Enhanced Oil Recovery State of the Art and the case for CO_2 EOR under the Alberta / Canada Grand Bargain

Clean Resources Innovation Network

Novel Hydrocarbon Extraction Theme

January 14, 2026

Outline

EOR overview – Richard Baker

- What is EOR?
- Primary, secondary, tertiary

State of the Art of EOR in Canada / USA / International

- Chemical – Eric Delamaide - IFP
- CO_2 EOR – Richard Baker
- Foam and Nanoparticles - Ali Telmadarreie - CNERGREEN

CO2 situation in Canada – Richard Baker

- **Factors to consider for CO2 flooding**
  - Economics: Risk vs. rewards
  - Non-economical factors: infrastructure, local know how, uncertainty
- **CCS vs. CCUS**
- **CO2 Aquifer (CCS) vs. Depleted Gas Reservoirs (CCS) vs. CO2 EOR (CCUS)**

EOR overview

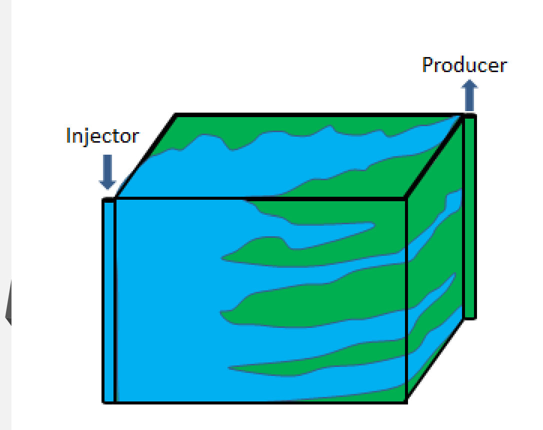
Richard Baker

Overview of Enhanced Oil Recovery

Enhanced Oil Recovery (EOR) refers to a collection of methods used after both primary and secondary recovery to extract extra oil that would otherwise be trapped in the reservoir or not produced at the economic limit of the recovery process.

- Improvement in Displacement Efficiency
- Improvement in Volumetric Efficiency

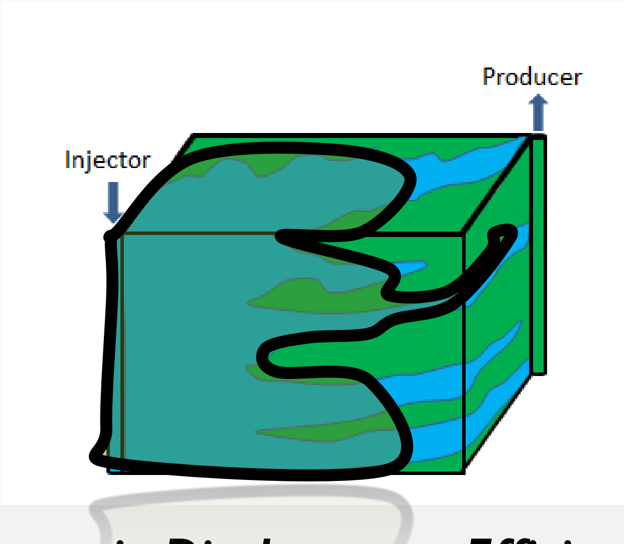
EOR



Waterflood

Waterflood contacted volume

Secondary Recovery Waterflood

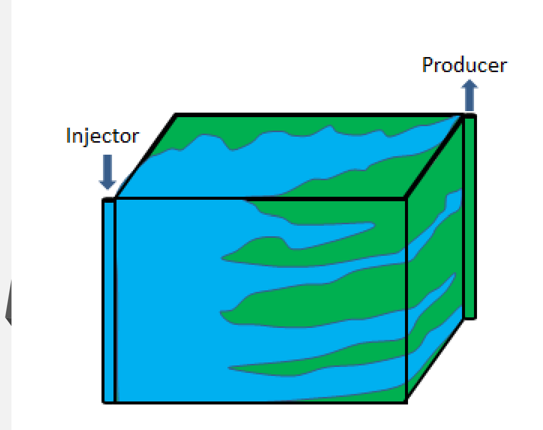


Polymer Flood + Surfactant

Improvement in Displacement Efficiency ↑ (surf) + Improvement in Volumetric Efficiency ↑

What is Enhanced Oil Recovery

Enhanced Oil Recovery (EOR) refers to a collection of methods used after both primary and secondary recovery to extract extra oil that would otherwise be trapped in the reservoir or not produced at the economic limit of the recovery process.



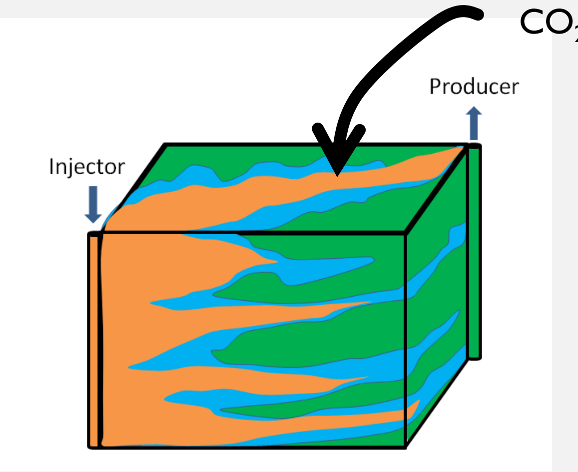
Waterflood

Waterflood contacted volume

Secondary Recovery Waterflood

EOR

CO_2 Flood



CO_2 flood contacted volume

Improvement in Displacement Efficiency ↑

EOR overview:

Methods used depend on oil viscosity, depth, driving force mechanism, recovered amount and reservoir permeability

Covered in today's CRIN session

Technology	Conventional API> 19	Heavy Oil API<19	Extra Heavy Oil & Oil Sands API<12	Shale Oil
Water flooding / Water Alternating Gas	X	X		
CO_2	X	X		X
Polymer / ASP flooding	X	X		
Surfactant and Nanoparticles infused water flooding	X			X
Thermal Steam (CSS / SAGD)		X	X	
Thermal Microwave / Electric			X	
Thermal Steam Solvent / CO_2*			X	
Sound	X			

* Covered during NHE CRIN 2025 October session by Alex Filstein

Chemical Flooding

Eric Delamaide - IFP

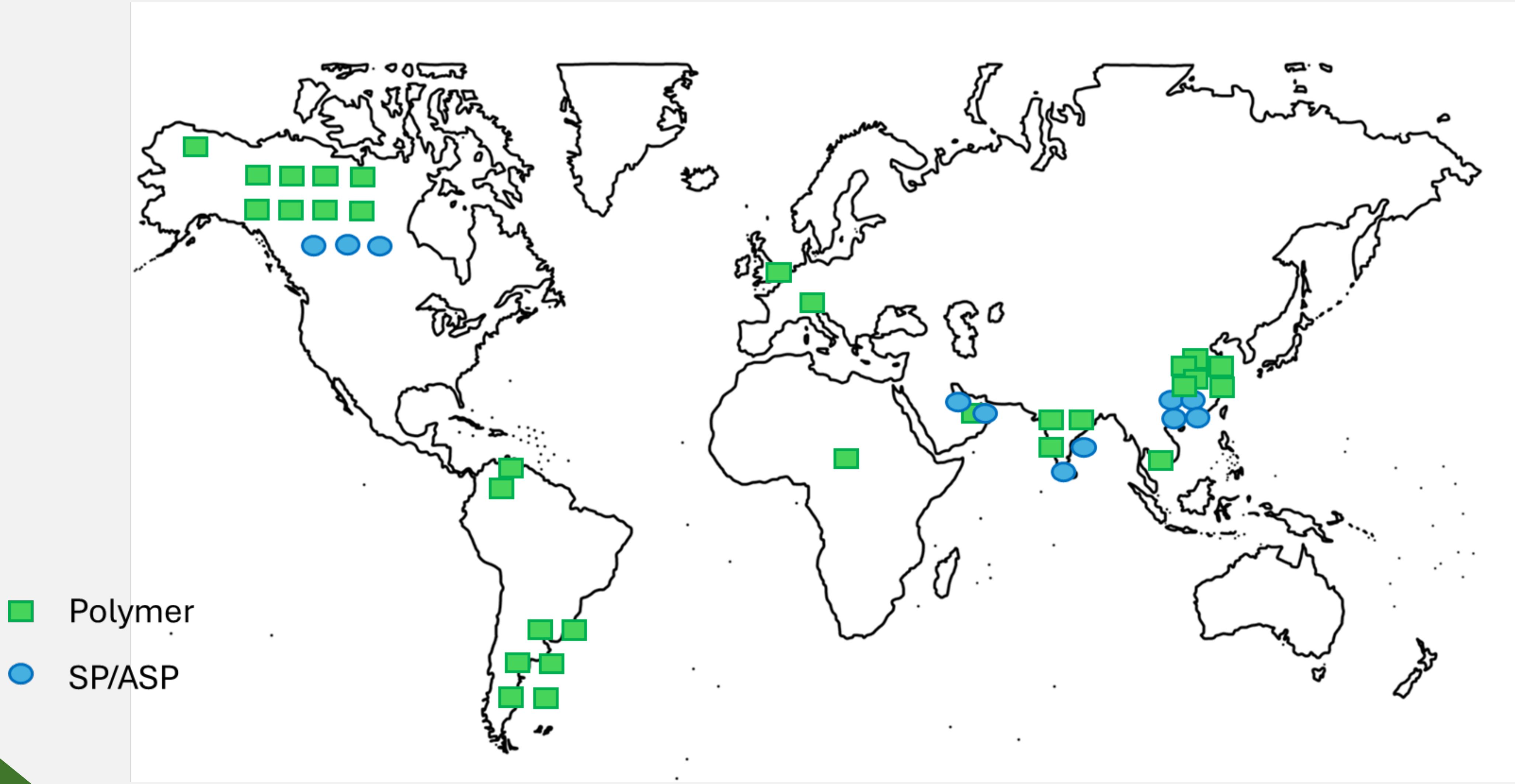
Chemical EOR basics: Main components

Polymer
- Makes water more viscous
- Improves sweep efficiency

Surfactant
- Reduces capillary forces trapping oil in the reservoir (Sr)
- Ensures foam stability

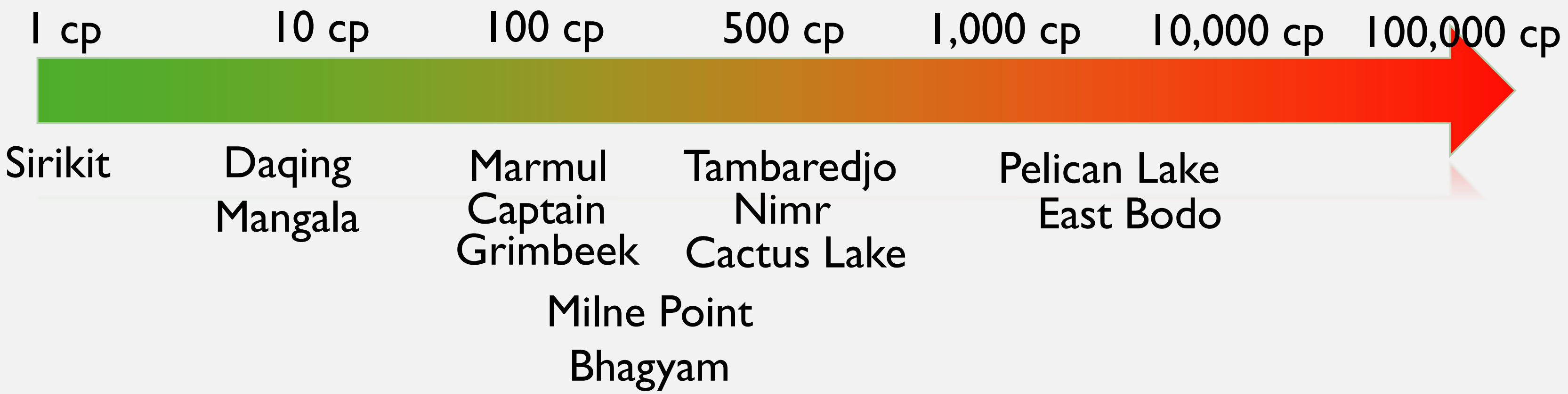
Alkali
- Generates surfactant in the reservoir
- Reduces surfactant adsorption

Chemical EOR expansions



Polymer successes

- Polymer injection is a PROVEN, COMMERCIAL technology
  - Large scale expansions in multiple countries
  - More planned, in the works, unpublished
  - Heavy oil
  - Over 500 kbopd, "Incremental" RF: 1-20%STOOIP



Polymer challenges

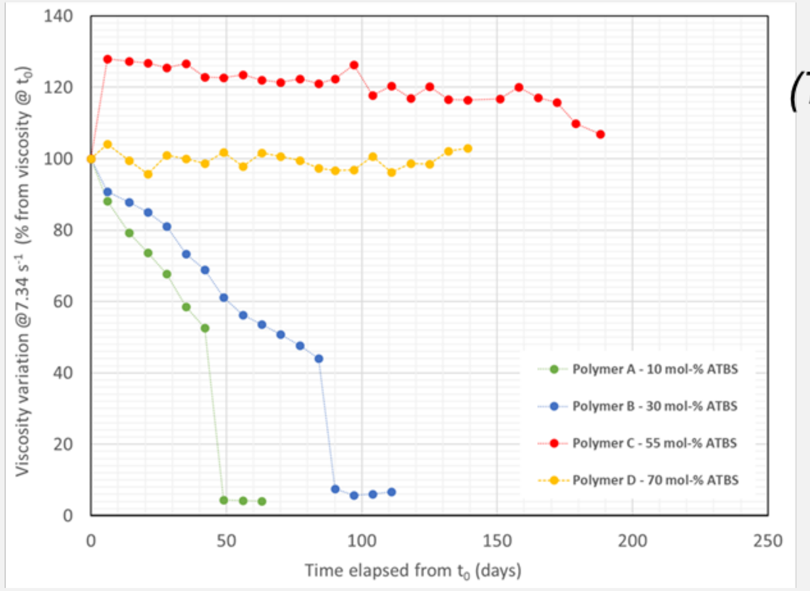
- Limit in permeability?
  - 20-30 mD?
- High TDS/hardness & temperature polymers
  - Economics can still be challenging in extreme conditions

Synthetic Formation Brine (SFB)

