maximum credit
2.5 – 4 kg of CO_2	20%
1.5 – 2.5 kg of CO_2	25%
0.45 – 1.5 kg of CO_2	33.4%
0 kg – 0.45 kg of CO_2	100%

Carbon intensity of gray hydrogen ~9 kg CO_2/kg H_2

  - Maximum credit depends on satisfying prevailing wage requirements
  - Not stackable with 45Q carbon sequestration credits
- IRS rule development – expect out in October.
  - *Additionality, Locality, Timing requirements are expected*
- IRA Investment Tax Credits
  - 30% cost of refueling stations, 15% of the cost of commercial fuel cell vehicles
  - 30% of cost of hydrogen storage equipment

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Breakdown of CO_2 Delivery and Injection Costs from Small Scale Hydrogen Production at SARTA to Three Oilfields*

Destination	Distance (mi.)	Capture and Compression ($/tCO2)	Trucking ($/tCO2)	Total EOR/Storage ($/tCO2) with Injection
ECOF	22	50	6	67
MCOF	83	50	17	78
Core Energy	450+	50	82	143

ECOF - East Canton Oil Field – Stark County - inactive
MCOF - Morrow Consolidated Oil Field – Central Ohio -- inactive
Core Energy – Michigan – active

Emissions and Production Costs for Fuel Cell and Conventional Transit Buses Using Hydrogen and Diesel

Vehicle & Fuel Type	Well-to-Wheels CO_2 Emissions (kg/mile)	Unit Production Cost for fuel ($/dge)	Average Miles Traveled per dge	Production Cost per Mile Traveled
FCEB: H_2 from electrolysis with renewable power	0.40	$4.99	7.0	$0.71
FCEB: H_2 from natural gas with CO_2 sequestration	0.57	$1.70	7.0	$0.24
FCEB: H_2 from natural gas without CO_2 sequestration	1.84	$1.13	7.0	$0.16
ICEB: Low-sulfur diesel	2.93	$0.84	3.7	$0.23

Average fleet fuel efficiency for FCEBs comes from the National Renewable Energy Agency's evaluations of vehicle deployments at transit agencies as of 2018 available at https://www.nrel.gov/docs/fy19osti/72208.pdf. *See also* https://afdc.energy.gov/data/. Average fleet fuel efficiency for diesel transit buses comes from the U.S. Department of Energy's Alternative Fuels Data Center's most recent estimate of average fuel economy by major vehicle category available at https://afdc.energy.gov/files/u/data/data_source/10310/10310_fuel_economy_by_vehicle_type_3-26-20.xlsx

Comparison of Cost and Carbon Intensity for Various Small-Scale Hydrogen Production Options.

Method	Cost (\$/kg H_2)	Carbon Intensity ($kgCO_2e/kg\ H_2$)
SMR: delivered via LH_2[a]	5.93	9.81[b]
SMR: onsite, no capture	3.22	8.98
SMR: RNG, no capture	4.49	2.22 – 5.32[c]
SMR: onsite with capture (blue)		
- with geological storage	3.65	2.44
- with EOR/ECOF	3.52	4.17
- with EOR/MCOF	3.47	4.40
- with RMC	3.27	2.44
Electrolysis (green) – no grid	7.43	2.58

- This hydrogen is compressed and liquified in Sarnia, Ontario, Canada, and delivered ca. 270 miles in LH_2 tanker trailers to SARTA. Importantly, this method of delivery arrives under pressure, and little or no additional on-site hydrogen compression is required for storage. This cost needs to be accounted for in a true apples to apples comparison.
- The incremental carbon footprint assumes negligible boil-off losses at the Sarnia trailer refill and during transit, and emissions of 220 gCO_2e/tonne/mile due to fuel consumption.
- The lower bound represents WWTP RNG at 19.34 gCO_2e/MJ and the upper bound represents landfill RNG at 46.42 gCO_2e/MJ.

