



**EERC**



UNIVERSITY OF  
**NORTH DAKOTA**



Critical Challenges. Practical Solutions.



Energy & Environmental Research Center (EERC)

# SCALING UP TO INDUSTRIAL CCUS PROJECTS

A Regional Perspective

North Dakota, USA

CCS Technical Workshop 2020

Tokyo, Japan

January 23, 2020

John Hamling

Assistant Director for Integrated Projects



# EERC

## QUICK FACTS FY18



CONTRACT  
FUNDING



**\$44** MILLION

TOTAL ACTIVE  
CONTRACTS



**189**

**78%**  
OF CONTRACTS  
WERE WITH

PRIVATE  
INDUSTRY



EERC RESEARCH  
REPRESENTS  
APPROXIMATELY

**50%**

OF THE TOTAL  
EXTERNALLY FUNDED  
RESEARCH AT UND

ECONOMIC  
IMPACT  
IN THE GRAND  
FORKS REGION



**\$112.9**  
MILLION



**HIGH-BAY  
TECHNOLOGY  
DEMONSTRATION**

**FUEL  
PROCESSING**

**MOBILE  
LABORATORIES**

**WATER USE  
MINIMIZATION  
TECHNOLOGY**

**FUELS OF THE FUTURE**

**NATIONAL CENTER  
FOR HYDROGEN  
TECHNOLOGY**

**CHEMICAL STORAGE**

**LABORATORIES**

**IN-HOUSE  
FABRICATION SHOP**

**TECHNOLOGY  
DEMONSTRATION**

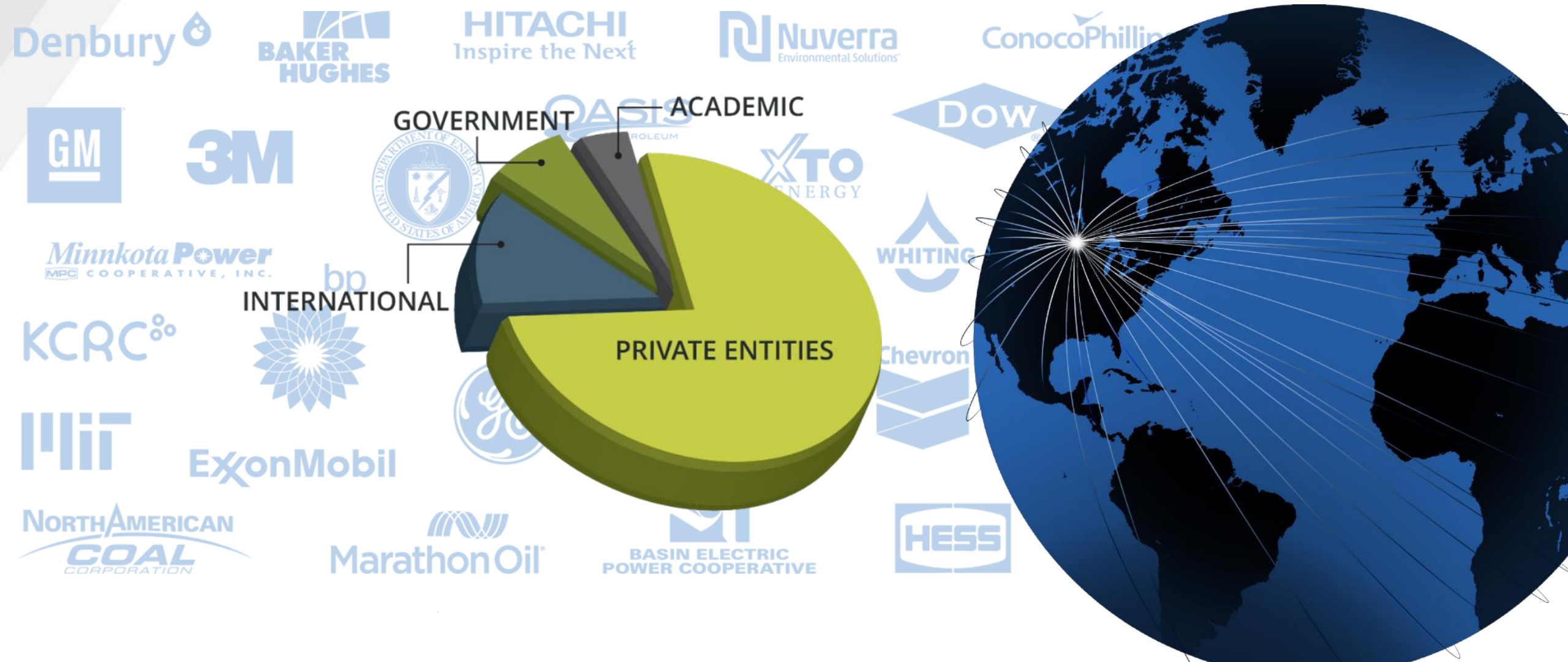
**OFFICES**

**DISCOVERY HALL  
MEETING AREA**

254,000 SQ FT OF FACILITIES

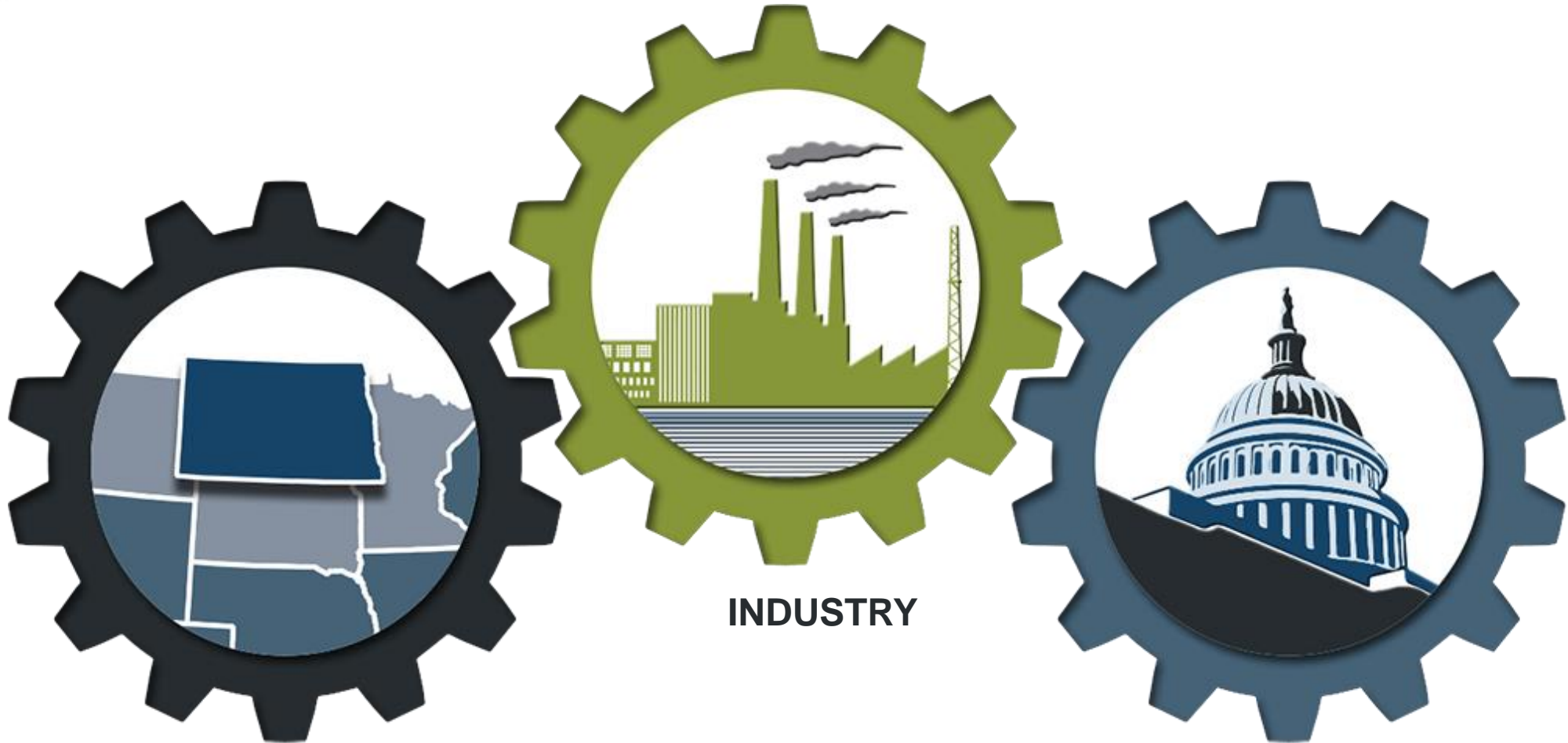
# WORKING AROUND THE GLOBE

MORE THAN 1300 CLIENTS IN 53 COUNTRIES



# CLIENT-FOCUSED

THIS IS HOW WE WORK



**STATE ENTITIES**

**INDUSTRY**

**GOVERNMENT  
(U.S. and others)**

Critical Challenges. Practical Solutions.

# EERC VISION

TO LEAD THE WORLD IN  
**DEVELOPING SOLUTIONS**  
TO ENERGY AND ENVIRONMENTAL  
CHALLENGES.



# A STATE OF ENERGY

Population – ~760,000 (~70,000 square miles)

CO<sub>2</sub> emissions – 34th – ~56 million tonnes per year

## Total Energy Production 6<sup>th</sup>

- Oil – 2nd
- Natural gas – 10th
- Coal – 8th
- Wind – 10th
- Ethanol – 10th

## Agricultural products

- 19 – top three



# A RESOURCE MANAGEMENT PHILOSOPHY

Mission to promote and prudently develop North Dakota's oil, gas, fossil, and renewable energy resources.

*“Public interest to promote geologic storage of carbon dioxide...”*

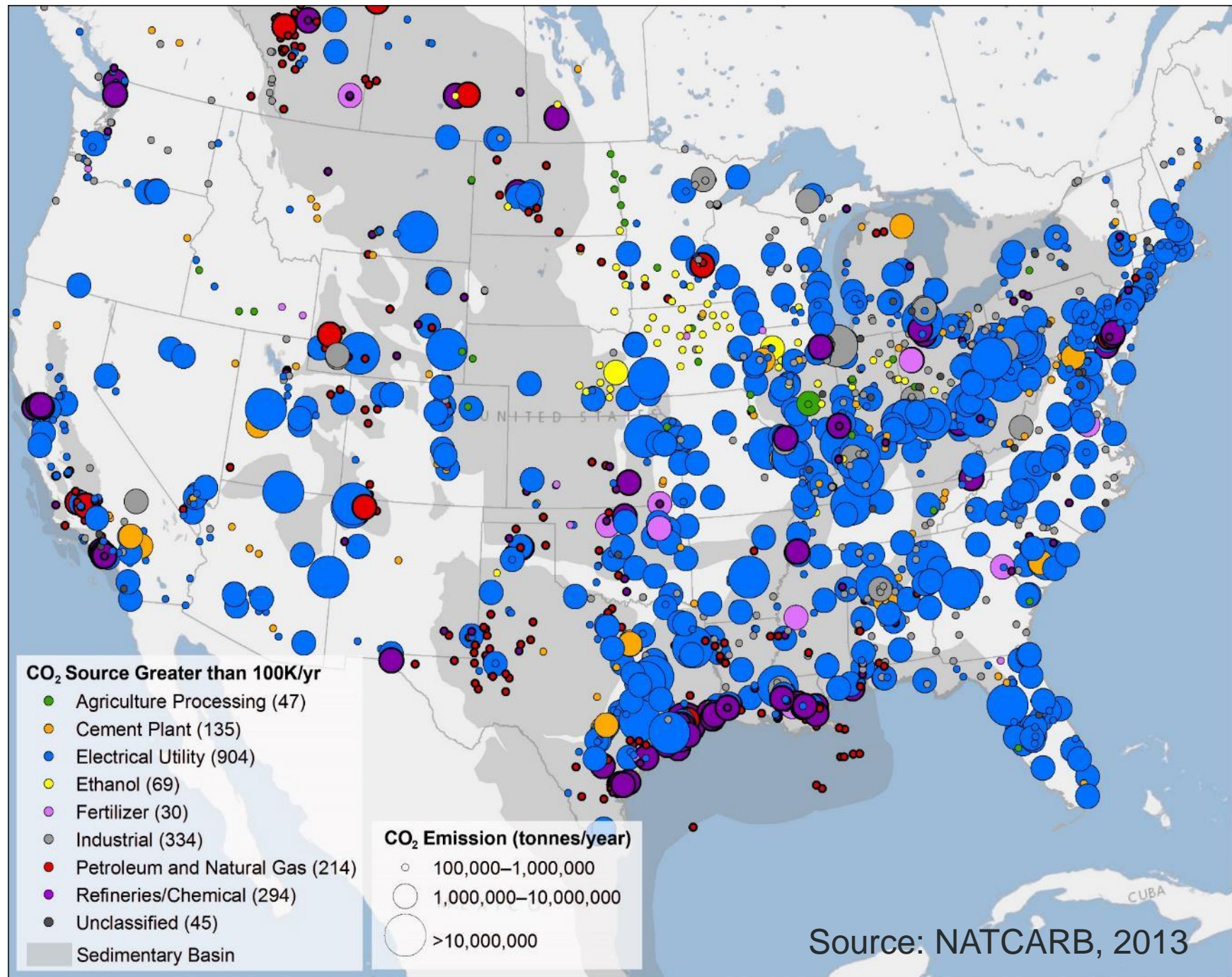
Carbon capture, utilization, and storage (CCUS) is a key to leveraging a tremendous endowment of fossil energy to provide secure, reliable, affordable, safe, clean energy.

