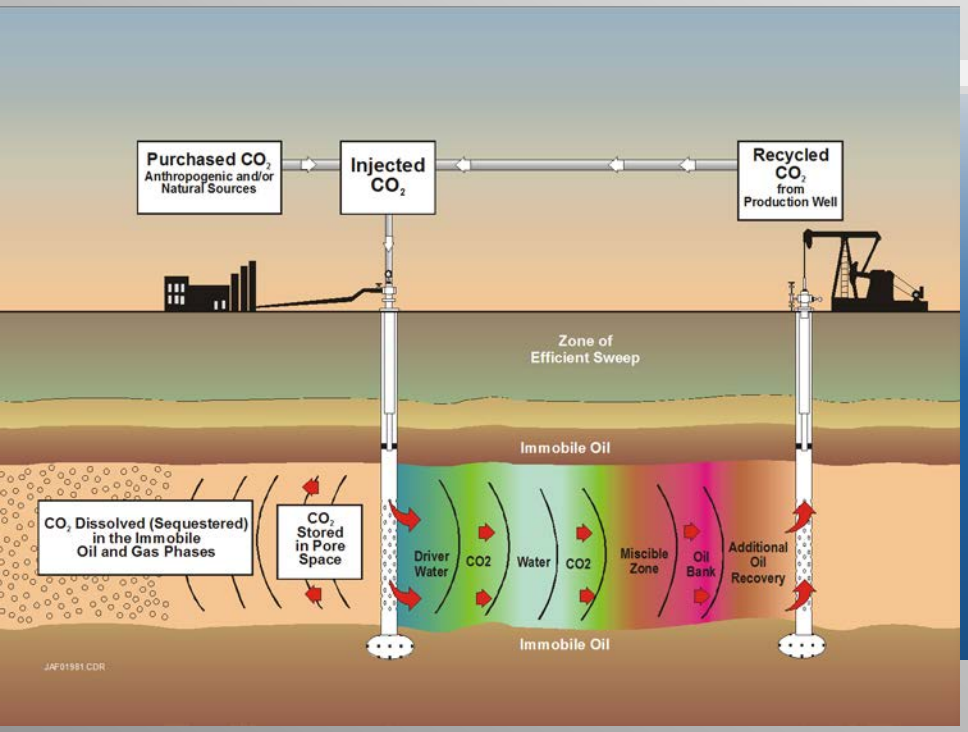

Next Generation CO_2 Enhanced Oil Recovery

Phil DiPietro

Presented at the Carbon Dioxide Utilization Congress, San Diego, California

DOE/NETL-2016/1774

February 19, 2014

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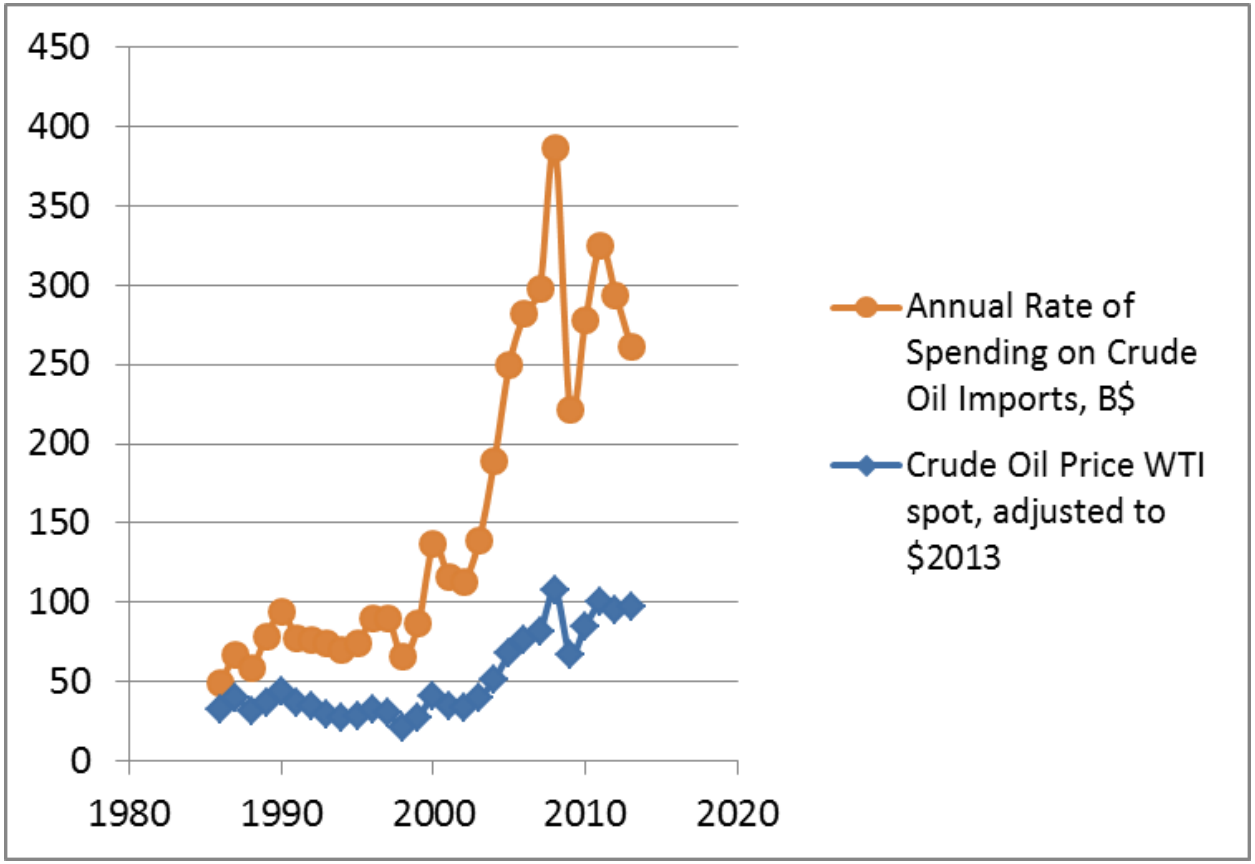
Talk Outline

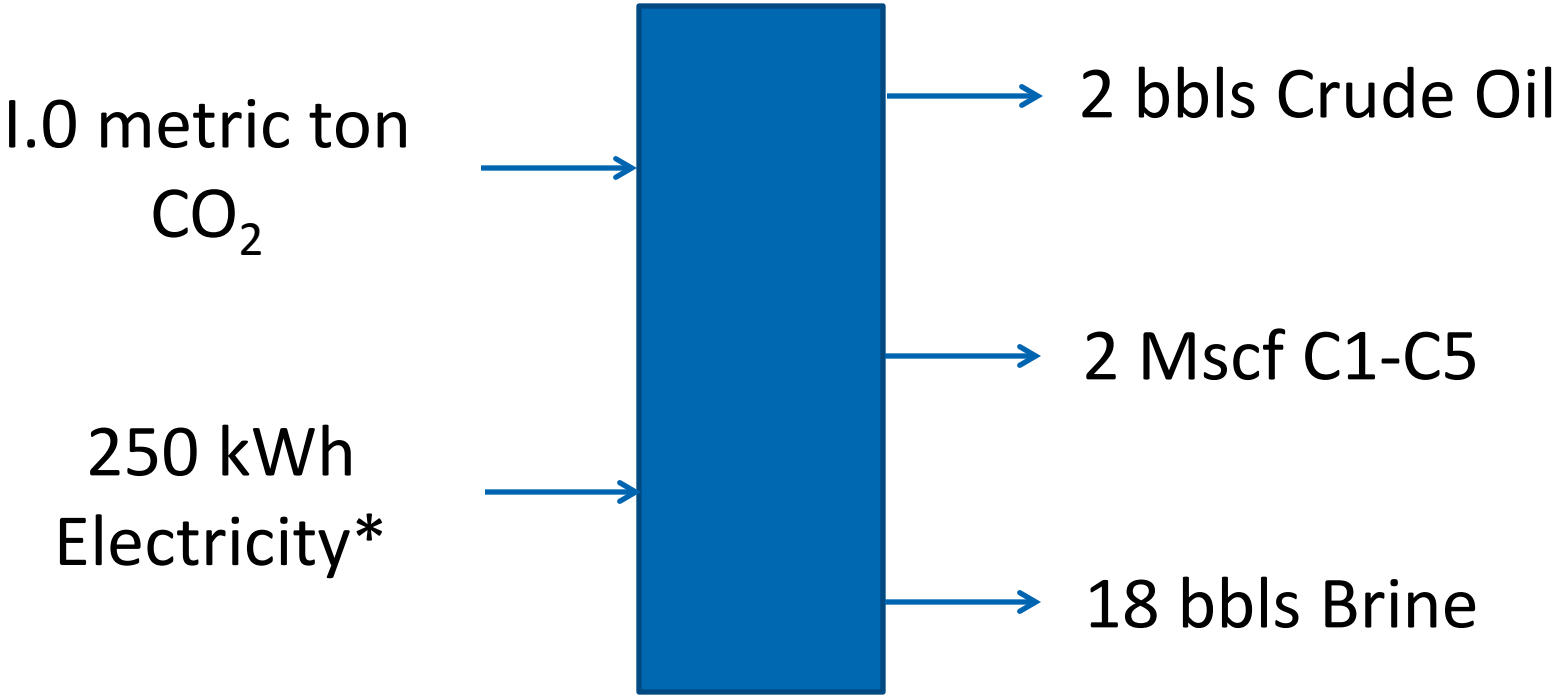
- Primer on CO_2 Enhanced Oil Recovery
- Current Status of CO_2 EOR in North America
- Next Generation CO_2 EOR Technology
- The Size of the Resource

Oil Dependency is a Drain on the U.S. Economy



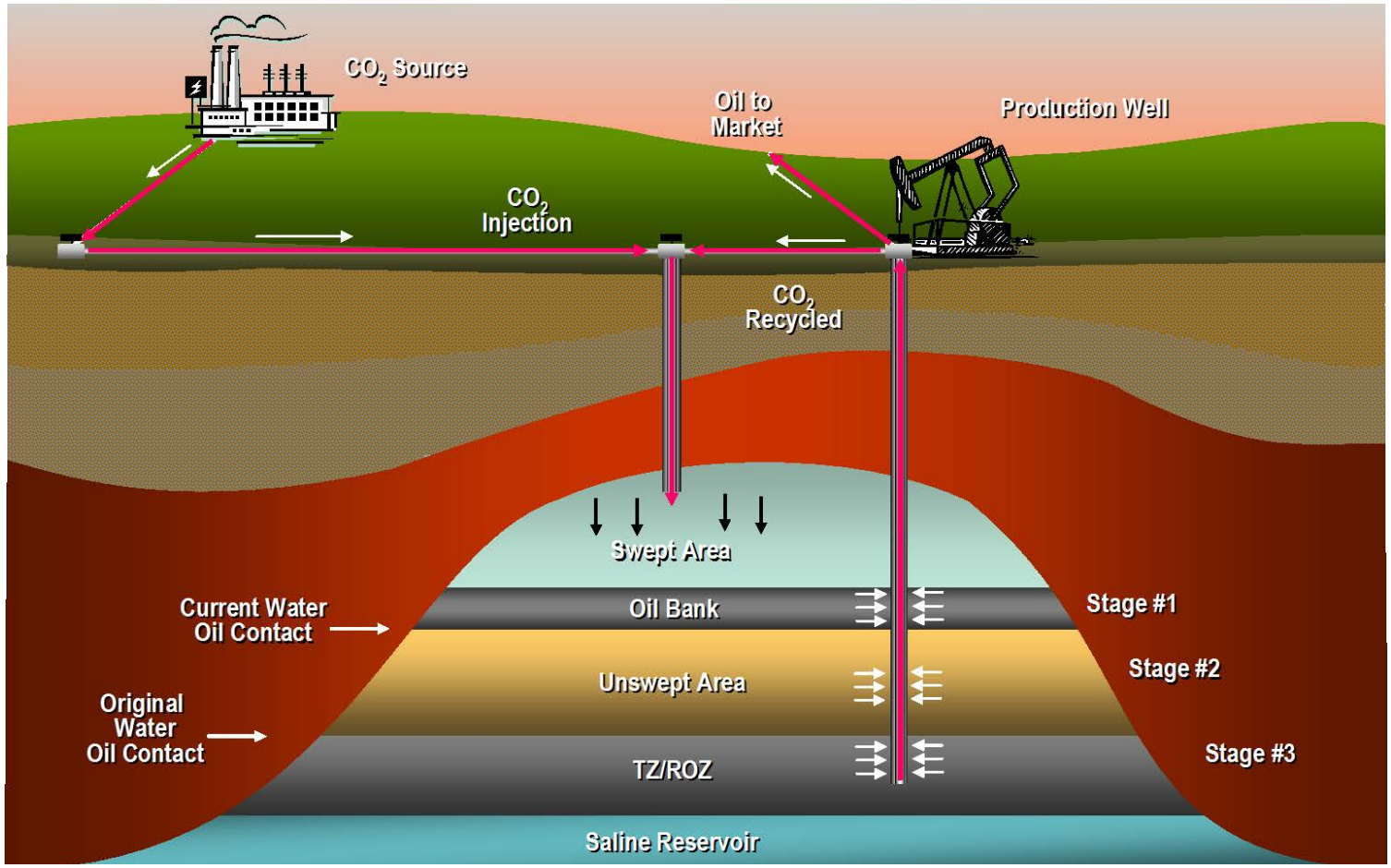
AEO2014er http://www.eia.gov/forecasts/aeo/er/index.cfm Bureau of Labor Statistics http://www.bls.gov/cpi/tables.htm