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Carbon Sequestration

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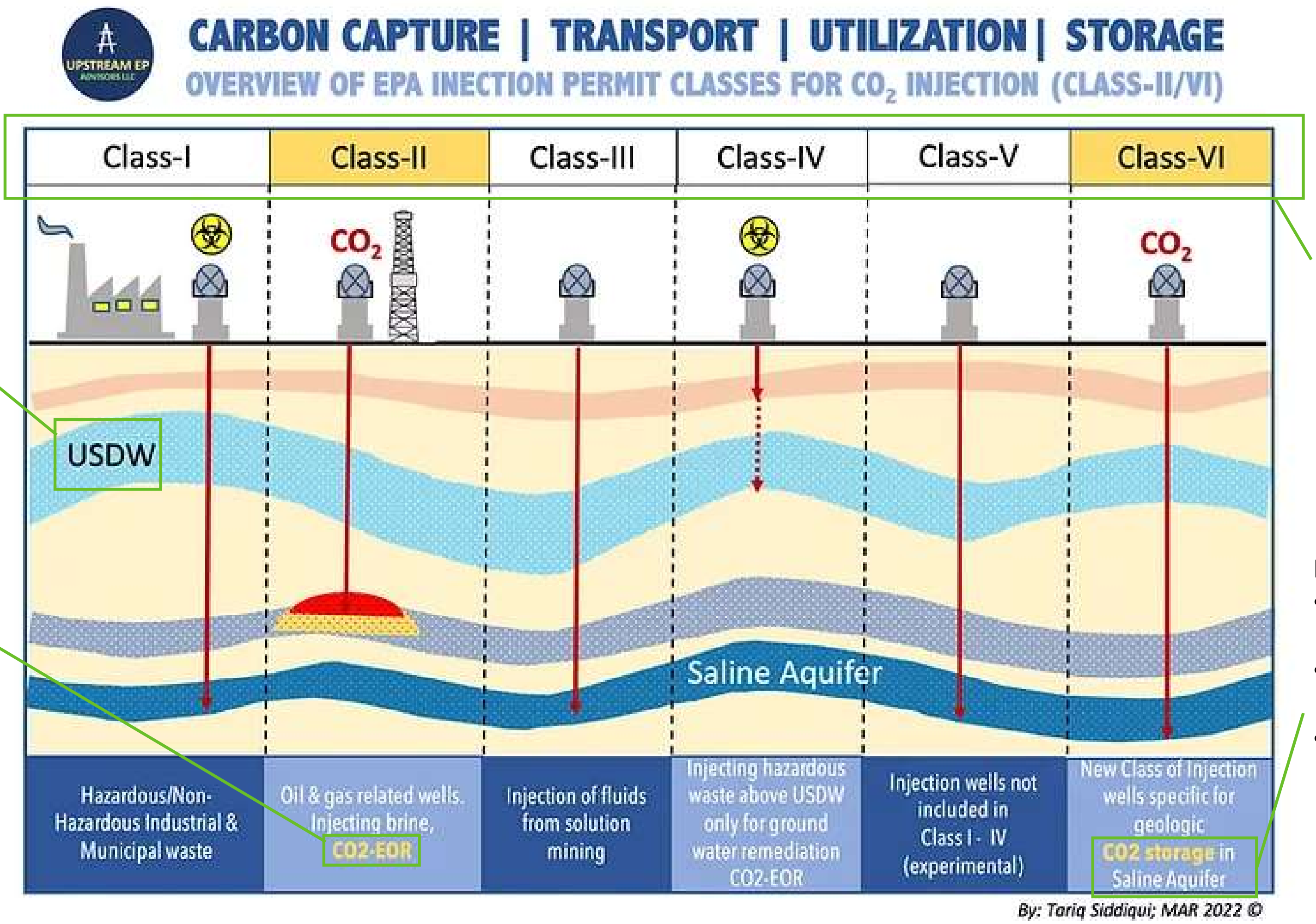
"Underground Sources of Drinking Water"

"Enhanced Oil Recovery"



Classifications based on type of injection, depth of injection, and impact on USDW

Primary Targets:

- Deep saline aquifers
- Depleted oil & gas fields
- Unmineable coal seams

(Upstream EP Advisors, 2022; Zhang & Song, 2014)

Class II vs. Class VI Wells

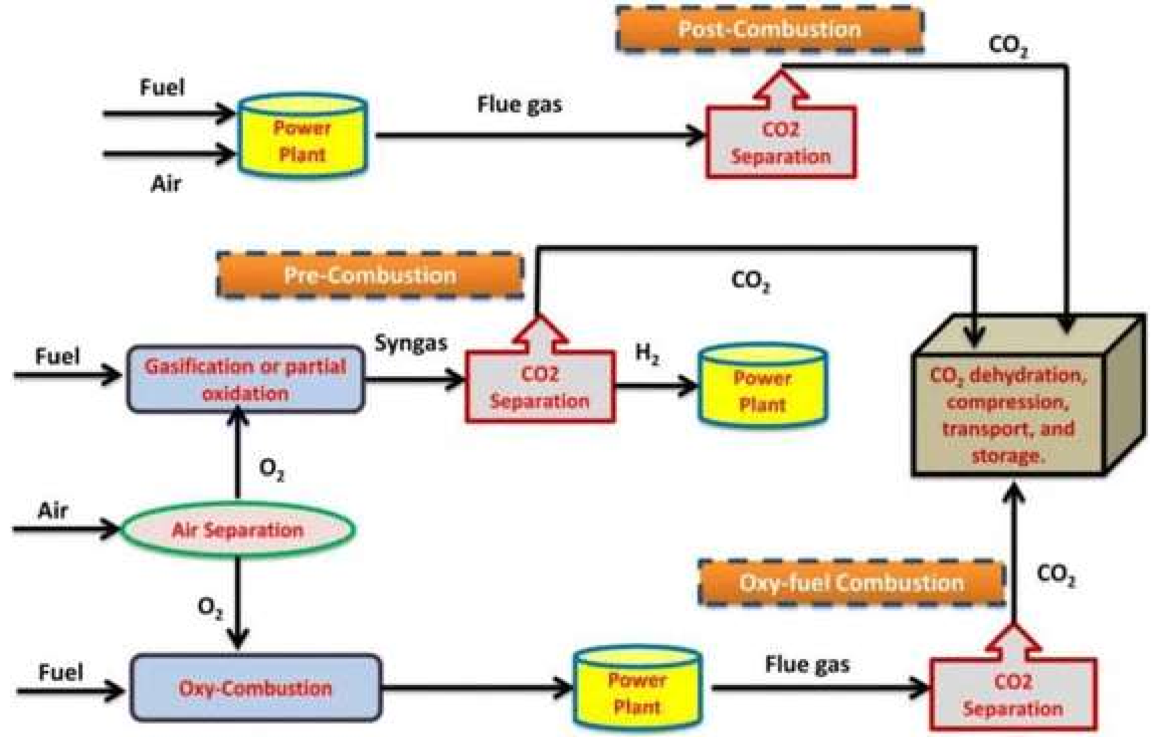
	CLASS II WELLS	CLASS VI WELLS
Purpose	• Oil and gas production, wastewater disposal, EOR	• Long term CO_2 storage
	UNIQUE CLASS VI CHARACTERISTICS	
Mechanics	• Larger expected fluid volumes, higher injection pressures, different physical/chemical properties of injection stream	
Risks	• EPA regulates separately because of unique risks to USDW • CO_2 large volumes, relative buoyancy, mobility, corrosive property in presence of water, potential impurities in injection stream	
Requirements	• Larger injection site "area of review": 3D extent of plume, area elevated pressure/fluids, surface area above • Comprehensive performance requirements • Shorter periods between testing and reporting • Seismicity information • Lifetime monitoring: injection pressure & groundwater quality • Post-injection care and emergency response	

