A Pipeline Operator’s View of Hydrogen and CO2 Pipeline Opportunities

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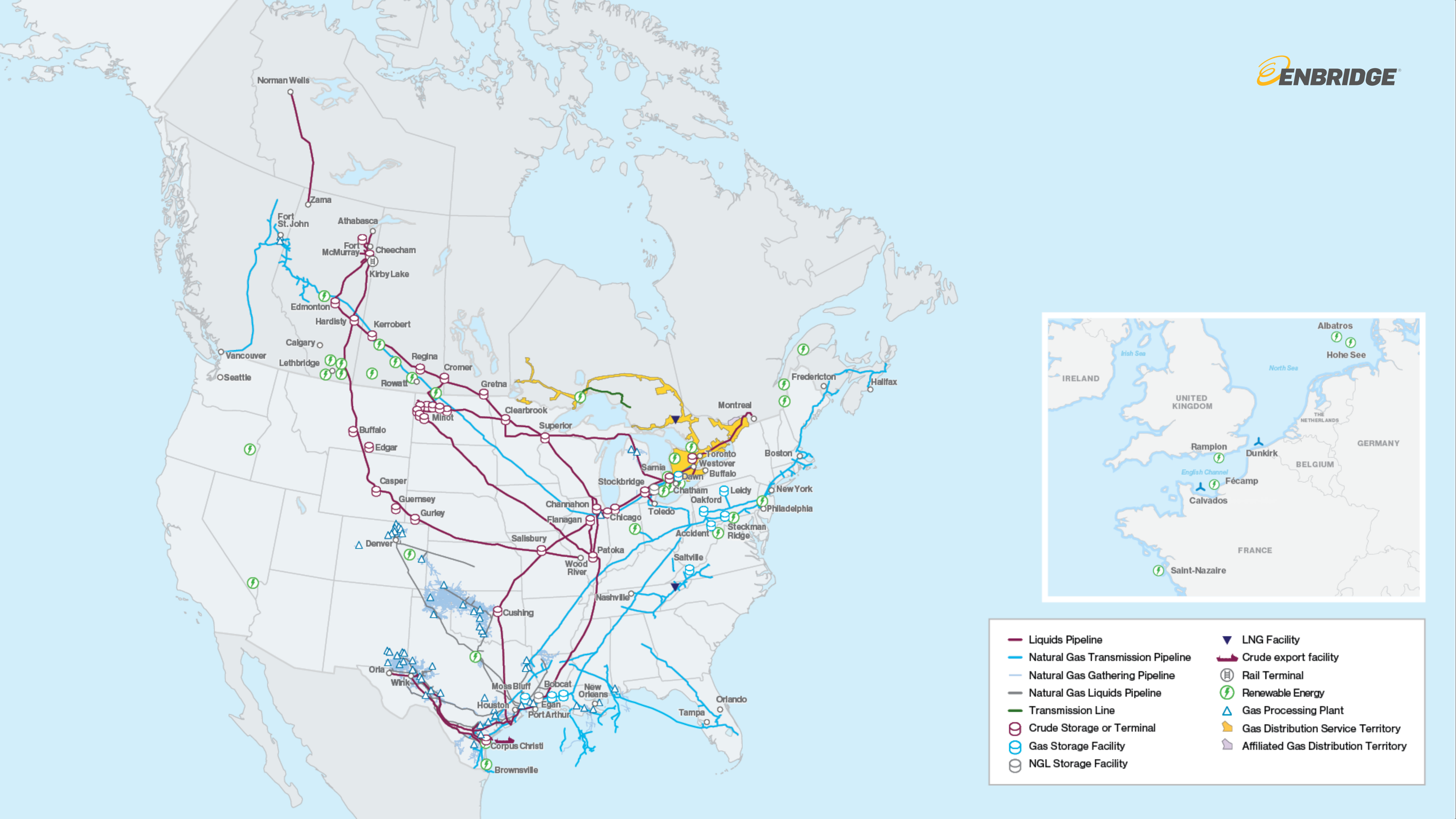
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Liquids Pipeline
Natural Gas Transmission Pipeline
Natural Gas Gathering Pipeline
Natural Gas Liquids Pipeline
Transmission Line
Crude Storage or Terminal
Gas Storage Facility
NGL Storage Facility
LNG Facility
Crude export facility
Rail Terminal
Renewable Energy
Gas Processing Plant
Gas Distribution Service Territory
Affiliated Gas Distribution Territory