CO_2 Enhanced Oil Recovery: Simplest Terms



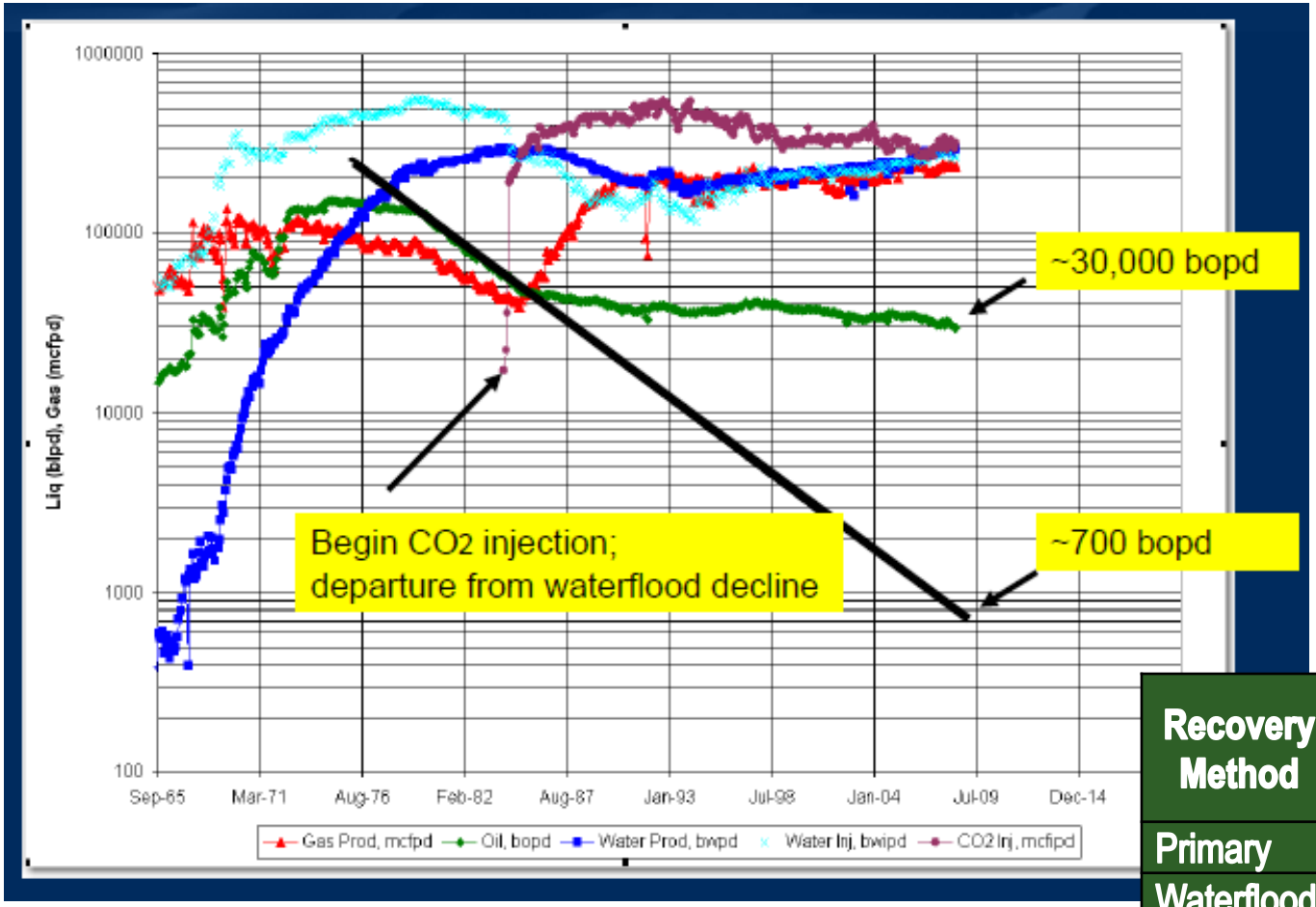
* http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Life%20Cycle%20Analysis/GtG-LCA-of-CO2-EOR.pdf

CO_2 EOR process: CO_2 is injected into an oil-bearing formation. If the pressure is high enough, it forms a miscible phase with crude oil it contacts. The phase has lower viscosity than crude oil. It also creates a small volume expansion, pressure drive. The phase is mobilized and flows to production wells. CO_2 is separated from the produced crude oil and recycled.



Source: Advanced Resources International

CO_2-EOR results from the Denver Unit of the Wasson Oil Field (Occidental Petroleum)



Recovery Method	Oil Recovery Efficiency (%OOIP)
Primary	17.2%
Waterflood	30.1%
CO2 Flood	19.5%
Total	66.8%

Source: NETL 2011 http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=391

Top CO_2 EOR Companies in the United States

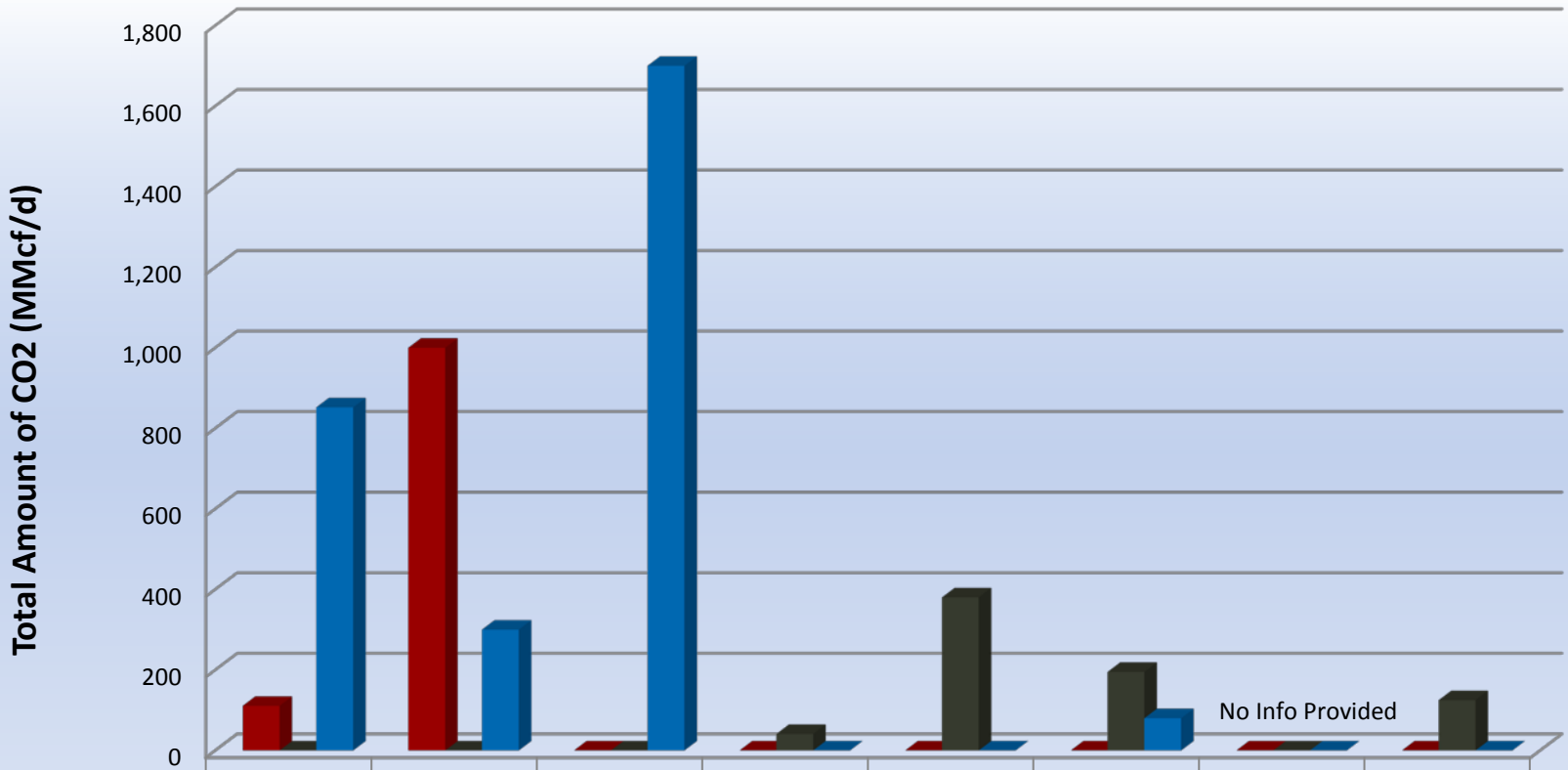
Company	2012 Crude Oil Production from CO_2 EOR (Mbbl/d)	# of Active Projects in 2012	Cumulative percent of total production from CO_2 EOR
Occidental	88.0	31	31%
Denbury Resources	39.7	22	45%
Kinder Morgan	31.6	3	56%
Chevron	24.2	7	65%
Hess	20.5	4	72%
Whiting Petroleum	20.0	4	79%
Anadarko	13.8	7	84%
Merit Energy	13.6	7	88%
Other	32.8	39	
Total	**284.2**	**124**	

Other includes: ExxonMobil, ConocoPhilips, Apache, Chaparral Energy, XTO Energy, Devon, Energen Resources, Legado, Fasken, Resolute Natural Resources, Core Energy, Great Western Drilling, Orla Petco, Stanberry Oil, and George R. Brown.

Source: Kuuskraa, V.A. July 2012. QC updates carbon dioxide projects in OGJ's enhanced oil recovery survey. Oil&Gas Journal.

Different Approaches to CO_2 Supply

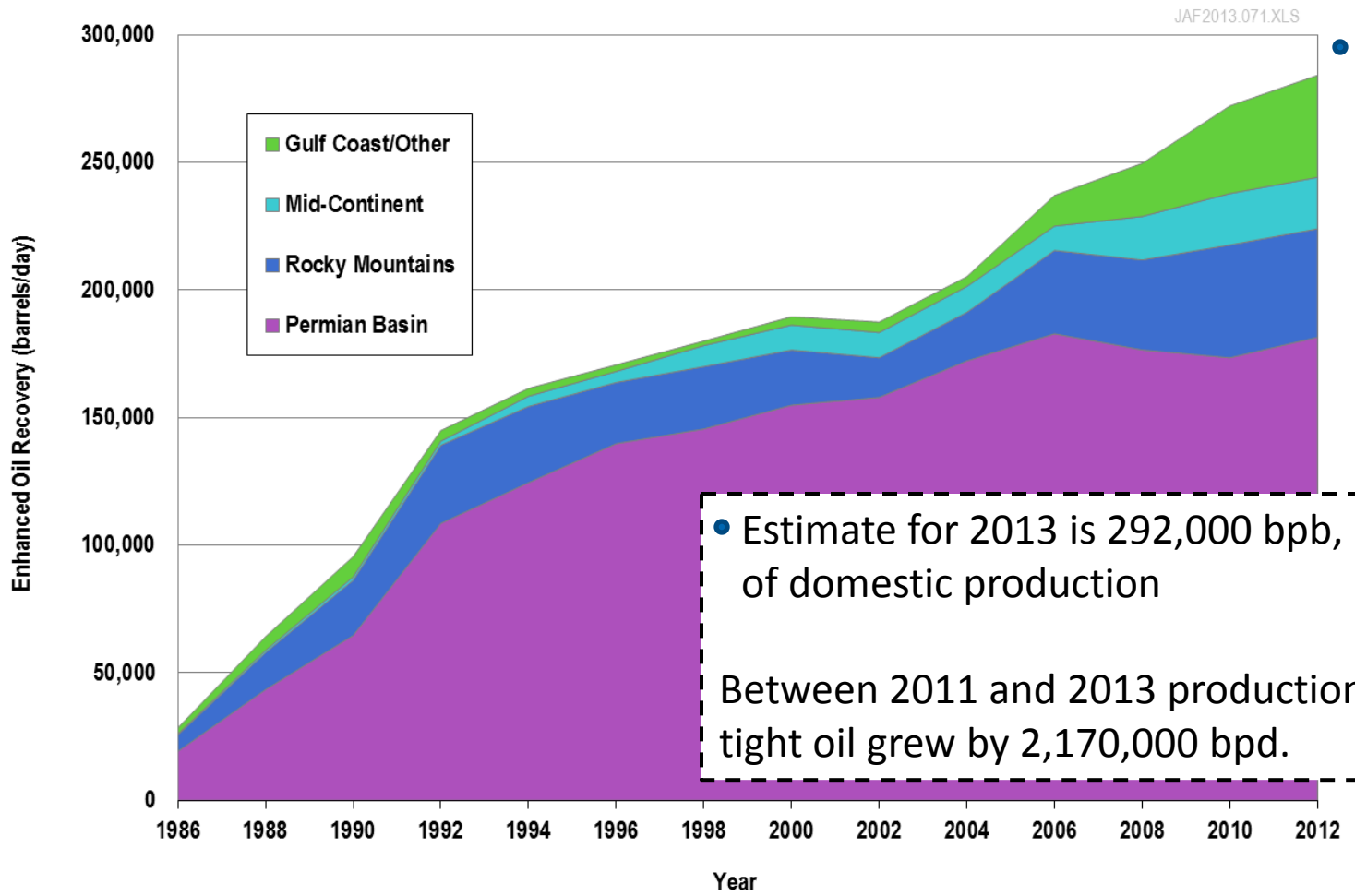
Amount Sold, Purchased, and Produced in 2010



	Denbury Resources	Kinder Morgan	Occidental Petroleum	Chaparral Energy	Whiting Petroleum	Hess Corporation	Chevron Corp.	Anadarko Petroleum
Sold to 3rd Parties	111	1,000	0	0	0	0	0	0
Purchased from 3rd Parties	0	0	0	41	380	195	0	125
Produced & Utilized Internally	852	300	1,700	0	0	80	0	0

Information compiled from SEC filings

Regional Trends in Crude Oil Production from CO_2 Enhanced Oil Recovery



- Estimate for 2013 is 292,000 bpb, 3.8 % of domestic production

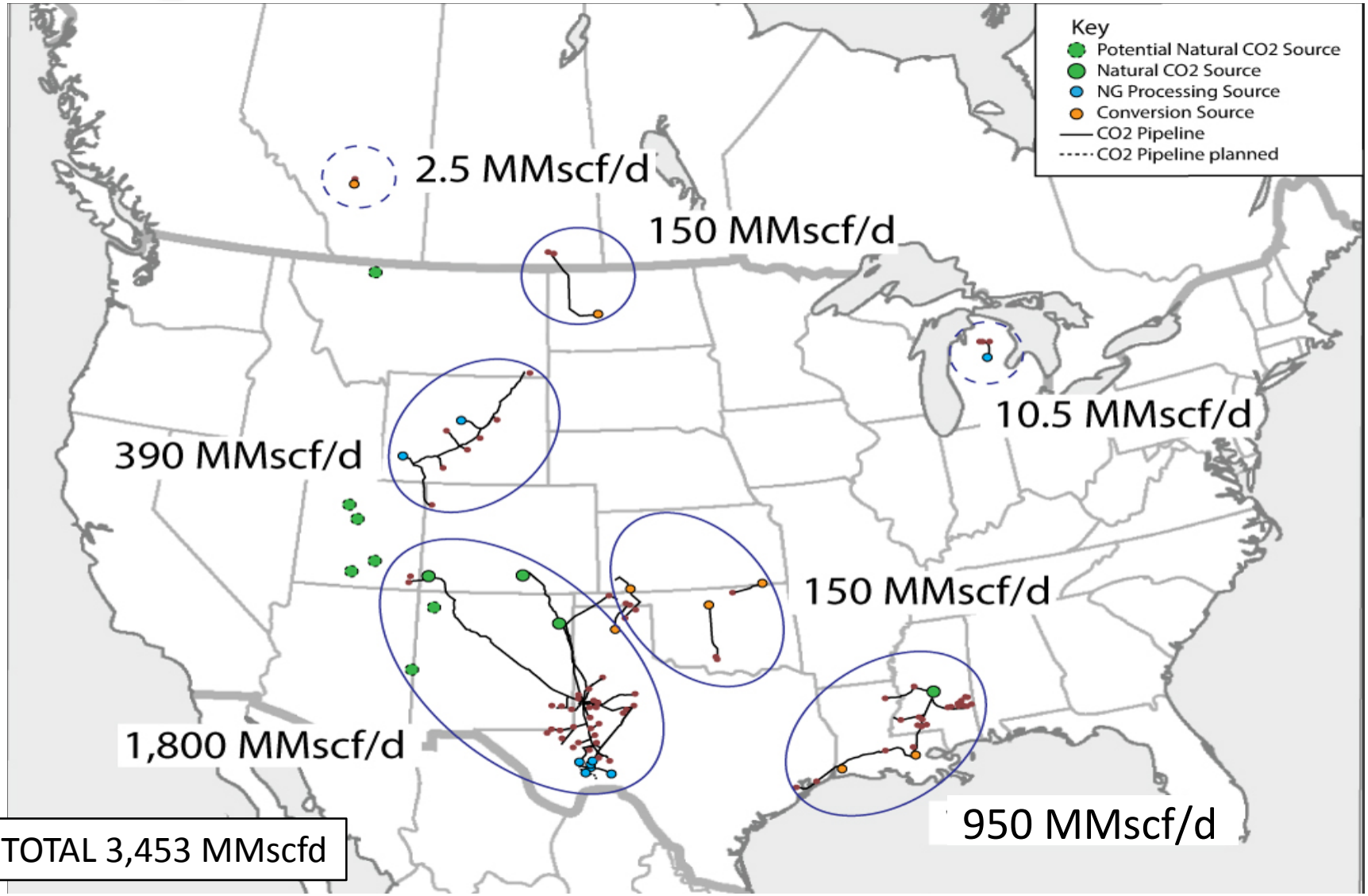
Between 2011 and 2013 production from tight oil grew by 2,170,000 bpd.