(CRS Report, 2022)

Injection Mechanisms

Capturing CO_2

1. Post-combustion capture
2. Pre-combustion capture
3. Oxy-fuel capture

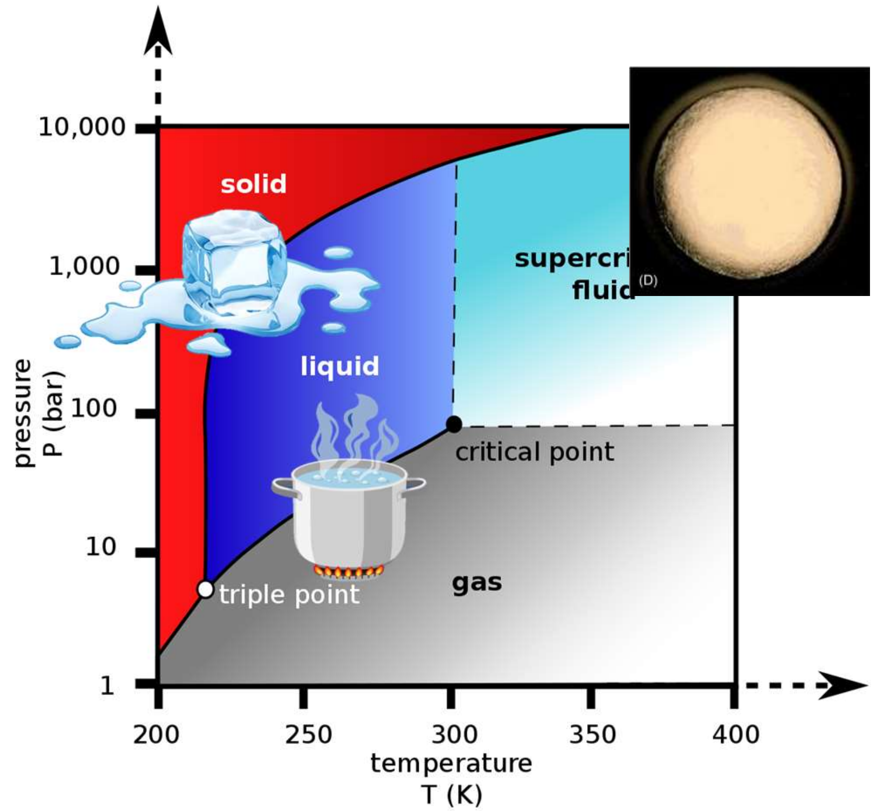


(Eldardiry and Habib, 2018)

Injection Mechanisms

Transporting CO_2

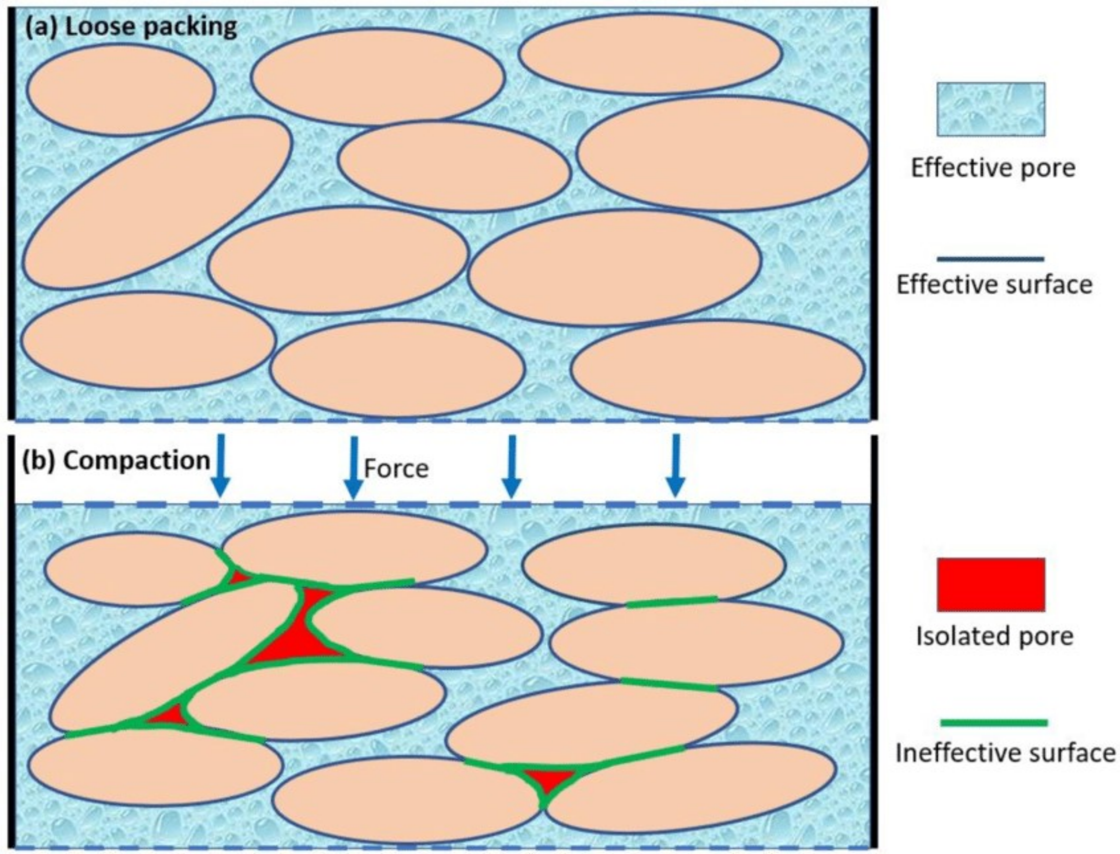
- Compressed into supercritical fluid
  - No distinct liquid or gas phase
- Pressure increases for injection
- Advantages:
  - More dense than gaseous form = less reservoir volume + more storage
  - Stays in form b/c of natural underground properties