Public accustomed to energy industry and the role it plays.



# CO<sub>2</sub> POINT SOURCES WITH EMISSIONS GREATER THAN 100,000 METRIC TONS/YEAR

Many industrial sources of anthropogenic CO<sub>2</sub> are in proximity to sedimentary basins that provide the opportunity for geologic CO<sub>2</sub> storage.



# REGIONAL POTENTIAL

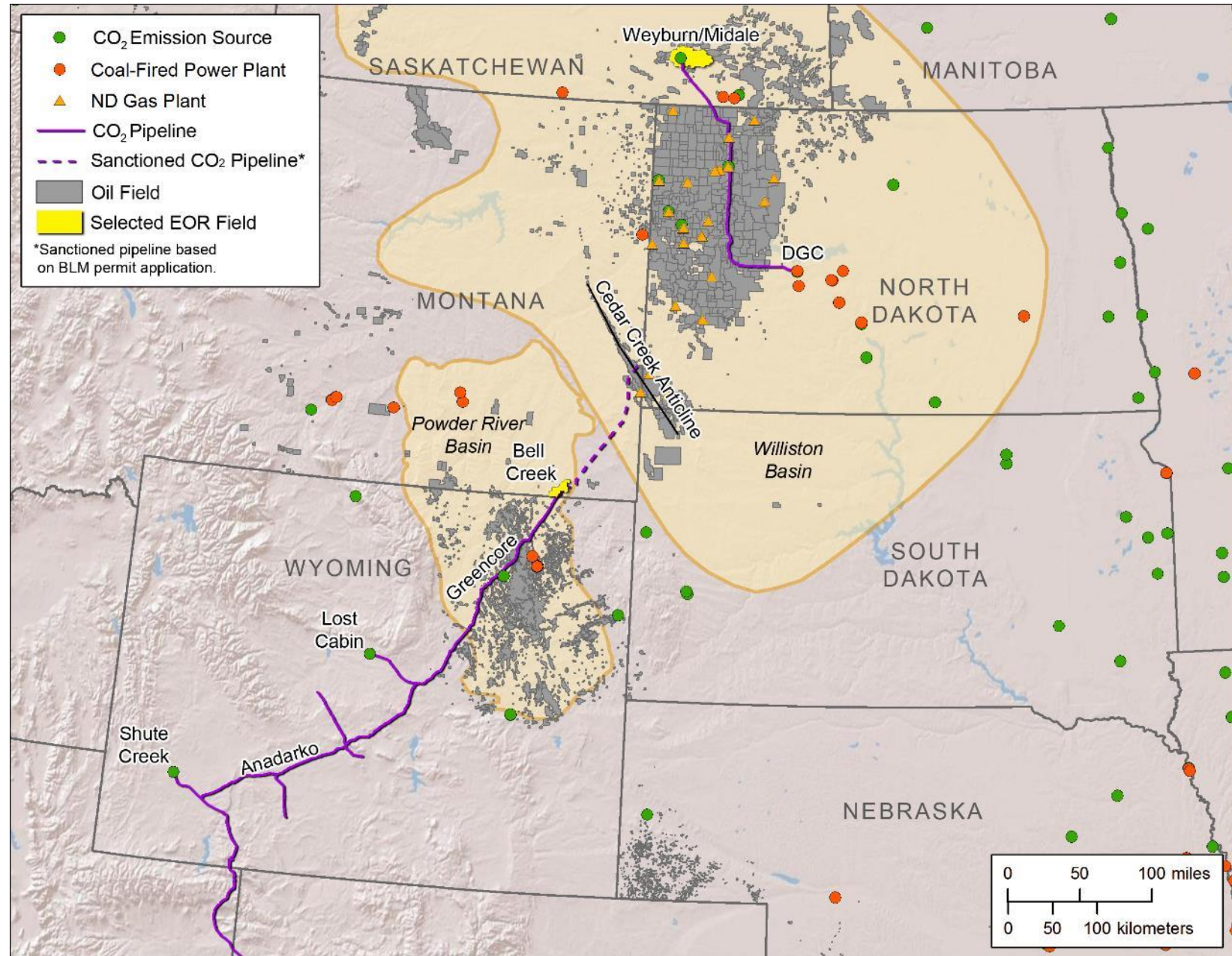
## A Prolific Oil-Producing Region in North America

- Conventional
- Unconventional
- Stacked horizons
- Residual oil zones (ROZs)?

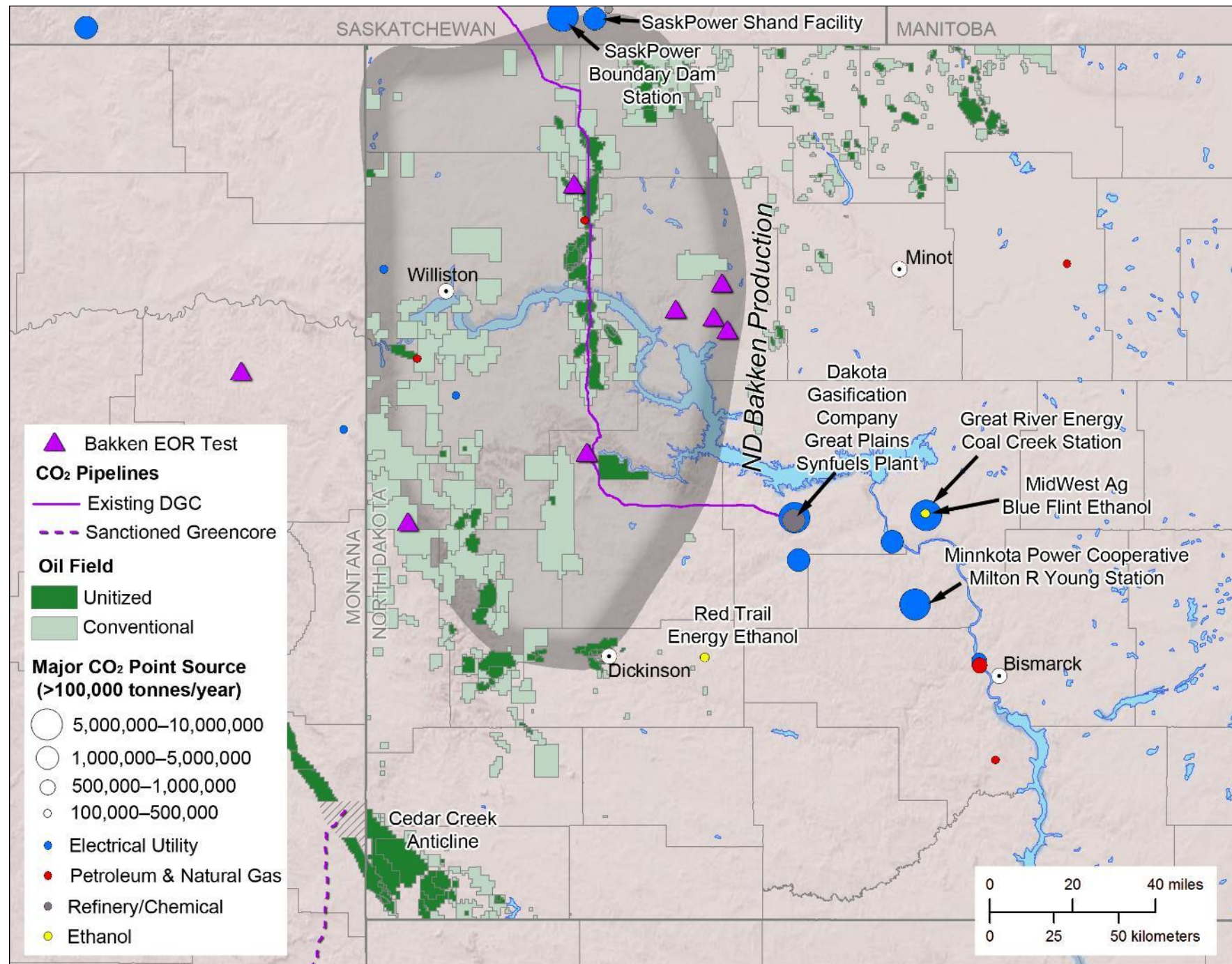
Abundant Anthropogenic CO<sub>2</sub>  
Sources Proximal to Enhanced  
Oil Recovery (EOR) and Storage  
Opportunities

Growing CO<sub>2</sub> Transportation  
Network

Massive CO<sub>2</sub> Storage Potential in  
Deep Saline Formations







## ENORMOUS EOR OPPORTUNITY

**86 conventional unitized fields:**

- 280 million to 630 million bbl of incremental oil
- 47 million to 283 million metric tons of CO<sub>2</sub> needed