Source: Includes Advanced Resources Int'l. adjustments to Oil and Gas Journal EOR Survey, 2012.

May 17, 2012

Modified from Melzer 2012, Murrell 2013; 6th Wyoming Annual CO2 Conf; DiPietro et al., 2012, Denbury Resources Investor Report 12/2011; www.zero.no.

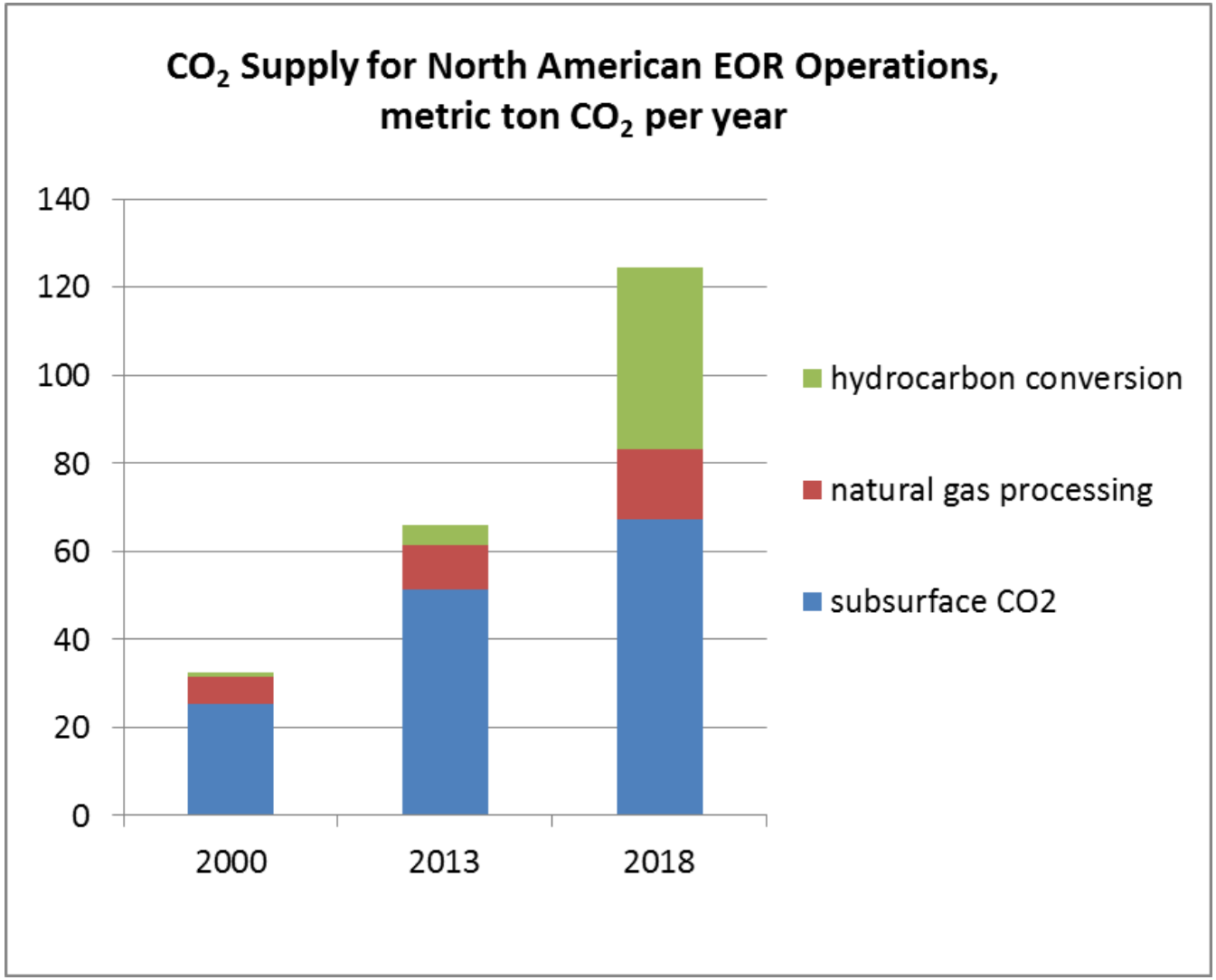
CO_2 EOR Supply in 2013



TOTAL 3,453 MMscfd

0.0193 mtCO_2 per year / MMscf/d

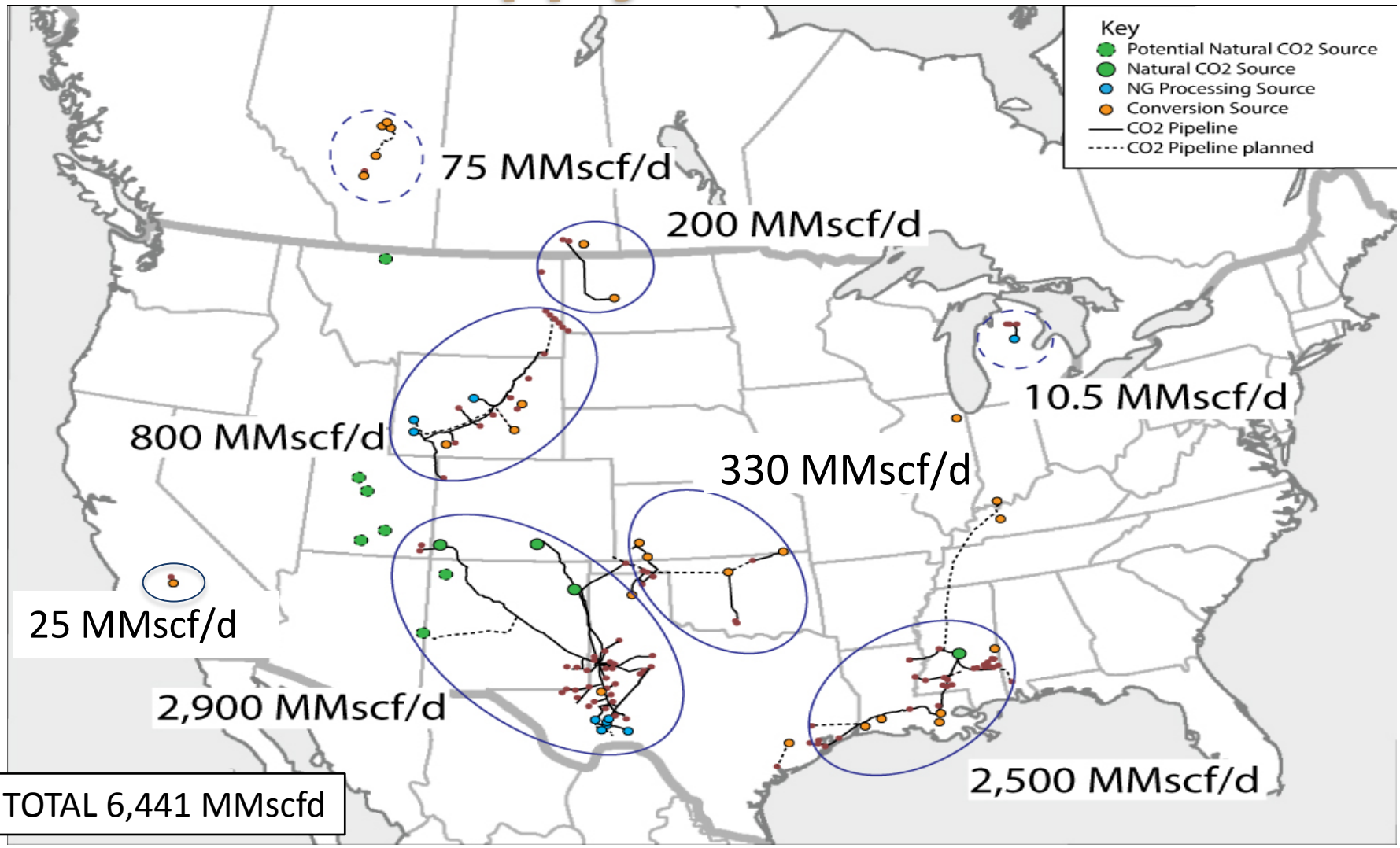
http://www.co2conference.net/wp-content/uploads/2013/12/2-Dipietro-CO2-Supply-2013_v7.pdf



http://www.co2conference.net/wp-content/uploads/2013/12/2-Dipietro-CO2-Supply-2013_v7.pdf
http://www.netl.doe.gov/research/energy-analysis/publications/details?pub=3f351674-9457-49d2-9034-78178131cd3e

Modified from Melzer 2012, Murrell 2013; 6th Wyoming Annual CO2 Conf; DiPietro et al., 2012, Denbury Resources Investor Report 12/2011; www.zero.no; Chaparral Report to Investors. 2012 .

CO2 EOR Supply in 2018?



TOTAL 6,441 MMscfd

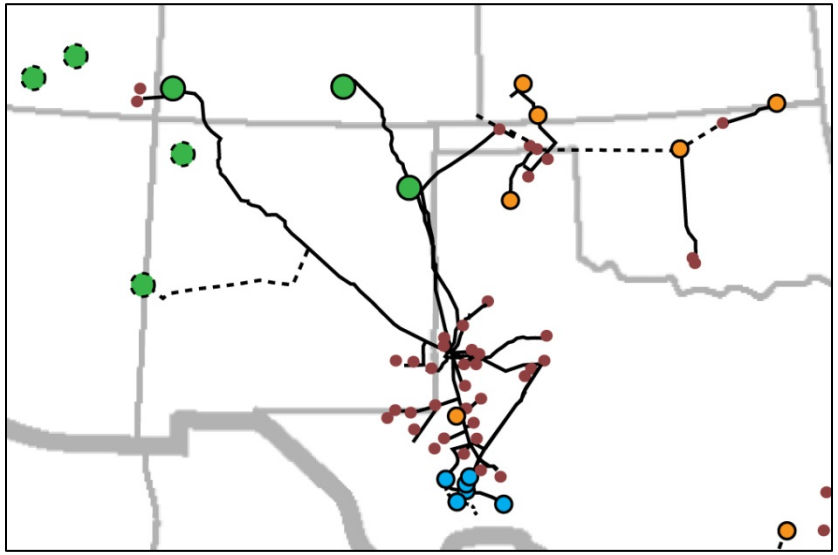
0.0193 $mtCO_2$ per year / MMscf/d

http://www.co2conference.net/wp-content/uploads/2013/12/2-Dipietro-CO2-Supply-2013_v7.pdf

Permian Basin

Incremental Supplies (2013 – 2018)

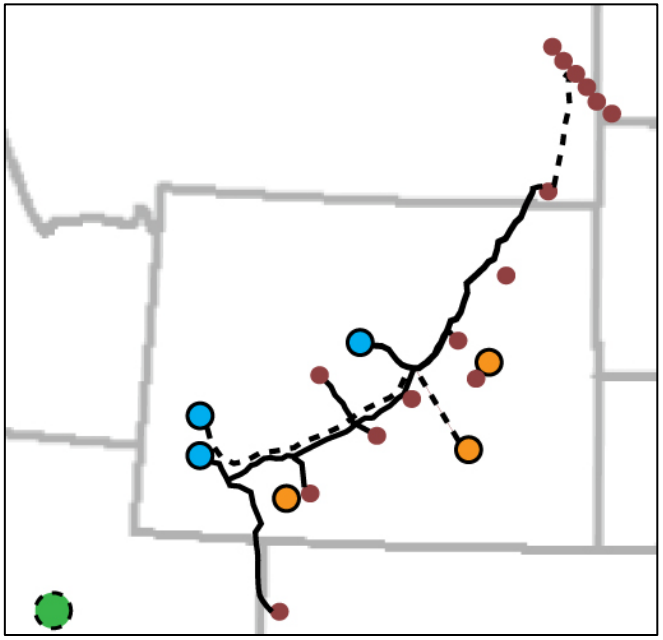
- Summit (140)
- St. Johns (200-450)
- McElmo (200)
- Bravo (80)
- Doe Canyon (65)
- Century (170)



	2013	*2018*
CO_2 Supply (MMscfd)	1,800	*2,900*
Crude oil Prodn (Mbpd)	196	*315*
CO_2 Utilization Eff (scf/bbl)	9,200	*9,200*

http://www.co2conference.net/wp-content/uploads/2013/12/2-Dipietro-CO2-Supply-2013_v7.pdf

Rocky Mountain



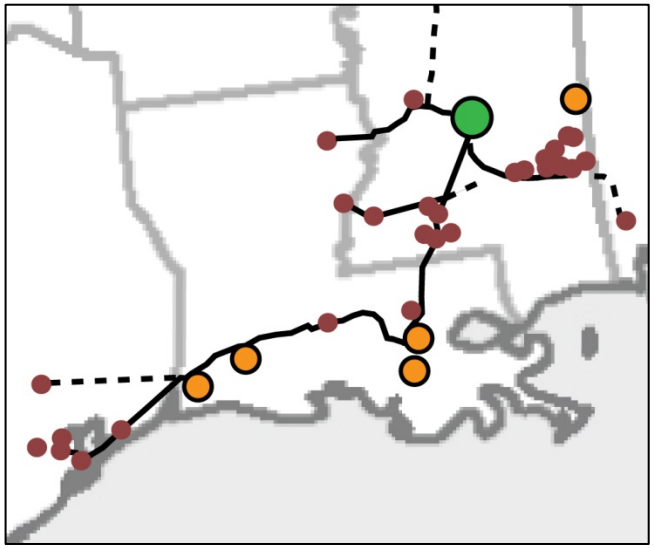
Incremental Supplies (2013 – 2018)