(Eldardiry and Habib, 2018; National Energy Technology Laboratory, n.d.; Cunico & Turner, 2017)

Pore Space

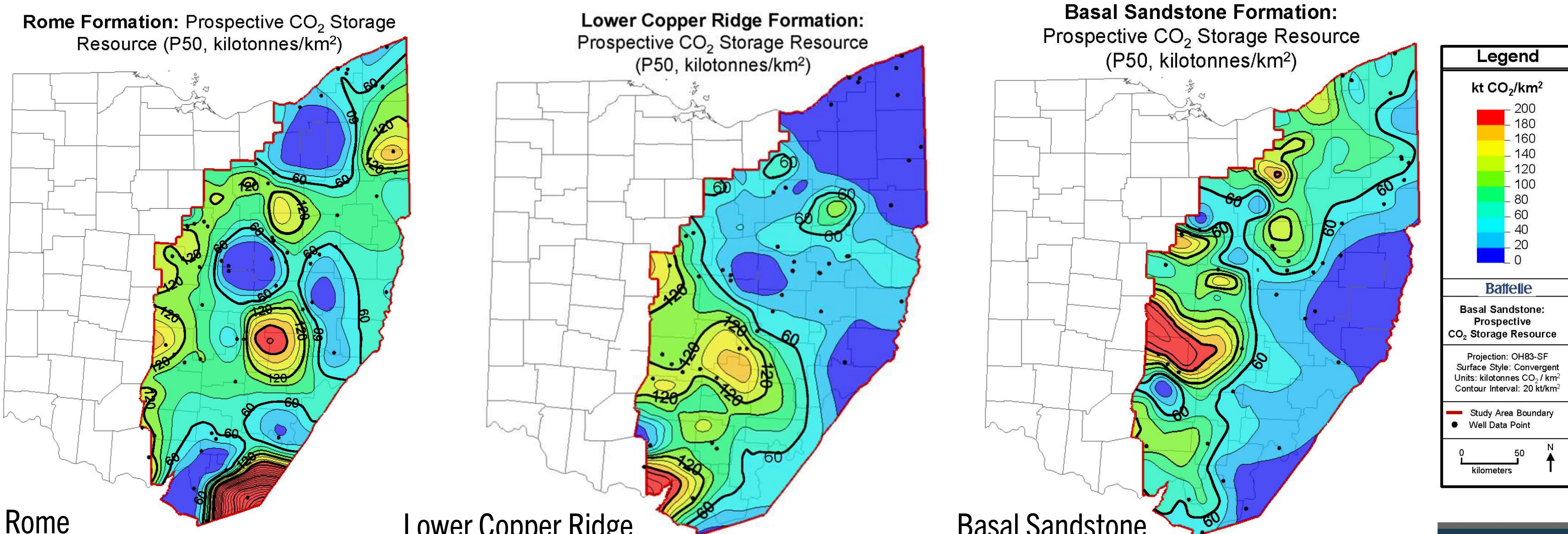
- ND 38-22-02: **"Pore space"** means a cavity or void, whether natural or artificially created, in a subsurface sedimentary stratum.
- **"Total Porosity"** is the ratio of total pore space irrespective of weather they are connect or not to the bulk volume
- **"Effective Porosity"** is the ratio of connected pore spaces to the bulk volume. This is the actual pore space from where fluid can flow to the producing wells



(Li et al., 2021)

CCS Geology in Ohio

Total Prospective Storage by Formation



Rome
5,556 Mt

Lower Copper Ridge
3,561 Mt

Basal Sandstone
3,904 Mt

Mt = megatonnes, kt = kilotonnes

(Fukai et al., 2016)