About us

Enbridge is North America's leading energy infrastructure company

Liquids Pipelines

- ~28,661 km/17,809 mi of pipe
- Moving 3 million barrels/day

30%
of crude oil produced in North America

Natural Gas Pipelines

- 118,763* km/73,796* mi of pipe
- Moving 25.7 Bcf/day

20%
of the natural gas consumed in the U.S.

Natural Gas Utilities

- 3.9 million retail customers
- Serving 670+ communities

75%
of Ontario residents' energy needs delivered

Renewable Power

- 45+ renewable power facilities
- 2,174 MW generating capacity

966,000
homes powered by our assets

* Includes DCP Midstream assets

Major Sources of Energy in the U.S. (Q1/Q2 2022)

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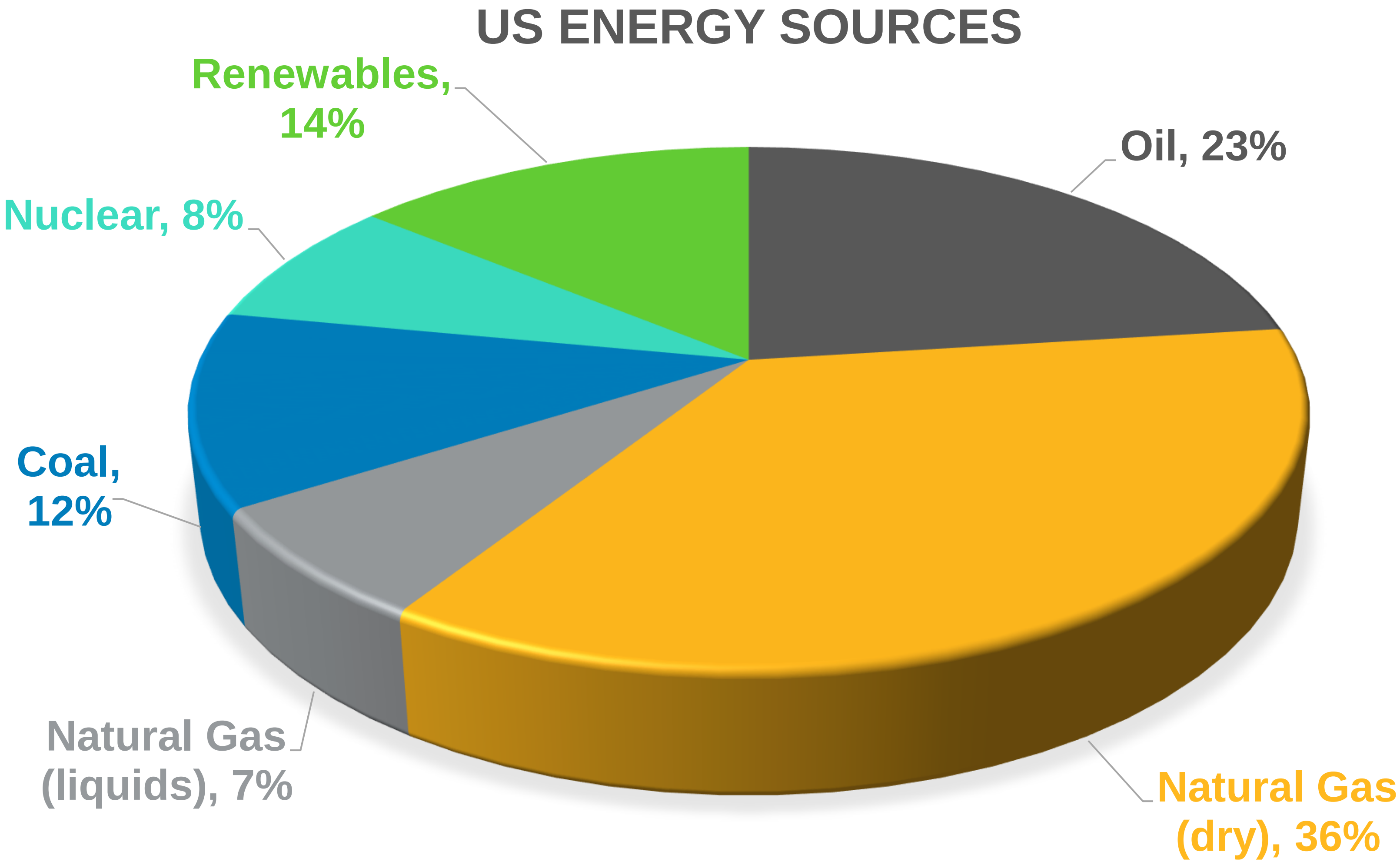
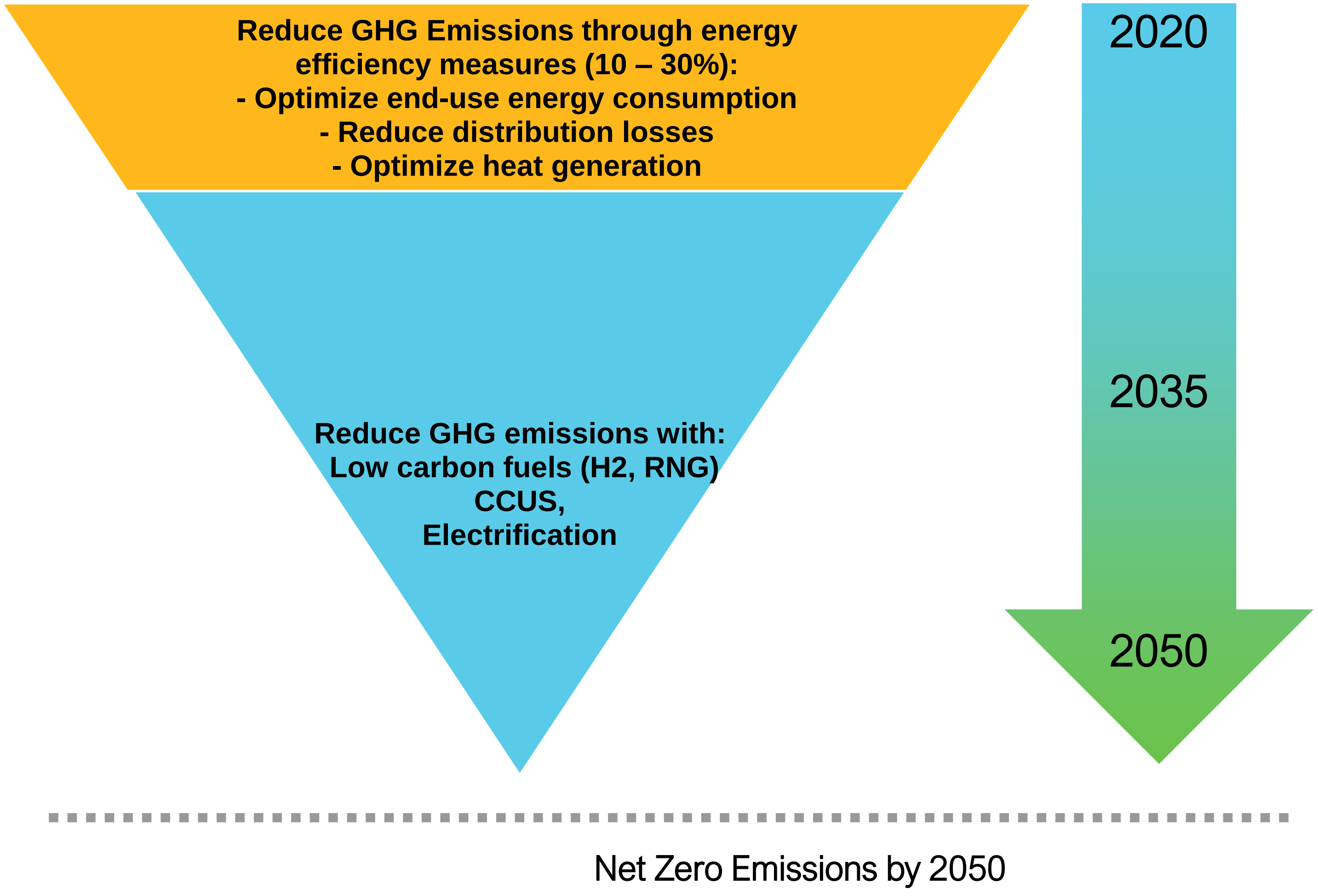
- The largest source of energy in the Unites States is oil and natural gas.
- Oil and natural gas accounts for 66% of the energy we use (according to the U.S. Energy Information Administration, Oct. 2022)
- Other sources include coal, nuclear, and renewables