- LaBarge (130)
- Lost Cabin (30)
- CES (50)
- Linc/carbon energy (100)

	2013	*2018*
CO_2 Supply (MMscfd)	390	*700*
Crude oil Prodn (Mbpd)	44	*80*
CO_2 Utilization Eff (scf/bbl)	8,800	*8,800*

http://www.co2conference.net/wp-content/uploads/2013/12/2-Dipietro-CO2-Supply-2013_v7.pdf

Gulf Coast



	2013	*2018*
CO_2 Supply (MMscfd)	950*	*2,200*
Crude oil Prodn (Mbpd)	36.5	*110*
CO_2 Utilization Eff (scf/bbl)	26,000	*20,000*

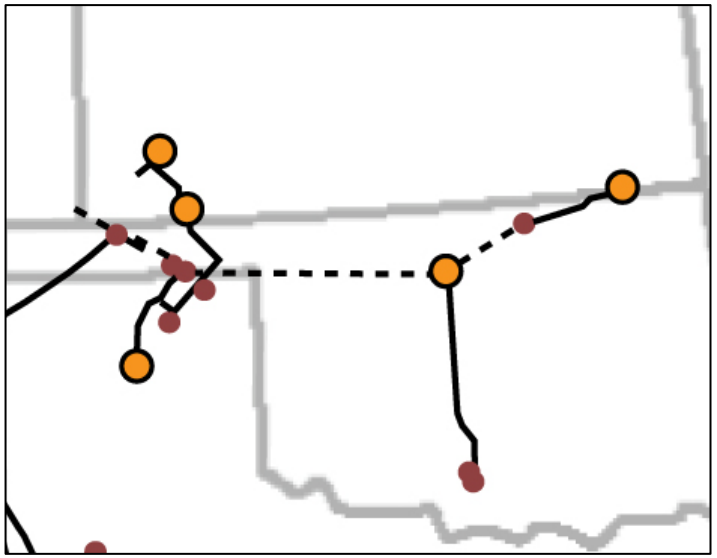
*supply for EOR only

Incremental Supplies (2013 – 2018)

- Jackson Dome (120)
- Mississippi Power (140)
- Lake Charles (200)
- Ammonia (85)
- NRG (85)
- Air Products (40)
- PCS Nitrogen (20)
- Leucadia (200)
- Other (355)

http://www.co2conference.net/wp-content/uploads/2013/12/2-Dipietro-CO2-Supply-2013_v7.pdf

Mid Continent



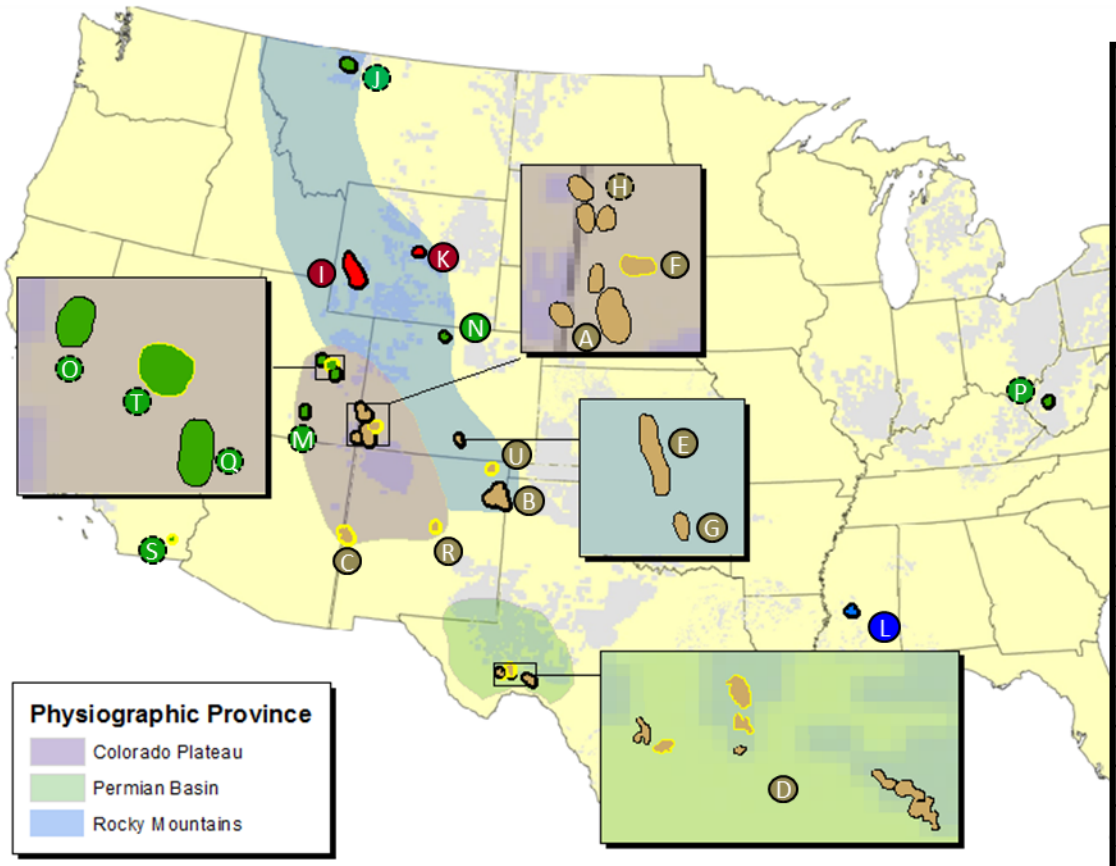
Incremental Supplies (2013 – 2018)

- Chaparral Burbank (100)
- Bravo Dome (35)
- Coffeyville (30)
- Enid, Borger, Garden City (15)

	2013	*2018*
CO_2 Supply (MMscfd)	150	*330*
Crude oil Prodn (Mbpd)	21	*47*
CO_2 Utilization Eff (scf/bbl)	7,100	*7,100*

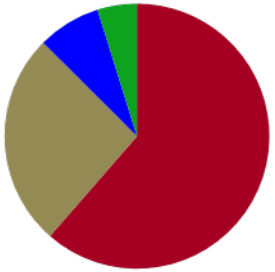
http://www.co2conference.net/wp-content/uploads/2013/12/2-Dipietro-CO2-Supply-2013_v7.pdf

Figure 2. Subsurface Sources of CO_2 in the United States

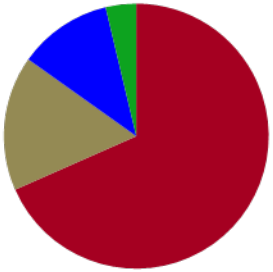


A. McElmo Dome
B. Bravo Dome
C. St. Johns/Springerville
D. Val Verde Basin
E. Sheep Mountain
F. Doe Canyon
G. Oakdale
H. Lisbon
I. Big Piney-Labarge
J. Kevin Dome
K. Madden
L. Jackson Dome
M. Escalante
N. McCallum
O. Gordon Creek
P. Indian Creek
Q. Woodside
R. Estancia
S. Imperial
T. Farnham Dome
U. Des Moines

TRR (169 TCF total)



net ERR (78 TCF total)



Discovered, producing

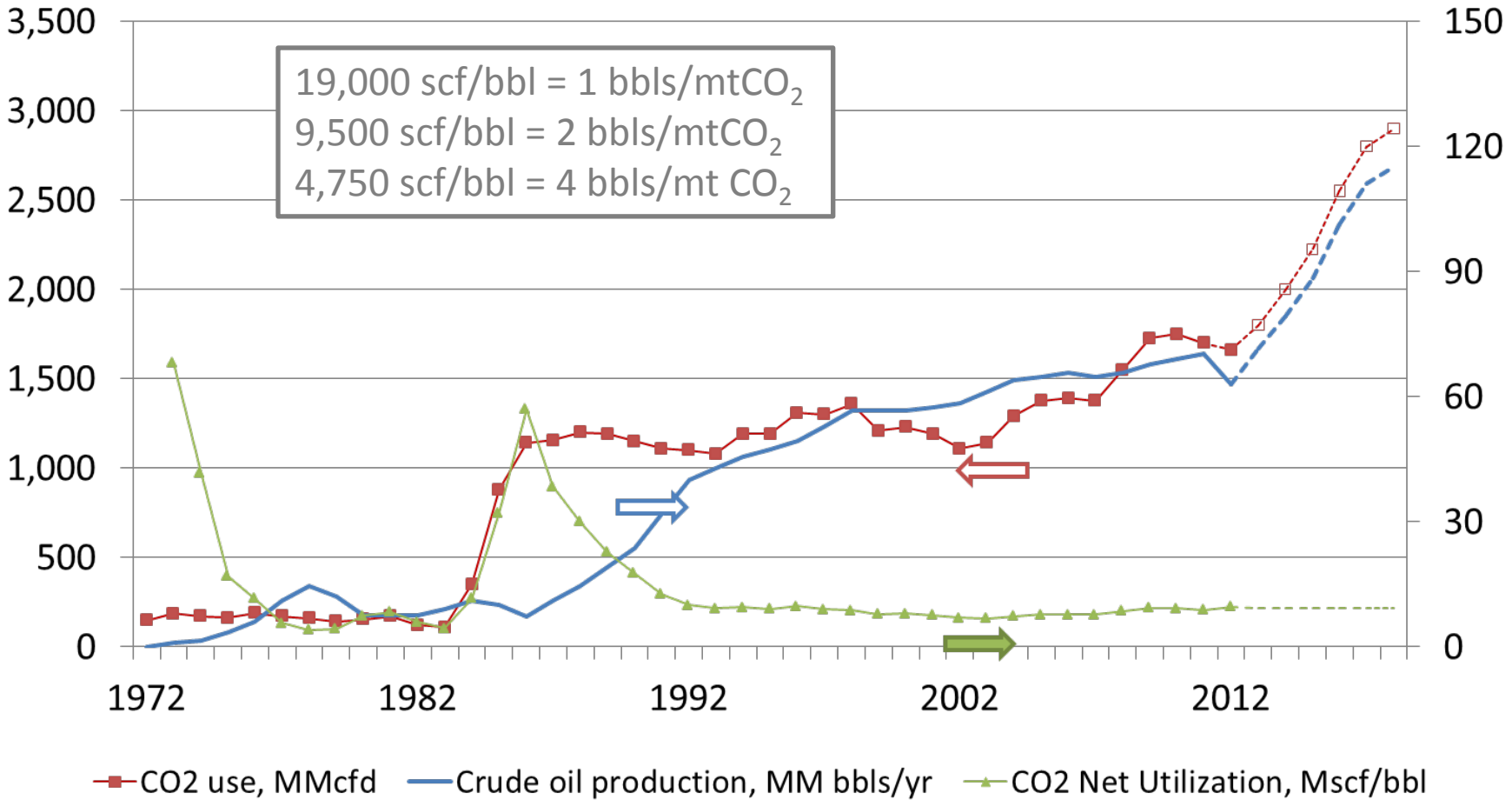
Discovered, not producing

CO_2 System that the Reservoir Feeds

- Permian Basin
- Rocky Mountain
- Gulf Coast
- Un-connected

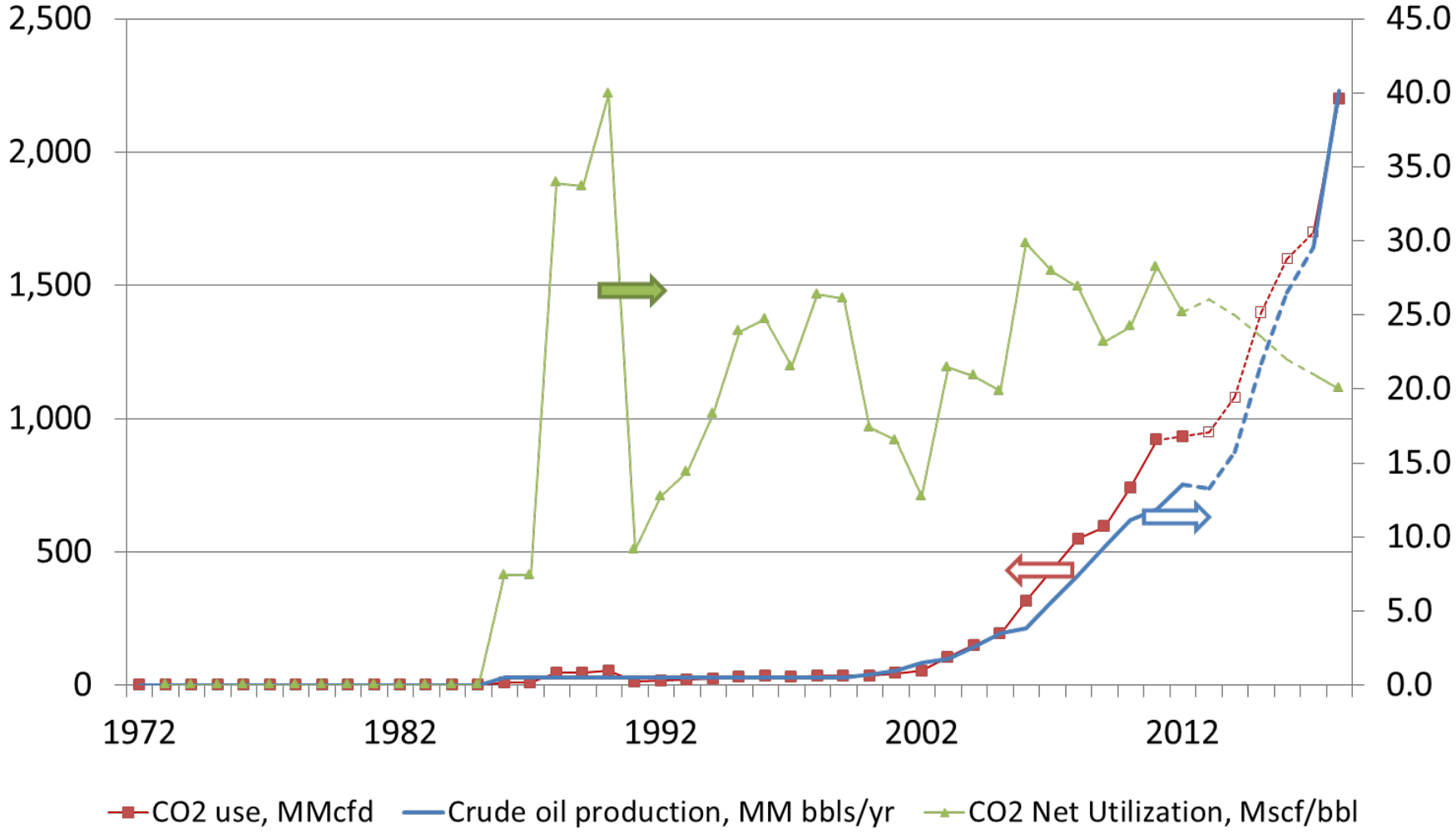
52.9 MMmtCO2 per TCF

Permian Basin CO2 EOR: CO2 sales, Crude oil Production, and CO2 net utilization



http://www.co2conference.net/wp-content/uploads/2013/12/2-Dipietro-CO2-Supply-2013_v7.pdf