Monitoring Migration

- Variation from baseline measures
- Methods regulated

Observation wells

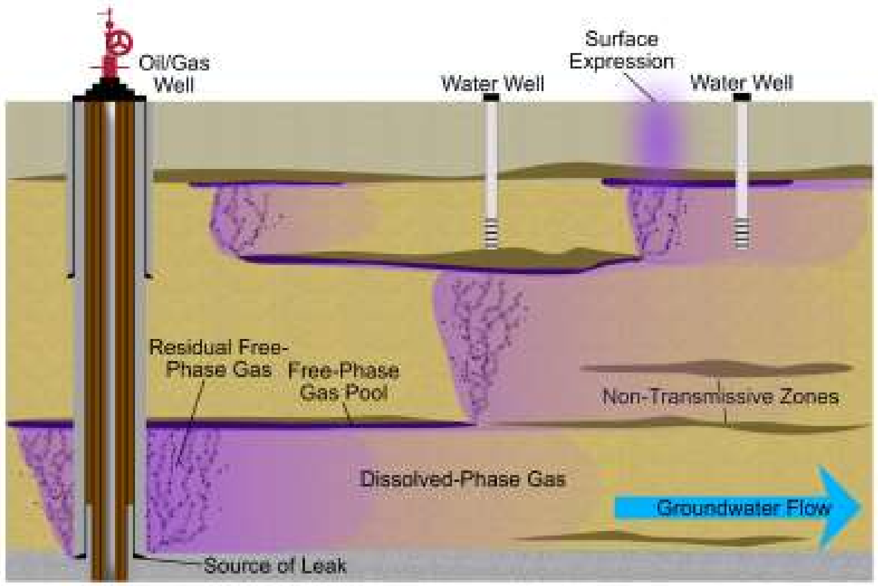
Temperature sensors

Microphone systems

Annual pressure

Electrical imaging

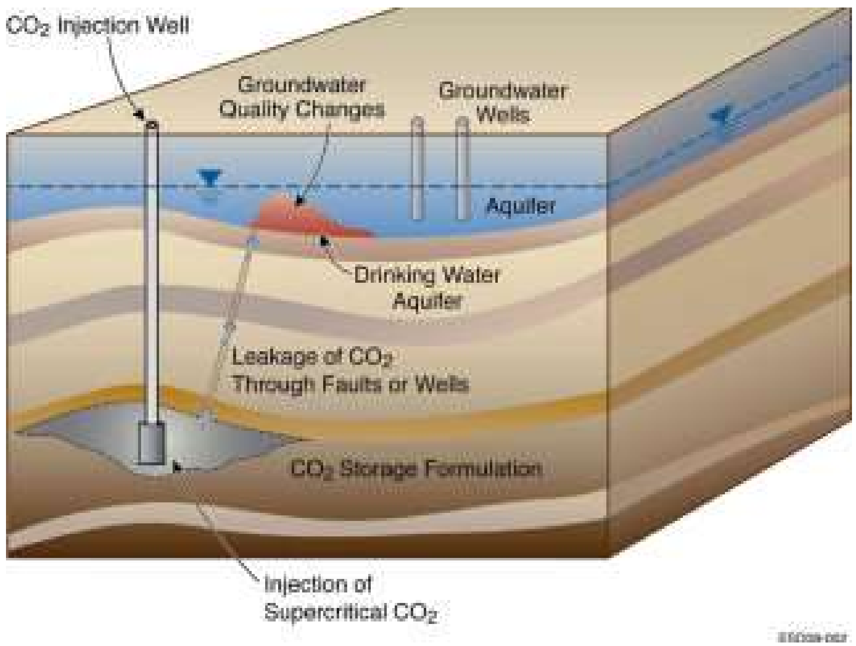
Seismic imaging



(Molofsky et al., 2021)

Groundwater Contamination

- Types of leaks:
  - Well leakages
  - Fault leakage
  - Cap rock leakage
- Methods of contamination:
  - CO_2= ↓ pH= ↑ dissolved minerals= ↑ hazardous trace elements
  - Brine leaks=adsorption of trace elements

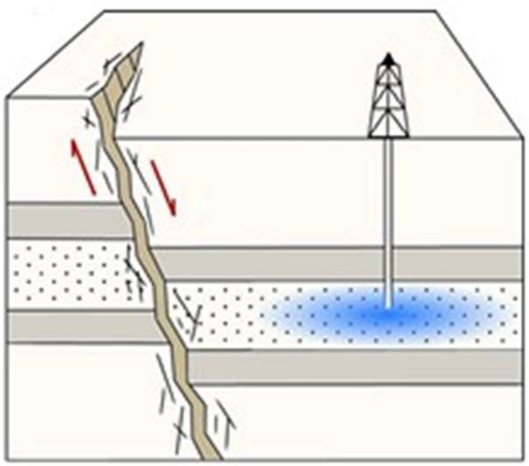


(Apps et al., 2010; Bacon et al., 2014; Eldardiry & Habib,2018)

Injections Risks

Earthquakes

1. Injection induced
2. Natural earthquakes



LESS LIKELY WHEN

- High hydraulic diffusivity (ratio of permeability and storage capacity of aquifer)
- Gradual increase in injection rate

OTHER FACTORS

- MIT and Carnegie Mellon scholars say generating huge faults extremely low
- Ohio Oil & Gas Division 2.1M limit

(Alghannam & Juanes, 2020; Ma et al., 2022)