Na^+ (mg/L)	75,357
K^+ (mg/L)	3,316
Ca^{2+} (mg/L)	14,659
Mg^{2+} (mg/L)	4,777
Sr^{2+} (mg/L)	294
Ba^{2+} (mg/L)	4
Cl^- (mg/L)	159,299
HCO_3^- (mg/L)	47
TDS (mg/L)	257,753
Hardness index R^+	0.20

$$R^+ = \frac{[Ca^{2+}]+[Mg^{2+}]}{[Na^+]+[K^+]+[Ca^{2+}]+[Mg^{2+}]}$$

Relative viscosity loss in long-term anaerobic stability tests

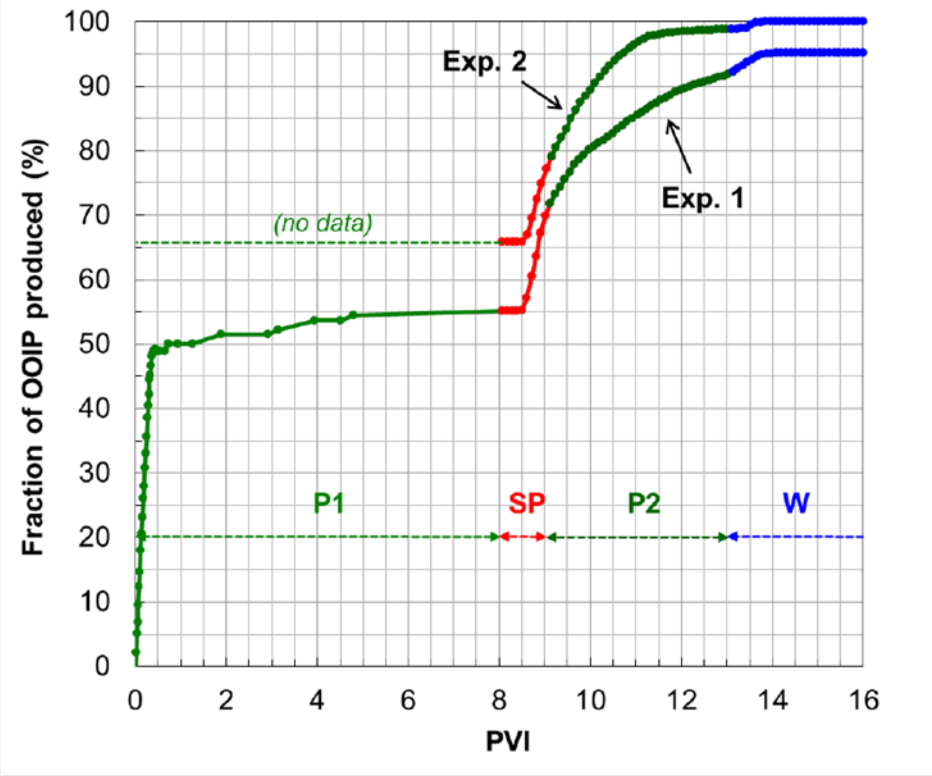


(T=88°C)

(SPE-218776)

Surfactant/ASP

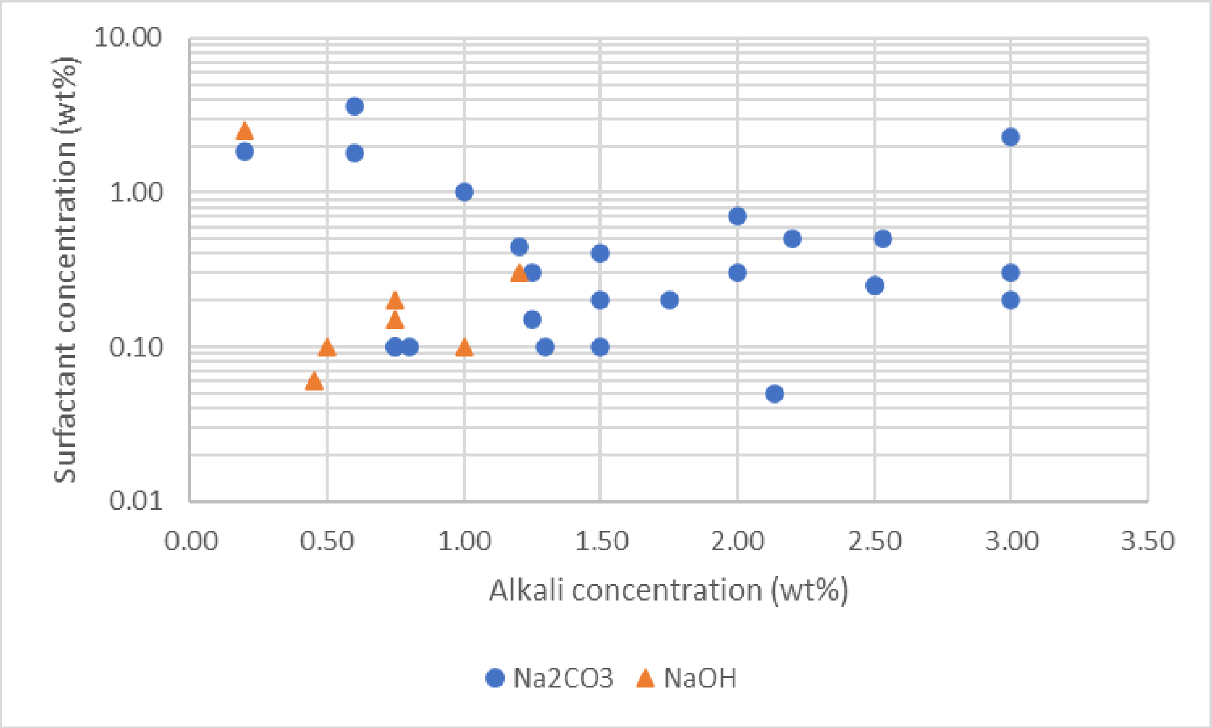
- Surfactant
  - Reducing IFT
  - Changing wettability
  - Reducing Sor
  - Expensive!
  - Higher TDS, hardness increase adsorption ($$)
  - Clay, limestone increase adsorption ($$)



(SPE 169697)

Alkali Surfactant Polymer (ASP)

- Alkali
  - Can generate surfactant
  - Reduces adsorption
  - Requires soft water

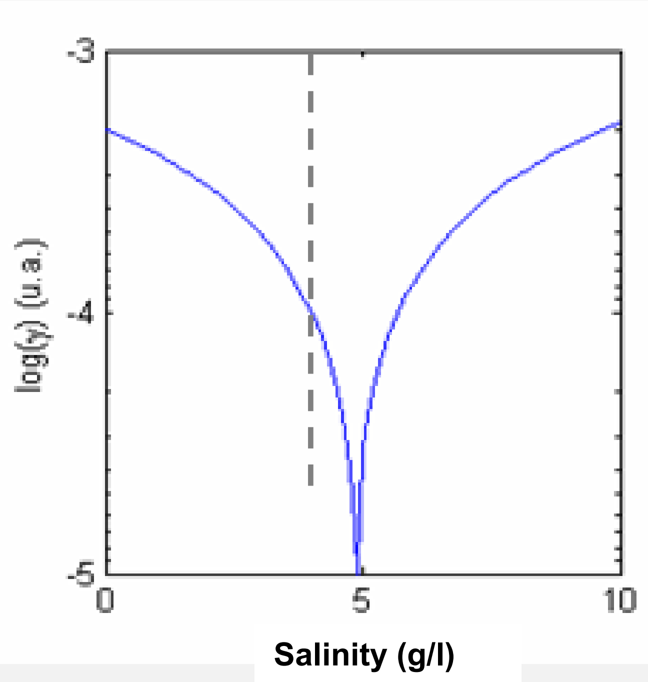



(SPE-165285)

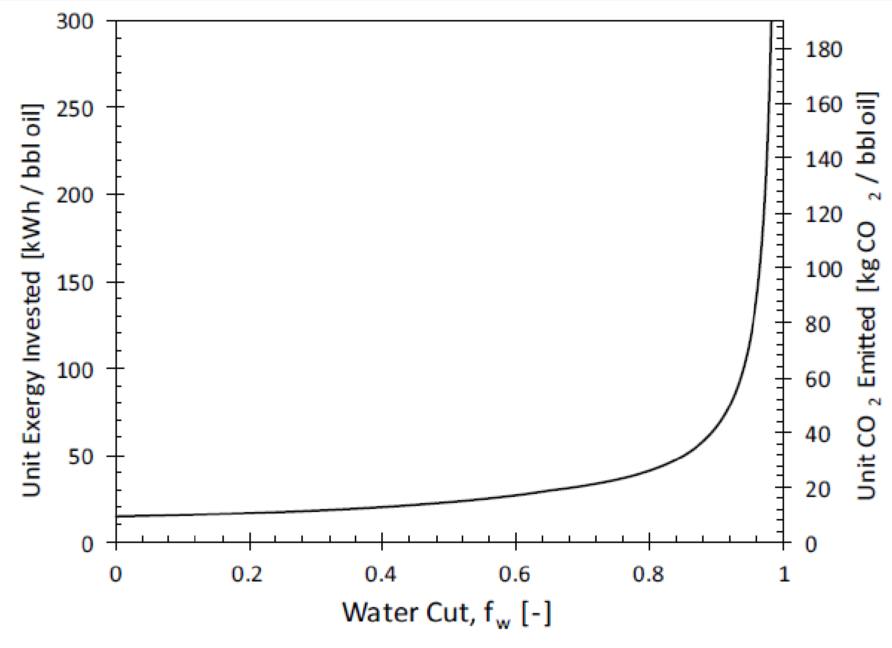
Surfactant/ASP summary

- Many pilots
- Few large-scale expansions so far
  - Canada
  - China
  - India, Oman
- Issues
  - Complexity
  - Economics
  - SP vs. ASP (scaling…)

Interfacial tension vs. salinity

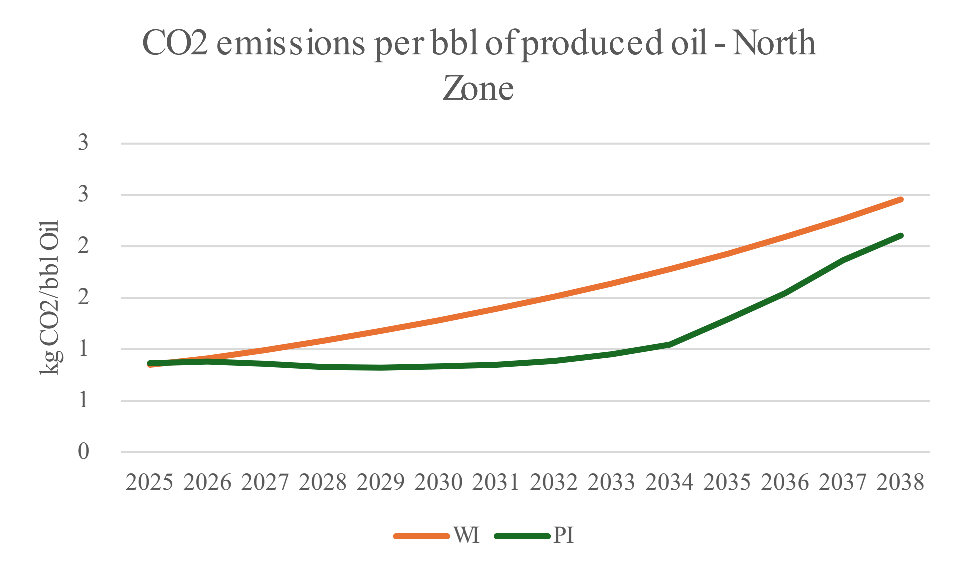


Chemical EOR reduces carbon emissions



(Farajzadeh et al., Nature, 2021)

Reduction	Increase
Reduction in water production reduces power usage and CO_2 emission	Polymer manufacturing and logistics
	Additional facilities
	Additional production chemicals



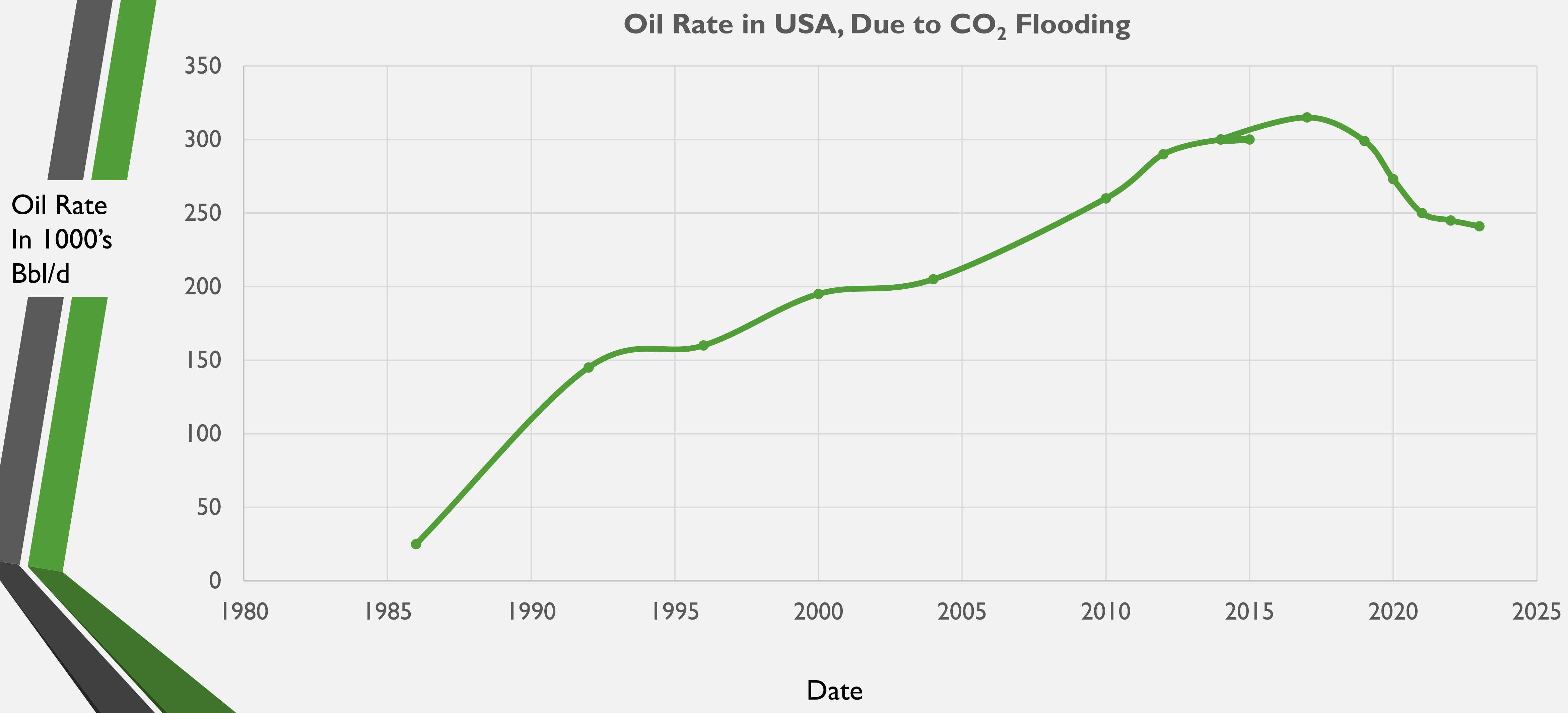
Status on EOR (CO2 miscible flooding, CCUS): Oil and CO_2 Production Data

Why use empirical data?