Mississippi / Gulf Coast CO2 EOR: CO2 sales, Crude oil Production, and CO2 net utilization



http://www.co2conference.net/wp-content/uploads/2013/12/2-Dipietro-CO2-Supply-2013_v7.pdf

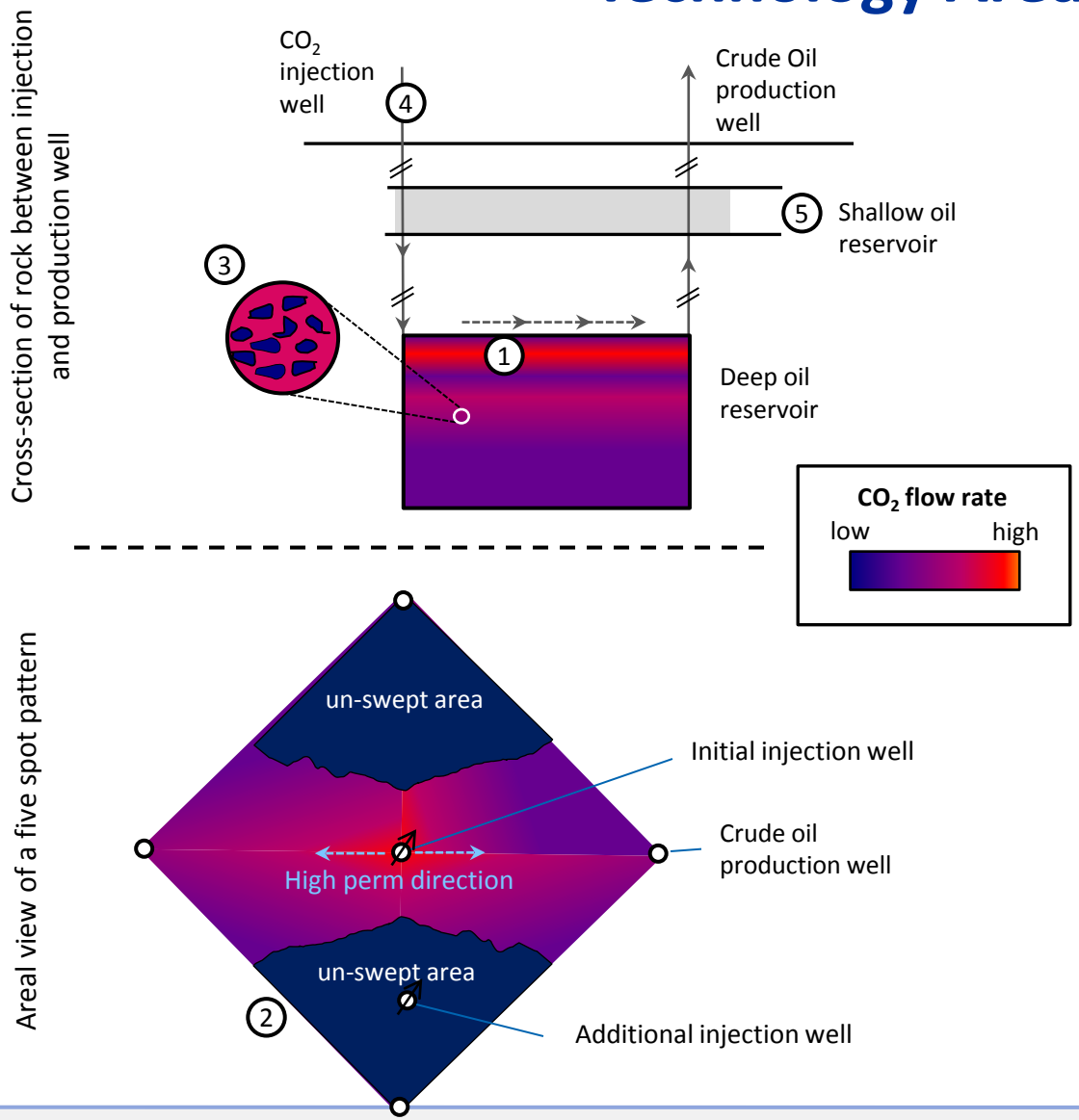
Next Generation CO_2 EOR Technology

- **Advanced CO_2 EOR technology can both**
  - improve the incremental recovery from ~18% original oil in place (OOIP) to 25% and
  - improve CO_2 utilization efficiency from 2 bbls/mtCO_2 to 3.9 bbls/mtCO_2 provide

- **Benefit: 2 - 4 MM barrels per day of domestic crude oil production for 50 years.**

- **Reference points:**
- **Current U.S. crude oil production rate: 7.7 million barrels per day**
- **Current CO_2 EOR production rate: 0.3 million barrels per day (60 MM metric tons CO_2 /yr)**

Next Generation CO_2 Enhanced Oil Recovery: Technology Areas



1. **Improved Conformance Control.** Reduce the unproductive channeling of CO_2 through high permeability reservoir flow paths
2. **Advanced Flood Design.** Target and produce the high oil saturation reservoir segments bypassed or poorly swept by the waterflood.
3. **Enhanced Mobility Ratio.** Reduce fingering, create a more uniform and effective flow front in swept areas.
4. **Increased volumes of efficiently-injected CO_2.** Improve sweep efficiency and reduce oil saturation toward the theoretical maximum.
5. **Near-miscible CO_2 EOR**. Apply CO_2 EOR in shallow reservoirs that are close to but not above minimum miscibility pressure (MMP).

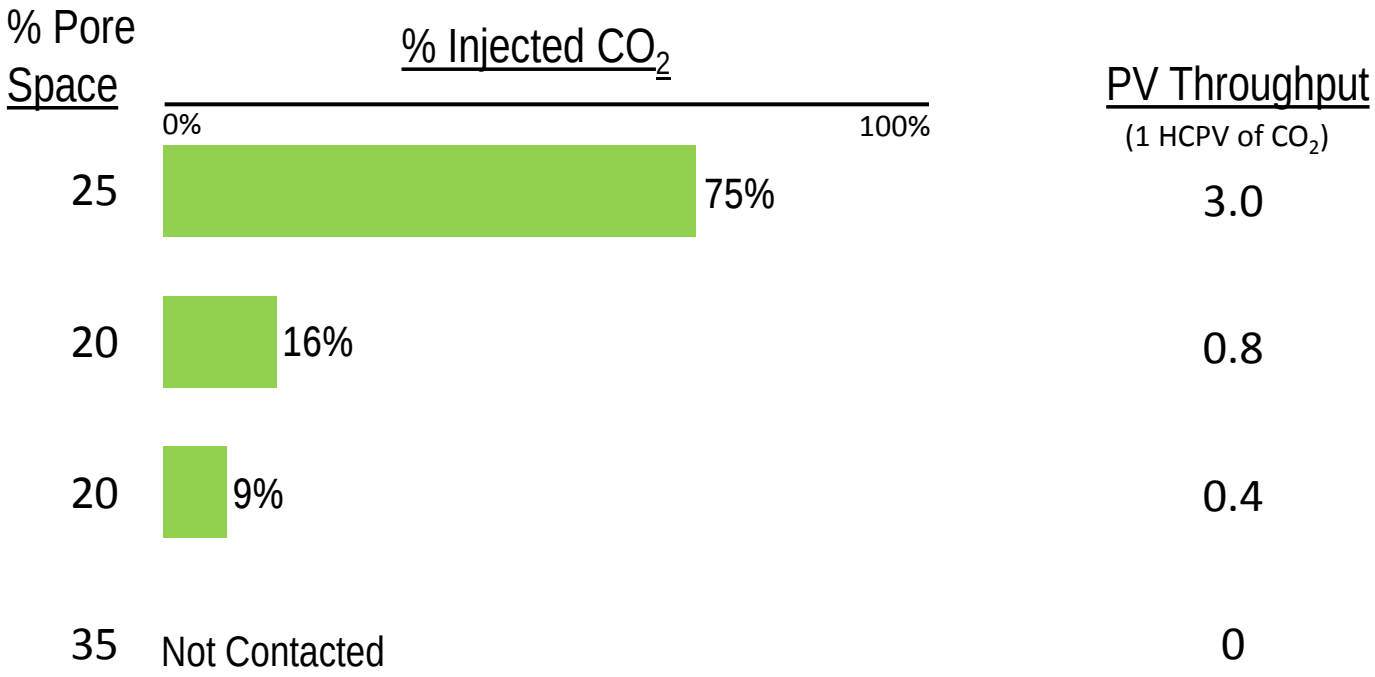
Also required for next generation CO_2 EOR are three enabling technology that cross-cut the primary technologies:

- **Robust reservoir characterization**
- **Enhanced fluid injectivity via near well completion**
- **Extensive monitoring, diagnostics and process control.**

http://www.netl.doe.gov/research/energy-analysis/publications/details?pub=84d08acd-e46f-409a-8f87-521ca9544cae

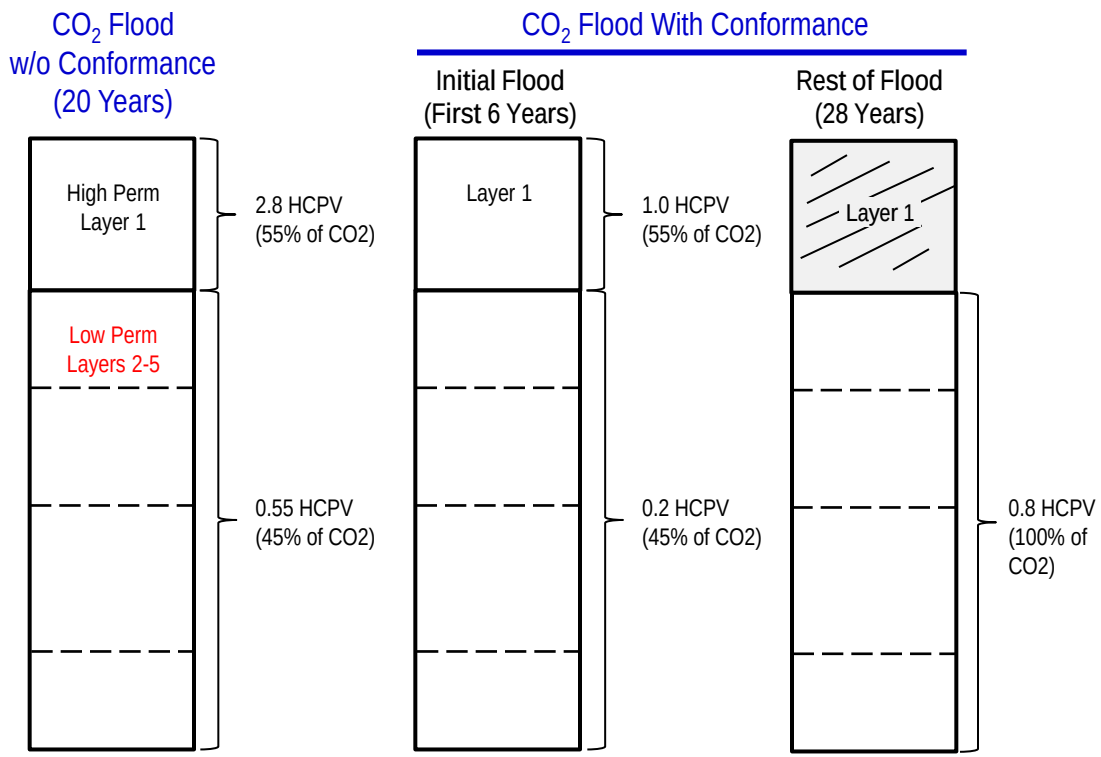
Reservoir Conformance Pilot at Wasson (Denver Unit) CO_2 Flood

Installation of reservoir surveillance at the Wasson (Denver Unit) CO_2 flood showed high CO_2 channeling through a small portion of the reservoir's pore space.



Source: Advanced Resources International

III.1. Application of Reservoir Conformance



- Example oil reservoir has a coarsening upward deposition; Dykstra-Parsons coefficient of 0.76.
- Objective is to efficiently flood as much as possible of the reservoir's heterogeneous pay with 1 HCPV (or 1.5 HCPV) of CO_2.
- Reservoir Conformance involves: (1) mapping reservoir flow paths; (2) remediating high permeability channels; and (3) monitoring flood performance.

http://www.netl.doe.gov/research/energy-analysis/publications/details?pub=84d08acd-e46f-409a-8f87-521ca9544cae

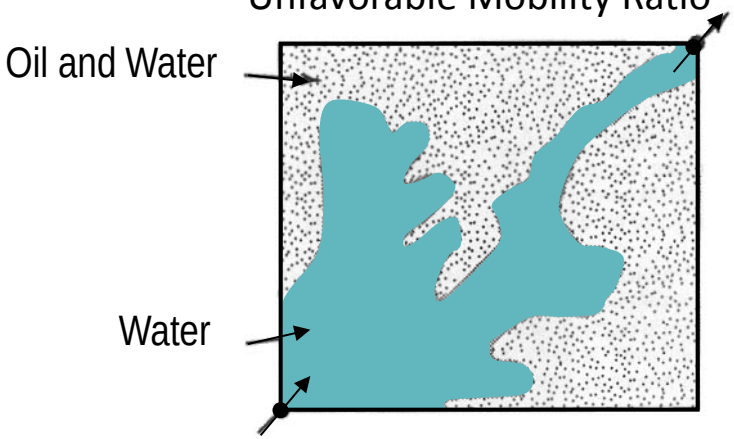
Modeling Enhanced Mobility Control

The viscosities of the injected fluids (CO_2 and water) are lower than the viscosity of the reservoir oil, leading to viscous fingering of the CO_2 through the reservoir's oil and thus inefficient sweep of the reservoir.

To model Technology #3, we raise the viscosity of the water (in the WAG process) to 2 cp. To counter the loss of fluid injectivity, Technology #3 also includes the Enabling Technology of "Enhanced Fluid Injectivity" to maintain water injectivity at SOA levels.