Economics and Regulation of Carbon Sequestration

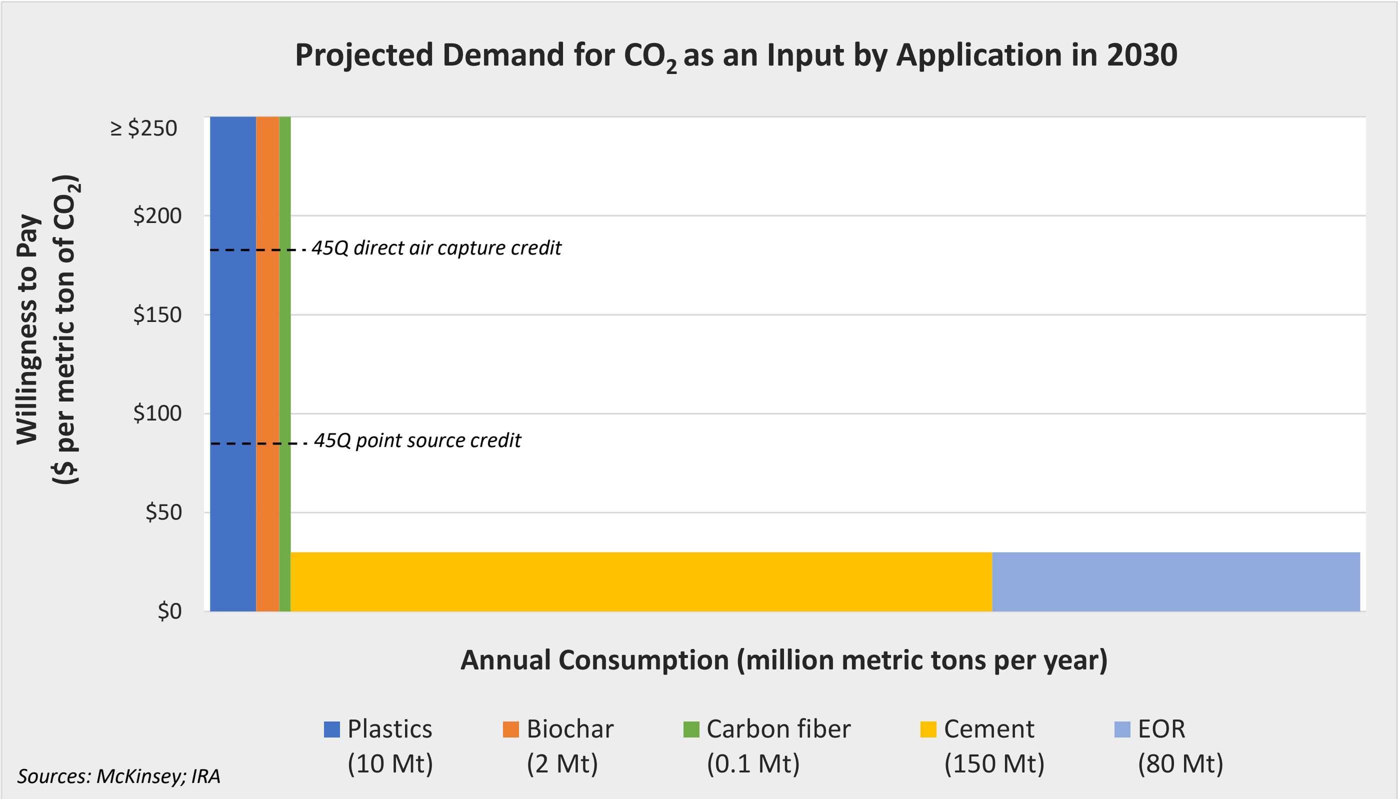
Mark Henning

Energy Policy Center

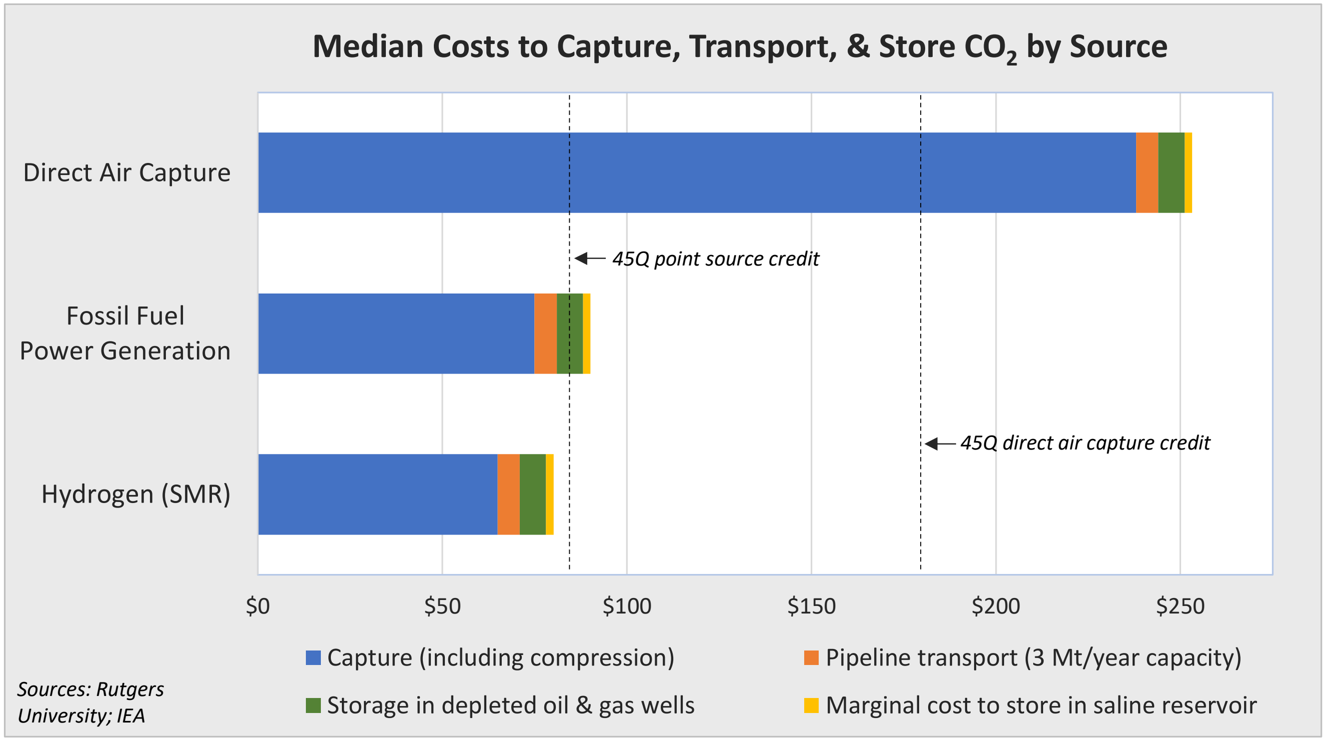
Cleveland State University

Economics of Sequestration: Demand Side

- Likeliest near-term CO_2 revenue stream will be claiming $85/tonne credit from point sources (e.g., industrial processes and power generation)
- Capture from high-emitting point sources more mature than direct air capture.



Economics of Sequestration: Supply Side



- Chart based on midpoint of estimated cost ranges
- Truck transportation (not seen here) >2x pipeline transport
- 341.7 kt of H_2 demand met by natural gas in Ohio by 2030 => 3.1 Mt of CO_2
  - 9 kg CO_2/kg H_2 production from SMR (Argonne)

Range of Estimated Costs

Category	Cost Item	Low	High
Capture	Direct Air Capture	$134.00	$342.00
	Fossil Fuel Power Generation	$50.00	$100.00
	Hydrogen (SMR)	$50.00	$80.00
Storage	Depleted oil & gas well	$1.02	$13.23
	Saline reservoir	$3.05	$15.27
Transport	3 Mt/year capacity	$4.48	$7.53
	10 Mt/year capacity	$2.34	$3.87

State Regulation of CO_2 Injection Wells

- Primary enforcement authority ("primacy") for all injection wells originates with US EPA.
- To date, US EPA has directly approved permits for two CO_2 injection wells. Two additional permits are nearing approval by US EPA.
  - Permitted wells in Illinois have been operational since 2017; combined storage rate of 1.3 Mt/yr.
  - Wells nearing approval in Indiana will have combined storage rate of 1.6 Mt/yr.
- States can be granted primacy for CO_2 injection wells by US EPA.
  - Two states have received primacy, ND in 2018 and WY in 2020.
  - ND has approved four wells; one additional well pending.
    - First state-approved Class VI well in U.S. went operational in July 2022.
    - Currently permitted wells have combined storage rate of 7.1 Mt/yr.
    - Pending well planned storage rate of 6.0 Mt/yr.
  - WY has permits pending for three well operations with combined storage rate of ~20 Mt/yr.
- State-level primacy can expedite approval process.
  - Approval of two operational CO_2 injection wells that went through U.S. EPA process took 6 years.