Early theoretical models are way too optimistic

Richard Baker

Oil Rate in USA due to CO_2 Flooding



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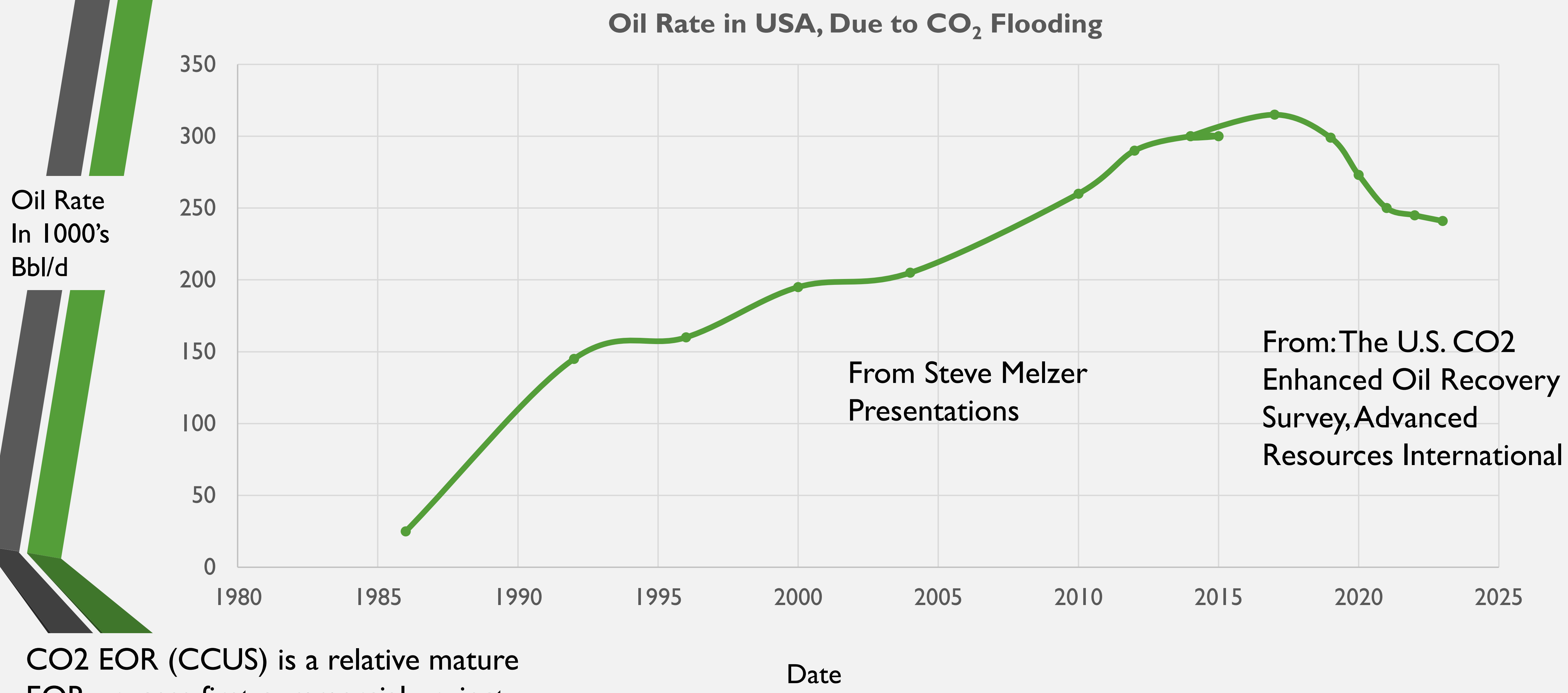
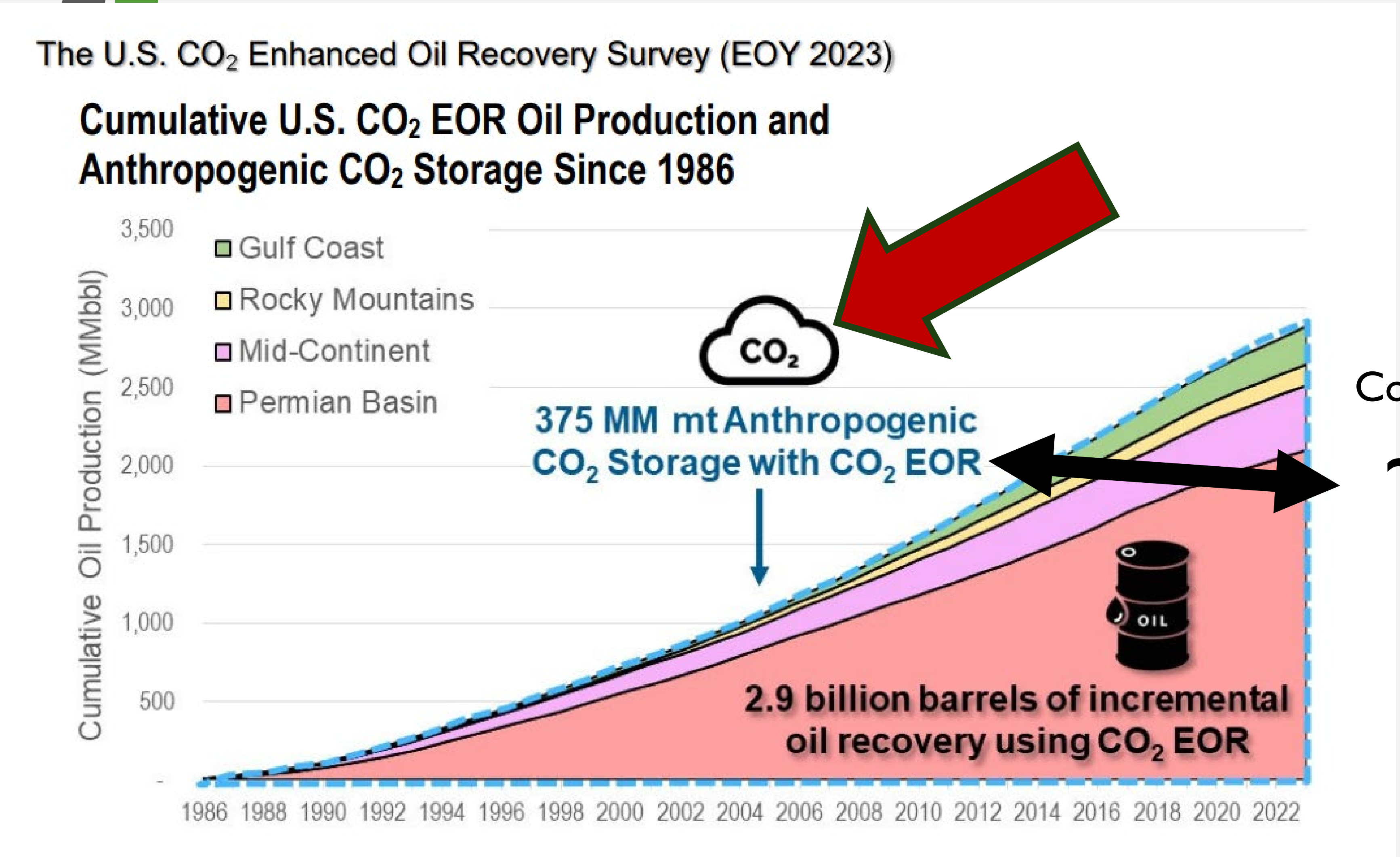


CO2 EOR (CCUS) is a relative mature EOR process first commercial project 1973

USA Oil Production by Region



Compares with Aquifer Injection

~52.6 Mt CO_2

~50-65

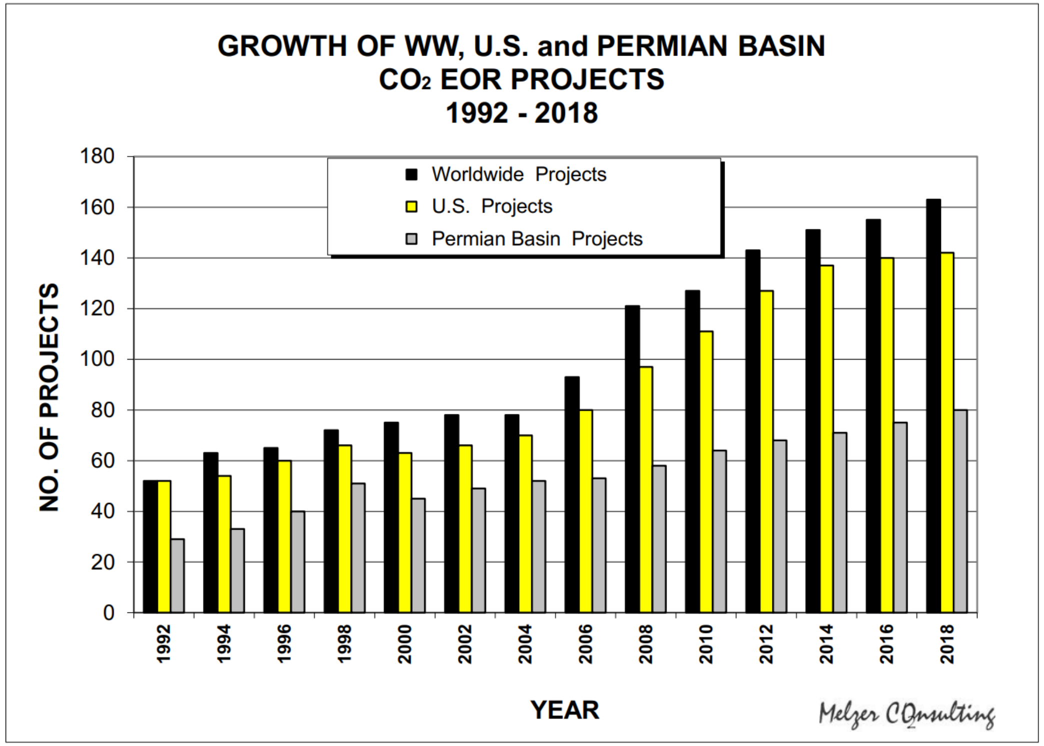
Compares with Weyburn

~40 Mt CO_2

From: The U.S. CO_2 Enhanced Oil Recovery Survey, Advanced Resources International