**200+ conventional fields**

- >1 Bbbl of incremental oil
- >358 million metric tons of CO<sub>2</sub> needed

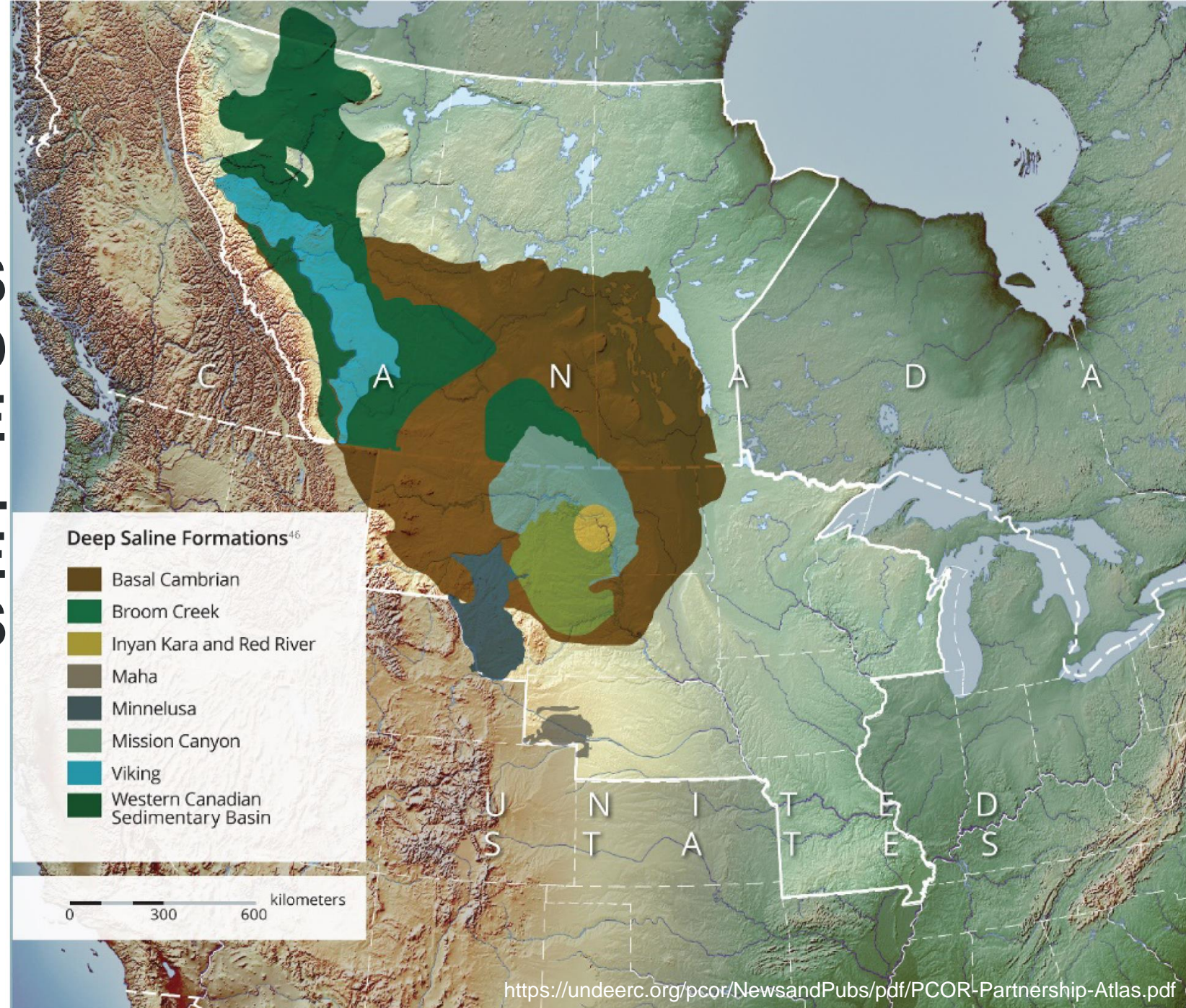
**Conventional + Bakken Petroleum System:**

- 4 Bbbl–7.6 Bbbl of incremental oil
  - 2 Btons–3.8 Btons of CO<sub>2</sub> needed
- ...or more

# ENORMOUS DEDICATED STORAGE POTENTIAL IN DEEP SALINE FORMATIONS

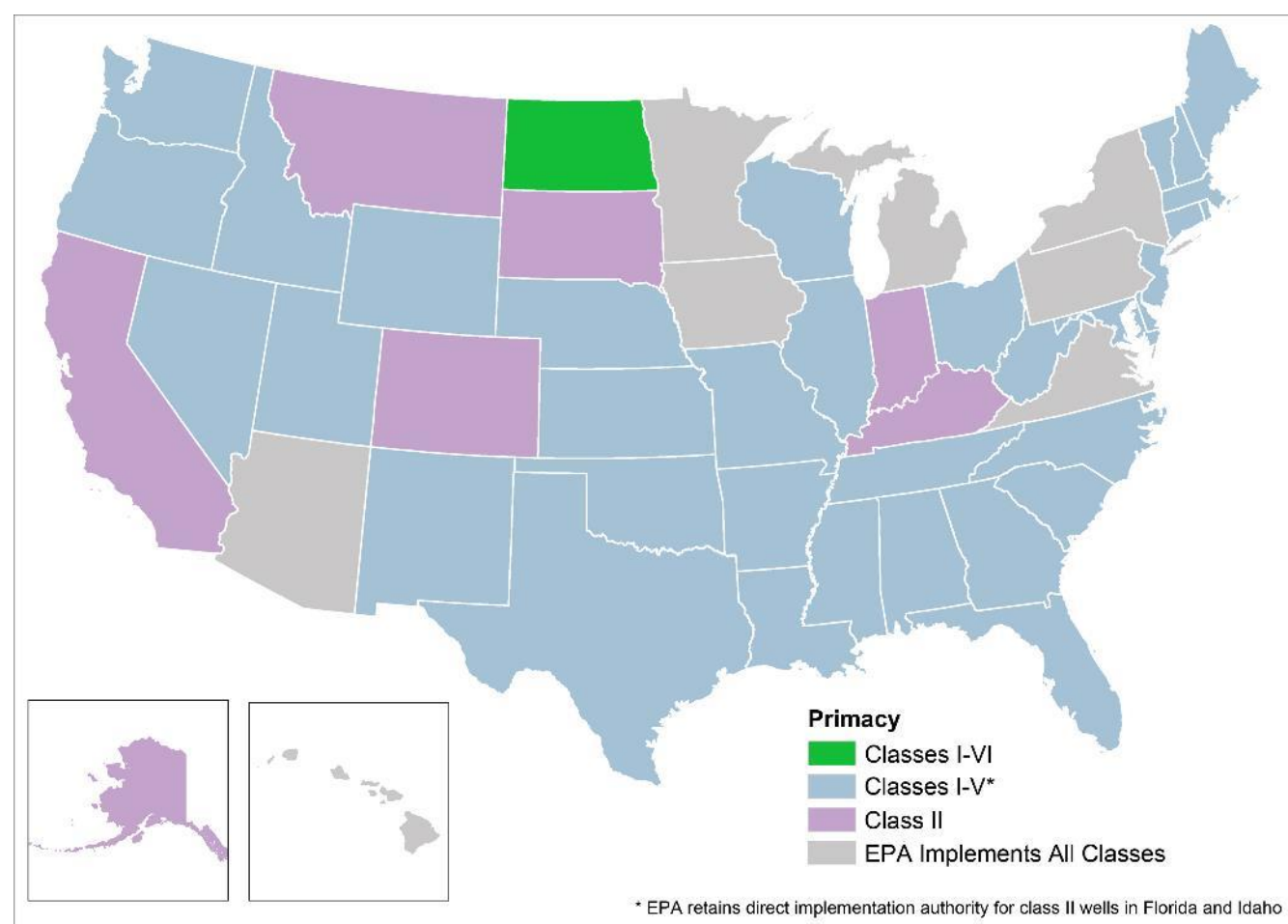
*More than 330 GT of  
storage potential,*

*100+ billion tonnes in ND alone.*



# UNDERGROUND INJECTION CONTROL

## NORTH DAKOTA'S GOT CLASS! I, II, III, IV, V, AND VI



Class I	Class II	Class III	Class IV	Class V	Class VI
ND Dept of Health	NDIC Oil & Gas Division	ND Geological Survey	ND Dept of Health	ND Dept of Health	NDIC Oil & Gas Division
Hazardous and nonhazardous fluids (industrial and municipal wastes).	Brines and other fluids associated with oil and gas production.	Fluids associated with solution mining of minerals.	Hazardous or radioactive wastes. This class is banned by EPA.	Nonhazardous fluids into or above a USDW and are typically shallow.	Injection of carbon dioxide for long-term storage.



# PRUUDENT REGULATIONS THAT ENABEL CCUS

Codified in North Dakota Law



## CHAPTER 38-22 CARBON DIOXIDE UNDERGROUND STORAGE

**38-22-01. Policy.** It is in the **public interest** to promote the **geologic storage of carbon dioxide**. Doing so **will benefit the state** and the global environment by reducing greenhouse gas emissions. Doing so will help ensure the viability of the state's coal and power industries, to the **economic benefit** of North Dakota and its citizens. Further, geologic storage of carbon dioxide, a potentially **valuable commodity**, may allow for its ready availability if needed for commercial, industrial, or other uses, including enhanced recovery of oil, gas, and other minerals. Geologic storage, however, to be practical and effective **requires cooperative use** of surface and subsurface property interests and the collaboration of property owners. Obtaining **consent from all owners may not be feasible, requiring procedures that promote, in a manner fair to all interests, cooperative management, thereby ensuring the maximum use of natural resources.**

Carbon dioxide storage facility administrative fund (\$0.01/ton): administrative costs associated with regulating storage facilities.

Carbon dioxide storage facility trust fund (\$0.07/ton): cost of long-term monitoring.

**Certificate of Project Completion – Release of Bond – Transfer of Title and Custody**

**ANCILLARY  
REGULATORY  
MECHANISMS  
FACILITATE  
INDUSTRIAL  
CCUS**

State issues certificate of project completion (all criteria met – at least 10 years postinjection)

- Releases responsibility, regulatory requirements, and bonds
- Transfer of title and custody to storage facility and stored CO<sub>2</sub> state
- State oversees/responsible for monitoring and managing the storage facility until such time as federal government assumes responsibility (assures site access/confidence)

State retains all authority to regulate future mineral and UIC activities

- protection from recapture of incentives.

State issued determination of storage (facilitate trading and incentive programs)



# INCENTIVES

## West Coast LCFS Markets

- Credits trading up to \$213 per ton.
- Stacked with 45Q

## 45Q Tax Credits

- Projects beginning construction before January 1, 2024, can claim credits for 12 years after operations begin.
- Tax credits claimed by the taxpayer capturing the emissions or transferred to operators of CO<sub>2</sub> EOR projects.
- Tax credit for CO<sub>2</sub> stored in a qualified EOR project (10-year ramp up to a maximum of \$35/tonne in 2026).
- Tax credit for CO<sub>2</sub> stored in a saline formation (10-year ramp-up to a maximum of \$50/tonne in 2026).

## North Dakota CCUS Incentives

- Coal conversion tax: tax reduction with CO<sub>2</sub> capture (up to 50%)

- No sales tax on capture-related infrastructure
- No sales tax on CO<sub>2</sub> sold for EOR

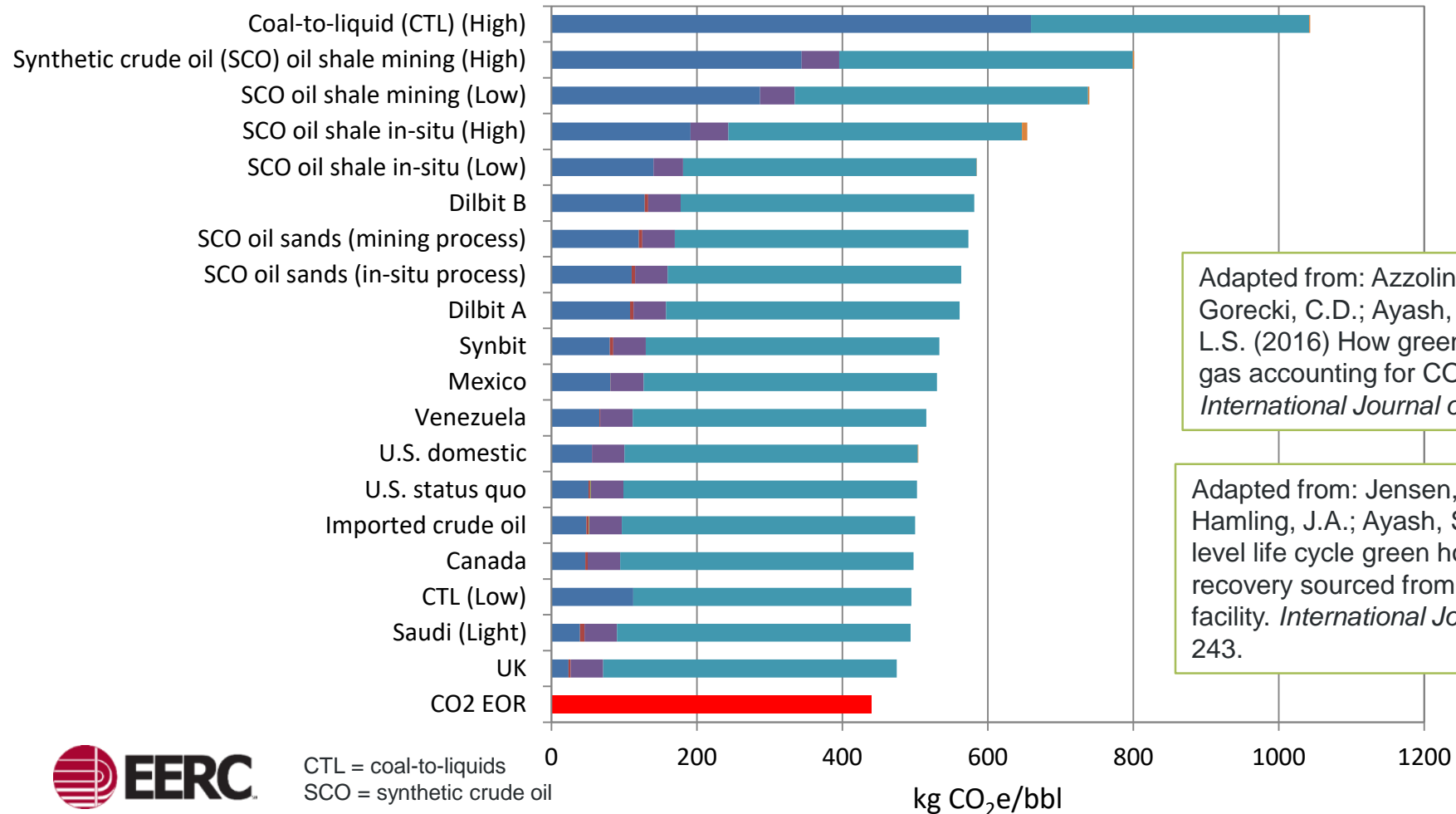
- No sales tax on construction of pipeline.
- Property tax-exempt for 10 years (equipment)