  - Approval of wells in ND has taken less than one year.

Ohio's Class VI Primacy Strategy

- Ohio must demonstrate that its statutes and regulations meet US EPA requirements for effectively preventing endangerment of underground sources of drinking water (USDW).
- Ohio General Assembly passed (governor signed) HB 175, effective July 2022, directing ODNR to begin Class VI well primacy application process.
  - ODNR has engaged US EPA on crosswalk process to map state regulations to federal requirements.
  - Members of state legislature have been engaged and presented with model enabling statutes that meet federal requirements.
    - Legislative Service Commission will review and research relevant parts of ORC.
  - Wyoming example as template.
  - Ohio's 2-for-1 regulatory requirement could impede primacy application process.
    - General Assembly resistant to exemptions.

EPA Crosswalk: Requirements for Permitting, Operating, and Decommissioning

Statutes and regulations must establish minimum technical criteria for:

- Permitting
  - Geologic site characterization
  - Area of review and corrective action
  - Financial responsibility
- Well construction
- Operation
  - Mechanical integrity testing
  - Monitoring
- Well plugging
- Post-injection site care
- Site closure

Availability of funding for each stage of well life must be assured (see Wyoming special revenue account).

Other States Seeking Primacy

Class VI Application Process: Pre-Application Actvities → Completeness Determination → Application Evaluation → Rulemaking and Codification → Applications Approved

- ❑ Louisiana.
  - *Rulemaking and Codification* stage.
  - US EPA issued notice of intent to approve Class VI primacy in May 2023.
- ❑ Arizona, West Virginia, and Texas.
  - *Pre-Application* stage (further along than Ohio).
    - Crosswalk completion (review and amend UIC statutes and regulations to comports with Class VI federal requirements).
    - Compile "critical elements" (letters from governor and attorney general; program description; public participation documentation).
- ❑ Colorado, Montana, Nebraska, and Pennsylvania.
  - Initial exploration of required legislation and engagement with US EPA.