Status of CO_2 Flooding

The Permian Basin and Worldwide Project History

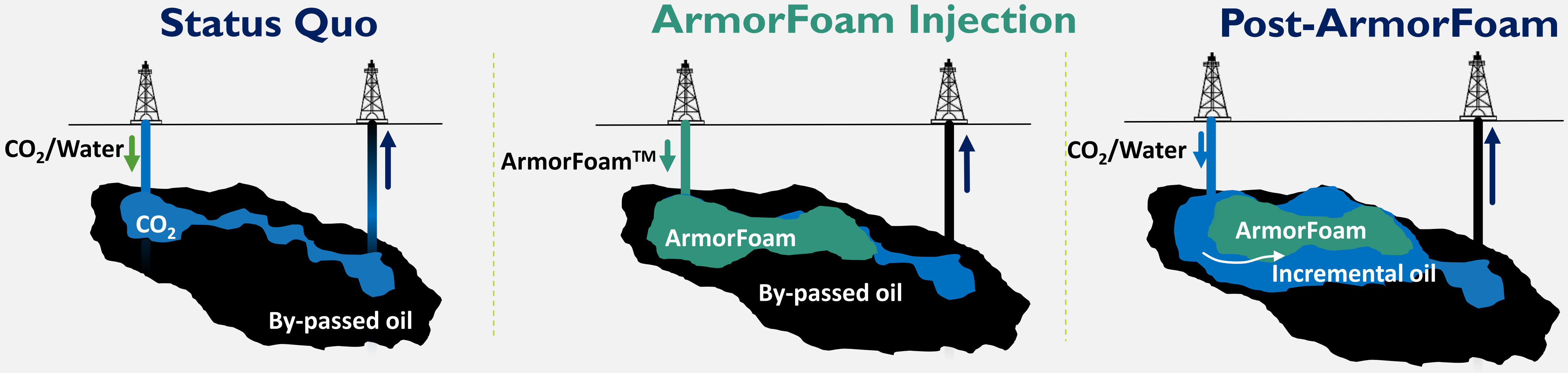


elzer COnsulting

Foam and Nanoparticles

Ali Telmadarreie - CNERGREEN

ArmorFoam™ blocks short circuits, creates new pathways that produce more oil

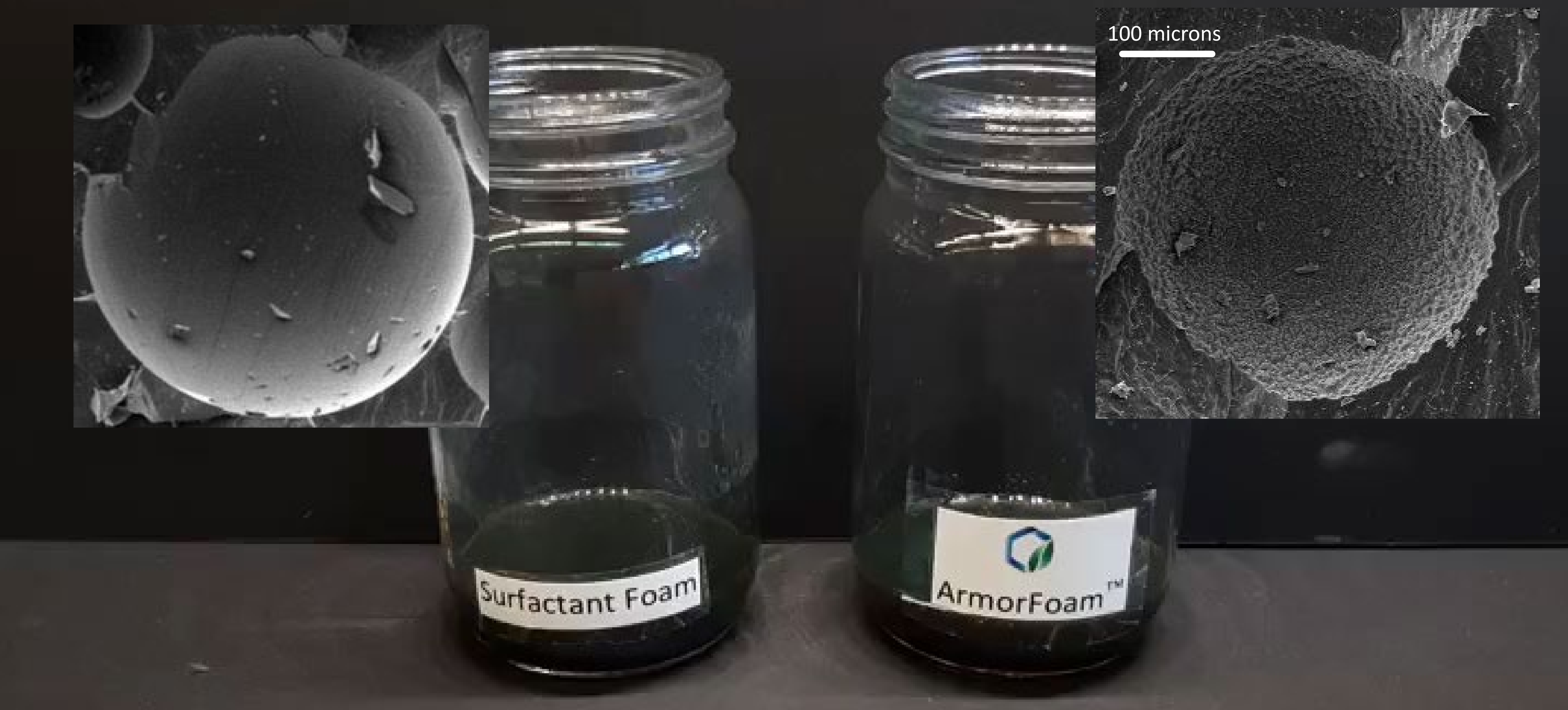


Status Quo:

- CO_2 Recirculation
- CO_2 storage
- Oil recovery
- CO_2 / bbl Emissions

Post-ArmorFoam:

- CO_2 Recirculation
- CO_2 storage
- Oil recovery
- CO_2 / bbl Emissions



Higher ArmorFoam™ stability translates to less chemical and fewer treatments

ArmorFoam pilot summary

CO_2 utilization improved by 50%

Operator, Well	Problem	Solution: ArmorFoam™ Treatment			
		Timeline	CO_2 saving	Oil rate	Incremental oil
Operator A, well #1	Oil production is limited by CO_2 handling capacity	2023	+20k tons	+10-20%	+3500 bbl
Operator A, well #2	Conformance, high CO_2 injection/production	2024-2025	+2k tons	+5%	+2000 bbl
Operator B, well #1	Declining oil rate in newly drilled well	2024	+5K tons	+50-200%	+4000 bbl
Operator C, well #1	High injectivity, gas breakthrough and declining oil rate	2024-2025	40 % reduction in gas rate	20%	TBD
Operator D, well #1	Conformance, high CO_2 production	2025	Increase in pressure	Reduction in GOR maintained for 10+ months	TBD

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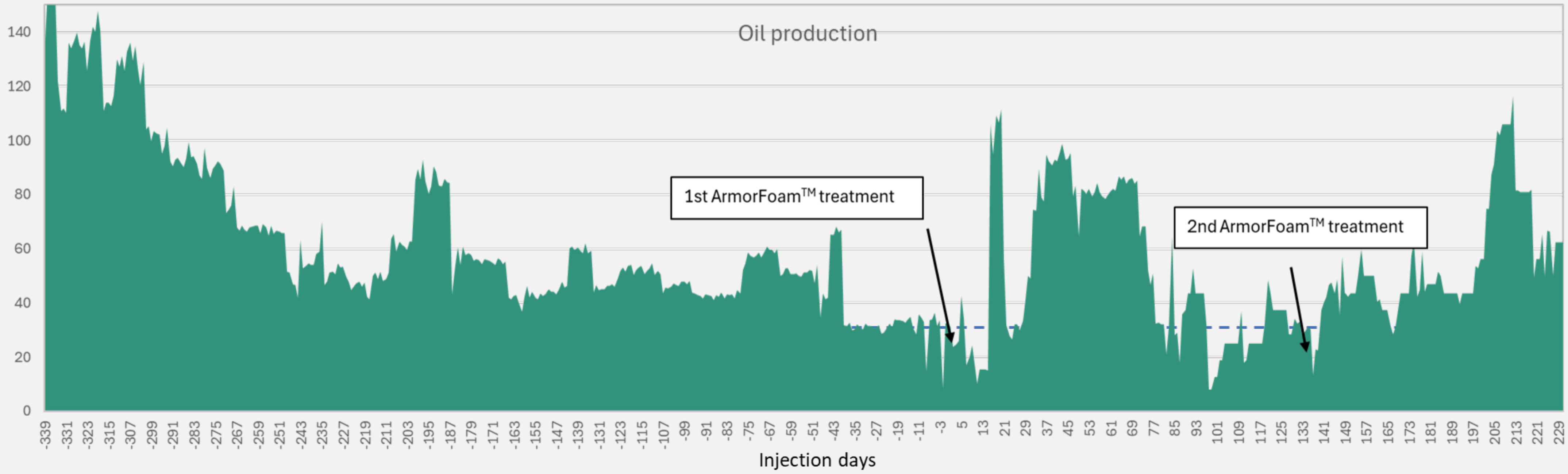
Clean and Efficient Hydrocarbon Production

Pilot Result Example



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ArmorFoam™ Applications

- CO_2 EOR/CCUS
- Waterflood and gas conformance
- CCS (near future)

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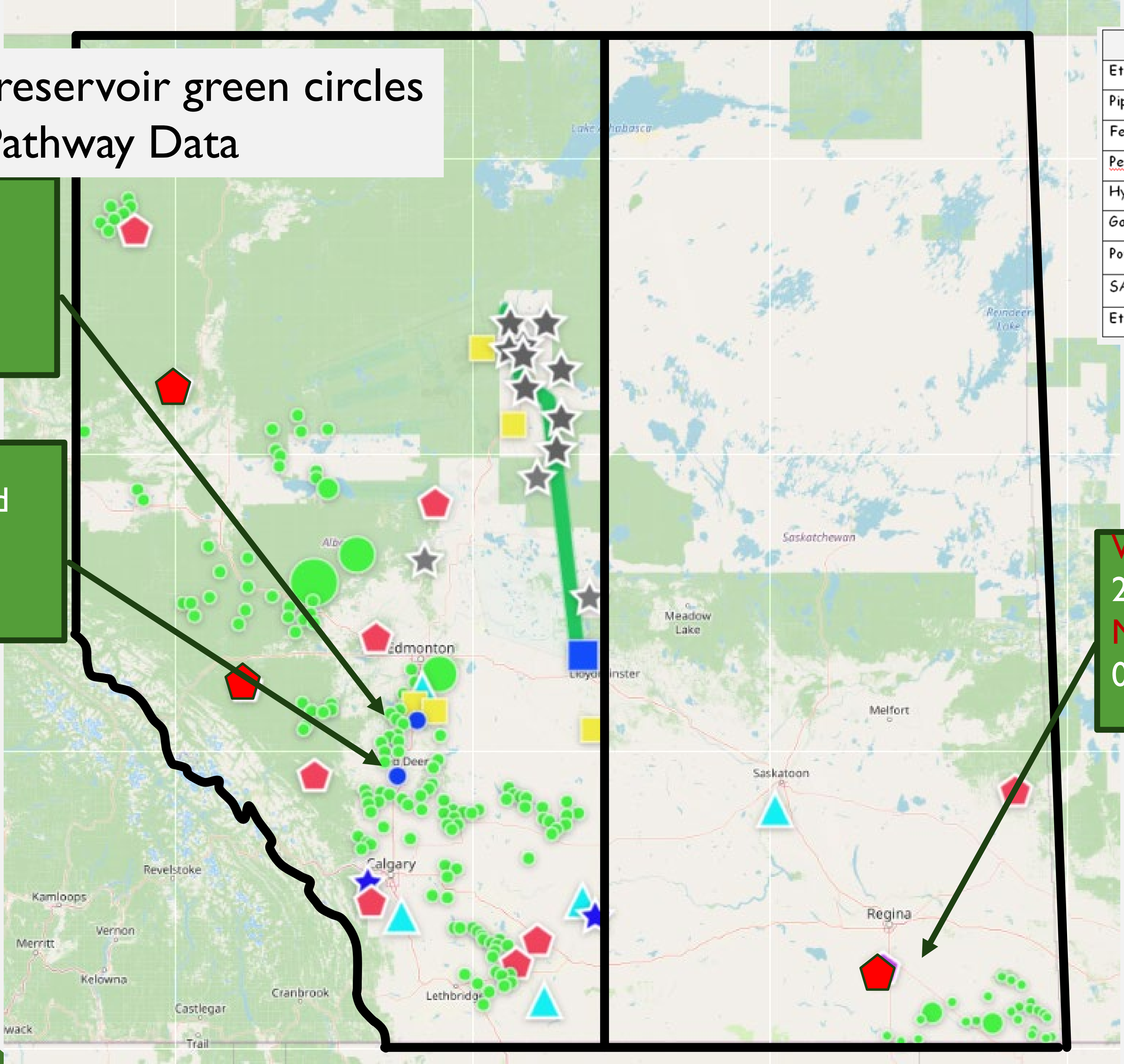
CO_2 Situation in Canada and US

EOR screened reservoir green circles Updated with Pathway Data

Clive 5.5Mtonnes,
1.5 Mt/yr ~0.780 bbl/d

Joffre 1.5Mtonnes,
0.02 Mt/yr ~0.600 bbl/d
Chigwell 1.6 Mtonne
0.2 Mt/yr no oil rate



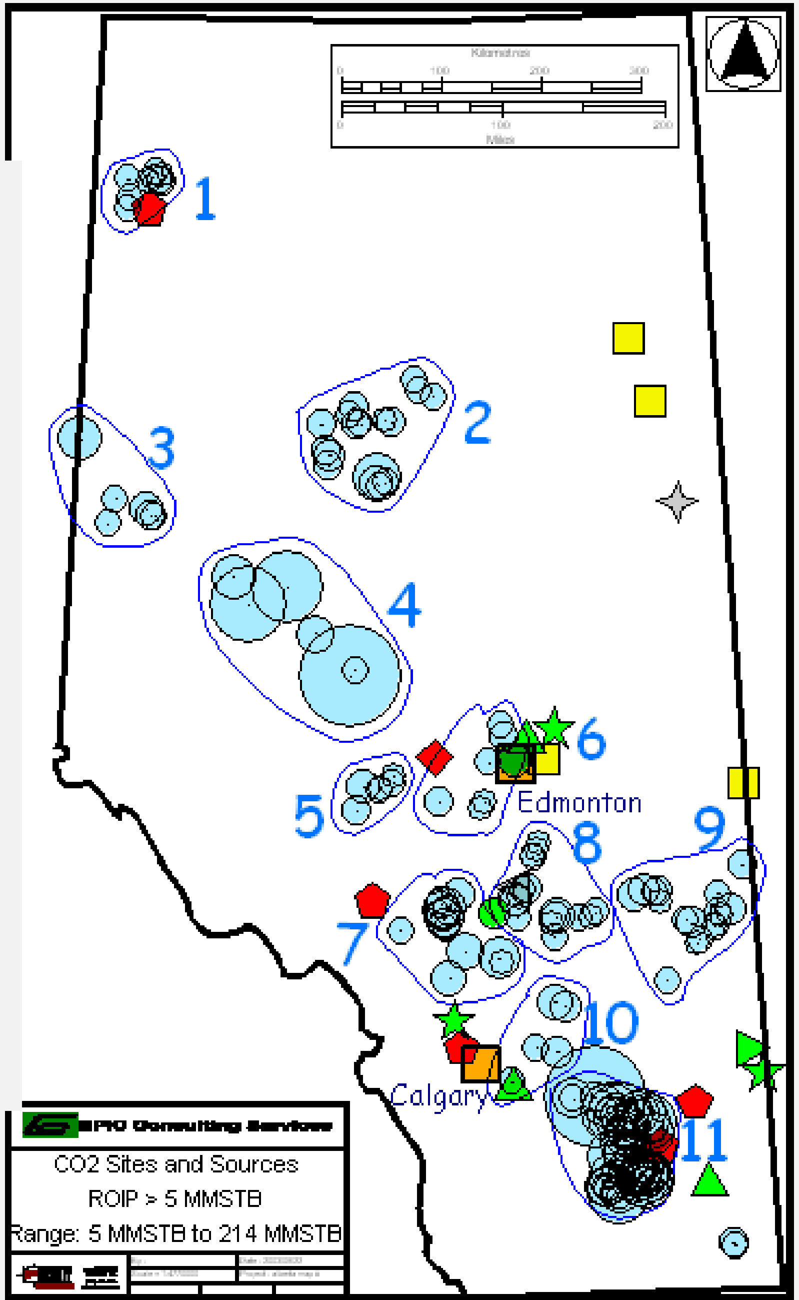
CO_2 Source	Symbol	Purity
Ethane processing	★	97
Pipelines	▷	97
Fertilizer plant	△	95 - 99
Petro-chemical plant	●	90 - 97
Hydrogen	□	40 - 46
Gas plant	⬟	30 - 40+
Power plant	◆	17 - 99
SAGD operation	✧	?
Ethanol production	◁	?