Decarbonization of Large Volume Customers

- Energy efficiency
  - Reduce end-use energy consumption
  - Reduce distribution and radiation losses
  - Improve efficiency of heat generation equipment
- Low carbon fuels for boilers
  - Renewable Natural Gas (RNG)
  - Hydrogen
  - Biomass, digester gas, biofuels, syngas
- Carbon Capture Utilization and Storage (CCUS)
  - Capture CO2 from boiler stacks
- Electrification
  - Replace gas boiler with electric boiler, provided low carbon electricity is available



Why Blend Hydrogen in a Natural Gas Pipeline?

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- Hydrogen is abundant and can be produced using sustainable energy sources.
- Adding hydrogen to natural gas can significantly reduce greenhouse gas emissions (if the hydrogen is produced from low-carbon energy sources)
  - Biomass, solar, wind, nuclear, fossil resources with carbon capture
- Hydrogen may be carried through to end-user systems or extracted to be used in fuel cells (automotive or stationary)
  - Use in fuel cells reduces petroleum consumption and improves air quality (reduces emissions)
- Transport hydrogen gas via pipeline is preferred over transport as a liquid in trucks or tankers
  - More economical, higher safety
- May provide an economical means to store energy produced from renewable sources such as wind or solar, capturing otherwise curtailed or unused power
- Pipeline infrastructure is already in place!

Natural Gas Transmission Pipeline Networks in the North America

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- Earliest cross-country gas transmission lines were built in the 1920's and many are still in-service
- Early Enbridge gas line was built in 1943 to support WW II
  - Big Inch Pipeline: 24 in. OD crude oil pipeline (1400 mi. Longest pipeline to date) – later converted to gas, still in-service today
- Thousands of miles of natural gas pipeline were constructed in the 1950's and 1960's. – about 75% of the US gas transmission system was built prior to 1980
- Over the past several decades, transmission pipeline mileage has seen only modest growth.

Pipeline Challenges Associated with Hydrogen

- Hydrogen is a fundamentally a different fuel with lower heating value and the effects of blending must be carefully assessed prior to introduction
  - Pipeline expansion activity will be needed to offset the reduced heating value of hydrogen relative to natural gas.
- Transmission Pipelines: Material degradation needs to be carefully managed:
  - Hydrogen will degrade linepipe properties resulting in reduction in ductility, fracture toughness and reduction in fatigue resistance
    - Review of existing pipeline networks must be completed to remove/mitigate materials that are not hydrogen compatible
  - Process for converting existing pipeline infrastructure to blended hydrogen service is not standardized
- Leak Management/Metering
  - Detecting and minimizing leaks, meter accuracy