Example A

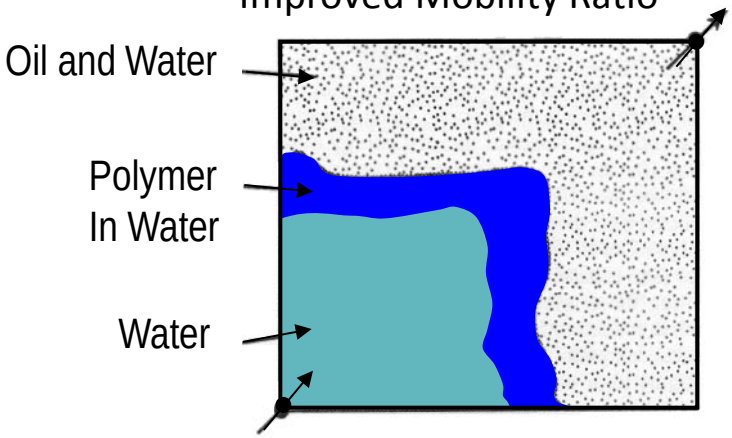
Unfavorable Mobility Ratio



Waterflood

Example B

Improved Mobility Ratio



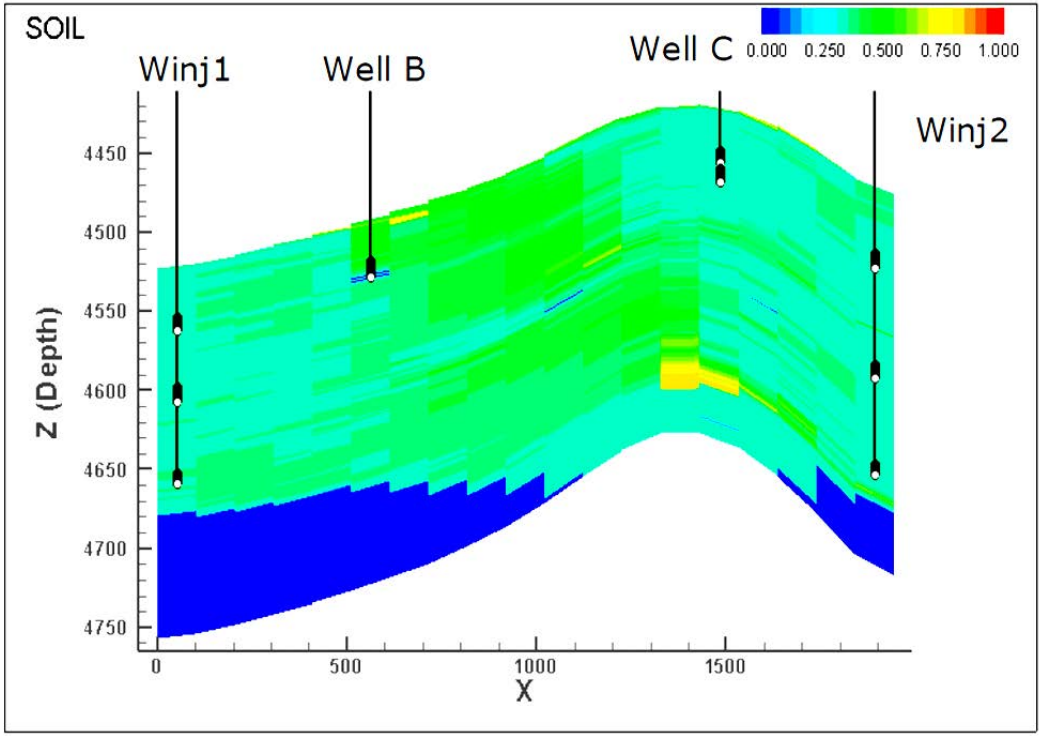
Viscosity Enhanced Flood

*Assuming equal relative permeability for oil and water.

Source: Adapted by Advanced Resources Int'l from "Enhanced Oil Recovery", D.W. Green and G. P. Willhite, SPE, 1998.

Mapping the Remaining Oil Saturation Distribution

Oil Saturation Distribution Prior to CO_2 Flood



Reservoir characterization is essential for mapping the location and richness of the remaining oil saturation prior to the CO_2 flood:

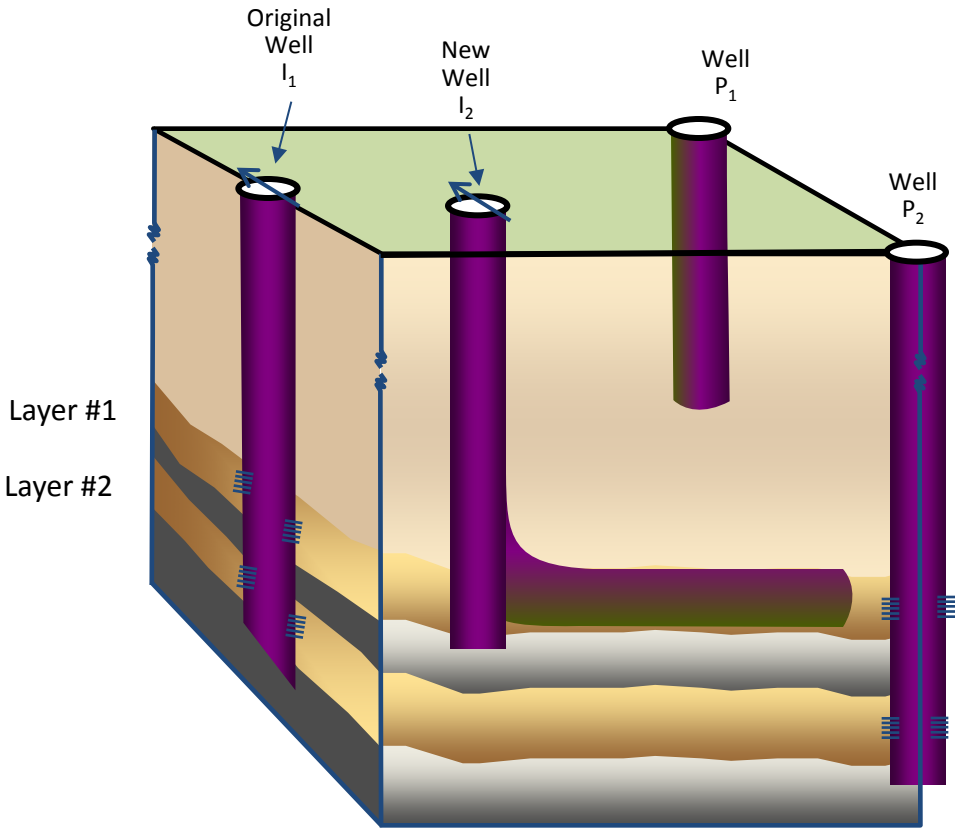
- Remaining oil saturations in reservoir intervals efficiently swept by waterflood are 25% to 35%.
- Remaining oil saturations in reservoir intervals poorly or unswept by waterflood can be over 50%.

The figure on the left, for the Reinecke oil field in West Texas, illustrates the use of detailed characterization to define the distribution of the remaining oil saturation in the reservoir.

Source: SPE 154181, Zhou, D., Yan, M., and Calvin, W.M., "Optimization of a Mature CO2 Flood – From Continuous Injection to WAG", prepared and presented at the Eighteenth SPE Improved Recovery Symposium, Tulsa, Oklahoma, USA, 14-18 April 2012.

Modeling Advanced CO_2 Flood Design

A second CO_2 injection well is used to flood low permeability Layer #1 (1/2 of 5 spot pattern).



A variety of advanced CO_2 flood and well placement designs can be used to contact more of the oil left behind after a water flood.

- The example on the left illustrates the placement of a short-lateral horizontal CO_2 injection well to target the high remaining oil saturation (Sor = 50%) Layer #1.
- Alternative flood designs can also include converting an inverted 5 spot pattern to a line drive CO_2 flood, infill drilling and/or use of horizontal production wells.

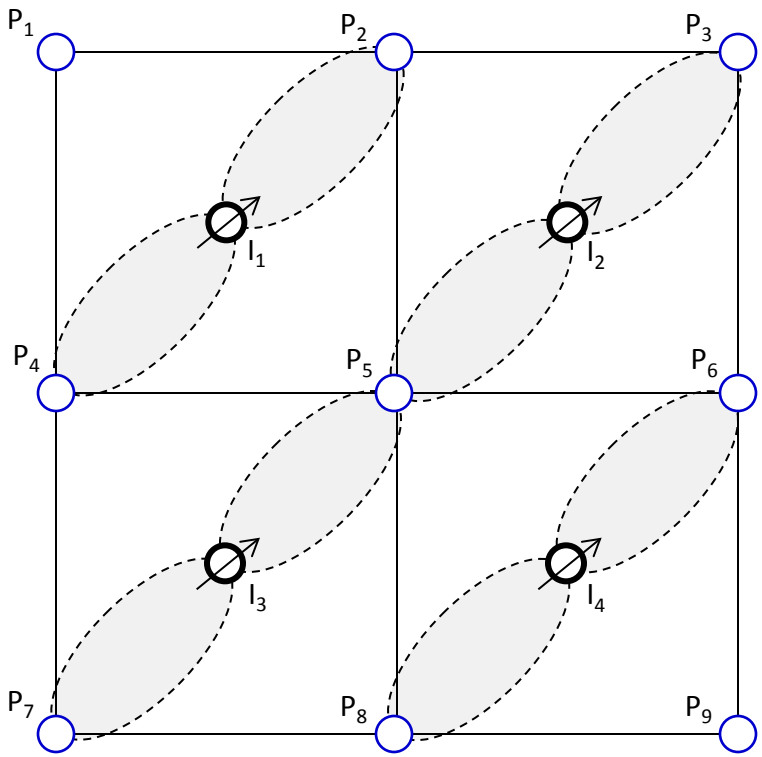
A robust program of reservoir "surveillance" is essential for determining how efficiently the advanced CO_2 flood design contacts the oil reservoir.

Source: Advanced Resources International, Inc., 2013

Pattern Realignment

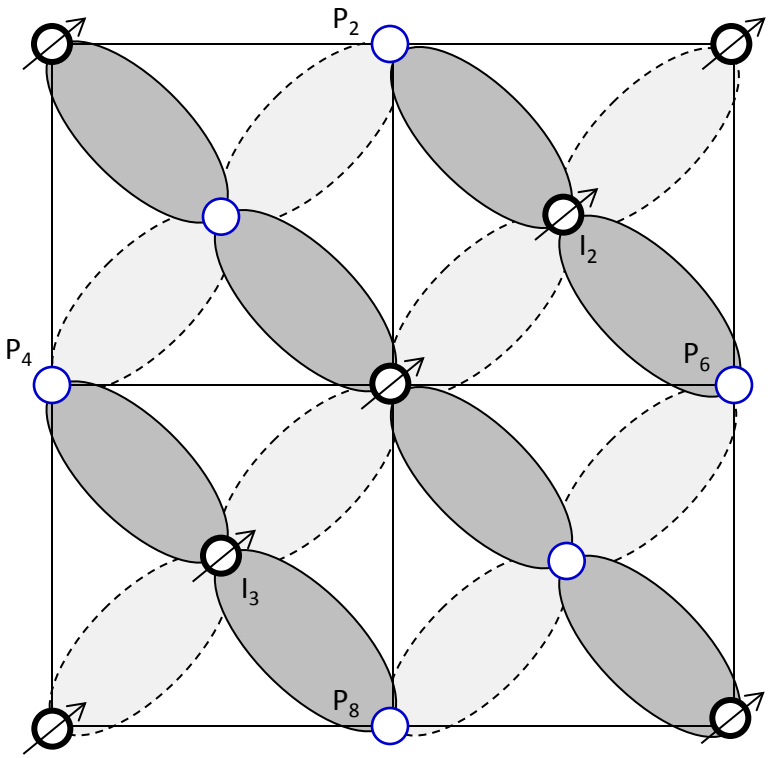
Pattern realignment can help contact additional reservoir volume in high permeability anisotropy settings.

Original Pattern
(4 Injectors, 9 Producers)



Direction of permeability anisotropy

Pattern Realignment
(7 Injectors, 6 Producers)

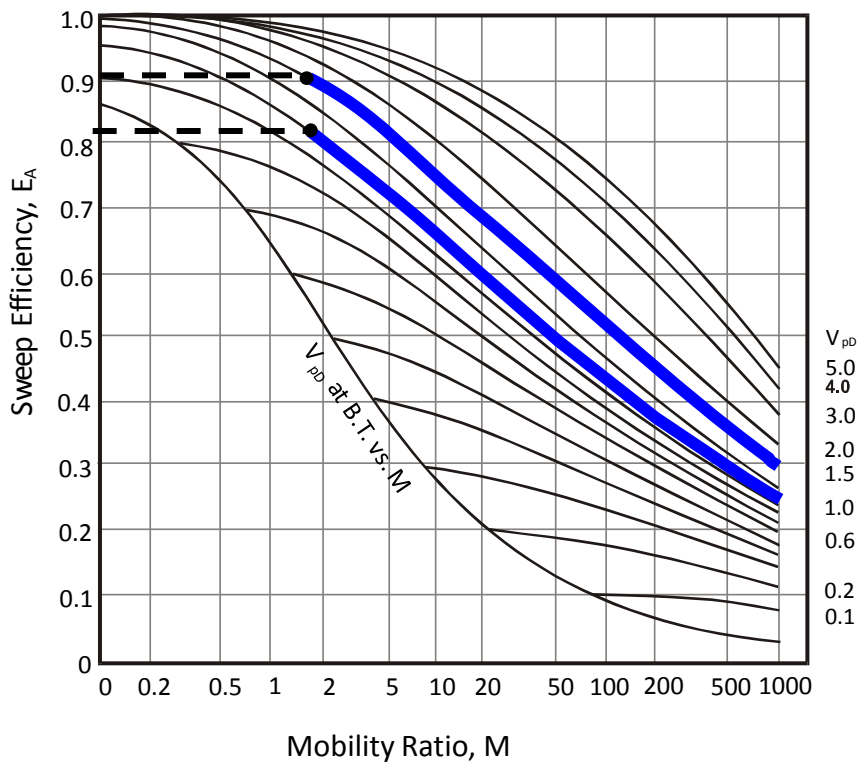


- Convert P1, P3, P7, and P9 to CO_2 injectors
- Convert I1 and I4 to oil producers

Source: Advanced Resources International, Inc., 2013

Increased Sweep Efficiency

Areal Sweep Efficiency in Miscible CO_2 Flooding as a Function of HCPV CO_2



Note: V_{pD} is hydrocarbon pore volumes of injected CO_2.