- No sales tax on CO<sub>2</sub> EOR infrastructure
- 0% extraction tax for 20 years for tertiary incremental recovery
- Production tax still applies



# LIFE CYCLE ANALYSIS RESULTS INDICATE EOR WITH CAPTURED CO<sub>2</sub> FROM ANTHROPOGENIC SOURCES RESULTS IN LOWER-CARBON-INTENSITY OIL

■ Extraction ■ Port-to-Port ■ Port-to-refinery ■ Refinery ■ Combustion ■ Upstream electricity



Adapted from:  
Mangmeechai, A., 2009, *Life Cycle Greenhouse Gas Emissions, Consumptive Water Use and Levelized Costs of Unconventional Oil in N. America*. Dissertation, Carnegie Mellon University: Pittsburgh, PA.

Adapted from: Azzolina, N.A.; Peck, W.D.; Hamling, J.A.; Gorecki, C.D.; Ayash, S.C.; Doll, T.E.; Nakles, D.V.; and Melzer, L.S. (2016) How green is my oil? A detailed look at greenhouse gas accounting for CO<sub>2</sub>-enhanced oil recovery (CO<sub>2</sub>-EOR) sites. *International Journal of Greenhouse Gas Control*, 51:369–379.

Adapted from: Jensen, M.D.; Azzolina, N.A.; Schlasner, S.M.; Hamling, J.A.; Ayash, S.C.; Gorecki, C.D.; (2018) A screening-level life cycle green house gas analysis of CO<sub>2</sub>-enhanced oil recovery sourced from Schute Creek natural gas-processing facility. *International Journal of Greenhouse Gas Control*, 78:236–243.

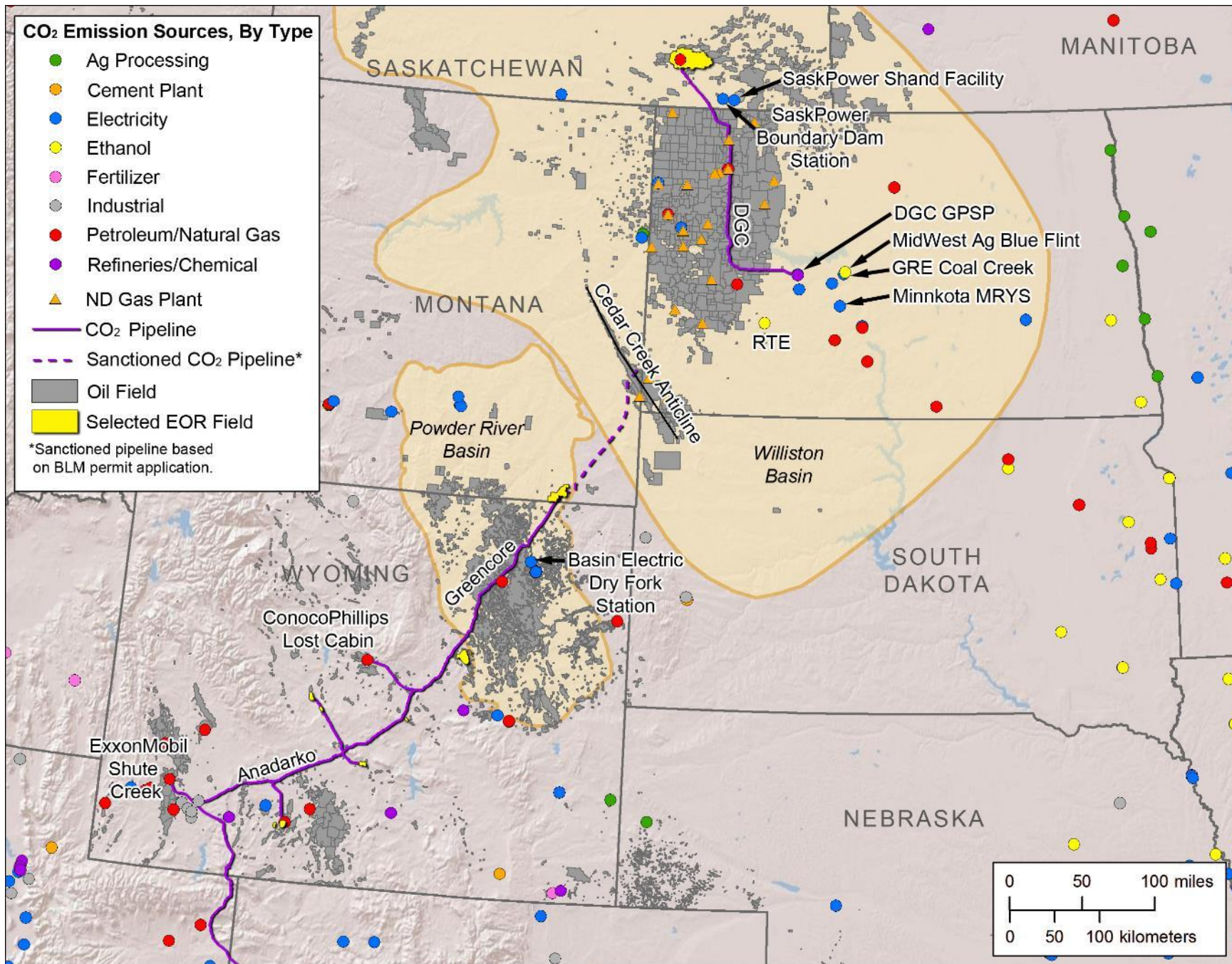


CTL = coal-to-liquids  
SCO = synthetic crude oil

# ENGAGED PARTNERS



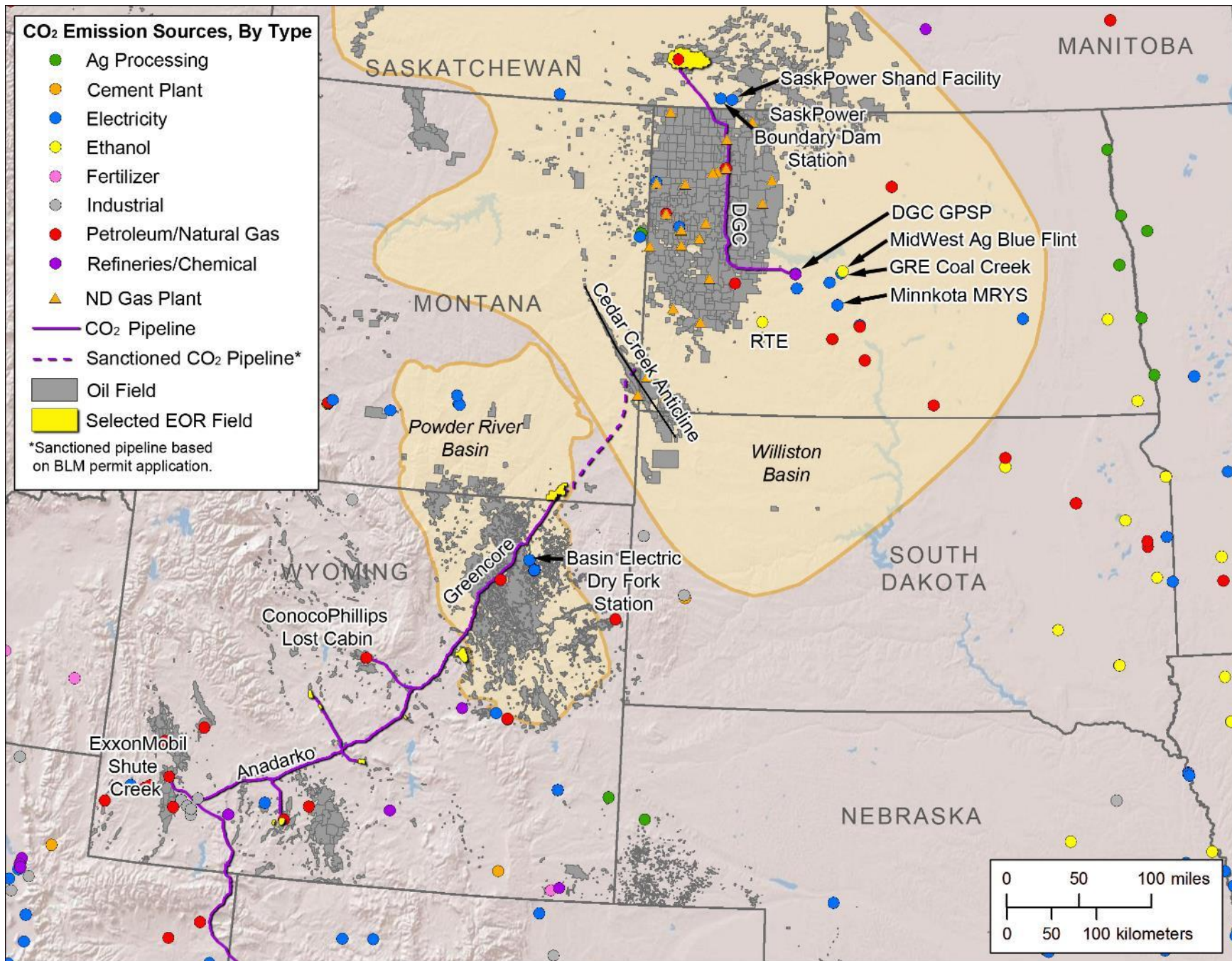
Critical Challenges. Practical Solutions.



## Commercial Industrial CCUS Projects

- Basin Electric Power Cooperative, Dakota Gasification Company Great Plains Synfuels (commercial)
- Basin Electric Power Cooperative Ammonia Process Liquefaction Plant (commercial)
- SaskPower Boundary Dam Carbon Capture Project (commercial)
- Exxon Mobil Shute Creek Natural Gas Processing (commercial)
- ConocoPhillips Lost Cabin Natural Gas Processing (commercial)
- Shell Quest CCS Facility\* (commercial) – Alberta, Canada

\*not pictured.