Weyburn 40Mtonnes,
2 Mt/yr ~18,000 bbl/d
Midale 5 Mtonne
0.2 Mt/yr 2-5000 bbl/d

● Oil target

Infrastructures: CO2 Sites & Sources

From 2007 Epic Presentation Circles Oil Reservoirs OOIP



Background Only

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SAGD operation	✦	?
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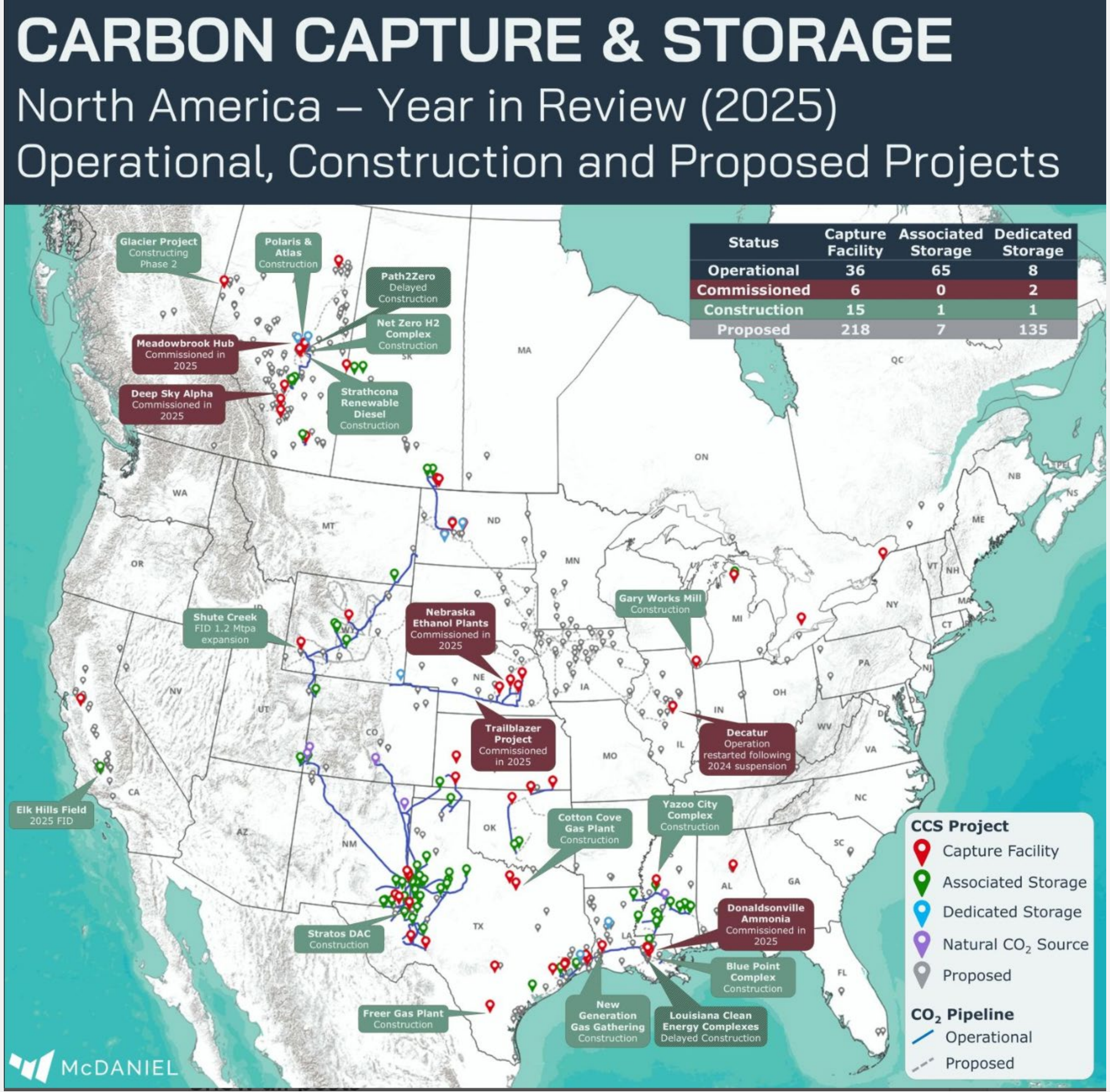
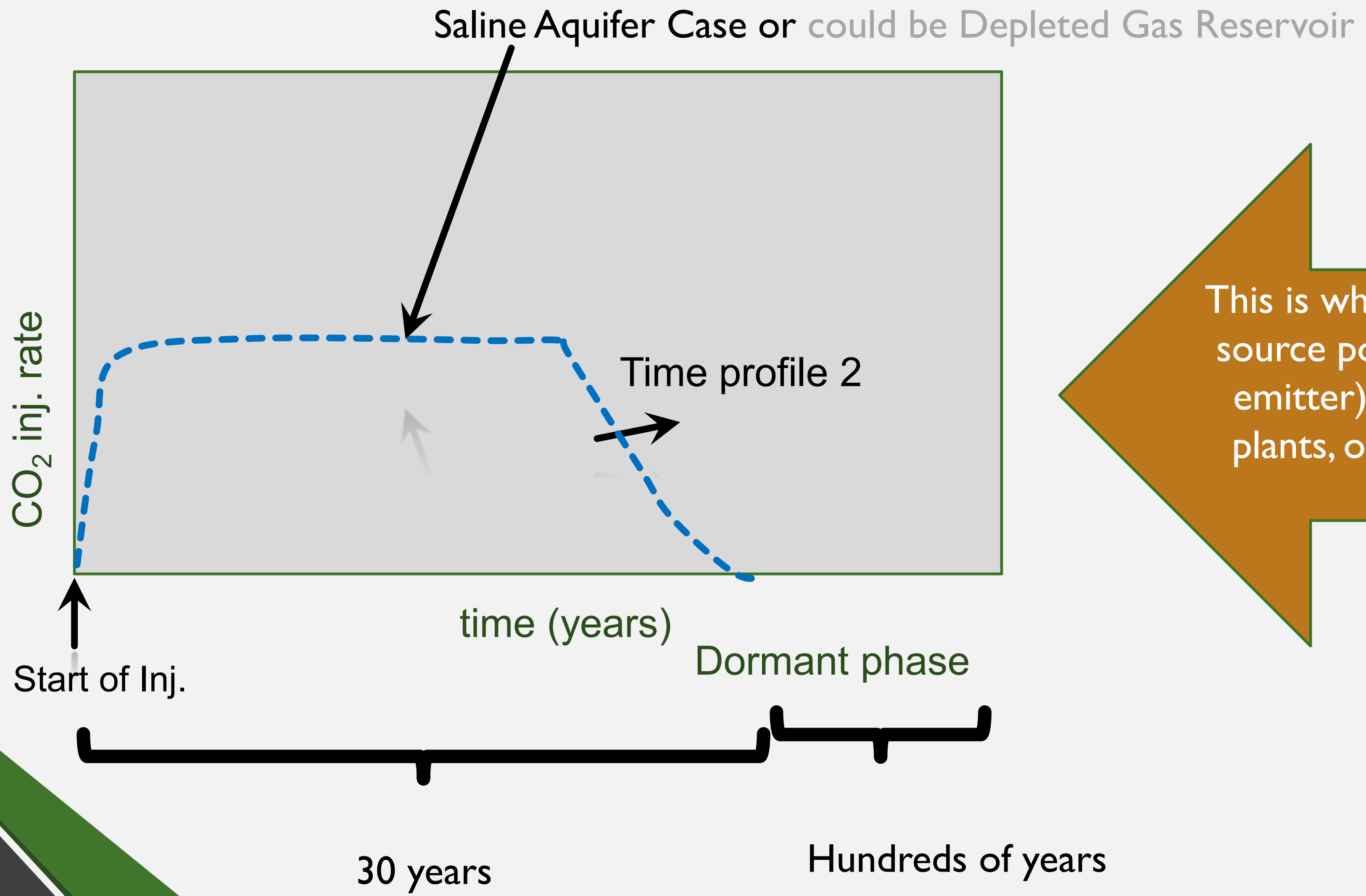
McDaniel's CCS Map



Background for EOR: CO_2 utilization, CCUS (miscible flood, EOR) vs CCS Aquifer Injection

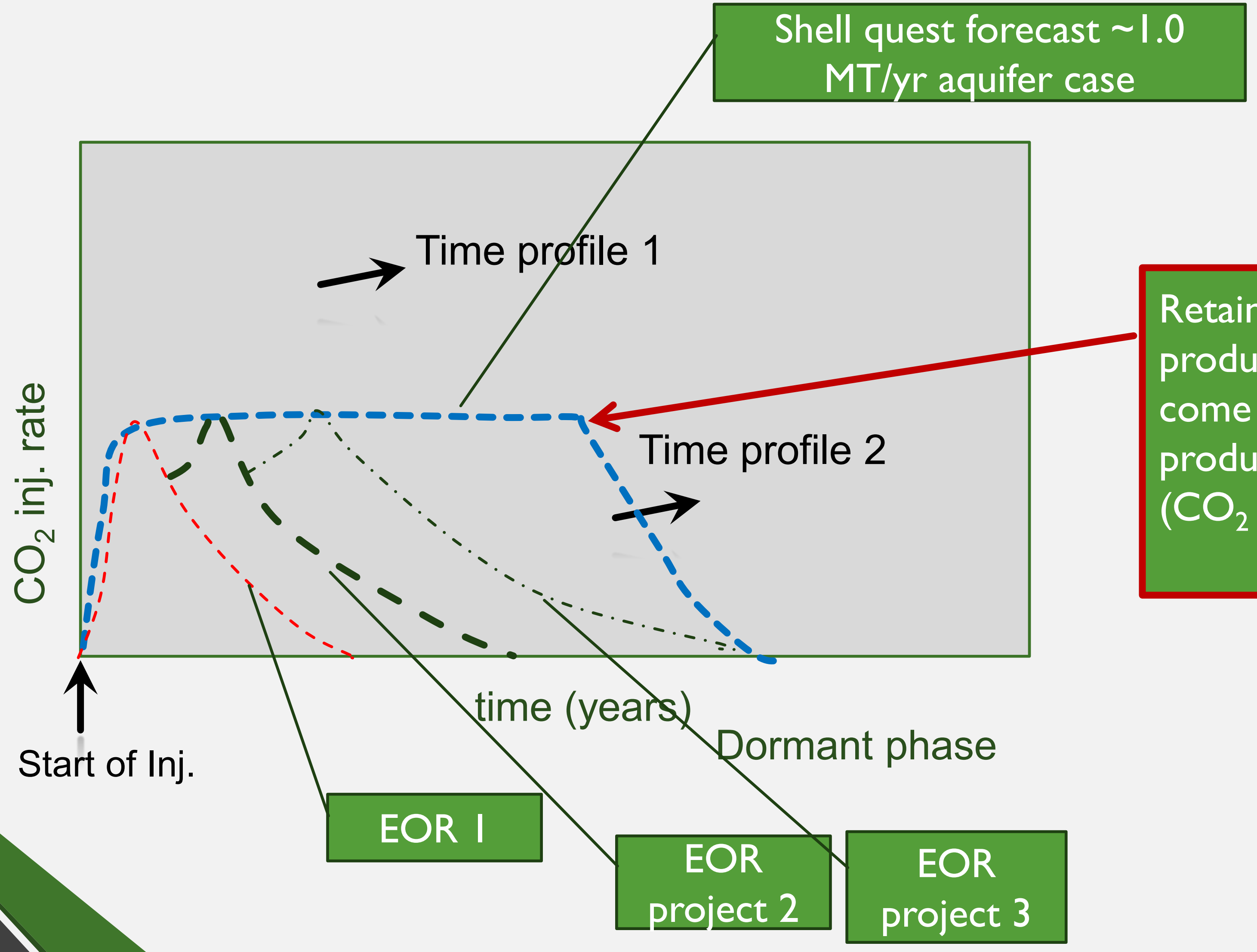
Plateau Injection rates are important to Emitters

- In order to get a realistic time profile (need plateau) {like a gas field development}:



This is what we want from a source point of view (CO2 emitter): fertilizer, power plants, oil sands upgrader etc,

Important to Load Level: Need to Aggregate CO2 Miscible Projects



Retained CO_2 = {total CO_2 injected – produced CO_2} thus new patterns come on to maintain plateau: produced CO_2 ~ Number of patterns (CO_2 injected/pattern) constant

Economics of CCS/CCUS: how much benefit does EOR bring?

Richard Baker November 8 2023

BRE Group

Objective of Model

- **Compare:** Saline Aquifer (CCS) vs. (EOR) CO_2 miscible flood (CCUS)
- *the model is similar to the cash flow analysis to a hypothetical joint venture company composed of CO2 Capture, CO2 transport, and CO2-EOR firm. {Vertical Integrated Company vs. partnership}*
  - Thus, we assume that the firm either has sufficient taxable earnings to claim the full value of the tax credit, or that tax credits are transferable.
- The purpose of the analysis is to determine the overall cash flow to the system, and as a result, we model the entire system as a single unit
  - *Reservoir is ~273 MMbbl reservoir*

Executive Summary for Economics of CCS/CCUS: how much benefit does EOR bring?