Gaps - Transmission Pipeline Integrity

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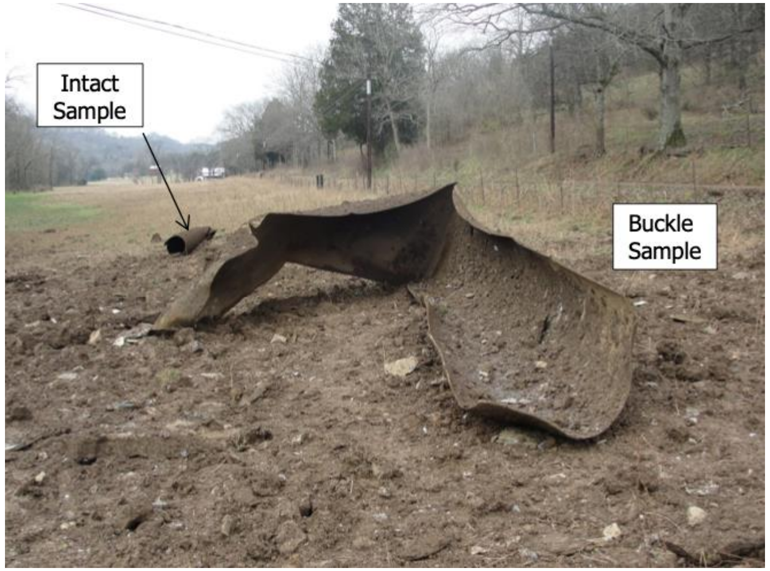
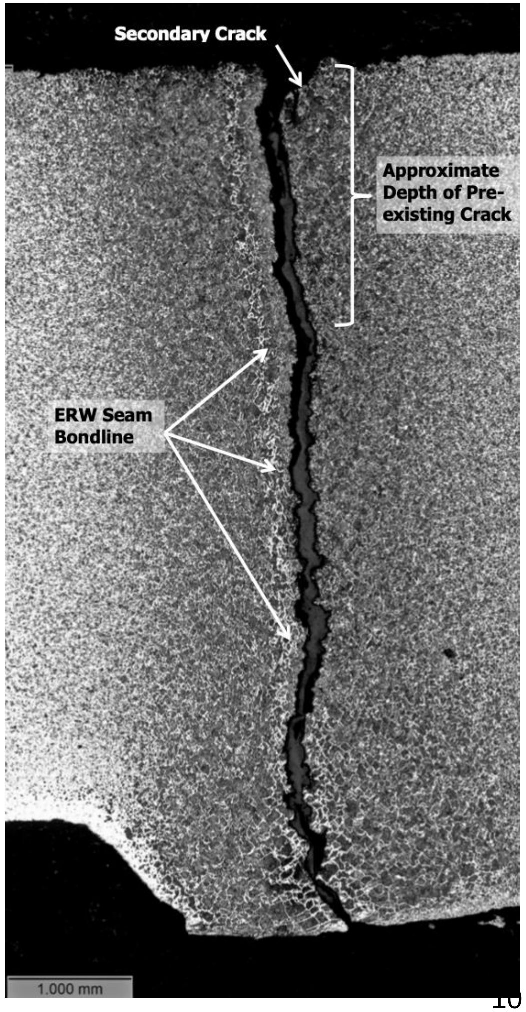
What needs to be addressed to safety blend hydrogen in natural gas pipelines?

Steel Pipelines	• *Lack of Fatigue Crack Growth data for blended hydrogen/natural gas environment with loading ratio (R-ratio) representative of transmission pipelines.*
Damage Assessment Models	• *Lack of accurate material toughness data in blended hydrogen needed. Needed for damage assessment models.*
Valves/Sealing Materials	• *Several publications have been released but need matrix of acceptable sealing materials for various sealing designs based on hydrogen blend % (create a design guide).*
In-Line Inspection	• *Higher sensitivity/lower detection thresholds for indications required.* • *Circumferential Flaw Detection* • *Hydrogen tolerance of ILI tools*
Codes and Standards	• *Gaps in industry guidance documents related to materials, design, integrity management, safety, electrical codes, leak detection, etc.*

Example of Hydrogen Embrittlement Failure

- Occurrence: In-service rupture of a transmission pipeline, East Tennessee Natural Gas system, MP 49.147
  - 22 in. OD x 0.281 in. WT, Grade API Grade X42
- Incident Date: December 15, 2018
- Root Cause: Combination of pre-existing flaw and hydrogen embrittlement of the hard microstructures in the course-grain heat affected zone of the weld seam (electric resistance welded, ERW)
  - Two possible sources of hydrogen: cathodic protection system, corrosion reaction (both can supply atomic hydrogen at the steel surface)
  - Hydrogen embrittlement of the ERW seam reduced fracture toughness of the seam and combined with a pre-existing flaw, resulted in failure at operating pressure of the pipeline.