## Announced Industrial CCUS Projects

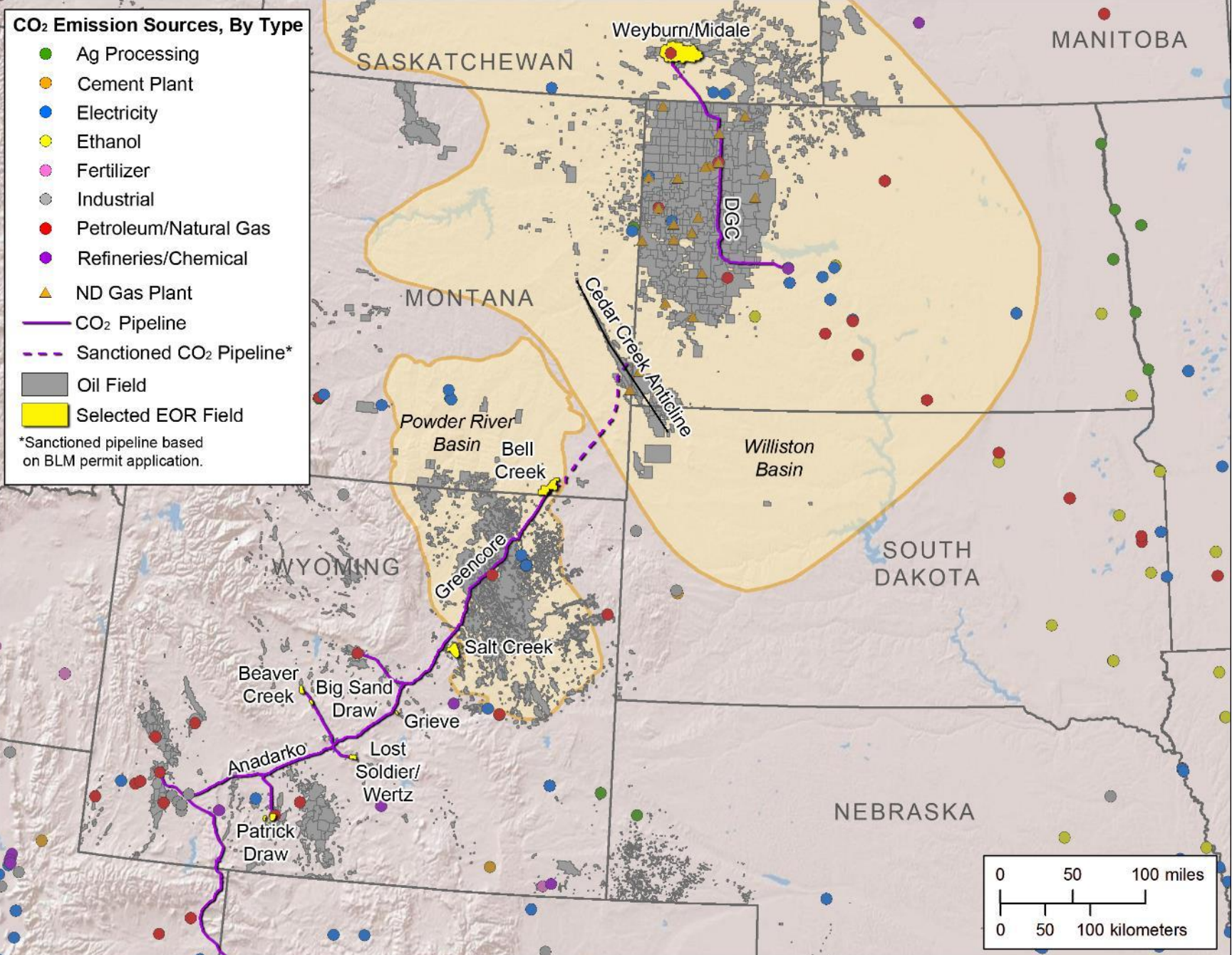
- Red Trail Energy – **Richardton Ethanol Facility** (precommercial/FEED)
- Minnkota Power Cooperative **Project Tundra** – Milton R. Young Station (precommercial/FEED)
- Basin Electric Power Cooperative Dry Fork Station (precommercialization/FEED)
- Great River Energy **CCS<sup>2</sup>** - Coal Creek Station (feasibility)
- Midwest AgEnergy – Blue Flint Ethanol Facility (feasibility)
- SaskPower Shand Power Station (feasibility)

# CO<sub>2</sub> Transportation Network

**CO<sub>2</sub> Emission Sources, By Type**

- Ag Processing
- Cement Plant
- Electricity
- Ethanol
- Fertilizer
- Industrial
- Petroleum/Natural Gas
- Refineries/Chemical
- ▲ ND Gas Plant
- CO<sub>2</sub> Pipeline
- - - Sanctioned CO<sub>2</sub> Pipeline\*
- Oil Field
- Selected EOR Field

\*Sanctioned pipeline based on BLM permit application.



DGC line (commercial)

- 205-mile 14" - 12"

Greencore Pipeline (commercial)

- 232-mile long 20"
- (725 MMscf/day)
- Anadarko CO<sub>2</sub> pipeline interconnect

Greencore Pipeline Expansion (sanctioned)

- 110-mile expansion to Baker, MT, and Cedar Creek Anticline

North Dakota Industrial Sources Line(s) (conceptual)

DGC Food-Grade Truck Facility (commercial)



# RED TRAIL ENERGY, LLC

## North Dakota Ethanol Production

### Reduced Carbon Intensity of North Dakota Ethanol Production Through Geologic CO<sub>2</sub> Storage

#### Incentive Programs

- Low-carbon fuel standard (LCFS) programs (~\$200/tonne)
- 45Q (\$50/tonne)



Image Credit: Red Trail Energy

#### SUBTASK 1.3 – INTEGRATED CARBON CAPTURE AND STORAGE FOR NORTH DAKOTA ETHANOL PRODUCTION

Kerryanne Lerox, Ryan Maggierich, Nicholas Azzolina, Melanie Jensen, José Torres Rivera, Nicholas Boschart, Nicholas Kalerus, Scott Ayash, Lonny Jacobson, and Charles Gorecki  
Energy & Environmental Research Center  
The effort was funded through the EERC-DOE 2009 Program on Research and Development for Fuel Energy Related Research Cooperative Agreement No. DE-FE000205

**ABSTRACT**  
The Energy & Environmental Research Center (EERC), in partnership with the U.S. Department of Energy (DOE), North Dakota ethanol producer Red Trail Energy (RTE), and the North Dakota Industrial Commission (NDIC), conducted a preliminary assessment for integrating small-scale carbon capture and storage (CCS) at an industrial ethanol production facility near Richardson, North Dakota.

This preliminary assessment included a technical evaluation of CCS implementation at the RTE site, development of a provisional field implementation plan (FIP), and economic analysis. Results indicated that commercial CCS is a technically and economically viable option for the significant reduction of CO<sub>2</sub> emissions from ethanol generation at the RTE facility.

The RTE facility produces approximately 163,000 tonnes of CO<sub>2</sub> annually from the ethanol fermentation process. If a CCS project is implemented, the RTE site could store approximately 3.2 million tonnes of CO<sub>2</sub> during a 20-year period of injection.

**Surface Features at the RTE site near Richardson, ND**

**Economic Analysis**  
A preliminary economic assessment was conducted for CCS implementation at the RTE site to evaluate potential costs. Results of this analysis support ethanol CCS as an economically viable option for the RTE facility.

**Average Annual Operating Expenses (\$1.9 M)**

Electricity	28%
Water	30%
Steam	8%
Other	3%
Capital Expenses	47%

**Average Capital Expenses (\$29.0M)**

Process System and Equipment	47%
Electricity	30%
Water	8%
Steam	3%
Other	2%

**Life Cycle Analysis (LCA)**  
Results of a LCA suggest that implementing CCS at the RTE facility could reduce the net CO<sub>2</sub> emissions by 40%–50%. This reduction in CO<sub>2</sub> emissions results in a greatly reduced carbon intensity (CI) value. Validation of CCS to reduce the CI value of ethanol production may allow producers to expand marketability of their fuel within developing low-carbon fuel programs such as those in California and Oregon.

**Field Implementation Plan**  
An FIP was developed that includes the design and installation of infrastructure necessary for the capture and secure storage of CO<sub>2</sub> at the RTE site. The FIP consisted of the activities necessary to implement CO<sub>2</sub> geologic storage at the RTE site and estimate future costs:

- CO<sub>2</sub> capture and transport
- Plans for CO<sub>2</sub> injection permitting
- Ethanol CCS pathways for low-carbon fuel programs
- MUM program
- Designs for monitoring and injection wells
- Well characterization and testing plan

The RTE FIP includes designs for both a Class VI injection well and a dedicated monitoring well.

**Future Activities**

- Attain pathway approvals for implementing CCS into low-carbon fuel programs.
- Ongoing communication with North Dakota Industrial Commission to permit a monitoring well and a Class VI injection well.
- Collect pertinent data needed to refine engineering designs of capture system such as current flow rates and CO<sub>2</sub> stream composition.
- Update LCA model, where applicable, as low-carbon fuel pathways develop and details become publicly available.
- Refine economic analysis to incorporate financial details such as interest rates, market changes, pore space payments, etc.
- Develop and execute a community outreach plan to educate/inform the North Dakota public about CCS.
- Drill a stratigraphic test well to gather site-specific geologic data to improve the geologic model and AOR predictions.

Image Credit: Energy & Environmental Research Center



Operated by Minnkota Power Cooperative, the Young Station is a mine-mouth generating station that uses lignite coal supplied from the adjacent BNI Coal mine. Unit 2, a 455-megawatt unit that began commercial operation in 1977, is the target for Project Tundra.

Project Tundra is in the advanced research and design phase. If the project moves ahead, construction will commence in 2022-2023

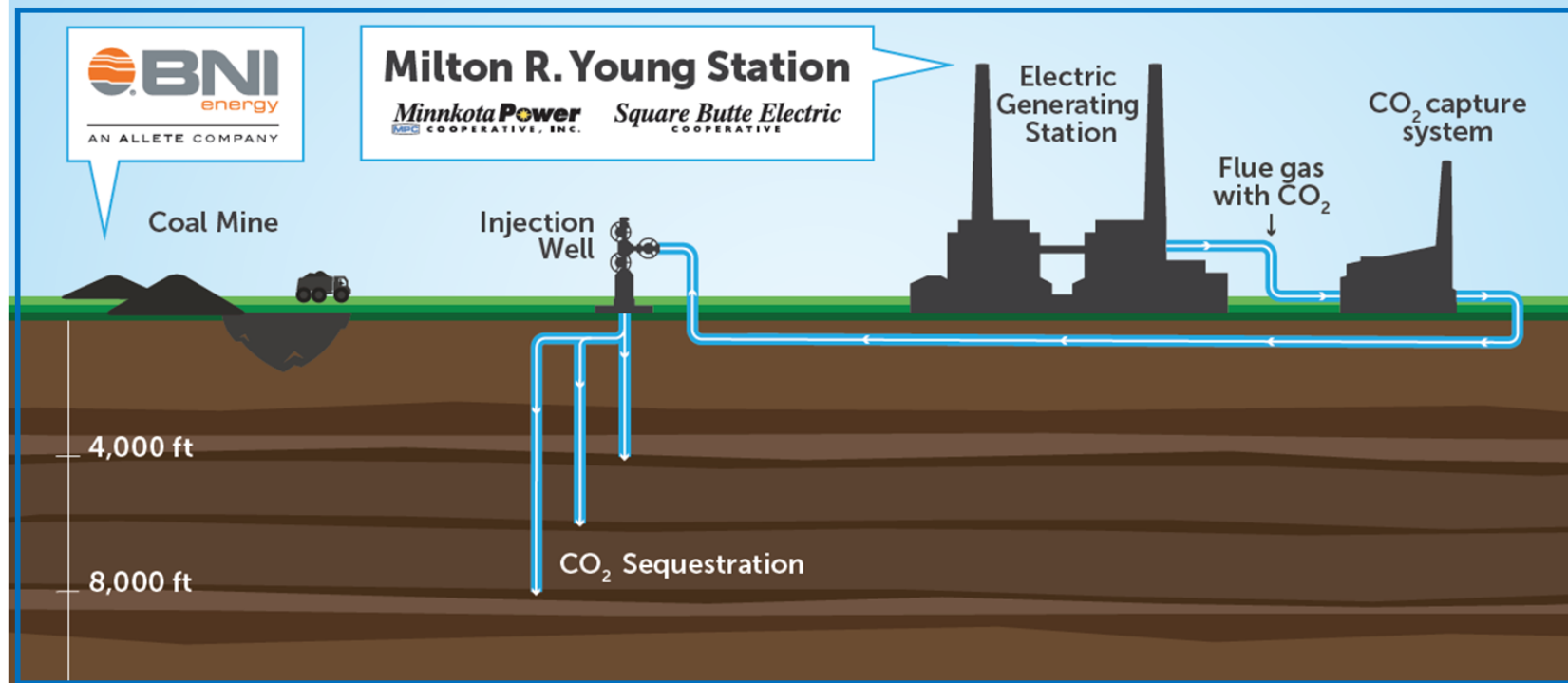
Precommercial:

Front-end engineering and design (FEED)

90% postcombustion CO<sub>2</sub> capture (~4 million tons per year).