1. CCUS (EOR) case has Net Present Value@10% of 1300 MM$, Internal Rate of Return of 29.6%, and Pay out 7 years for 100% of Carbon Tax "revenue" (80USD $/bbl, CO_2 ta=130$/tonne)
2. Saline aquifer has Net Present Value of 233 MM$ Internal Rate of Return of 13.3 %, and Pay out 15 years for 100% of Carbon Tax "revenue"
3. The **real advantage** of EOR is that it dramatically improves the robustness (anti-fragility)*** of the hub

BRE Group

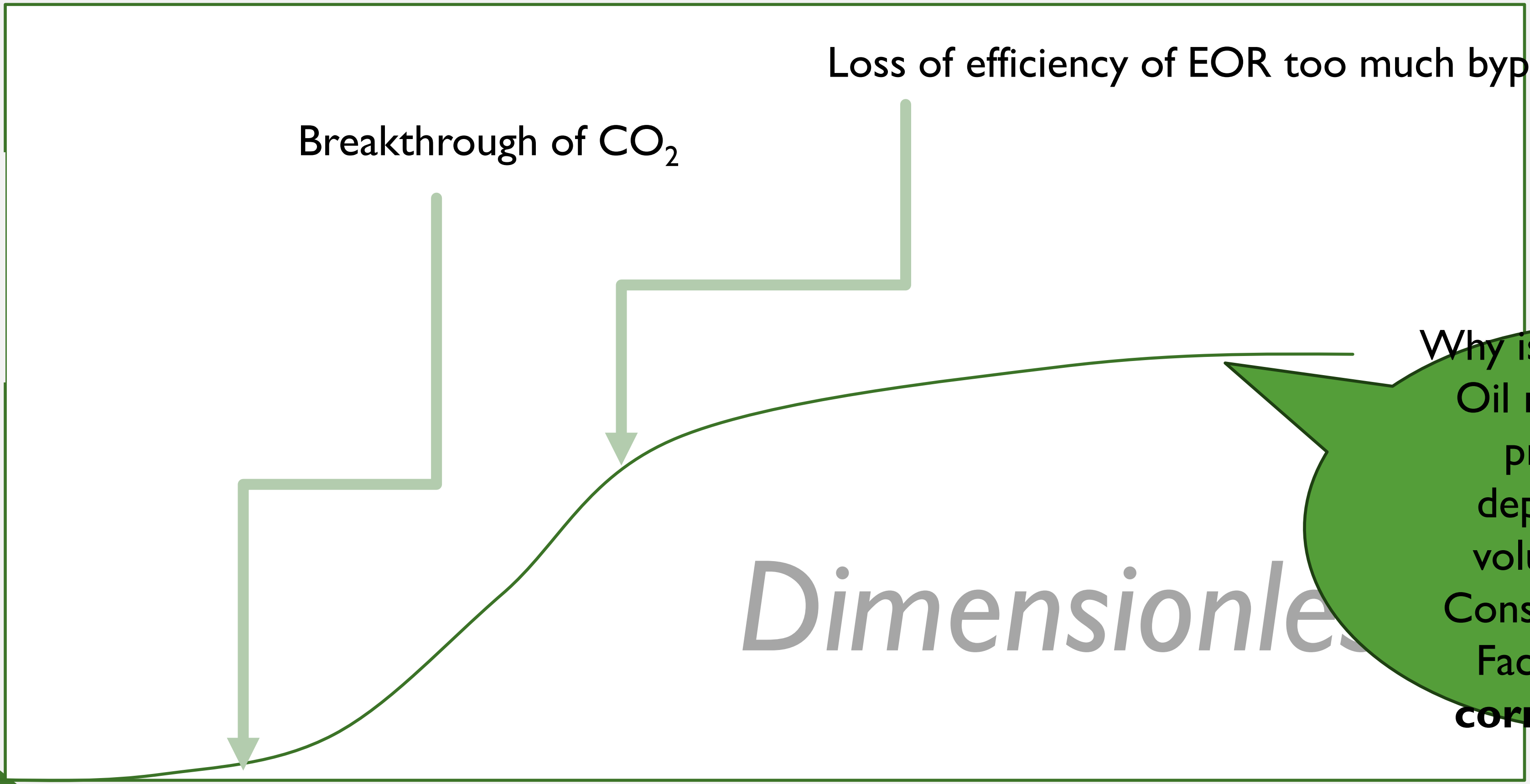
*** **Antifragile: Things That Gain from Disorder, Taleb 2014**
*** **utube video antifragility taleb + Kahneman**

Technical Data (methodology)

How do we get our oil + CO_2 production forecast?

By Analogy

Typical CO2 Incremental Recovery vs. HCPVI (CO_2 only)

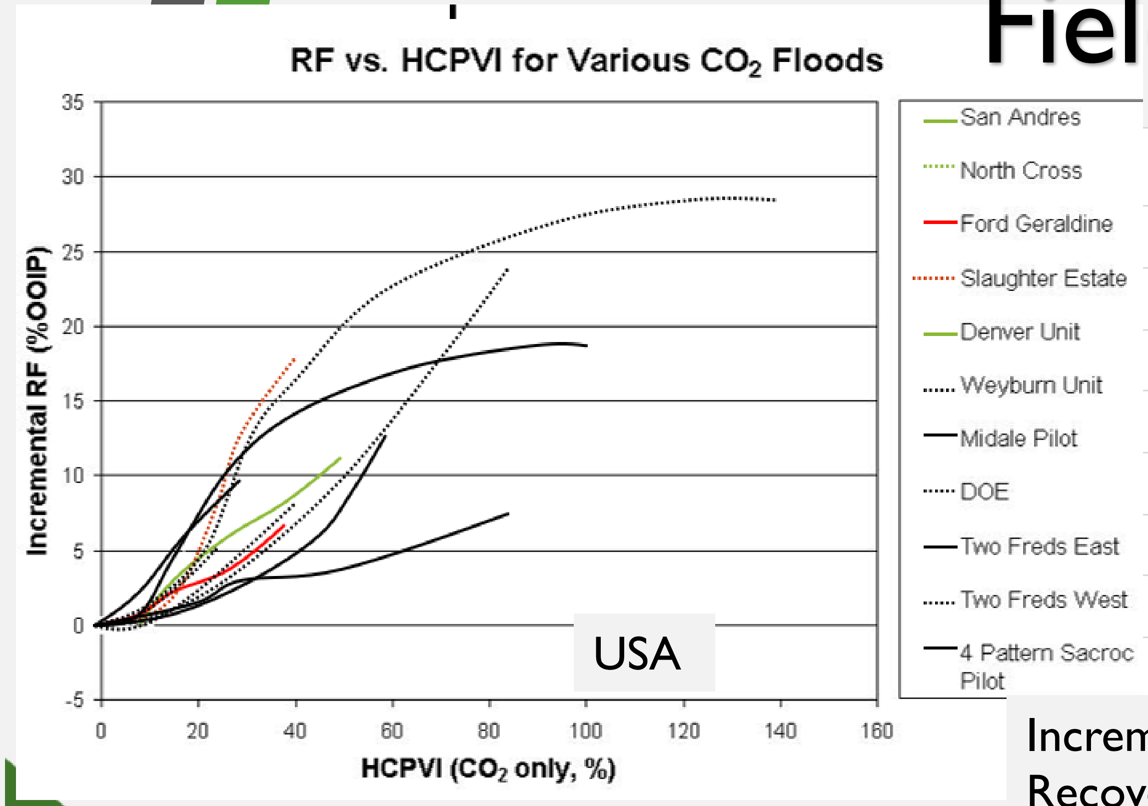


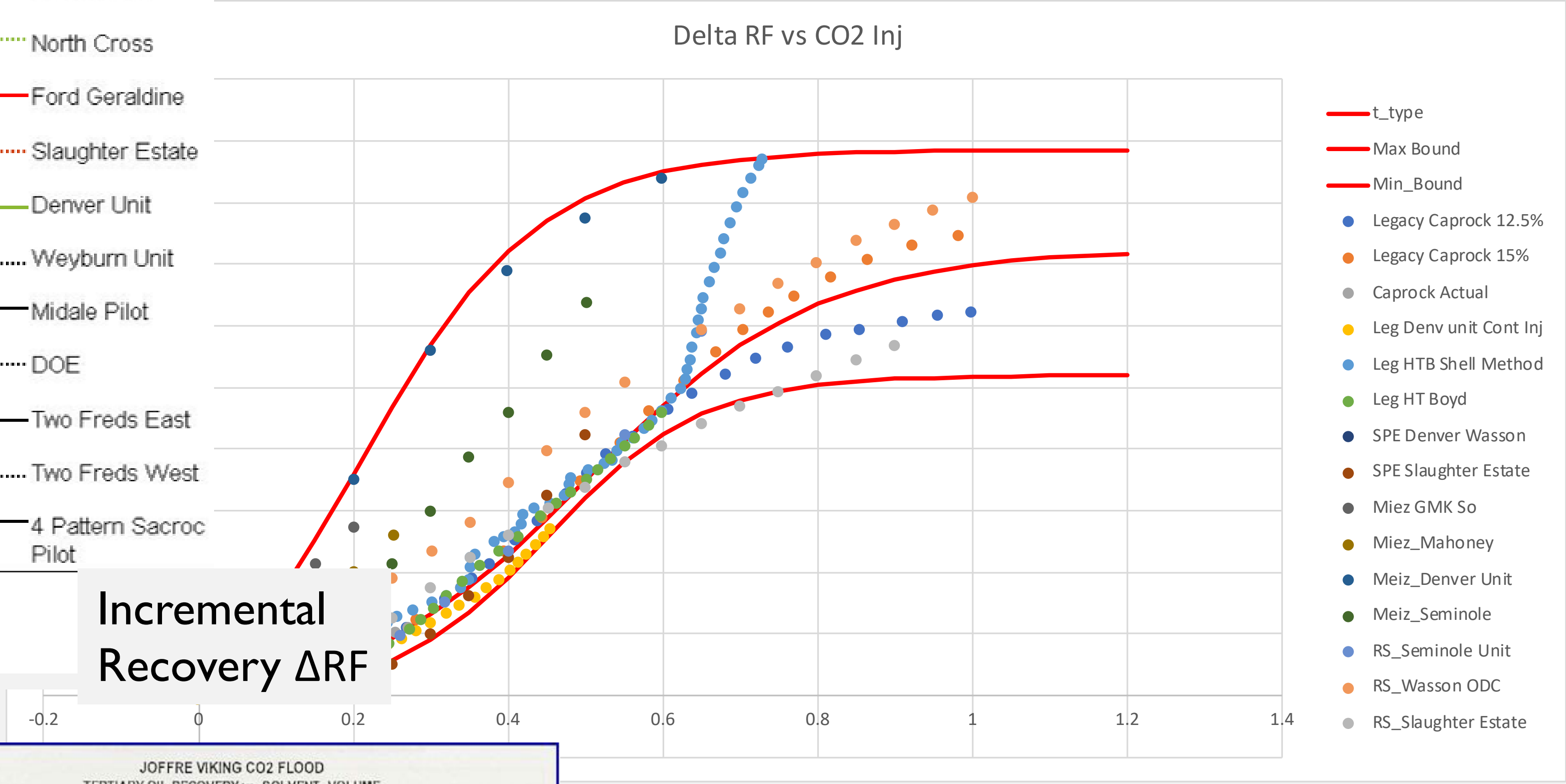
Incremental Recovery ΔRF

Why is this important? Oil rates and CO2 production is dependent upon volumes injected Constant Utilization Factors **are not correct** for timing

Hydro-Carbon Pore Volume {HCPVI} (CO_2 only)

Field Performance 30 projects





Incremental Recovery ΔRF

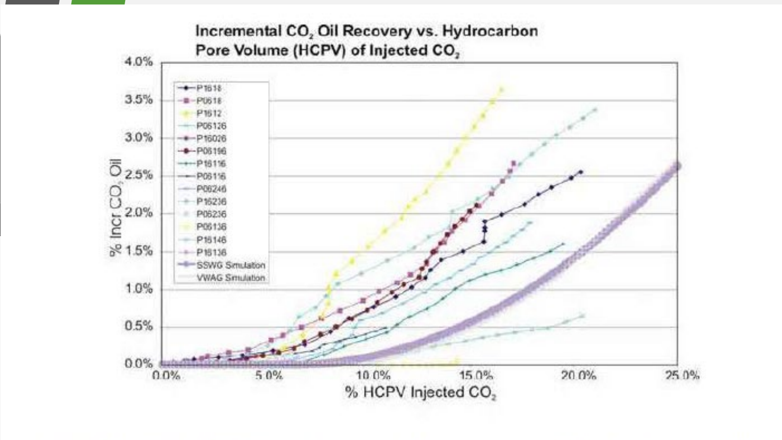
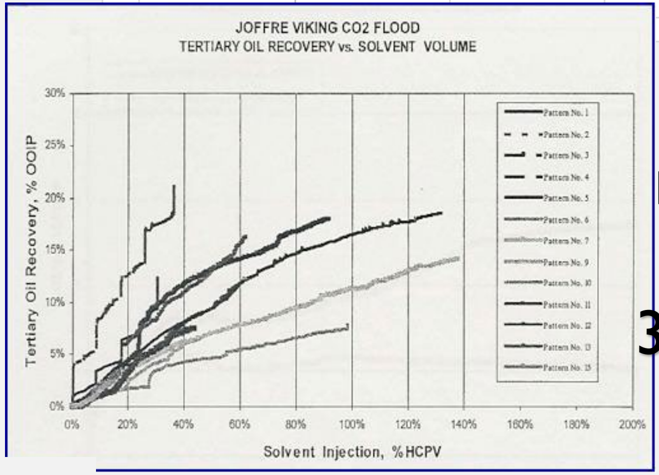


Figure 2.33: Phase 1A performance. Incremental oil production vs. CO_2 injection by production well.