Further Information is Available

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PRCI Report: *Emerging Fuels - Hydrogen SOTA, Gap Analysis, Future Project Roadmap*

- Report PR-720-20603-R01, Nov 2020
- Goal - develop a concrete path forward to define necessary projects aimed at providing critical information for companies to safely and reliably inject hydrogen into pipelines at specified blend levels.
- Provides description of worldwide projects, state-of-the-art analysis, gap analysis, and recommendation for R&D topics
- Addresses integrity, safety, network and end-use equip., metering and gas quality, network management and compression, inspection and maintenance, hydrogen-natural gas separation, and underground storage

Summary of Thoughts

- Use of existing natural gas infrastructure represents great potential for transport of hydrogen and progress toward a low carbon energy future
- Technical and economic challenges need to be resolved through research to safely and reliably transport blended hydrogen.
- Engagement in industry projects and research efforts is key in understanding and navigating the technical challenges
- Conversion from natural gas to blended hydrogen is not standardized within the industry and requires case-by-case assessments/engineering analysis considering materials of construction, H2 blend %, and operating parameters.
- Enbridge is developing a foundation of knowledge and experience to successfully blend hydrogen into its existing network. Continued engagement is key!

Carbon Capture and Storage – What is it?

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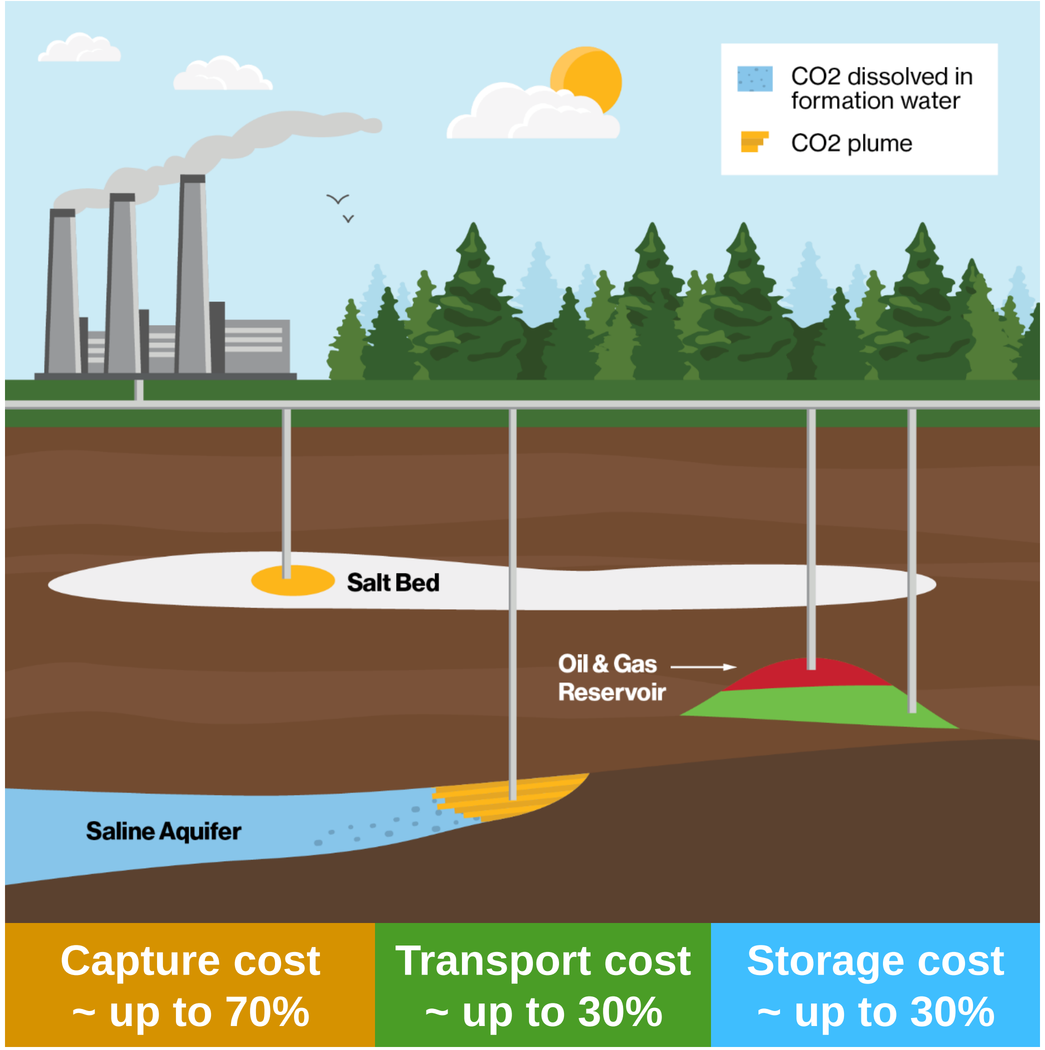
Carbon capture and storage (CCS) takes carbon dioxide (CO2) emissions from industrial facilities and permanently stores them deep underground. CCS is a viable way to meaningfully reduce greenhouse gas emissions from critically important industries. CCS moves us toward a cleaner future at the lowest possible cost to the economy.