Preparing to pursue federal and state permits required to build CO<sub>2</sub> capture facility and store CO<sub>2</sub> in deep geologic formations.

Exploring ND EOR opportunities.



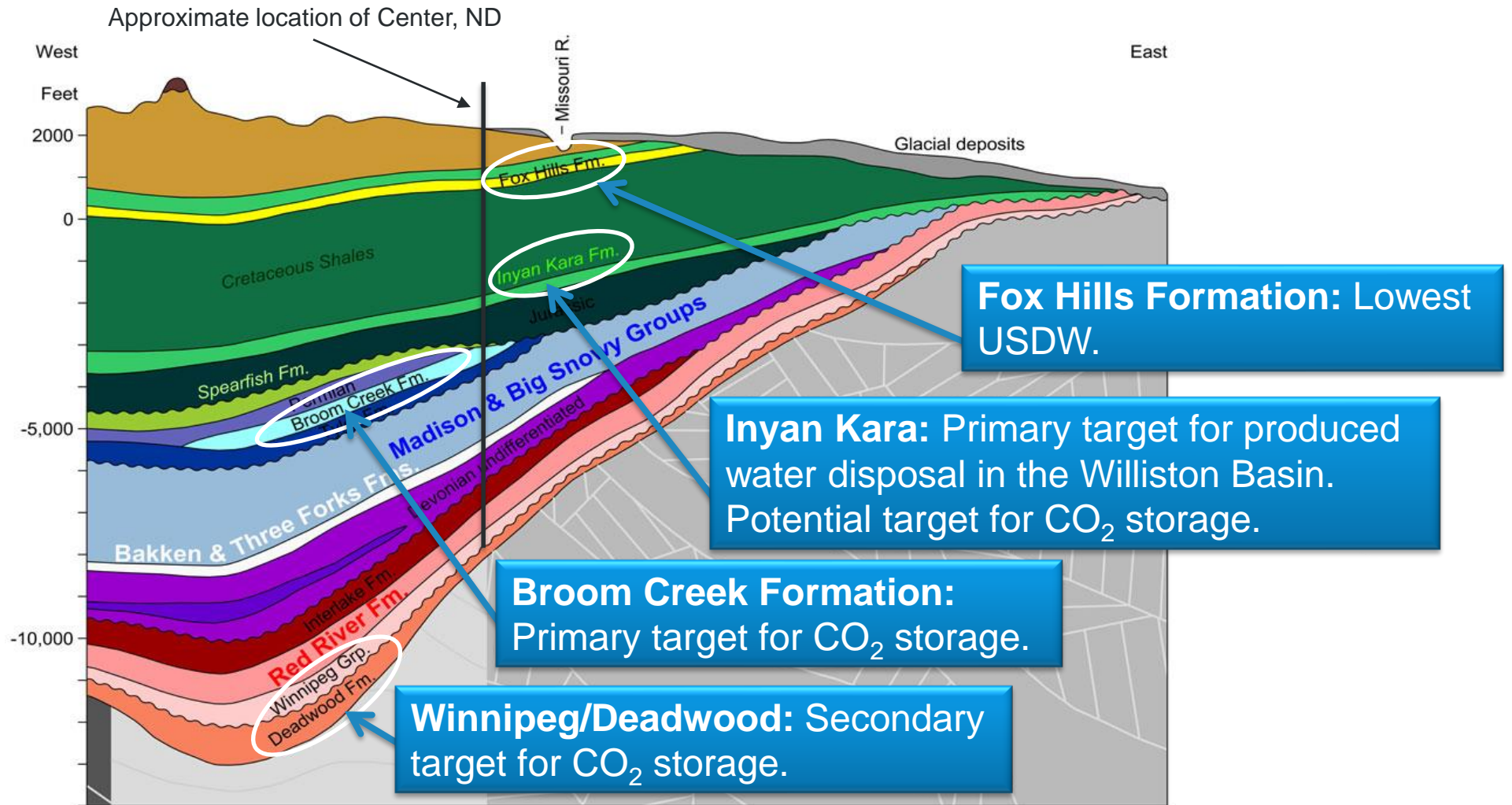


# NORTH DAKOTA CarbonSAFE



Image Credit – EERC

# CARBONSAFE ZONES OF FOCUS



# STEPS & TIMELINE TO IMPLIMENT INDUSTRIAL PROJECTS

# DRIVERS FOR INDUSTRIAL CCUS



# OBSTACLES FOR INDUSTRIAL CCUS



# ENABLERS OF INDUSTRIAL CCUS



Bismarck Tribune

Join

## Carbon capture and storage projects advancing at ethanol, coal plants

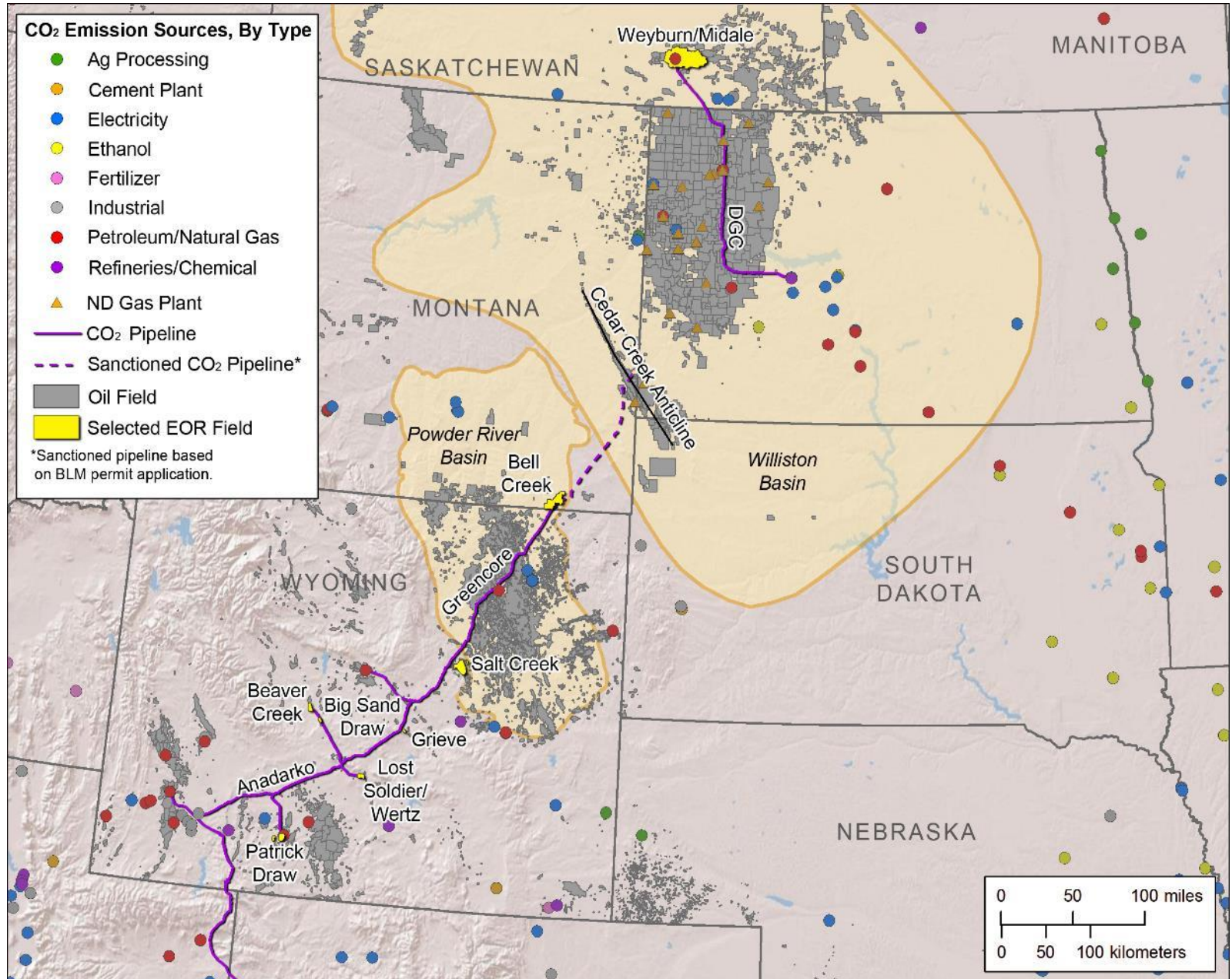
Amy R. Sisk Dec 10, 2019

Subscribe for 23¢/week



John Bauer, director of North Dakota generation at Great River Energy, stands by a photograph of Blue Flint Ethanol and Great River Energy's Coal Creek Station. The two entities are collaborating on a carbon capture storage project.

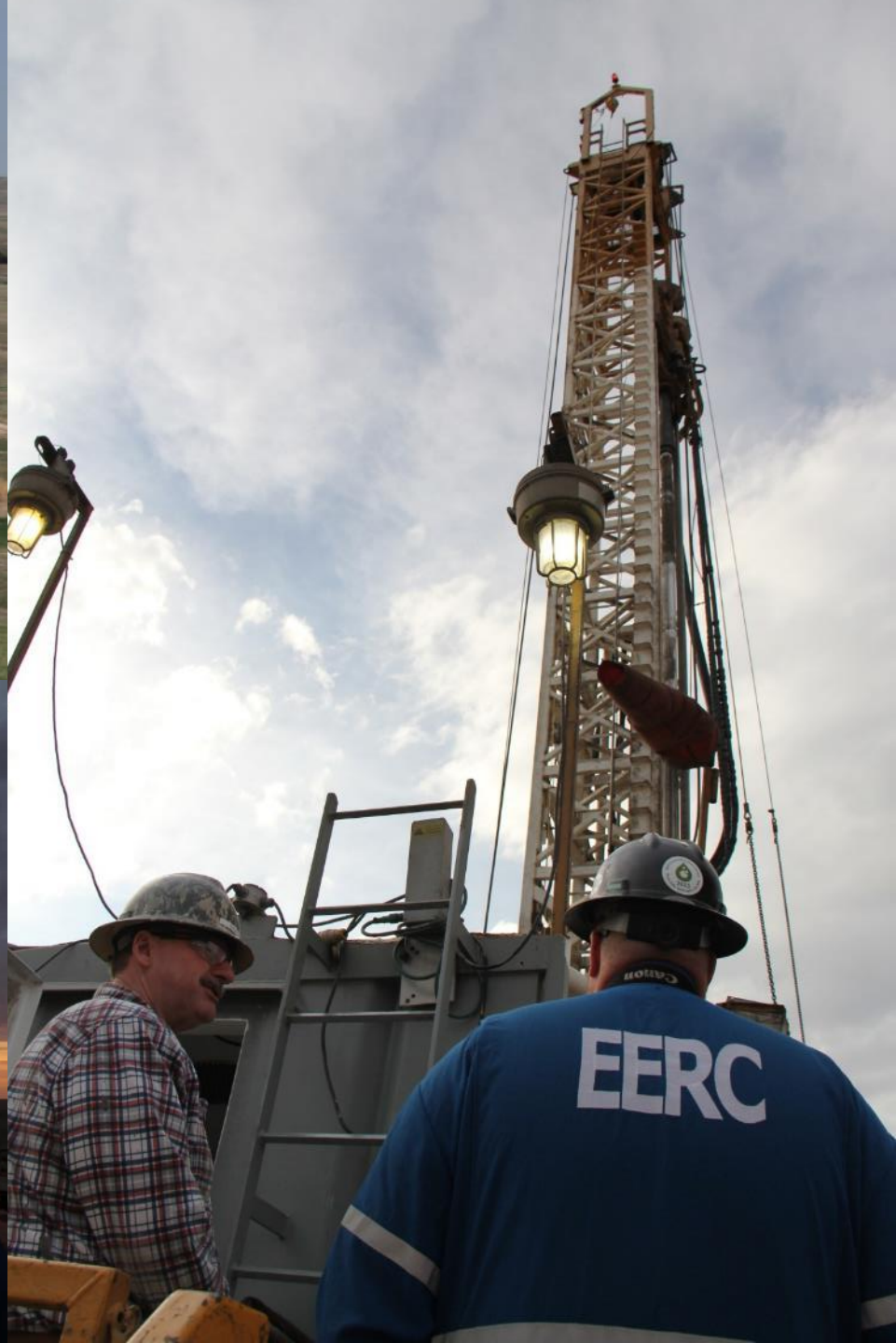
Mike McCleary





# NORTH DAKOTA

## BRINE EXTRACTION AND STORAGE TEST



# GEOLOGIC CO<sub>2</sub> STORAGE

## CONSIDERATIONS FOR INDUSTRIAL PROJECTS

- Buoyant fluid
- Large volumes = large footprint
- Transportation
- Access to pore space
  - Leasing, unitization/amalgamation, trespass
- Regulatory compliance
- Assuring permanence for incentives or credits
  - Conformance and storage efficiency