Weyburn

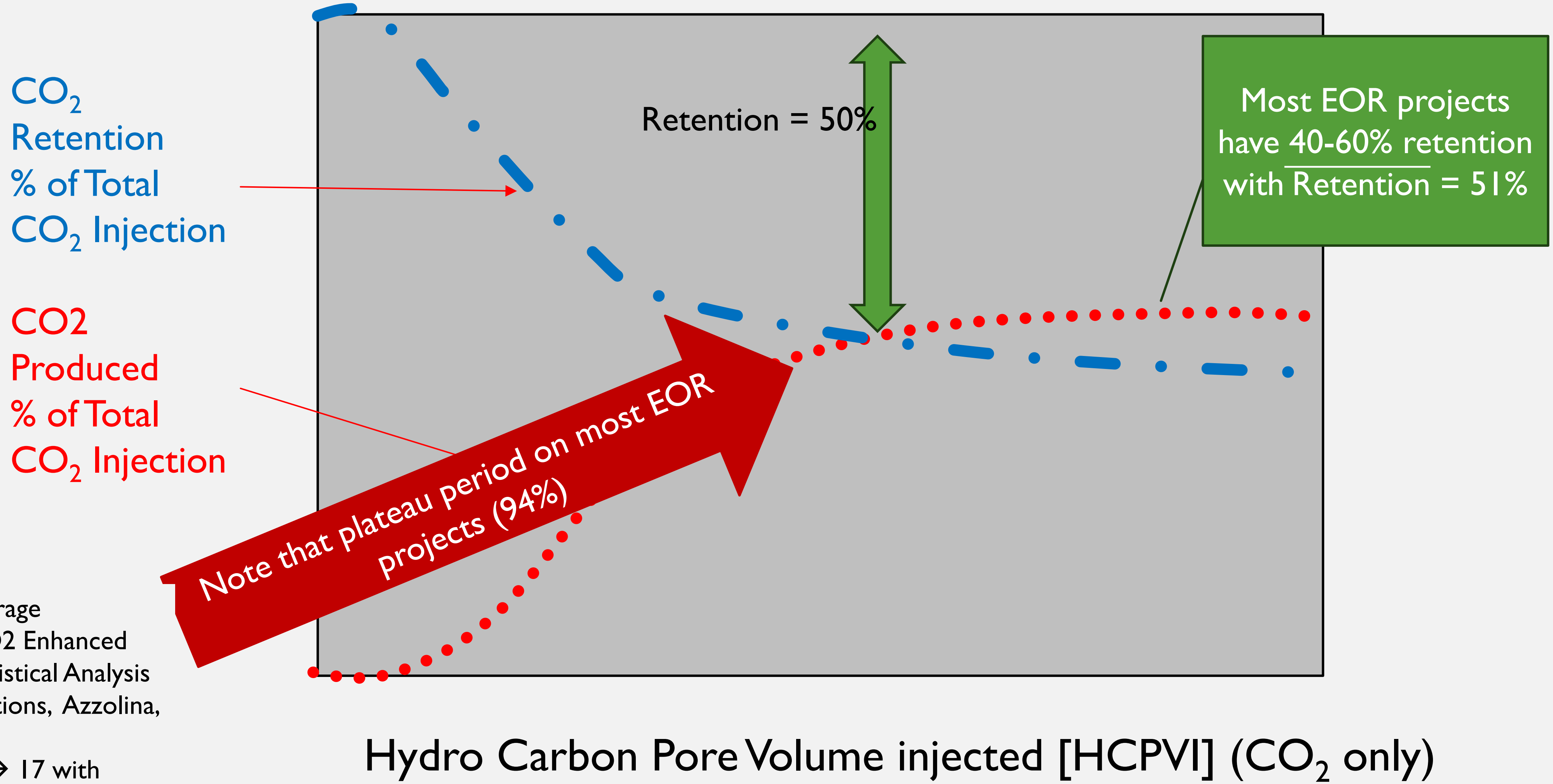


Joffre

Hydro-Carbon Pore Volume {HCPVI} (CO_2 only)

30 projects = USA + Cdn CO_2 Floods

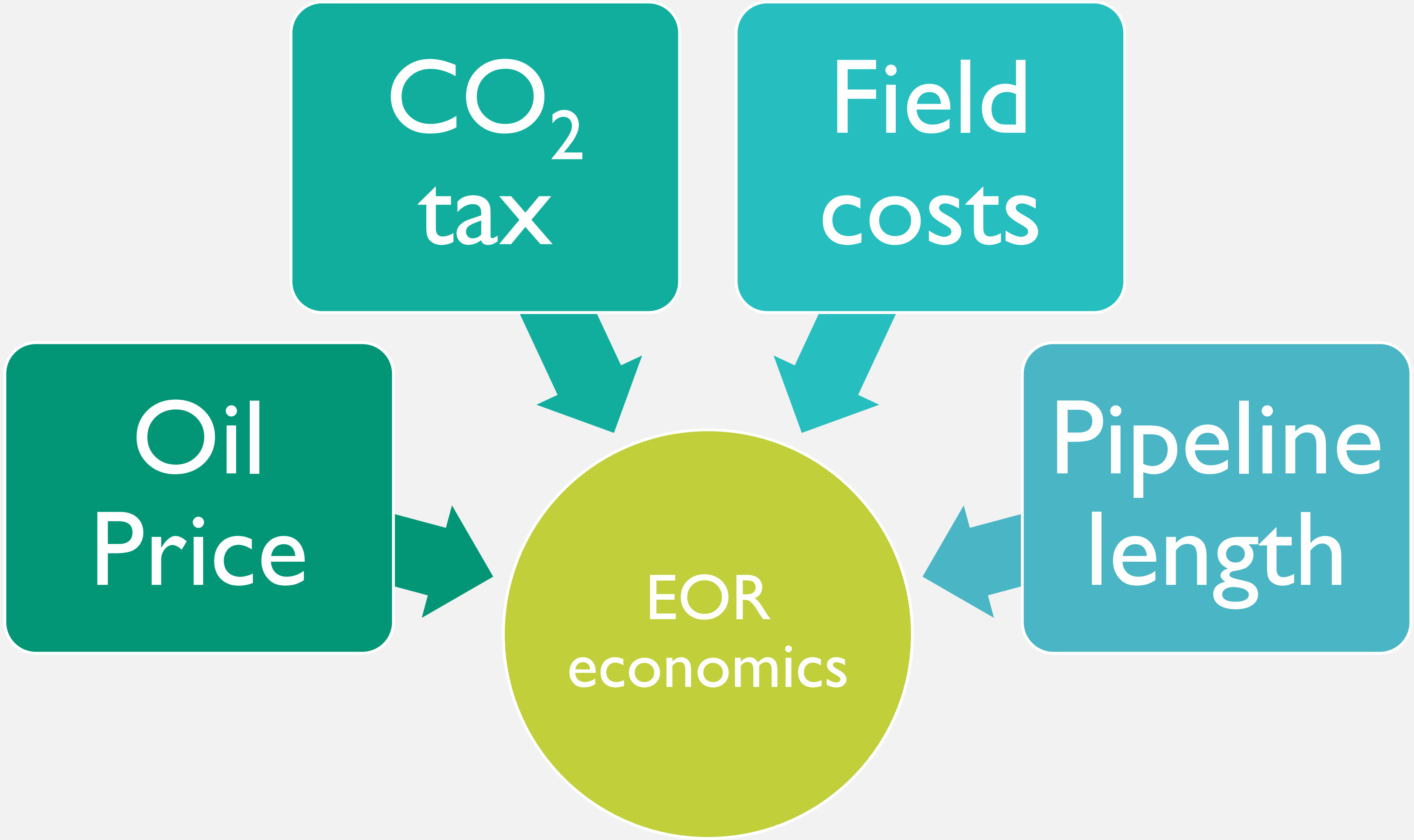
Need to know how much recycle CO2 there is:

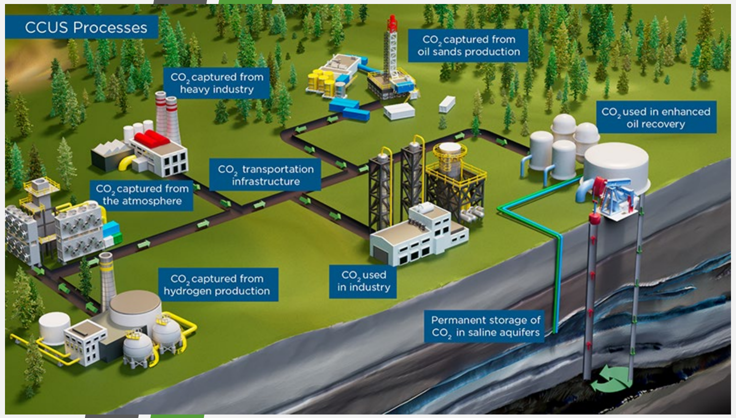


Reference: CO_2 Storage Associated with CO2 Enhanced Oil Recovery, A Statistical Analysis of Historical Operations, Azzolina, Melzer 2015
→ 27 CO2 floods → 17 with CO2 prodn data

Economic Data (assumptions)

What Controls the EOR (CCUS)





CO_2 Flood Economic Parameters

Recycle Plant Capital and Operating, Produced volumes, composition

No separation plant: CO2 and NGL

Pipeline Capital and Operating, Distance/size

Is this reservoir a good CO_2 flood candidate?

Oil Production + CO_2 Profile Function of: Utilization Factor, Reservoir, Number of Patterns, Slug Size, Heterogeneity

Cost of CO_2

Purity, amount, pressure

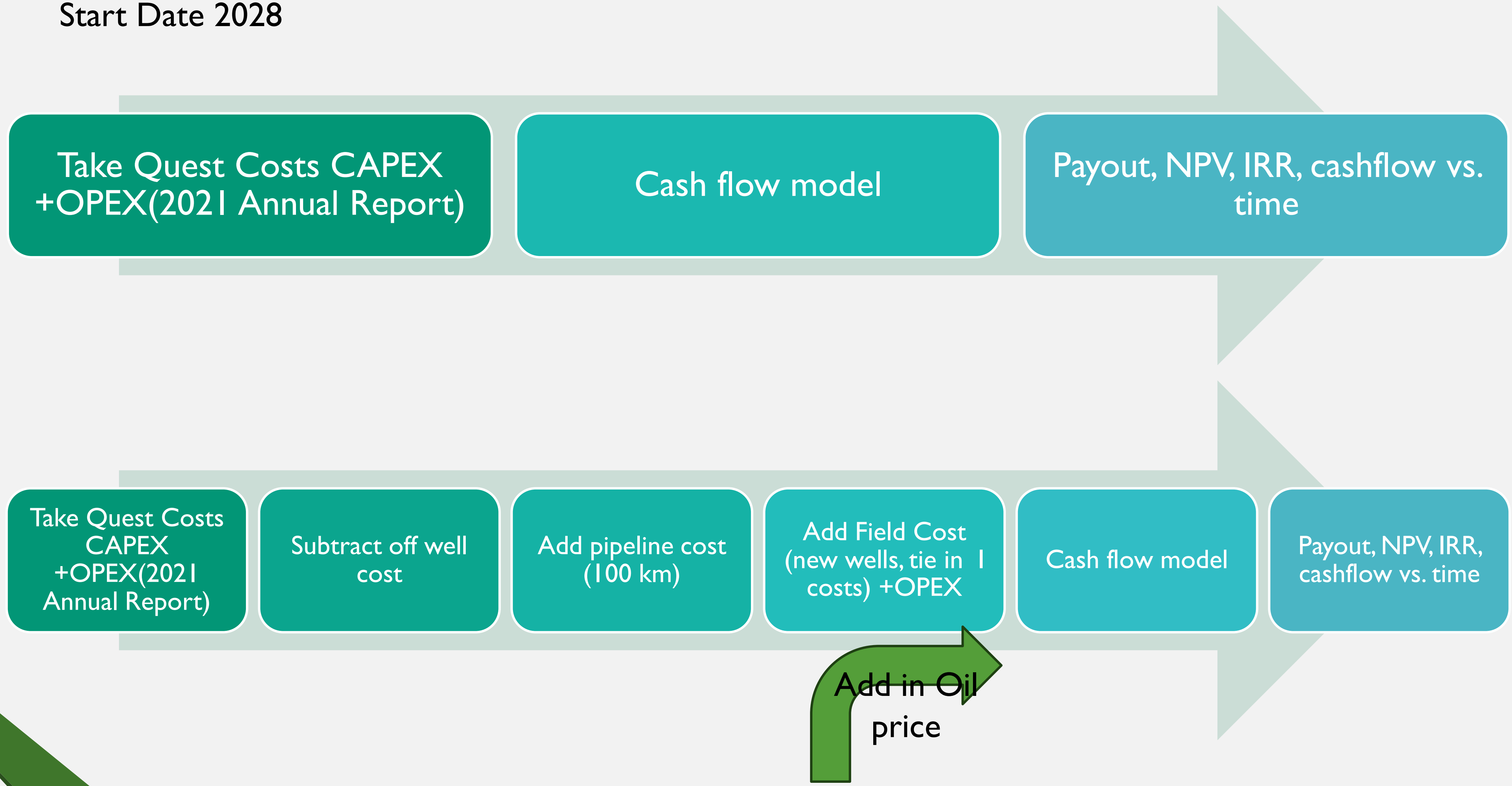
Cost of Implementation

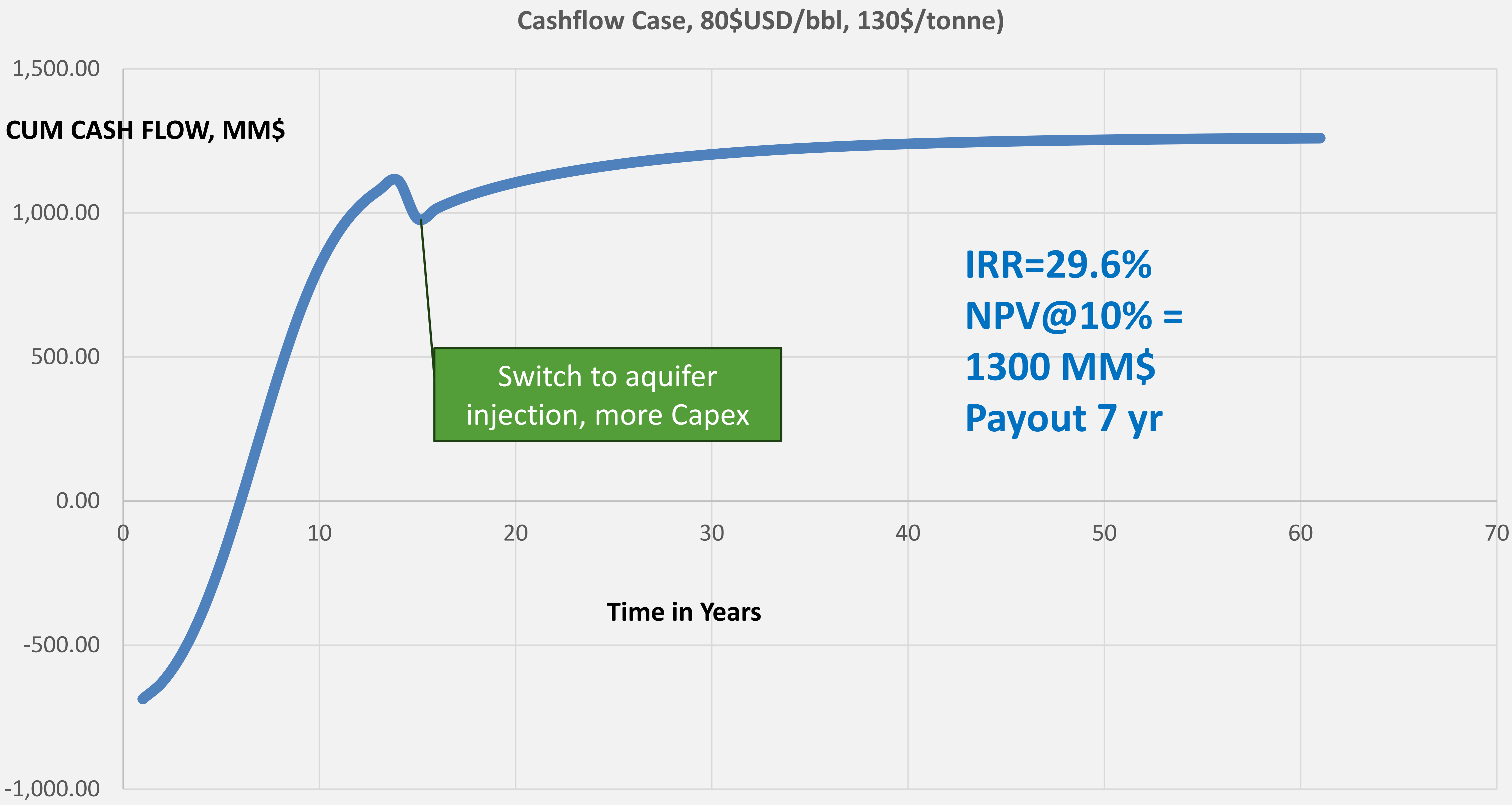
Drilling New Wells if Required, Installing Equipment, etc.