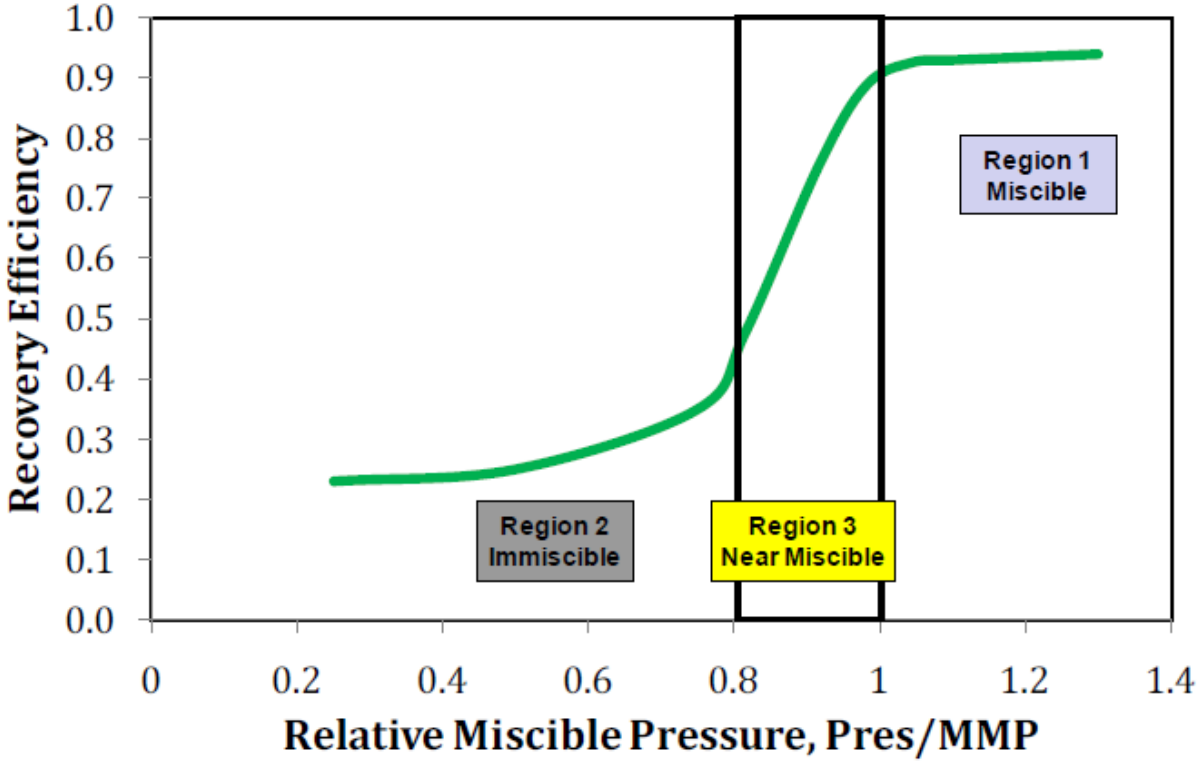
Higher HCPVs of injected CO_2 enable more of the reservoir's residual oil to be contacted and displaced by the injected CO_2.

Increasing the volume of CO_2 injected (VpD), from 1.0 HCPV to 1.5 HCPV, should improve the areal sweep efficiency from about 82% to about 92% for a 1.43 mobility ratio WAG flood.

Source: Claridge, E.L., "Prediction of Recovery in Unstable Miscible Displacement", (J)SPE 12(2) 143-155 (April 1972).

Technology #5: Near-Miscible CO_2-EOR

As reservoir pressure enters the near-miscible range (0.8 to 0.95 of MMP), the vaporization of light hydrocarbon components from the crude oil into the CO_2 vapor phase begins, the mixing of CO_2 and oil phases progresses, and the interfacial tension (IFT) of the system is lowered, all contributing to improved oil recovery efficiency.



Source: Ly Huong Bui, Near-Miscible CO_2 Application to Improve Oil Recovery, Submitted to the graduate degree program in Chemical and Petroleum Engineering and the Graduate Faculty of the University of Kansas in partial fulfillment of the requirement for the degree of Master of Science.

Near-Miscible CO_2-EOR

To model near-miscible reservoirs using PROPHET2, Sorm (residual oil saturation to CO_2) values are set for each field, using reservoir pressure as a percent of MMP.

Using University of Kansas near-miscible studies and near-miscible PROPHET2 test runs, Sorm values range from 0.25 for fields with reservoir pressure at 80% of MMP, to 0.1 for reservoir pressure at 100% of MMP (miscible).

Reservoir Pressure (% MMP)	Sorm
80%	0.25
85%	0.25
90%	0.20
95%	0.15
100%	0.10

Of the 77 near-miscible candidate reservoirs:

- 32 have reservoir pressure of 80% to 89% of MMP.
- 23 have reservoir pressure of 90% to 94% of MMP.
- 22 have reservoir pressure of 95%+ of MMP.

http://www.netl.doe.gov/research/energy-analysis/publications/details?pub=84d08acd-e46f-409a-8f87-521ca9544cae

Enabling Technology #1: Robust Reservoir Characterization

Reservoir characterization is essential for ensuring that the reservoir and CO_2 flood design engineers have sound data on the flow patterns, heterogeneity, and oil saturation distribution in the reservoir by:

- Mapping the remaining oil saturation to ensure that well placement and CO_2 injected are optimized to contact the reservoir's mobile and residual oil.
- Developing a rigorous understanding of areal and vertical reservoir heterogeneity to ensure that the increased volumes of injected CO_2 contact additional reservoir volume and do not merely circulate through high permeability reservoir intervals or directions.

Robust reservoir characterization is an essential Enabling Technology for Technologies #1 (Improving Reservoir Conformance) and #2 (Advanced CO_2 Flood Design).

http://www.netl.doe.gov/research/energy-analysis/publications/details?pub=84d08acd-e46f-409a-8f87-521ca9544cae

Enabling Technology #2: Enhanced Fluid Injectivity

A small, "tip screen-out" near-wellbore type of hydraulic stimulation can provide enhanced CO_2 and water injectivity, particularly when using higher viscosity injection fluids.

We calculated that a small hydraulic fracture, with a wing length (x_f) of 15 feet (wellbore skin of about -3) is sufficient, to raise injectivity by a factor of 1.5 to 2.

$$X_f = 2r_{ws}$$

$$r_{ws} = r_w\,(e^{-s})$$

$$-\,l_n\,(r_{ws}/r_w) = s$$

Where: $r_w = 0.33$ feet

$$X_f = 15 \text{ feet}$$

$$r_{ws} = 7.5 \text{ feet}$$

$$S = -3$$

http://www.netl.doe.gov/research/energy-analysis/publications/details?pub=84d08acd-e46f-409a-8f87-521ca9544cae

Enabling Technology #3: Monitoring, Diagnostics and Process Control

Enhanced CO_2 flood monitoring, diagnostics and process control ("reservoir surveillance") are essential for ensuring that field operators gain process performance data from within the reservoir (and not just from the producing wells). Monitoring and control systems:

- Enable tracking the location and stability of CO_2 flood front to assess the performance of reservoir conformance and mobility control technologies.
- Provide real-time information that increased injected CO_2 contacts additional reservoir volume and does not merely circulate through already swept reservoir intervals.

Monitoring, diagnostics and process control are an essential Enabling Technology for Technologies #1 (Improved Reservoir Conformance), #2 (Advanced CO_2 Flood Design), and #4 (Increased Volumes of Efficiently Used CO_2).

http://www.netl.doe.gov/research/energy-analysis/publications/details?pub=84d08acd-e46f-409a-8f87-521ca9544cae

Implementing "Next Generation" CO_2-EOR in the "Representative" Oil Field/Reservoirs

Implementing "Next Generation" CO_2-EOR Technology is not "free".

Significant additional capital investment, CO_2 purchase and recycle costs and higher O&M costs from more rigorous reservoir characterization and CO_2 flood.

Monitoring/management significantly increase total project costs.

Compared to $2,406 million under "Current Technology" the "Next Generation" CO_2 flood costs of $4,647 million.

	Current Technology	Integrated Application of Next Generation Technology
CAPEX Total ($M)	$ (361,293)	$ (677,769)
Total CO2 Costs ($M)	$ (1,676,753)	$ (2,743,723)
O&M Total ($M)	$ (368,296)	$ (1,225,102)
Total Project Costs ($M)	$ (2,406,342)	$ (4,646,594)

http://www.netl.doe.gov/research/energy-analysis/publications/details?pub=84d08acd-e46f-409a-8f87-521ca9544cae

CO_2 EOR in the Offshore Gulf of Mexico

Figure 2. Location of Fields Amenable to CO2 EOR in the Deep Gulf of Mexico

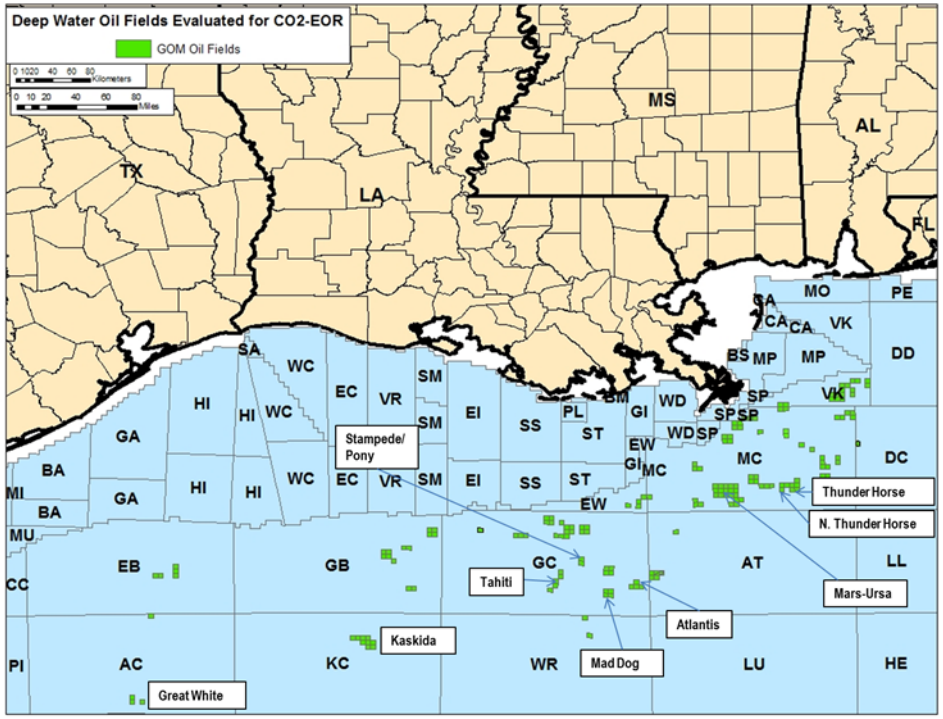
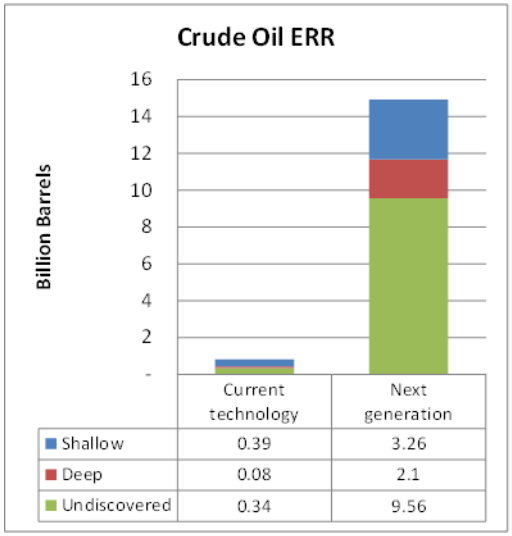


Table 3. Technically and Economically Recoverable Resource for CO_2 EOR in the Offshore Gulf of Mexico				
	Technical		Economic	
	Current	Next Gen	Current	Next Gen
Crude Oil Resource, Bbbls	23.5	52.9	0.8	14.9
CO_2 Demand, Tcf	235	285	5.8	73.9
Average CO_2 Use (scf/bbl)	10,000	5,400	7,200	5,000



http://www.netl.doe.gov/research/energy-analysis/publications/details?pub=e185884c-2423-47bb-a295-23614b4df5d3

Residual Oil Zone "Fairways"

Research Sponsored by
The Research Partnership to Secure Energy for America

16 November 25, 2013 JAF2013_072.PPT

The ROZ "Fairway Prize"

The Permian Basin ROZ "Fairway" map was prepared by Steve Melzer.

Our "quick look" indicates that ROZ "fairways" cover an area at least three times larger than the area covered by the 55 Permian Basin oil fields with below main pay zone ROZ resources.