*Because of a host of technical, social, regulatory, environmental, and economic factors, brine disposal tends to be more accessible and generally quicker, easier, and less costly to implement compared to dedicated CO<sub>2</sub> storage.*

# ACTIVE RESERVOIR MANAGEMENT (ARM)

## TWO COMPLEMENTARY COMPONENTS

### ARM Test

- Reduce stress on sealing formation
- Geosteer injected fluids
- Divert pressure from leakage pathways
- Divert pressure from CO<sub>2</sub> plume
- Reduce area of review (AOR) and amalgamated area
- Improve injectivity, capacity, and storage efficiency
- Validate monitoring techniques, and forecast model capabilities

### Brine Treatment Test Bed

- Alternate source of water
- Reduced disposal volumes
- Salable products for beneficial use

Brine extraction can enable dedicated CO<sub>2</sub> storage and improve the geologic CO<sub>2</sub> storage potential of a site.

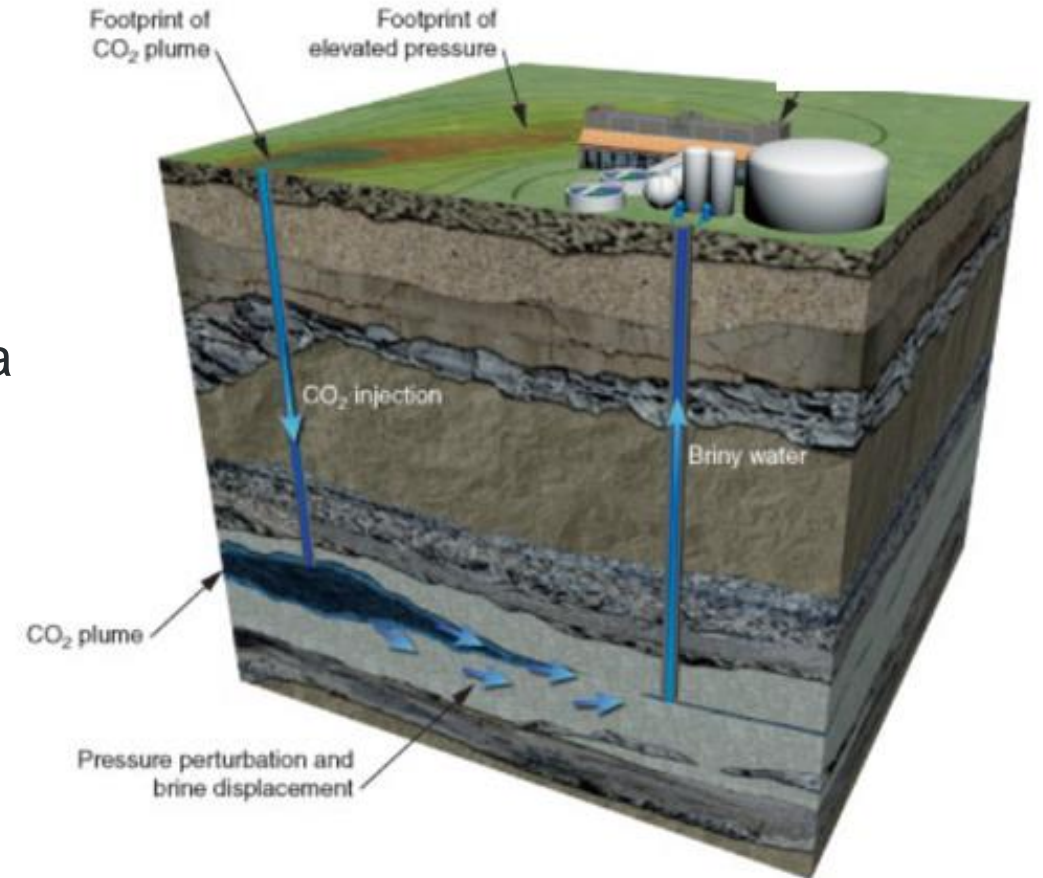


Illustration modified from Lawrence Livermore National Laboratory <https://str.llnl.gov/Dec10/aines.html>

# HOW ARM CAN ENABLE COMMERCIAL GELOGIC CO<sub>2</sub> STORAGE

## A HYPOTHETICAL EXAMPLE

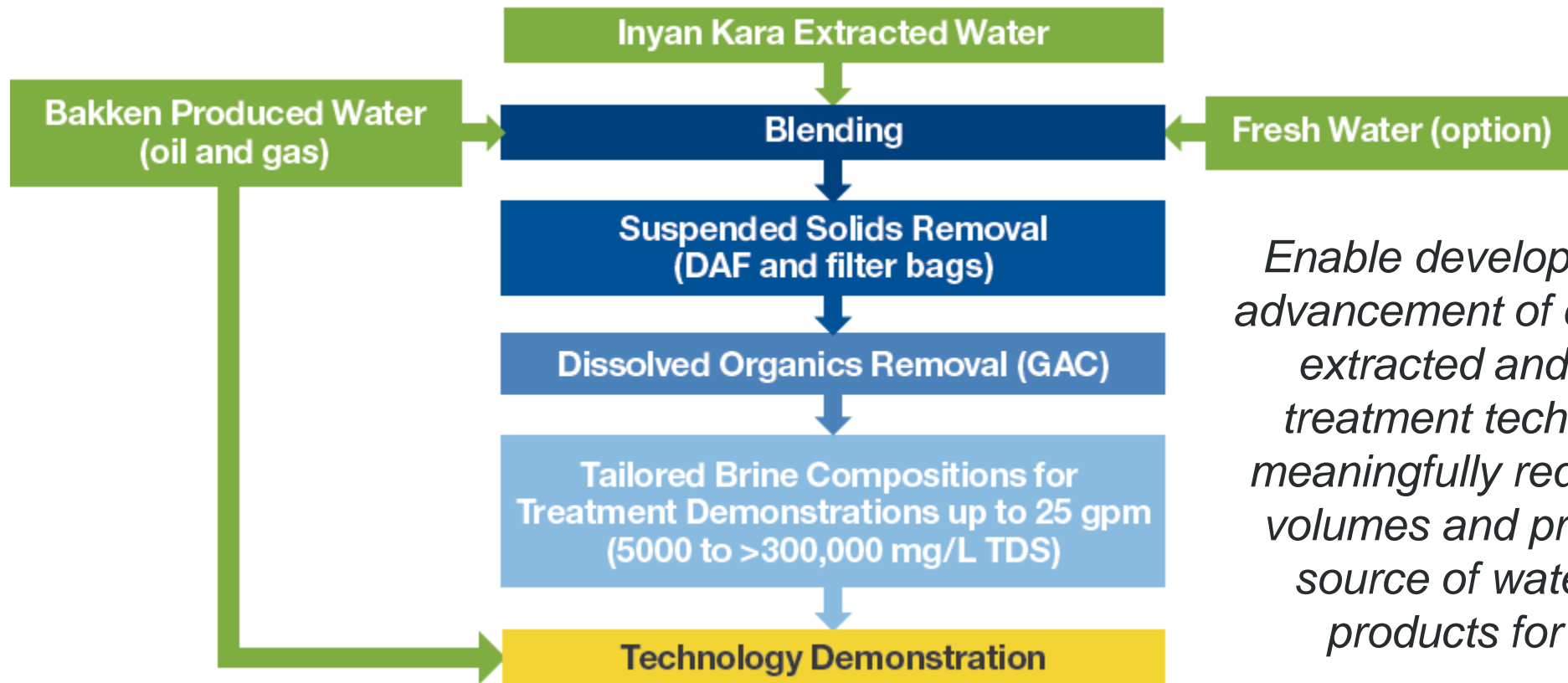
- Collaboration with Thomas Buscheck (Lawrence Livermore National Laboratory)
  - Model developed and calibrated for CO<sub>2</sub> storage in a continuous, open saline reservoir
    - ◆ Developed, in part, with data provided by the ND BEST project for SWD operations injecting into Inyan Kara Formation
- Modeled scenario
  - Inject 2.0 MT/year of CO<sub>2</sub> from October 1, 2008, to March 1, 2019, with concurrent SWD
  - Six brine extraction wells (~11,000 bpd/well) with reinjection >12 miles away
    - ◆ >95% reduction in AOR
      - From 249 km<sup>2</sup> to 9 km<sup>2</sup>
        - Area within reservoir with pressures 75 psi or more above the original reservoir pressure at the end of the injection period
    - ◆ > 90% reduction in postinjection monitor period
      - From 26 years to 2 years
        - Time for reservoir pressure to decline to less than 75 psi above original reservoir pressure at the injection well following injection period

# ACCOMPLISHMENTS

## ACTIVE RESERVOIR MANAGEMENT



# BRINE TREATMENT TECHNOLOGY DEVELOPMENT AND TEST FACILITY



*Enable development, testing, and advancement of commercially viable extracted and produced water treatment technologies that can meaningfully reduce brine disposal volumes and provide an alternate source of water and/or salable products for beneficial use.*

EERC JH53207A.AI

# ACCOMPLISHMENTS

## BRINE TREATMENT DEVELOPMENT FACILITY



North Dakota water treatment test bed facility available for demonstration of produced water treatment technologies.



Enable development, pilot testing, and advancement of commercially viable extracted and produced water treatment technologies that can meaningfully reduce brine disposal volumes and provide an alternate source of water and/or salable products for beneficial use.



TEST BED FACILITY CAN REPLICATE EXTRACTED WATERS THAT ARE REPRESENTATIVE OF LOCATIONS/SOURCES THROUGHOUT THE UNITED STATES



FACILITY CAN BE READILY ADAPTED FOR USE WITH ALTERNATE FLUID COMPOSITIONS OR TREATMENT PROCESSES

- Alternate water sources trucked and offloaded at site
  - Pretreatment and conditioning can be modified to replicate broader influent specifications
  - Blending of alternate fluid chemistries for demonstration of water or chemical treatment processes
  - Test beds for enabling technologies (e.g., power/thermal supply, pretreatment/conditioning...)
  - On-site SWD (saltwater disposal) and waste handling
  - Can accommodate propane (5000-gal tank) and/or noncontact cooling water (30 gpm)
- CONTROL ROOM**
- Influent and effluent flow rates and composition
  - Chemical usage
  - Energy and thermal use/load
  - EHS (environment, health, and safety) and operability systems (e.g., pretreatment systems, hazardous environment monitoring, etc.)