Other CCS Issues: Pore Space Rights and Unitization

- CO_2 storage would occur in pore space.
- Pore space ownership is unsettled in Ohio.
  - Surface or mineral estate?
- MT, WY, and ND have enacted statutes.
  - Pore space belongs to surface owner.
- Majority of case law in U.S. → "American Rule"
  - Supports surface owner as owner of pore space.
    - OK, LA, MI, NY, WY, CA, NM.
- Exceptions to "American Rule."
  - Courts in KY, TX: mineral owner possesses pore rights.
  - 2019: ND legislature enacted law restricting surface owners from seeking compensation for pore space use.
    - Previous case law recognized pore space belonging to surface owner.
    - 2022: State supreme court struck down statute and affirmed pore space rights of surface owners.

- What about unitization?
  - Share of land overlying a common storage space that must receive owners' approval for operations to commence (can be forced on remaining %).
  - States enacting statutes establishing pore space ownership also adopt language on conditions for unitization.
    - Wyoming: owners of 80% of land overlying a pore space unit must approve.
    - Montana and North Dakota: 60% approval required.

Industrial Clusters: The Net-Zero Challenge

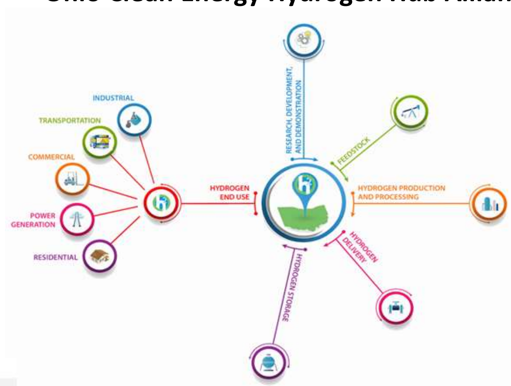
The World Economic Forum in collaboration with Accenture and EPRI has launched a global initiative to support industrial clusters in their paths to net zero. With industry responsible for 30% of global CO2 emissions, industrial clusters will be a critical player in accelerating the path towards net zero.

WORLD ECONOMIC FORUM

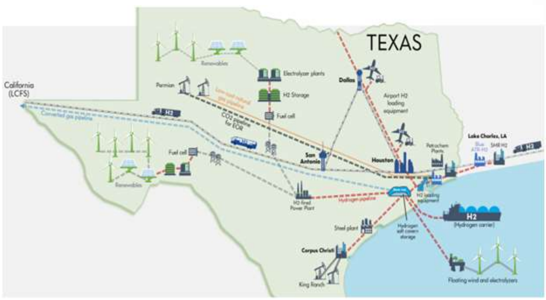
Geographic areas where co-located companies provide opportunities for scale, sharing of risk/resources, aggregation, and optimization of demand.

NATIONAL CAPITAL HYDROGEN CENTER
powered by CONNECTED DMV

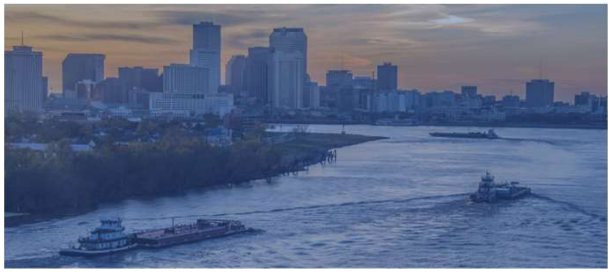
Ohio Clean Energy Hydrogen Hub Alliance



Greater St Louis-IL Regional Clean H_2 Hub Industrial Cluster



H2Houston Hub



Louisiana Future Energy Cluster (LFEC)

Thank You

QUESTIONS?

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Andrew Thomas directs the Energy Policy Center at the College of Education and Public Affairs at Cleveland State University, where for 13 years he has lead research on electricity regulation and markets, microgrids, transportation, energy storage, district energy, fuel cells and oil and gas development. He is also the director for the Renewable Hydrogen Fuel Cell Collaborative and the Midwest Hydrogen Center of Excellence. He received his J.D. from Loyola University of New Orleans, where he was a law review editor. He is chairman of the Ohio Oil and Gas Commission, which he has served on for six years.

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Mark Henning is principal researcher with the Energy Policy Center at Cleveland State University, a role he also performs on behalf of the Midwest Hydrogen Center of Excellence, a regional initiative for the advancement of hydrogen-powered, zero-emissions vehicles in Midwestern public transit. His research focuses on the hydrogen economy, microgrids, energy storage, sustainable transportation, oil and gas investment and climate-related financial risk. His current projects include research on behalf of the Federal Transit Administration, Stark Area Regional Transit Authority, JobsOhio, and Cuyahoga County's Department of Sustainability. He holds a BA in Economics, a Master of Public Administration, and an MS in Statistics, all from Cleveland State University.

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Shelbie Seeberg is a Research Assistant with the Energy Policy Center at Cleveland State University. Her research is centered on clean energy, climate action, regulatory analysis, and innovative applications for GIS. She holds three Bachelor's Degrees in Environmental Science, Environmental Studies and Urban and Regional Studies, representing her 2022 graduating class as Valedictorian. She also holds a Master's Degree in Legal Studies.