What is Carbon Capture and Sequestration?

- Capturing CO2 from large volume point sources emitters
- Purifying to maximize the CO2 content
- Transporting the CO2 to a suitable storage site
- Injecting the CO2 into deep geological formations for permanent storage using specially constructed and monitored wells
- Primarily targeting saline aquifers or depleted oil and gas reservoirs



Current Pipeline Technology for CO2 Transportation

LEADING PIPELINE RESEARCH

Catalog No. PR182-224504-R01

Pipeline Transportation of CO_2
SOTA, Gap Analysis and Future Project Roadmap

ALT-1-6

Contract PR182-224504

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Of

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1	September 1, 2023	First draft
2	October 13, 2023	Final Version
3	November 09, 2023	Revised Final Version

Review of PRCI CO_2 SOTA Report

Project Activities

Task 1 – Literature review which consist of two sub-tasks

- Mapping of current CO_2 pipeline project worldwide.
- SOTA analysis of existing data

Task 2 – Gap analysis of existing data

Task 3 – Roadmap proposing future R&D projects to address gaps

Task 1 – Existing CO2 Pipelines and Demand Forecast

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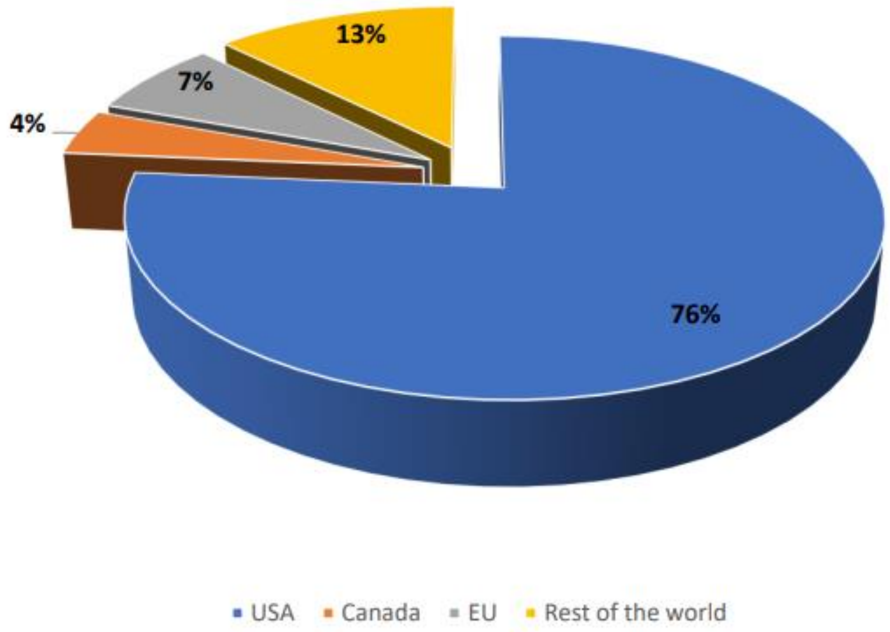
Existing CO2 Pipelines:

- 6000 miles worldwide, 5300 miles in North America
- Almost all CO2 pipelines are used for enhance oil recovery



Forecast for Future CO2 Pipeline Construction

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To achieve net-zero carbon emission objectives, substantial CO2 infrastructure is needed:

- According to a 2030 roadmap for Carbon Capture and Storage for E&P Companies, the United States is planning to build 29,000 miles (46,671 km) of CO2 pipelines
- For Europe, the EU Energy Roadmap estimates a total of12,427 miles (20,000 Km) of CO2 pipeline infrastructure is needed by 2050

Pipeline Challenges for CO2 Pipelines

The PRCI report gap analysis concluded four Focus Areas for CO2 Pipelines:

- Internal Corrosion
- Fracture Control
- Dispersion Modelling
- Re-purposing existing pipelines

Figure 2: Vehicle is Parked on HWY 433 - The White is Ice Generated by the Release of CO_2 - The Blue Arrow Points North (Aerial Drone Photograph Courtesy of the Mississippi Emergency Management Agency)

Review of PRCI CO_2 SOTA Report – con't

Internal Corrosion Focus Area - Literature Review

- The effect of trace elements on water solubility and corrosion.
- Thermodynamic models.
- Risk of water drop-out in different pipeline scenarios.
- Risk of hydrogen sulfide (H_2S) cracking.
- Risk of stress corrosion cracking from CO_2-CO-H_2O.
- Risk of cracking from hydrogen (H_2) gas.
- Risk of corrosion fatigue.
- Specifications for maximum trace element levels.
- Risk of damage to internal coatings.
- Test methods for corrosion and stress corrosion in CO_2-trace element mixtures.

Review of PRCI CO_2 SOTA Report – con't

Fracture Focus Area - Literature Review

- For CO2 (Gas) and CO_2 Liquid (Dense Gas Phase)
  - Fracture initiation
  - Fracture propagation and arrest
    - Decompression behavior
    - Numerical modeling
    - Crack arrestor technologies

Review of PRCI CO_2 SOTA Report – con't

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Safety and Dispersion Control – Literature Review

- Overview of current regulatory frameworks focused on safety aspects of CO_2 transportation.
- Historical factors influencing public acceptance of CO_2 pipeline routes.
- Modelling approaches for the analysis of atmospheric dispersion of CO_2 following a pipeline leak or rupture.
- CO_2 specific failure modes, release scenarios, and release parameters.
- Equations of State for specific Hydraulic Modelling and Flow Assurance purposes.
- Frame effect of potential solids formation on release and dispersion modelling.
- Impact of potential running ductile failure on consequence modelling set-up and results.
- Exposure levels for CO_2 and relevant consideration of indoor vs. outdoor receptors and physiological impacts on receptor response.
- Effective mitigation to limit CO_2 pipeline risk.
- Emergency response planning with respect to CO_2 including consideration of low temperatures formed during release and pipeline blowdown.

Review of PRCI CO_2 SOTA Report – con't

Re-Purposing Existing Pipeline for CO2 Service

1. Viability - identification of any fundamental characteristic which may prevent change in use.
2. Design and operability data assessment - design review and identification of all modifications necessary.
3. Detailed technical assessments.

Summary of Thoughts

- CO_2 Capture and Storage is an essential element to meeting net zero climate objectives
- Safe, efficient and reliable pipeline infrastructure is needed to met these goals
- Further attention is needed in research and industry commitment in the following areas
  - Internal Corrosion
  - Fracture Control
  - Dispersion Modelling
  - Repurposing existing lines

Questions?

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