### SITE SPECS

- 60' x 80' building (18-ft walls)
- 53' demonstration bay (accommodates semi tractor-trailer)
- 300 kW electric power
- Two overhead doors
- Demonstration bay, water pretreatment area, and control room
- Heated and insulated
- Air handling/exchange
- Hazardous environment detection and alarm
- Temporary water storage tanks for demonstration supply
- Waste handling and disposal on-site
- Pilot treatment rates ranging up to 25 gpm
- 30-60+ day extended-duration tests
- Capable of 24/7/365 operations

This is a collaborative effort with Nuvera Environmental Solutions and the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL).

ACKNOWLEDGMENT  
DOE Notice  
This document is a work product prepared by the Department of Energy under Award Number DE-FE0002015. This was prepared as an account of work sponsored by the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process disclosed, or represents that its use would not infringe upon privately owned rights. This document is the property of the United States Government and is loaned to you; it and its contents are not to be distributed outside your organization.

John Hamling, Marc Kurz, Ryan Klapperich, Lanny Jacobson, and Robert Jensen



# COST-EFFICIENT MONITORING

- Intelligent, adaptive, scalable, strategic
- Fast automated processing/quicker integration
  - Improve interpretations and performance forecasts
  - Actionable results that inform operational decisions
  - Integrated with autonomous operation
- Low environmental and operational impact
  - Autonomous, remote sensing, no umbilical, site access
- Viable long term (10–100 years postinjection!!!)
  - Cost effective, robust, reliable, site access, highly trainable
- Understood and effectively communicated
  - Public and regulatory acceptance
  - Deterministic

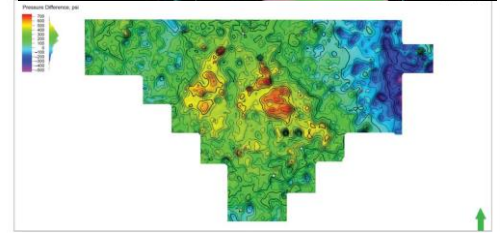
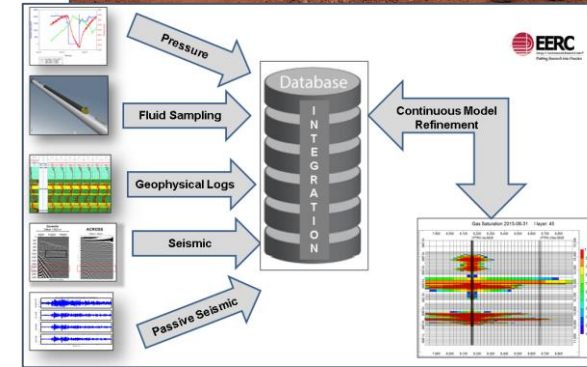
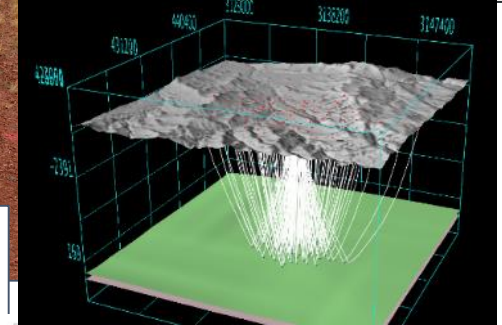
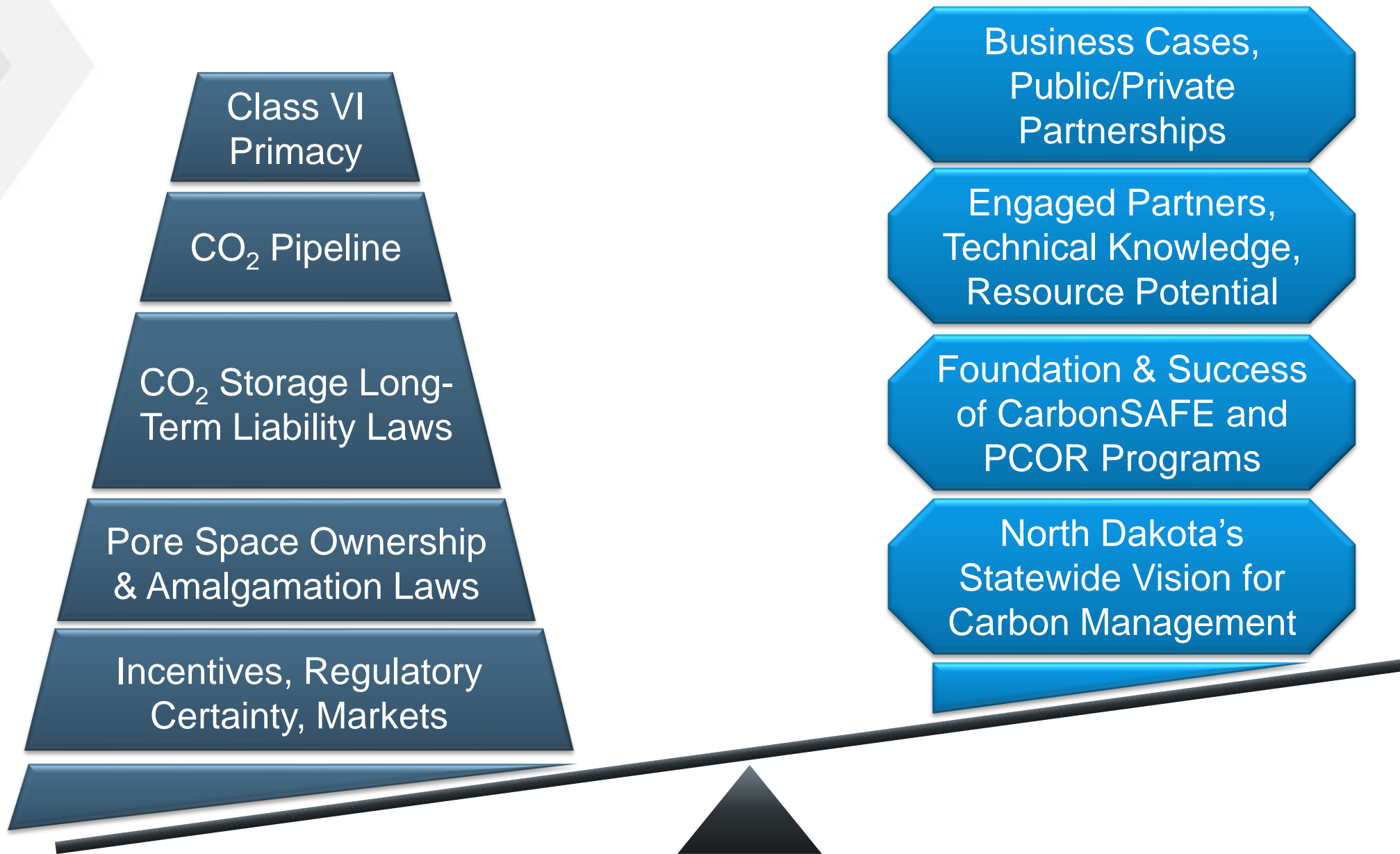


Fig. 14. Reservoir pressure differences between September 2015 and December 2016 inverted from measured InSAR data.









# QUESTIONS & DISCUSSION



**UND** UNIVERSITY OF  
NORTH DAKOTA

**John Hamling**  
**Assistant Director for Integrated Projects**  
jhamling@undeerc.org  
701.777.5472 (phone)

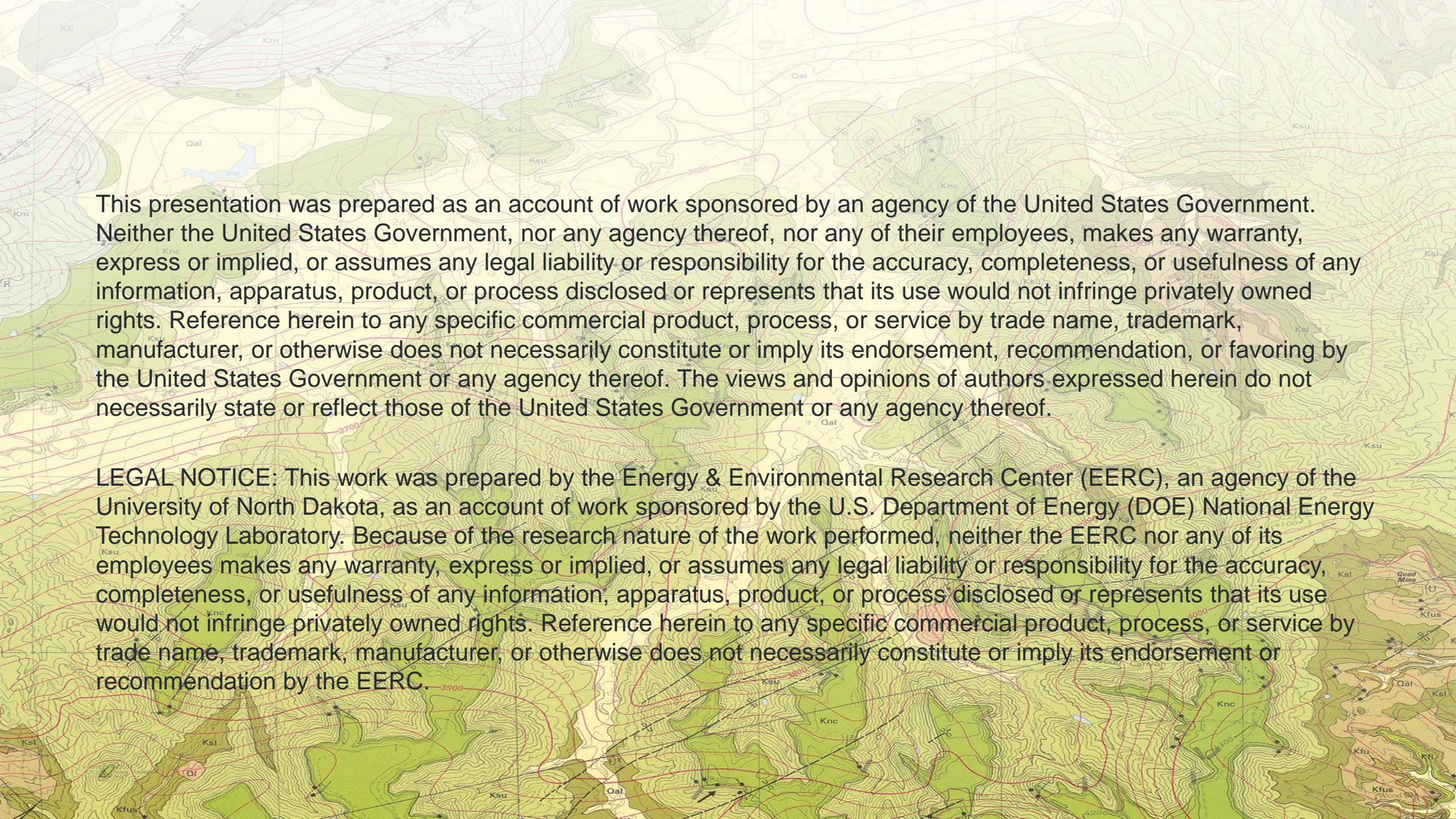
**Energy & Environmental  
Research Center**  
University of North Dakota  
15 North 23rd Street, Stop 9018  
Grand Forks, ND 58202-9018

www.undeerc.org  
701.777.5000 (phone)  
701.777.5181 (fax)

A wide-angle photograph of a university campus at sunset. The sun is low on the horizon, casting a warm glow over the scene. In the foreground, there are large trees with some yellowing leaves. In the background, several multi-story brick buildings and a parking lot with many cars are visible under a clear sky.

**THANK YOU**

Critical Challenges. Practical Solutions.



This presentation was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**LEGAL NOTICE:** This work was prepared by the Energy & Environmental Research Center (EERC), an agency of the University of North Dakota, as an account of work sponsored by the U.S. Department of Energy (DOE) National Energy Technology Laboratory. Because of the research nature of the work performed, neither the EERC nor any of its employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement or recommendation by the EERC.



**EERC**



UNIVERSITY OF  
**NORTH DAKOTA**



Critical Challenges. Practical Solutions.