However, additional work is required to establish the size, recoverability, economic feasibility and CO_2 requirements of producing ROZ "Fairway" resources with EOR.

http://www.co2conference.net/wp-content/uploads/2014/01/1-Kuuskraa_Midland_EOR_12_13.pdf

CO_2 EOR Resource

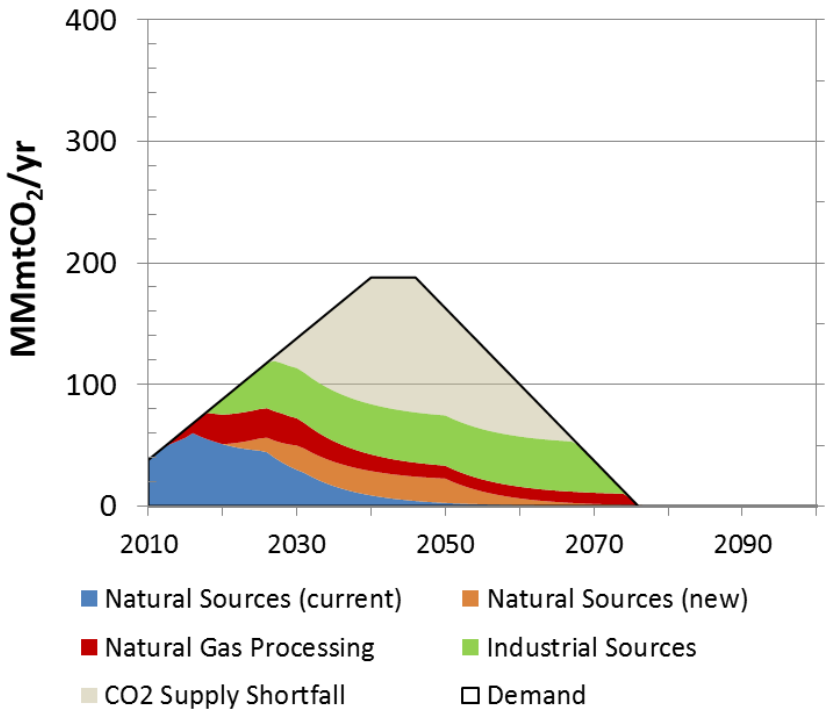
	# reservoirs	Oil, Bbbls	CO_2, BmtCO_2
Conventional onshore economic	458	19.0	7.5
Offshore GOM economic	18	0.8	0.3
Alaska economic	14	5.1	3.1
Conventional onshore economic Next Gen	490	40.6	7.7
Offshore GOM economic Next Gen	63	14.1	3.6
Alaska economic Next Gen	9	5.8	1.3
Residual Oil Zones, technical (Permian, Big Horn and Williston)	88	16.3	7.0
Fair way ROZ	?	?	?
Tight oil	?	?	?
Advanced Technology / non-conventional target sub total	682	82.7	23.0
Total	**1,140**	**102**	**30**

Adapted from *http://www.co2conference.net/wp-content/uploads/2014/01/1-Kuuskraa_Midland_EOR_12_13.pdf*

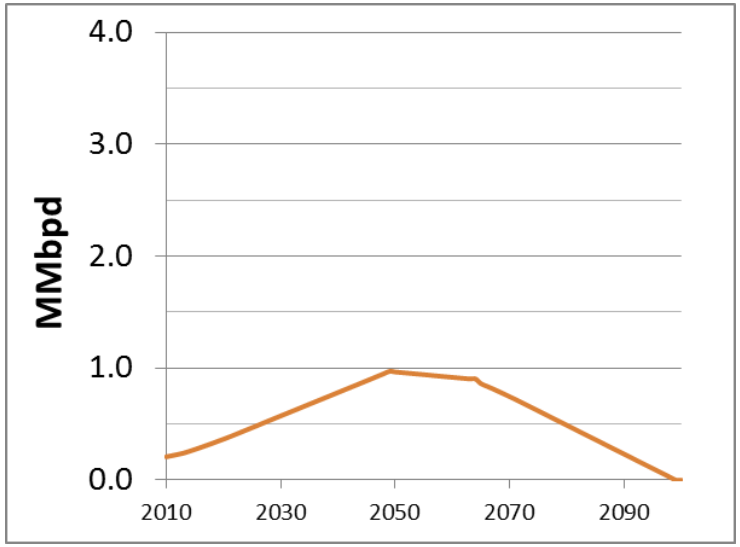
CO_2 EOR Deployment Scenario

Current Technology (19 Bbbls, 7.4 BmtCO_2)

CO_2 Demand/Supply

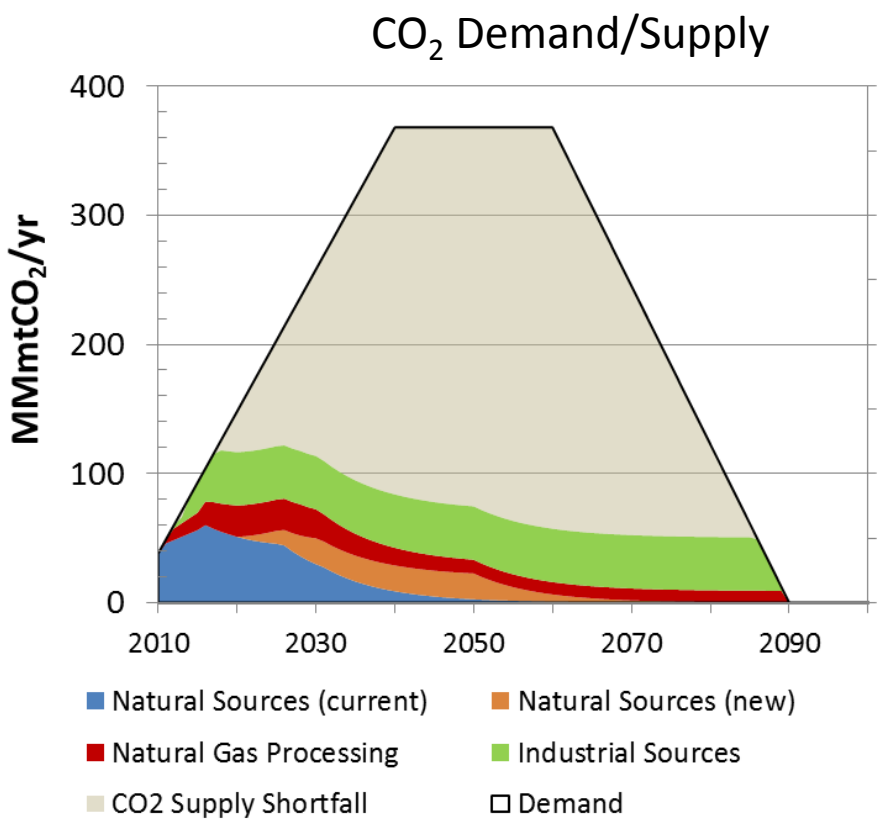


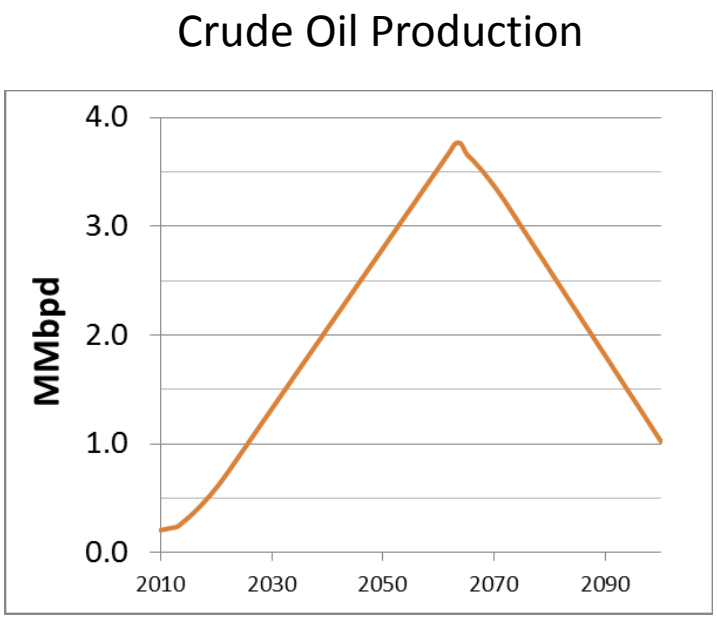
Crude Oil Production



CO_2 EOR Deployment Scenario

Next Generation Technology (69 Bbbls, 19 BmtCO_2)





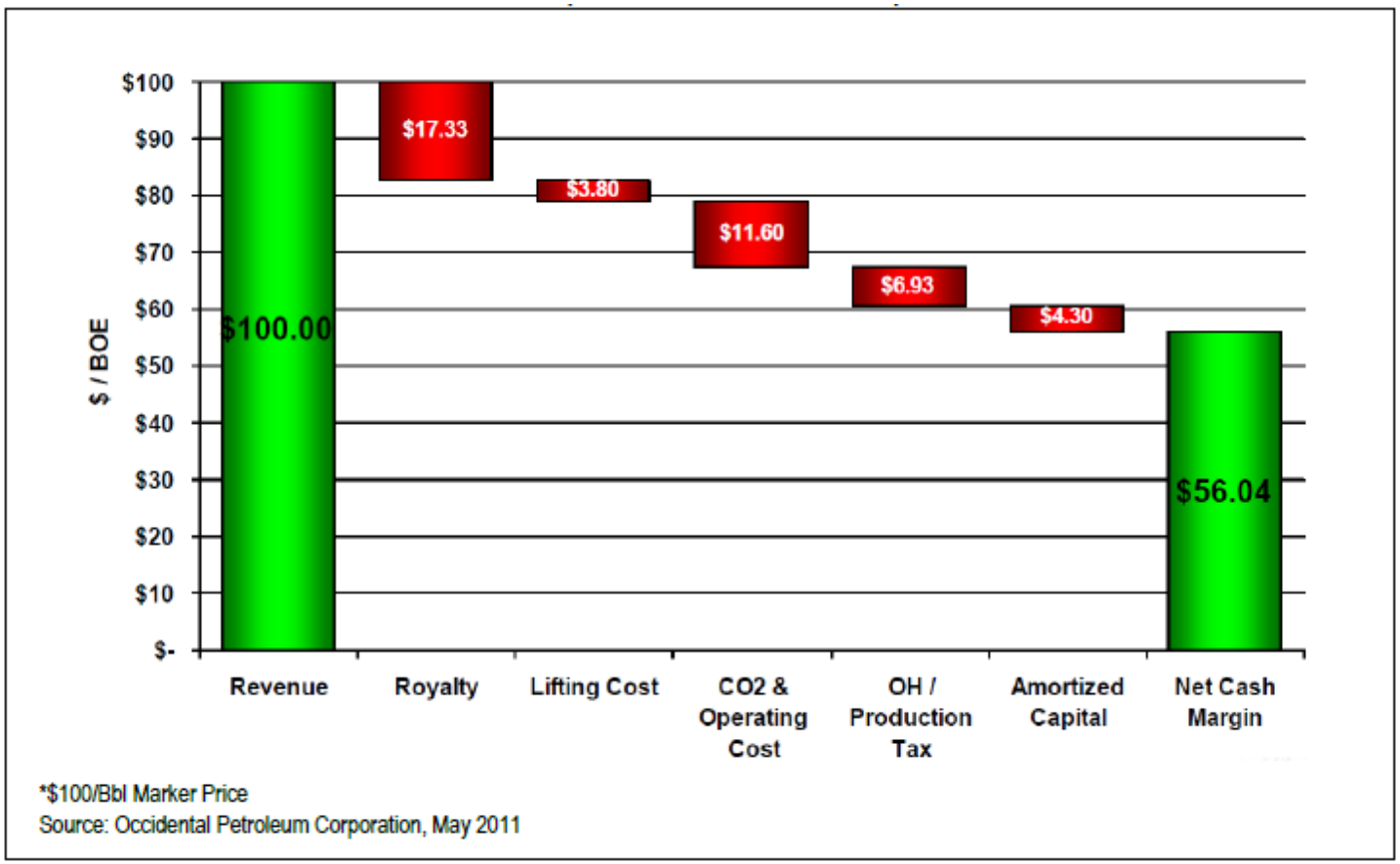
Thank you!

Joseph.dipietro@netl.doe.gov

CO_2 Price

- **CO_2 transferred by bi-lateral contracts (private)**
- **Varying degrees of complexity, typically have a floor with an adder tied to crude oil market price**
- **Rule of thumb is 2-3 % of the crude oil price**
  - $90/bbl * 2.0% = 2.25 $/mcf = 34 $/mt CO_2
  - Sustained high crude oil prices and progress up the supply curve is driving upward pressure on the % of crude oil heuristic.
- **Approaches to avoid bi-lateral monopoly issues**
  - Equity stakes, profit sharing
  - Onsite CO_2 generation

Typical Permian Basin CO_2 EOR Project Cost Structure (Occidental Petroleum)



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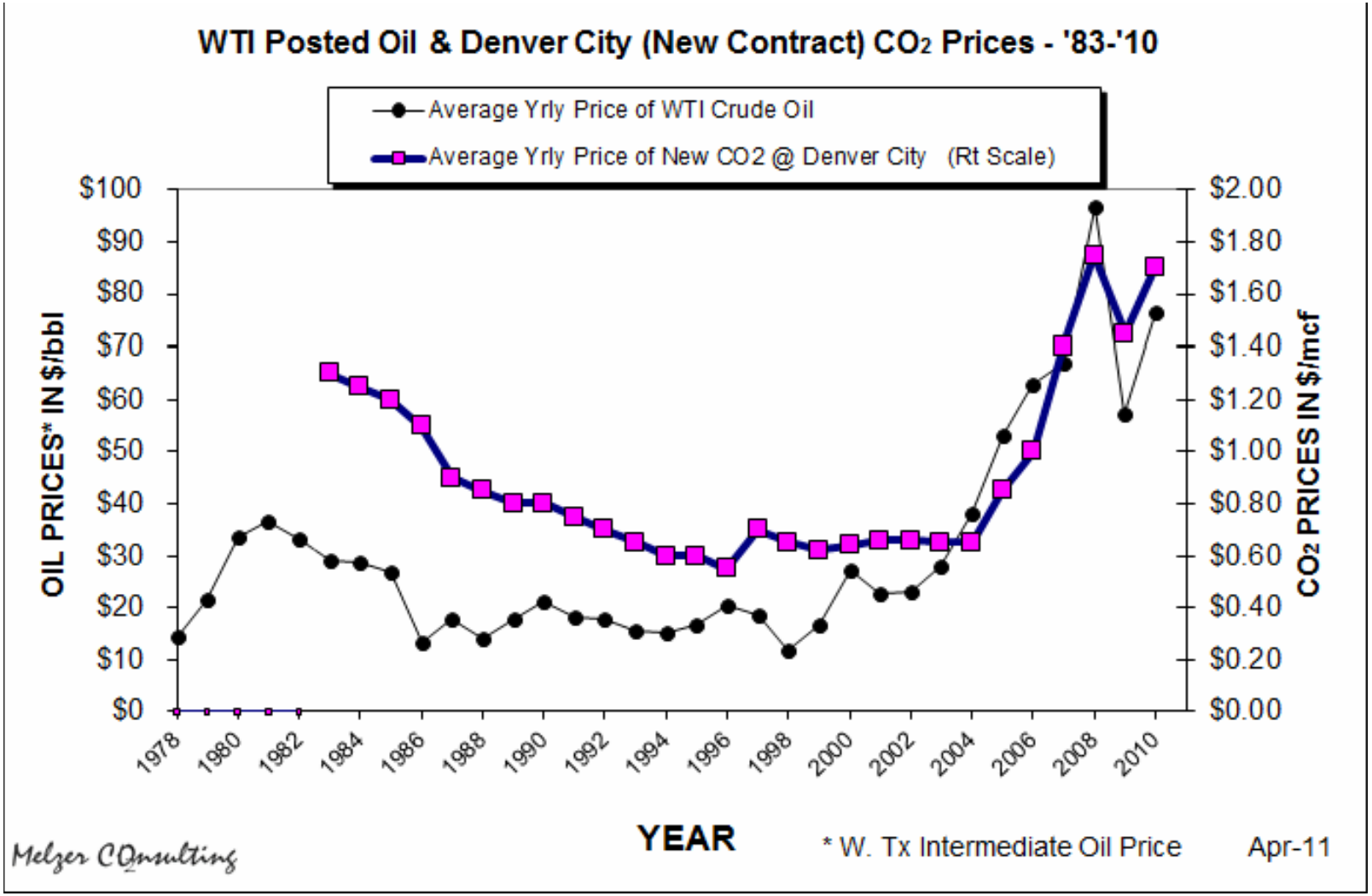
Source: NETL 2011 http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=391



http://www.co2conference.net/wp-content/uploads/2012/12/1.1-Moore_CMWorkshop_Summary2011-CO2FloodingConf.pdf