100km pipeline
EOR project buys plant → no CO2 purchase price
Royalty Flat 5%Alberta

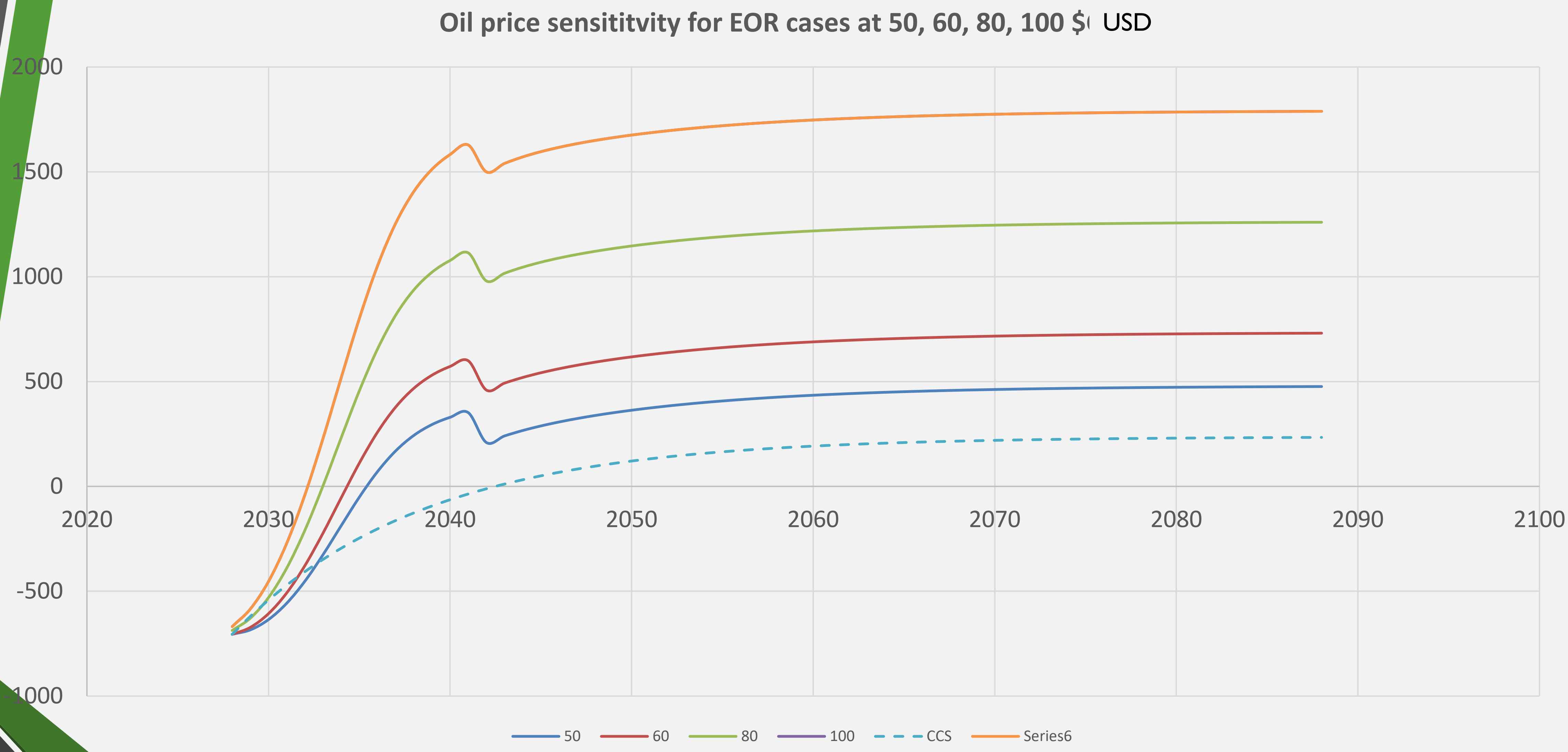
CO_2 Flood Economic Data Flow

Start Date 2028




Cashflow Case, 80$USD/bbl, 130$/tonne)
CUM CASH FLOW, MM$
1,500.00
1,000.00
500.00
0.00
-500.00
-1,000.00
0
10
20
30
40
50
60
70
Time in Years
Switch to aquifer injection, more Capex
IRR=29.6%
NPV@10% =
1300 MM$
Payout 7 yr

Cashflows



Oil price sensititvity for EOR cases at 50, 60, 80, 100 $(USD
2000
1500
1000
500
0
-500
-1000
2020
2030
2040
2050
2060
2070
2080
2090
2100
50
60
80
100
CCS
Series6

Conclusions

case	NPV@10	ROR	Payout (years)	Percentage of Carbon tax as revenue
EOR (CCUS) @80USD $/bbl	1300	29.6	7	100% @130$tonne
Saline Aquifer (CCS)	160	19	15	100% @130$tonne

- EOR dramatically improves CO2 storage effects 7 year payout vs. 13 Payout
- Multiple inputs and outputs and existing infrastructure improves stability and unlocks system growth
  - Example Railroads, St. Lawrence Seaway, Oil sand infrastructure

Conclusions: Improves Stability of System

Optionality (flexibility) for EOR

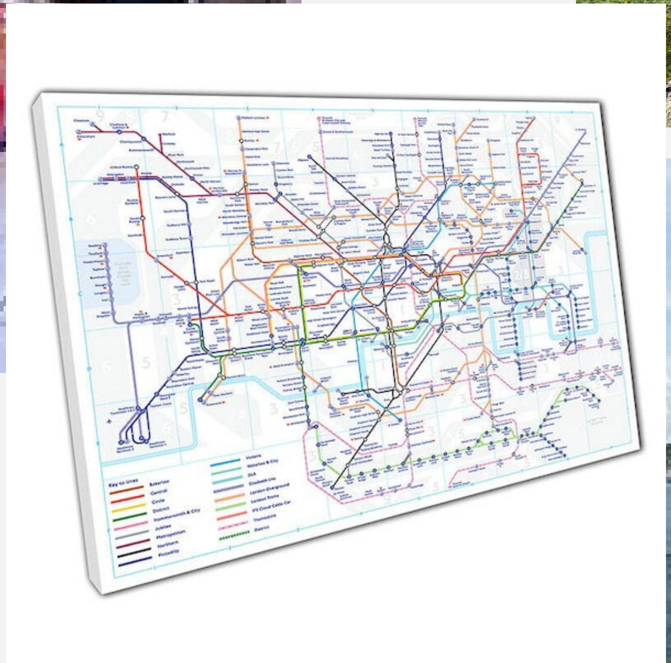
One leg table

Very Fragile system because of one source of revenue, depends upon politics

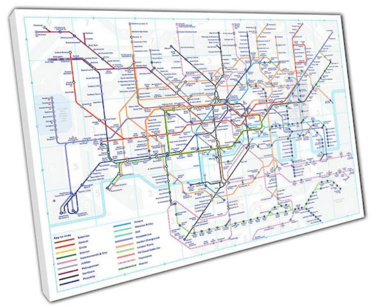
Sask Power

- Timing of EOR projects starting
- Timing of patterns rolling out
- Water Alternating Gas (WAG)
- Straight CO2 injection without production

Explanation Why Systems thinking is Pivotal



Explanation Why Systems thinking is Pivotal



- Enhanced Oil Recovery (EOR/CCUS) is analogous to the London Underground because the true value comes from **network effects and long-lived optionality**, not from a single project's early cash flow. If you had to rebuild the Tube today, the capital intensity and disruption would imply a long payback—yet the Underground has delivered outsized returns for more than a century because it created a stable, expandable platform. Once the **CCS/CCUS backbone** exists, each new station, connection, or upgrade has a much better return because it plugs into an already functioning system.
- EOR/CCUS works the same way for industrial decarbonization and energy security:
- **Backbone first, then cheap expansion.** A CO_2 trunkline, compression, and injection capacity are like the Tube's tunnels and core lines. After that, adding new emitters (capture sources) or new storage sites becomes progressively cheaper and faster—tie-ins instead of greenfield builds.
- **Lower "cost of entry" through reuse.** EOR/CCUS leverages existing wells, reservoirs with proven containment characteristics, established operating practices, rights-of-way, and experienced service supply chains. That reuse materially reduces capital, schedule risk, and "first-of-a-kind" uncertainty.

Explanation Why Systems thinking is Pivotal

- **Faster payout by creating early revenue and learning.** EOR can generate near-term cash flow from incremental oil while simultaneously building CO_2 transport and injection capability that later supports pure storage at scale. Even when EOR isn't the endpoint, it can function as the "early ridership" that helps finance and de-risk the network.
- **Stability through standardization.** Like mature rail systems, mature CO_2 and oilfield networks become predictable: standardized designs, repeatable permitting, known operating envelopes, and institutional know-how. That stability is exactly what enables large, long-duration investment—think oil sands infrastructure, the CO_2 pipeline web in the Permian, or offshore hub developments where shared infrastructure drives down costs.
- So the core message is: ***EOR/CCUS is not just a project—it's an infrastructure platform*.** The first builds look expensive and slow to pay back, but once the backbone exists, the network compounds value and improves payout time for every subsequent expansion.

Summary

Summary

- <u>Chemical EOR</u>
  - Polymer injection is a proven method for wide range of conditions (T, viscosity, TDS)
  - SP/ASP not as mature, can be challenging in spite of successes
  - Chemical EOR reduces carbon emissions over waterflood
- <u>CO2 EOR:</u>
  - Established technology;
  - < 400kbbls/d produced today in North America from EOR
- <u>Foam and Nanoparticles</u>
  - Improves CO2 injection sweep; higher recovery with less CO2 use and recycle
- <u>Use of CO2 for EOR vs disposal – economics</u>
  - Complex inputs; existing infrastructure improves system stability and economics
  - CO2 EOR cuts payout in half @ $80/bbl oil and @ $130/mt CO2 vs CCS

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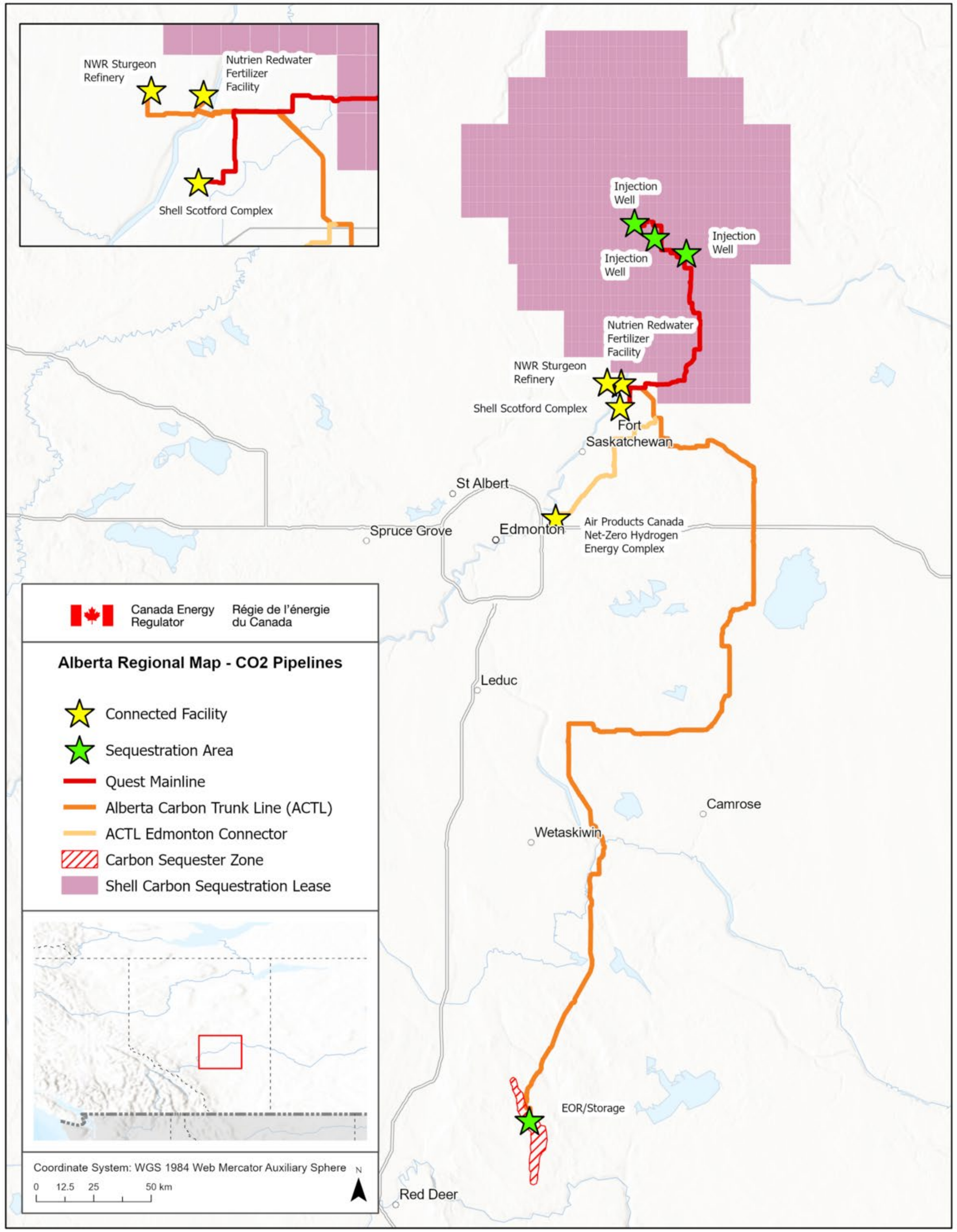

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